西伯利亚克拉通寒武纪沉积史:碳酸盐台地和盆地的演化

Sergei S. Sukhov
(俄罗斯西伯利亚地质、地球物理和矿产调查研究所)

[内容提要] 西伯利亚克拉通或古西伯利亚台地,其面积4000000km² 以上,是亚洲北部最主要的大陆地块之一。它以寒武系分布区域极为广泛、层序非常完整为特色。寒武系构成了遍及全区的下沉积盖层和出露在大的正向构造内。寒武纪时,研究区是重要的碳酸盐沉积区,有碳酸盐-硅质碎屑的混合沉积、蒸发盐、礁和深水盆地的碳酸盐沉积。半个多世纪来,区内进行了各种大型的旨在找烃的地质调查及有关的寒武系层理、古地理和古构造的重建,以及沉积环境的重塑。但关于沉积物内部构造的研究工作一直主要是根据传统地层学的"连续地层柱"概念。

有些工作者认为,古深度和地貌史或排列的各式各样的恢复不强调瞬时。只有最近10—15年,地下调查配合成因地层学和盆地分析概念的发展,使得有可能将生物群演化、沉积体边界的形状和类型以及它们的成因和对各种因素(诸如以上所述各种及相对海平面变化之类)的影响综合为统一的系统。这种区域继承观点的研究方法在60年代后期由Grachevsky(1969)提出,然后由Savistky(1979)和Astashkiu(1984)详尽阐述,其目的是重建西伯利亚克拉通盆地充填和发展中的动力学。

CAMBRIAN DEPOSITIONAL HISTORY OF THE SIBERIAN CRATON: EVOLUTION OF THE CARBONATE PLATFORMS AND BASINS

Sergei S. Sukhov
Siberian Research Institute of Geology, Geophysics and Mineral Resources (SNIIGG&MS), Krasny Pr., 67, 630104, Novosibirsk, Russia

The Siberian craton or the ancient Siberian Platform covering more than 4 million sq km is one of the major continental blocks in Northern Asia. It is marked by the extremely wide areal extent and the complete Cambrian sequence. The Cambrian appears to compose ubiquitously the lower sedimentary cover and be exposed within large positive structures. (Fig. 1). In Cambrian this region was an area of dominant carbonate deposition ranging from mixed carbonate-siliciclastic and evaporitic to reefal and deep basin ones. Various

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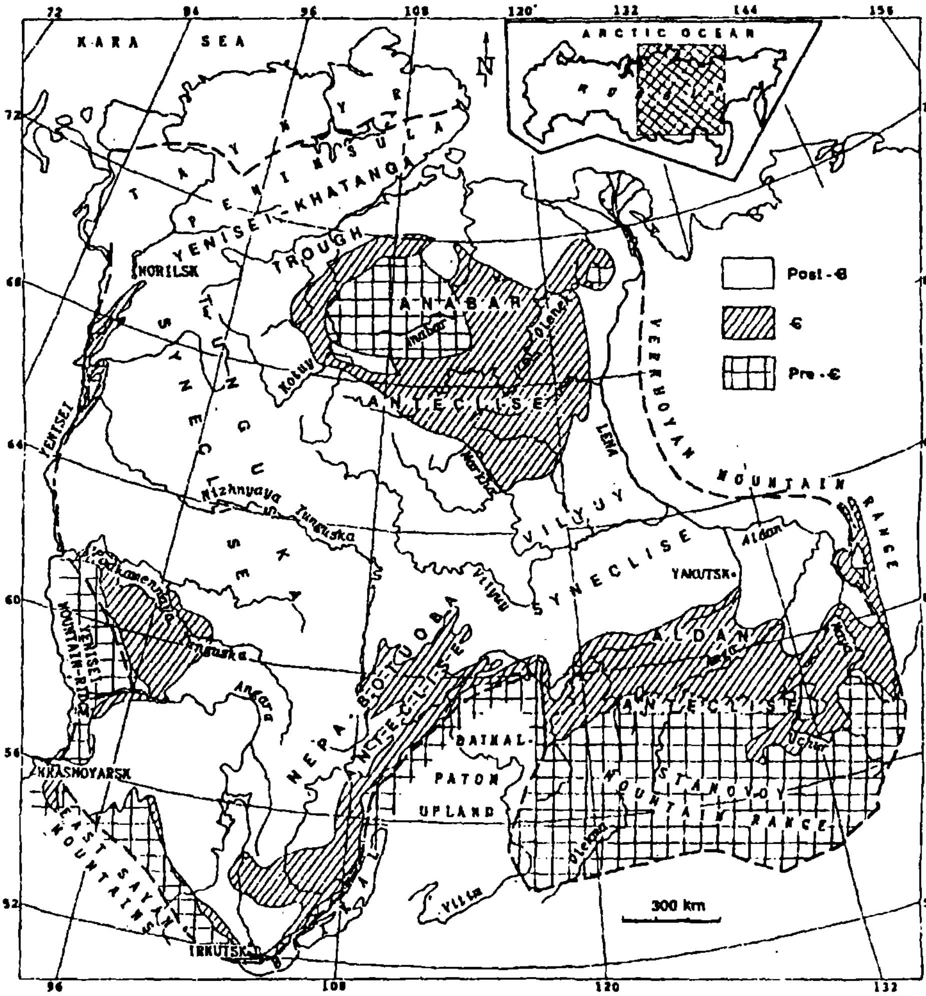


Fig. 1 Location map showing the Cambrian exposed on the Siberian craton and the largest present-day tectonic structures

lage-scale geological investigations aimed, first of all, at searching for hydrocarbons and related to the Cambrian stratification, paleogeographic and paleotectonic reconstructions, as well as restoration of depositional environments have been persued in the area for more than half a century. Nevertheless, they are still based mainly on conventional stratigraphic "layer-cake" conceptions about the internal structure of deposits.

The workers suggested essentially different reconstructions of paleobathymetry and morphological history or placed no emphasis on these moments (Savitsky et al., 1972, 1979; Pisarchik et al., 1975; Kirkinskaya and Trunov, 1975; Kokoulin and Rudavskaya, 1985; Repina and Rozanov, 1992; Kontorovich, 1994, 1995, and others). Only in recent 10—15 years expansion of subsurface investigations coupled with dissemination of genetic stratigraphy and basin analysis conceptions has alowed a possibility to combine into a unified system biota evolution, geometry and patterns of the sedimentary body boundaries and their genesis and effects on various factors, such as, above all, relative sea-level fluctuations. Such approach to the study of the region inherits ideas advanced by Grachevsky

(1969) in late 1960s and then elaborated by Savitsky(1979) and Astashkin(1984). Its purpose is to reconstruct dynamics in the development and infilling of the Siberian craton basins.

Environmental stratigraphy and facial zonation

Generally recognized facts are dissimilar material compositions and faunal characteristics of Cambrian deposits from the southwestern craton and those from the eastern and northwestern parts of the craton, as well as a specific pattern of the so-called transition zone which separates these two vast areas(and division of the Cambrian into three facial regions; Khomentovsky and Repina, 1965; Savitsky, 1972, 1979; Pisarchik et al., 1975; Kirkinskaya and Trunov, 1975; Chechel et al, 1977; Anon, 1983; Rozanov and Sokolov, 1984; Kokoulin and Rudavskaya, 1985; Melnikov, Astashkin et al., 1989; Astashkin et al., 1991; Repina and Rozanov, 1992; Pegel and Sukhov, 1996, and others). Furthermore, the entire Cambrian succession is clearly differentiated into stratigraphically isolated formation complexes which show obvious environmental and eustatic conditionality(Fig. 2). On the south-west of the craton, where the total Cambrian thickness reaches 2.5 km, the Lower Cambrian and the lower half of Middle Cambrian exhibit prevalence of evaporites (halite, dolomite, sulphate). Such composition, scarce findings, monotony, and endemism of fauna are associated with sedimentation in the closed shelf and lagoonal environments(Zharkov, 1966, 1970); Yanshin and Zharkov, 1974; Pisarchik et al., 1975; Chechel et al., 1977, and others). The overlying strata (Within upper Middle and Upper Cambrian) are composed of many-coloured terrigenous-argillaceous-carbonate rocks of the subaerial plain and shallow shelf (Zharkov et al., 1982).

Another formation complexes are common to the Cambrian on the eastern and northwestern craton. It is rich in various fossils among which aboudant are cosmopolitical taxa (Savitsky et al., 1972; Anon, 1983, and others). A three-member structure of the Cambrian succession is quite evident there. The lower unit (Tommotian and Atdabanian, Lower Cambrian) is composed of mottled bioturbated argillaceous limestone 150—200 m thick. The middle unit (Botomian and Toyonian, Lower Cambrian and lower Middle Cambrian) includes dark mudstone to black shale not more than 50—70 m thick. The upper unit constituting the bulk of the Cambrian sequence of the region consists of green-grey flyschoid silicate-carbonate rocks (in the lowermost portion-red nodular carbonate). The stratigraphic interval of the unit is represented by Middle (Mayan) and Upper Cambrian. Its total thickness is up to one kilometer and more. The Cambrian of the eastern craton is usually considered to have been formed in the open sea environment. Maximum depths of its deposition, however, are inferred to range from 100—200 m and shallower (Khomentovsky and Repina, 1965; Savitsky et al., 1972) to many hundreds of meters (Grachevsky et al., 1969; Savitsky, 1979; Sukhov, 1982; Astashkin, 1984).

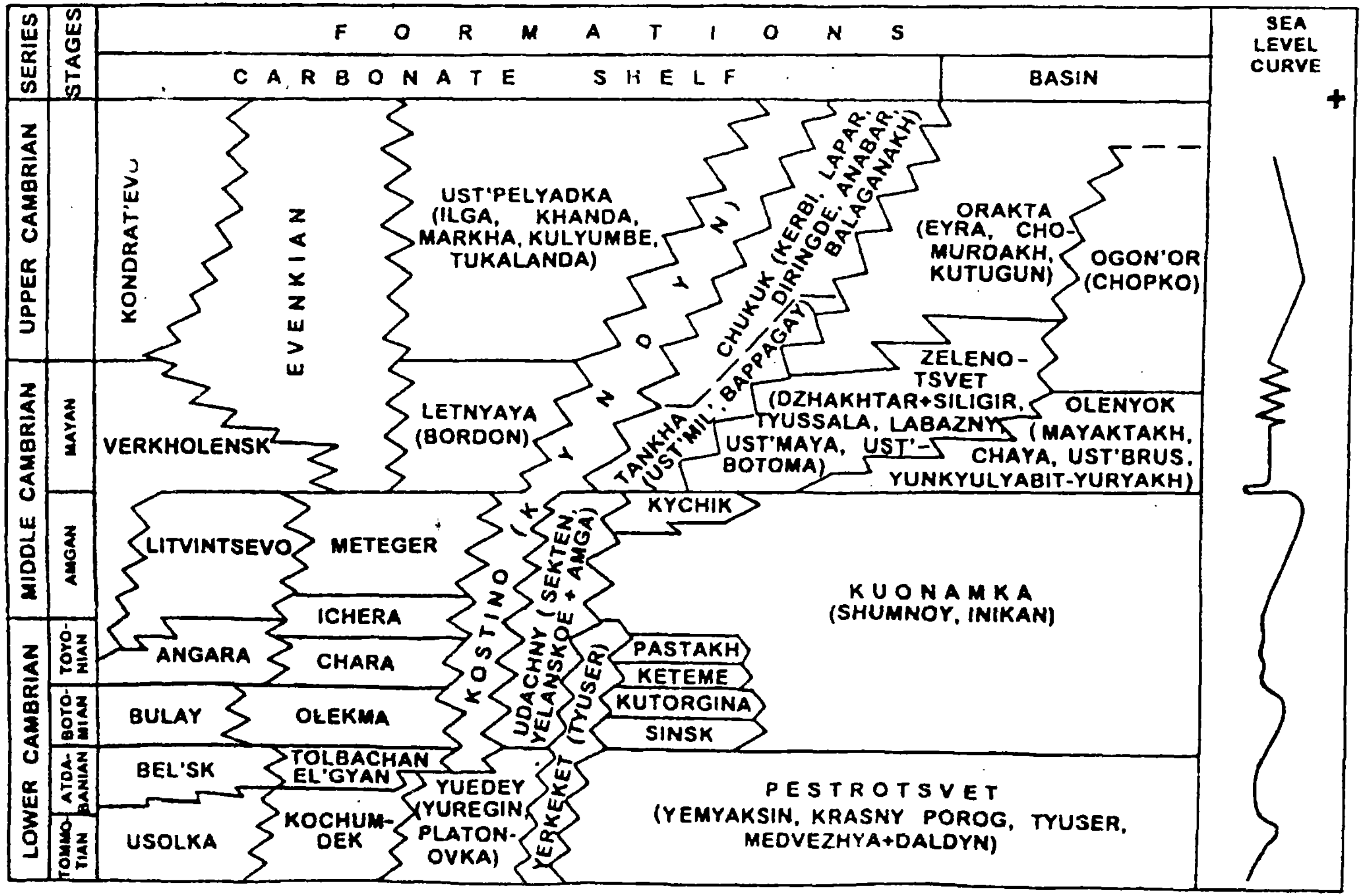


Fig. 2 Generalized stratigraphic chart for the Cambrian of the Siberian craton showing relationships of main units and their depositional environments with respect to relative sea-level fluctuations. Facial analogues in brackets. Modified after Anon(1983), Astashkin et al. (1991), Repina and Rozanov(1992)

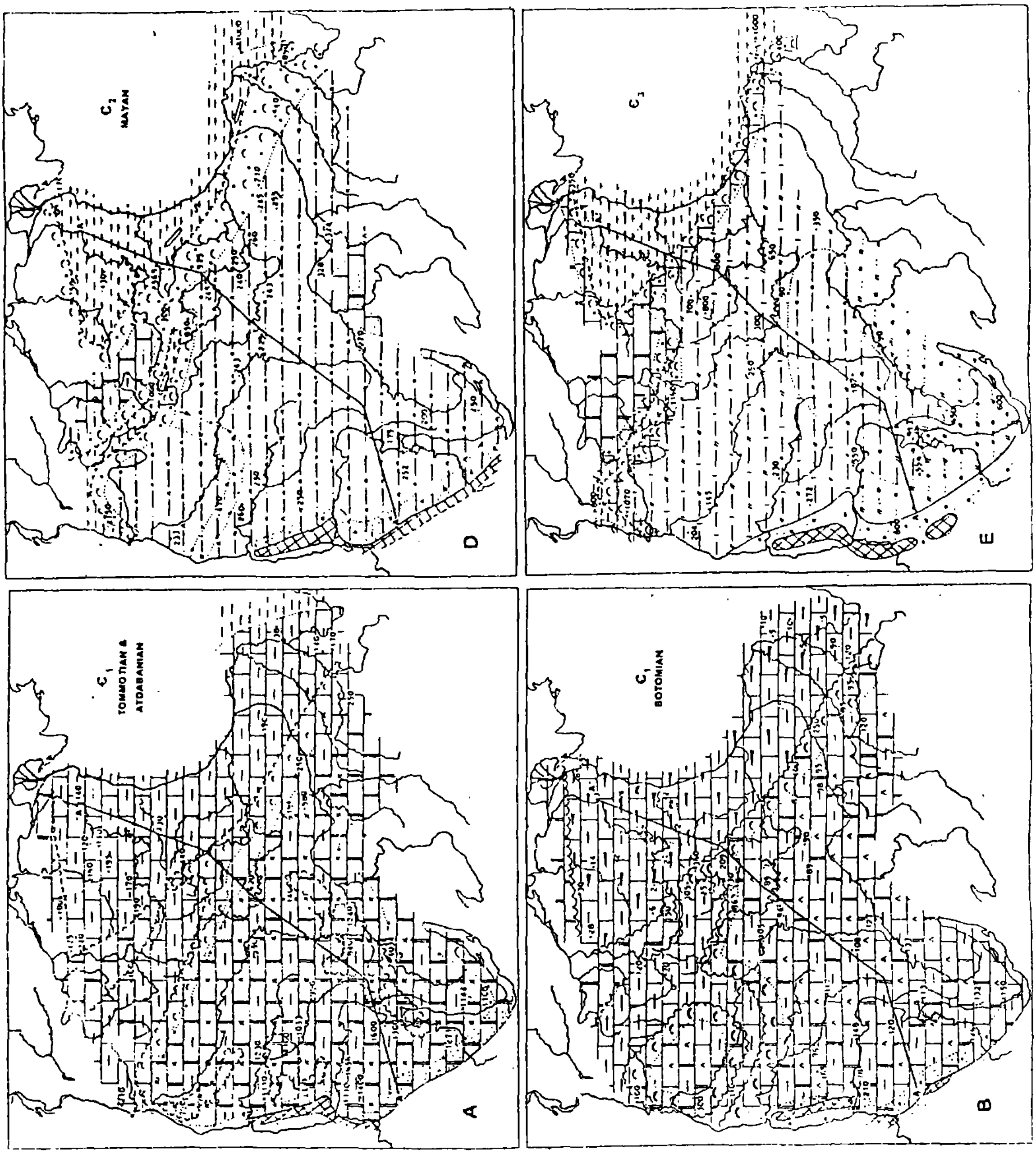
A relatively narrow belt-like zone that separates the regions mentioned above is characterized by predominance of light algal, archaeocyathic-algal calcareous boundstones and grainstones or dolomites. It is distinguished by a wide variety of its formations resulted from its margin-shelf genesis, bilateral contact with sharply different formation complexes, and displacement (mainly east- and northwards) with time. Maximum thickness up to 800 m is found in the stratigraphic interval from the Botomian base to the Amgan top, when the zone was a barrier-reef system (Savitsky, 1979; Astashkin, 1984; Rozanov and Sokolov, 1984).

Depositional history

The above facies zonation was retained in general terms during the entire Cambrian (Fig. 3). Its initiation goes back to Middle-Late Vendian. At that time infilling of the Siberian craton aulacogens was completed and deposition of the proper platform carbonate portion of the sedimentary cover (Late Pre-Cambrian—Early Paleozoic) started. Since that time evaporite sedimentation shows a tendency to be localized in the southern and southwestern parts of the craton, whereas open shelf one-in the eastern and northwestern portions (Chechel et al., 1977; Grishin et al., 1987; Melnikov, Astashkin et al., 1989). That is, initiation of future basins and carbonate platforms occurred.

Early Cambrian, Tommotian and Atdabanian

Evolution of architecture and depositional environments at the Vendian-Cambrian boundary and during the earliest Cambrian, as well as geodynamics of the Siberian craton and its immediate surroundings still remain rather obscure. Ambiguous correlations of different facies deposits and the absence of detailed depositional models make regional paleoreconstruction difficult. It is believed that, alongside with diastrophism, pulsatory relative sea-level rising, which commenced since Tommotian, was of great importance for depositional history of the craton. The first high maximum of transgression took place at the Tommotian/Atdabanian boundary (Fig. 2). It caused synchronous growth of organic buildups within the inner shelf and along its outer boundary and deepening of the open shelf area. In Tommotian and Atdabanian times the greatest subsidence compensated by cyclically aternated evaporites (halite-anhydrite-dolomite-silt) was common to the southwestern craton conjugated with its elevated rims (Figs. 3A, 4A). Maximum salt saturation of the Usol Formation (up to 45—65% reaching 95% in individual members) is marked just there. The highest areal extent of salt (up to 1.5 million sq km) is found in lower Atdabanian (Yanshin and Zharkov, 1974; Pisarchik et al., 1875, Chechel et al., 1977; Zharkov et al., 1978, 1982; Grishin et al., 1987; Melnikov, Astashkin et al., 1989). Along the northwestern and southeastern peripheries of the saliferous inner shelf or lagoon (on Nepa-Botuoba and Baikit anteclises, Bakhta megaswell, Suringdakon arch) the late Tommotian peak of transgression culminated in the development of pioneer archaeocyathic-algal buildups and reefs up to 130 m thick. These units overlapped by thick salt strata form the


C2 MAYAN
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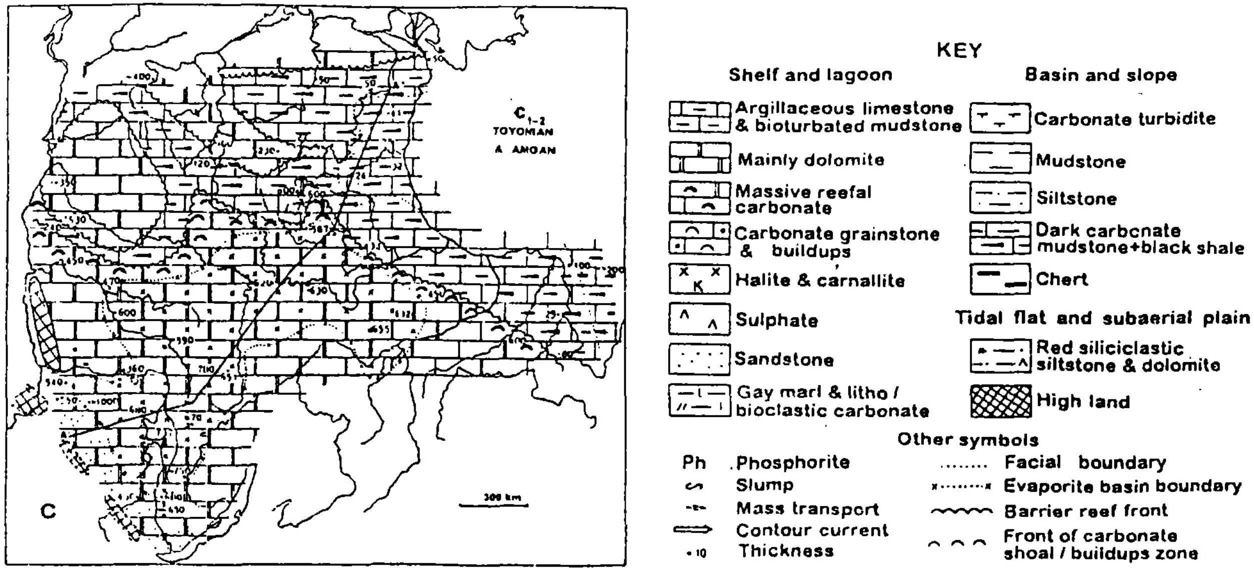

Fig. 3 Lithological-paleogeographic maps for the Cambroan. Growth and merging of carbonate platforms (Irkut-Olyokma, Turukhan, Kotui-Anabar, Anabar-Lena) accompanied by pushing the basins towards the Siberian craton periphery are observed. Cross-sections are shown in Fig. 4. Modified after Pisarchik et al. (1975) and Melnikov et al. (1989).

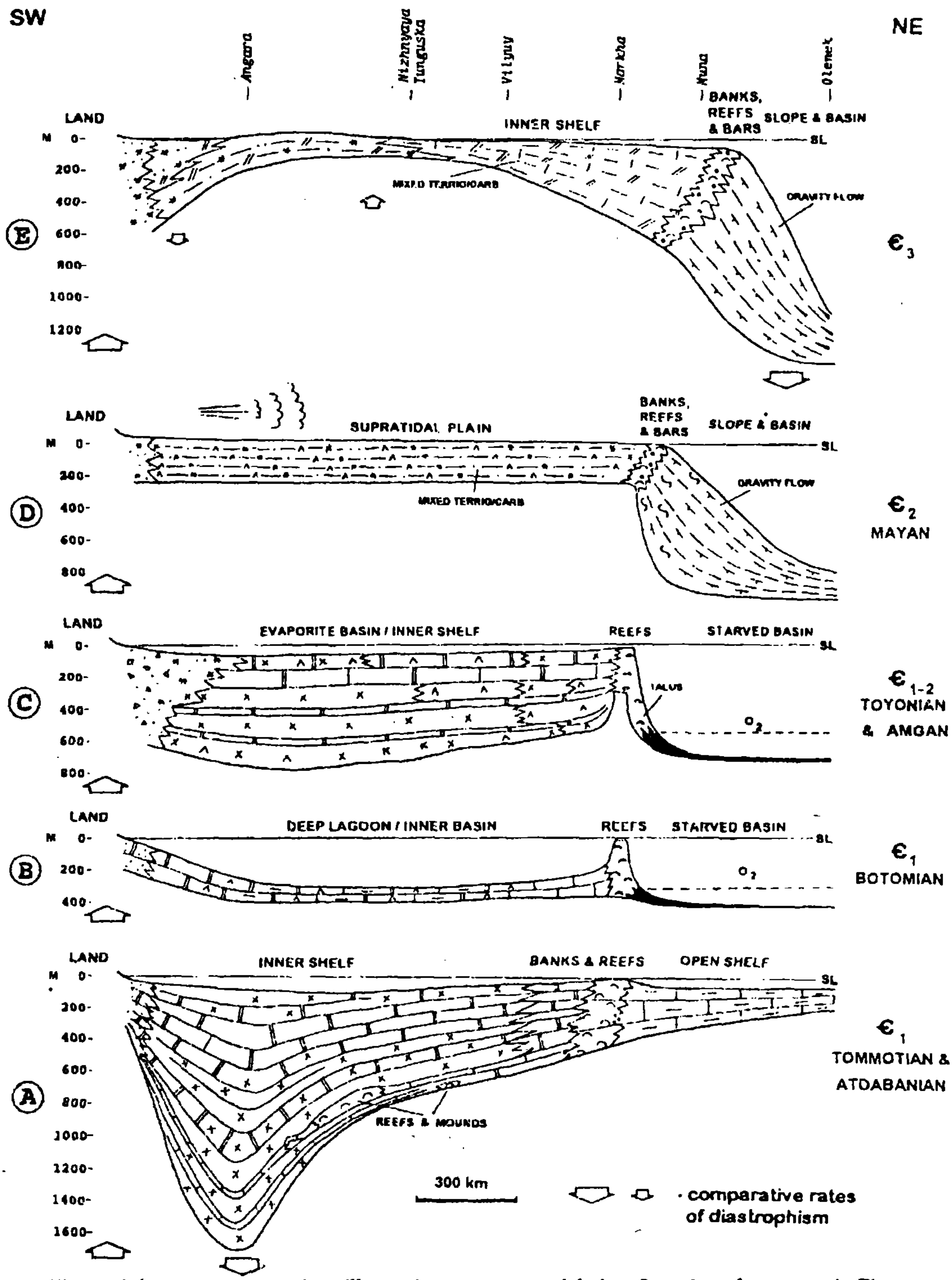

Fig. 4 Schematic cross-sections illustrating geometry and facies. Location of transects in Fig. 3

main part of the Osa producing horizon. In salt-free sequences the similar Tommotian-Atdabanian deposits, being frequently strongly dolomitized, marked the outer boundary of the inner shelf or outlines of incipient carbonate platforms, such as the gigantic Irkut-Olyokma in the central craton, Turukhan on the north-west Kotuy-Anabar on the north, and Anabar-Lena on the north-east. Vast areas, where mottled bioturbated argillaceous limestone (Pestrotsvet Formation and its equivalents) containing no archaeocyathic-algal buildups is widespread, mark areas of the open shelf paleodepressions, These depressions were later transformed into basins (Yudoma-Olenek on the east and Khantaika-Olenek on the north-west).

Botomian

Since Botomian sedimentation regime changed considerably over the whole craton due to significant sea-level rise of about 300—400 m (Figs. 3B, 4B). The starved basins (Yudoma-Olenek and Khantaika-Olenek) connected both with each other and with the ocean have originated at where marginal open shelves with good water circulation were previously located. Dark laminated mudstone of low open shelves with good water circulation were previously located. Dark laminated mudstone of low thickness (Kuonamka Formation and its equivalents) was deposited there. Mudstone with black shale (locally containing phosphorite) accumulated in the inner parts of the basins, which were most remote from the shelf margins and in close proximity to the continental slope (Bakhturov et al., 1988). The starved basins with the lowest thicknesses of up to 2—3 m were conjugated with carbonate platforms which were contoured by thick (300—400 m) archaeocyathic-algal reef-buildups of barrier type. Their extent from the south-east to the north-west exceeds 2. 5 thousand km (Astashkin et al., 1984).

It is most likely that in the time interval the previously single Turukhan-Irkut-Olyokma (Western) facies region was divided and two independent carbonate platforms (Irkut-Olyokma, with vast internal lagoon, and Turukhan) were isolated. These were separated by the Tynep basin penetrated deep into the craton (Melnikov et al., 1989). This basin is rather roughly delineated, particularly in its northern part, where it is assumed to connect with the Khantaika-Olenek basin. The same is true to the Turukhan platform outlines. Thin-bedded dark argillaceous-anhydritic limestone and dolomite were synchronously deposited on the drowned inner shelf of the Irkut-Olyokma carbonate platform, which was transformed into a deep lagoon or interior basin. They were replaced by red silicate-enriched dolomite towards the western periphery of this water area and oolite-grained carbonate towards the back-reef zone of the barrier system. A good connection of the lagoon to the open basins established in Botomian time is proved by similarity of trilobite complexes from these areas (Rozanov and Sokolov, 1984; Pegel and Sukhov, 1996, and others). Within the northern carbonate platforms, being less sizable than the Irkut-Olyokma-Turukhan, Kotui-Anabar and Anabar-Lena ones, dolomite deposition was dominant (Kostino, Kyndyn Formations).

Toyonian and Amgan

On the whole, the same deposiional environments as in Botomian time were retained during this period including starved basins, extended barrier reefs and inner shelf (Figs. 3C, 4C). Two phases are revealed in the evolution of this sedimentary system: Toyonian marked by relative sea-level stabilization and its frequent fluctuations and Amgan with a new pulsatory rise. The lowstand in Toyonian was responsible for deceleration of the upward reef growth, dolomitization and karsting as well as reef rim progradation, strengthening of bioturbation in the basin margins and on the fore-reef slopes. In the inner parts of the starved basins argillaceous-cherty mudstones were mainly deposited. The inner shelf or semi-isolated evaporitic basin, whose initial depth was probably 200—300 m and then decreased, was gradually being filled with salt and sulphate-argillaceous and silty dolomite. During early Toyonian alongside with halite, potash salt was deposited in the lowerest parts of the evaporite basin (Nepa depression; Chechel et al., 1977; Mashovich et al., 1991; Petrichenko and Chechel, 1991).

In Amgan reef upbuilding became more active accompanied by the ongoing deepening of marginal cratonic basins and craton-penetrating starved basins (Astashkin et al., 1984; Baskhturov et al., 1988, Melnikov et al., 1989). Thicknesses of the Toyonian-Amgan cherty-carbonate black shale reached 25 m only, whereas those of synchronous reef buildups of the carbonate platform margins were as high as 600 m. Growth of the latter was accompanied by progradation of the carbonate platform margins. The progradation was irregular both in time and area depending on particular paleogeographic environments. It was controlled, first of all, by directions in which fine silicate material was transported. Thus, in this time interval the reef rim appeared to have prograded for about 70 km on the southeastern Irkut-Olyokma carbonate platform (Aldan R. and Lena R.) and for a few tens of kilometers, locally even less, on the northeastern platform.

All sedimentary environments experienced considerable displacements, dominantly towards the east and north. Red silicate deposits (Verkholensk Formation and its equivalents) constantly advanced on the evaporitic basin or inner shelf from the west—southwest, i. e. elevated craton rims. Areas of halite sedimentation were gradually reduced. In Amgan it occurred chiefly in two separated areas—within the present Prisayan-Yenisei and Angara-Lena troughs on the west and in the Beryozovo depression on the east.

Mayan

A sharp sea-level fall at the Amgian-Mayan boundary led to that vast areas of the shallow inner shelf of the Irkut-Olyokma, Turukhan and, probably, other carbonate platforms were exposed and transformed into subaerial plains (Figs. 3D, 4D). The exposed carbonates of Amgan reef rims were partially dolomitized and karstified. Eolian supply of silicate clastics from the southwestern craton rim became more active. Water circulation in open basins was enhanced and resulted in that anoxic black shale sedimentation was immediately replaced by deposition of red bioturbated nodular limestone like that from the Olenek Formation. In Mayan delivery of abundant fine silicate and carbonate into the basins promoted accumulation of mass-transport and mudstone deposits 800—1000 m thick which subdued previous submarine relief. Penetrating into the craton, relatively narrow basins, like the Tynep one, were being filled with mixed halite-containing silicate-carbonate rocks in early Mayan (Melnikov, Yegorova et al., 1989). Later on these had ceased to exist and were overlain by supralittoral deposits of the Verkholensk Formation and its equivalents.

Despite considerable supply of fine silicate material, reef formation along the carbonate platform margins was being continued. It was rapidly prograding banks with shoals and carbonate bars. Their thicknesses carbonate platform eastwards during Mayan ranged between 150—200 km (Sukhov, 1982; Sukhov and Pegel, 1986). It was, probably, just the same in the northern direction inward the Khantaika-Olenek basin (Varlamov and Pak, 1993). Mayan strata overlying the carbonate platforms show extremely persistent thicknesses (around 200—250 m) and composition. They are composed of red siltstone, marl and mudstone with sulphate nodules. It indicates that the region was tectonically passive at that time and that sediments were accumulated in the supralittoral and coastal plain environments. In the second half of Mayan increase in amplitude of sea-level fluctuations caused frequent ingressions onto this plain.

Late Cambrian

A wide spectrum of depositional environments (from extremely shallow-water and subaerial to deep-water basinal ones) continued to persist on the Siberian craton during this time interval (Figs. 3E, 4E). General morphostructural orientations also remained unaltered. At the same time, however, the rate of basement subsidence in different parts of the craton changed. Besides the southwesterrn craton adjacent to the elevated rim, downward movements appeared to have been spread over vast expenses of the pericratonic basins and carbonate platform margins. Relative upwarping of the central craton combined with supply of abundant silicate-carbonate clastics into the basins contributed to continuation of relief levelling at the carbonate platform margins, which had started in Mayan, and to their transformation into a non-rimmed shelf (possibly, into a distally steepend ramp). Another sedimentary complexes and morphostructure of margins were most likely to have been formed on those sides of carbonate platforms to where unabundant silicate material was delivered (southern Kotuy-Anabar platform) or where these margins merged with continental slope during progradation (southern Verkhoyan Range).

In areas most distant from the craton center (Norilsk region, Kharaulakh Ridge, lower Olenek R.) dark argillaceous-carbonate, occasionally cherty rock to black shale and distal turbidite (Ogon'or, Chopko, and Kutugun Formations) were deposited. Their thickness is about 300—400 m. Many-colored mixed shallow-water to subaerial silicate-carbonate deposits were simultaneously accumulated over a vast area within the craton. Like in Mayan, carbonate buildups and sand bars were developed at the outer shelf. Although lithological complexes of the outer and inner parts of the craton are different, a phase of maximum deepening at the Saksian Stage base is well pronounced in both (Pegel and Sukhov, 1996).

Conclusions

Analysis of published materials coupled with recent data demonstrates that successive changes of sedimentation regime in different parts of the Siberian craton, or Siberian Platform, During Cambrian reflect a combination of both general evolutionary regularities of the self-develped carbonate systems and specific ones resulted from more local paleogeographic and tectonic events. The most essential sedimentation-controlling features were: rather high rate of general tectonic subsidence of the basement, unabundand supply of terrigenous material chiefly from the southwestern rim, intense carbonate bioproduction and evaporitic sedimentation on shelves synchronously, as a whole, with starved basin regime. There is rather distinct interrelation between compositions and morphostructures of sedimentary bodies and different-order relative sea-level fluctuations.

The Cambrian depositional history of the craton can be interpreted as a long-term tectonically passive evolution in the arid low-latitude environment of conjugated intra- and pericratonic basins and carbonate platforms. The origination of the system goes back to Late Pre-Cambrian and is, probably, initiated by tectonic events.

The carbonate framework morphology was evolving from single inner-shelf mounds to gigantic carbonate platforms. Being most intense in Mayan, they successively prograded, merged and transformed (in Late Cambrian) into non-rimmed shelves. The basins were pushed towards the open craton margins. Great differentiation of the Mayan thickness and composition within the craton were not controlled by its tectonic activization, as is the convention, long-term deep subaerial erosion and unconformity. These phenomena were the result of a short-term fall of relative sea-level and its lowstand during Mayan as well as basin infilling. It is also the reason that the hiatus at the Mayan basement which is believed to exist over the most part of the craton appears to be absent.

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