

LATE MIDDLE TO LATE ORDOVICIAN PHOSPHATE ACCUMULATION OF THE MOYERO RIVER SECTION (SIBERIA): A RECORD OF UPWELLING AND GLOBAL COOLING

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Abstract: The phosphate-bearing rocks (phosphate rocks and phosphorites) were studied over a 45-meter interval of the Moyero river section, covering the upper part of the Darriwilian and the lower part of the Sandbian stages of the Ordovician. These rocks were investigated by field observations and laboratory methods, including optic and scanning electron microscopy, X-ray diffraction analyses. The accumulation of phosphatic matter is manifested in carbonates, sandstones, and aleurolites in the form of grains (ooids and peloids), intraclasts, phosphatic and phosphatized shells. In argillites, it is represented by cryptocrystalline matter. Phosphate matter consists of fluorapatite. The peaks of phosphate accumulation are associated with the formation of layers of physically reworked granular phosphorites (condensation horizons) directly above the depositional sequence boundaries. The formation of the studied phosphate-bearing rocks during the Darriwilian-Sandbian transition was influenced by a combination of global (Great Ordovician Biodiversification Event (GOBE), reduction in sea surface temperature, atmospheric CO₂, high sea level, flooding of craton margins) and regional (equatorial position of Siberia, arid climate, facies) factors. Global conditions led to the enrichment of seawater with phosphorus and the effect of upwelling. Regional conditions determined the characteristics of phosphate formation. Studied phosphate-bearing rocks can be considered as a record of upwelling on the Siberian craton during the Middle-Late Ordovician transition and one of the manifestations of long-term global cooling started early in the Middle Ordovician.

Keywords: Middle Ordovician, Late Ordovician, upwelling, phosphates, Siberian platform, Paleoclimate.

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Introduction

Along with carbon, phosphorus is the most important bioelement, without which life on our planet is impossible. Therefore, the biospheric aspect of phosphorus is so important that without it, full-fledged presentation of the geochemistry of this small element is impossible [Yudovich et al., 2020]. Phosphorites are extremely important as an indicator of the biosphere evolution and paleoenvironmental conditions (upwelling, low sedimentation rates, transgression, etc.). Their accumulation also clearly correlates with climate changes the evolution of the biosphere. Their practical significance is also important: they are the source of phosphoric acid and rare earth elements. They are also widely used as natural fertilizers. [Frolov, 1993].

The widespread distribution of the Ordovician phosphate-bearing rocks on the Siberian platform has been known for a long time [Krasilnikova and Smirnov, 1955, 1962; Markov and Zanin, 1979; Zanin and Matukhina, 1983]. Their presence is noted mainly in the

deposits of the late Middle to early Upper Ordovician. They are represented by separate layers of granular phosphorites as well as carbonate and/or terrigenous rocks enriched with a phosphate component, represented by phosphatic ooids and phosphatized litho- and bioclasts. The Gurevsky phosphorite field, confined to the Chertovskian regional stage of the upper Ordovician, is one of the richest and best studied on the Siberian platform. It is located in the valley of the Podkamennaya Tunguska River [Dronov, 2013; Markov and Zanin, 1979]. Phosphorites in the Moyero river section have been noted by previous researches [Krasilnikova and Smirnov, 1962; Markov, 1969; Myagkova et al., 1963, 1977]. Some of them noted only single manifestations of phosphate accumulation in the form of a layer of phosphate conglomerate and enrichment of rocks with phosphate lingulid brachiopods [Myagkova et al., 1977]. At the same time, back in the 1950s, a special prospecting for phosphorus was carried out in the Moyero river valley. The high content of P_2O_5 (from 5 to 50 kg/m²) in the rocks was recorded [Krasilnikova and Smirnov, 1962]. However, details of the phosphorites distribution in the Moyero river section still require clarification.

The purpose of this work is to study and interpret the origin of phosphate accumulation in the Middle to Upper Ordovician interval of the Moyero river section. The authors refer the rocks containing more than 3–5% of phosphate matter to phosphate-bearing rocks. We distinguish phosphate rocks and phosphorites according to J. Trappe' nomenclature system [Trappe, 2001].

Geological Setting

The Siberian paleocontinent in the Ordovician embraced several basins. The largest ones are the Irkutsk Amphitheater (or the Irkutsk basin) and the Tungus Syncline (or the Tungus basin) [Dronov, 2013; Kanygin et al., 2007]. The Moyero river section is located in the northern part of Tungus basin adjacent to the Anabar land (Figure 1A).

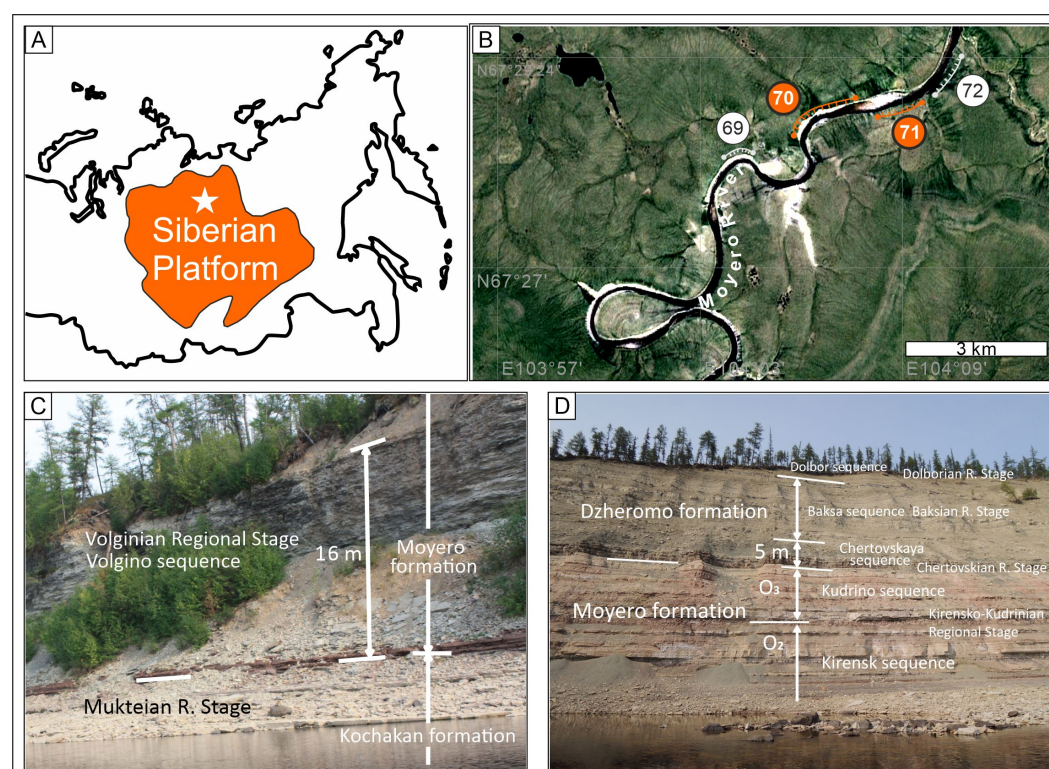


Figure 1. Geographical position and outcrops of the studied deposits. A) Position of the Moyero section on the Siberian platform indicated with a star. B) Satellite map, showing locations of the 69th to 72nd outcrops along the Moyero river. The studied outcrops, marked with orange colour. C) Field photo of 71th outcrop. D) Field photo of 70th outcrop.

In the Ordovician of the Tungus basin two carbonate series of contrast lithology could be distinguished: 1) warm water tropical carbonate series (Tremadocian-Floian) and 2) cool-water carbonate series (Sandbian-Katian) [Dronov, 2009, 2013]. These two series are separated in the Moyero river section by a relatively thick and well-developed transitional interval (Dapingian-Darriwilian) with alteration of cool water and warm water carbonates. The latter becomes less and less abundant upward the section.

The Moyero river reference section is one of the most complete and continuous Ordovician sections on the entire Siberian platform [Myagkova et al., 1963]. However, due to its remoteness, it remains rarely visited by scientists, as a result of which many aspects of sedimentology are insufficiently studied. Outcrops along the Moyero River are traditionally marked with specific numbers such as 69, 70, 71, 72 (Figure 1B) and so on given to them by O. I. Nikiforova in 1951 [Myagkova et al., 1977]. The Ordovician strata are almost horizontal or slightly tilted (2° to 3°) to the south. The Ordovician succession of the Moyero river is subdivided into four formations (from the base upward): Irbukli, Kochakan, Moyero, and Dzheromo formations [Kanygin et al., 2007]. Identified intervals of phosphate accumulation are from the Moyero and Lower part of the Dzheromo formations. Those formations crop out on the left and right banks of the river (outcrops 70 and 71, Figure 1B) about 1.5 km upstream the Bugarikta River mouth. The Moyero formation corresponds to the Volginian and Kirensko-Kudrinian Regional Stages of the upper Darriwilian and lower Sandbian stages [Tolmacheva and Dronov, 2008]. The Dzheromo formation corresponds to the Chertovskian, Baksian and Dolborian regional stages of the Sandbian and Katian Global stages [Kanygin et al., 2016].

Material and Method

Fieldworks for this study was conducted in July 2021, and July 2022. A total of more than a hundred samples were collected by A. Dronov and N. Lykov. These samples were studied by various methods. We used longitudinal and tangential 2.5 × 2.5 cm thin sections for lithological identification. Results of the microscopic study were confirmed by X-ray diffraction analyses. We used X-ray diffractometer Rigaku Miniflex 600 in the Geological department of Moscow State University. For the study, the sample weight (3.0 g) was grind to a fine powder (about 0.01 mm). The resulting powder was put into a cuvette 20 mm in diameter and 2 mm thick. The electric current is 15 mA, the operating voltage is 40 kV, the survey was carried out with an X-ray tube with a Si-anti-cathode. The resulting diffractogram was processed according to the PDXL-2 program. The mineral phases and their amount in the sample were determined.

Chemical composition of granular phosphorites and iron oolites was studied by X-ray spectral microanalysis in the Department of Petrology and Volcanology, Faculty of Geology of Moscow State University (analyst-researcher – V. O. Yapaskurt), using an analytical complex with a combined system of microanalysis, based on an electron scanning microscope Jeol IT-500 with energy dispersive spectrometer.

Results

Our research indicates that phosphate accumulation covers approximately 45 meters in the studied interval of the Moyero river section (outcrops 70 and 71, Figure 1B). However, the first appearance of phosphate minerals is noted even lower in the section in some nucleus of iron ooids (Figure 3), which compose a prominent layer at the base of the Volgino depositional sequence (Moyero formation, Volginian regional stage). This layer is interpreted as a transgressive lag at the base of the Transgressive Systems Tract of the sequence (Figure 1C and Figure 2). The Volginian deposits above this layer are represented by intercalation green-colored aleurolites and bioclastic limestones. Among these rocks, phosphate material is found only in bioclastic limestones as fragments of phosphatic brachiopods (Figure 3). Content of phosphatic components in these limestones is less than 1%.

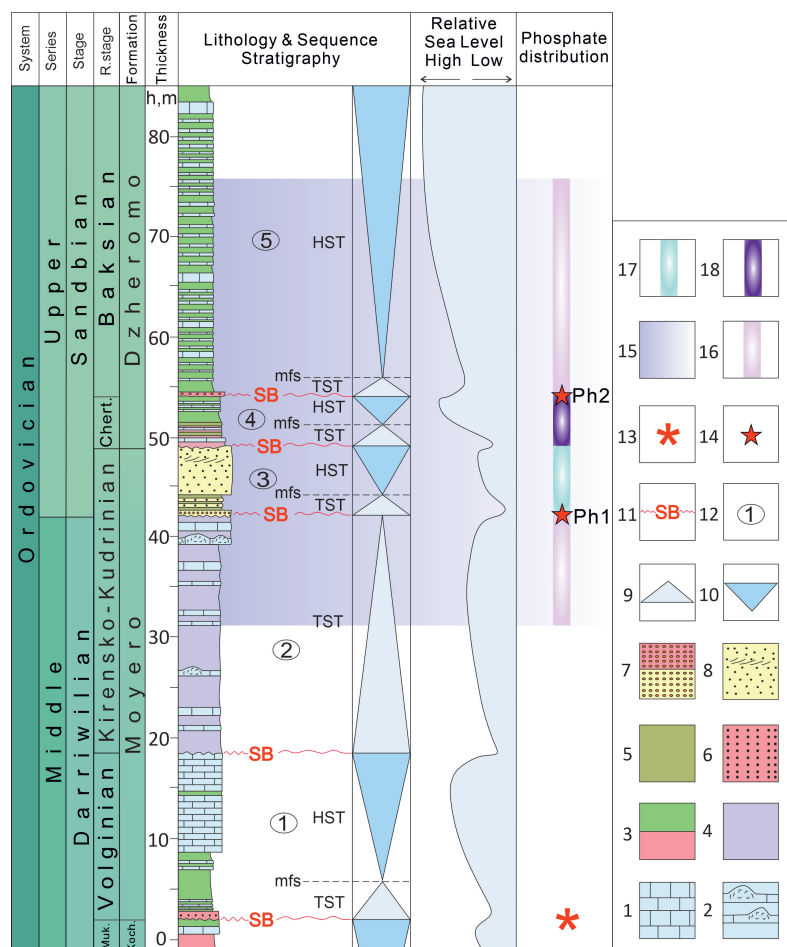


Figure 2. Simplified lithology and stratigraphy column of the studied section (Chert. = Chertovskian; Muk. = Mukteian; Koch = Kochakan). 1. Limestones. 2. Carbonate bioherms and banks. 3. Greenish and reddish aleurolites and argillites. 4. Violet and multi-coloured dolomitized aleurolites. 5. Greenish aleurolites with phosphate grains. 6. Iron oolites. 7. Granular phosphorites (reddish is hematized). 8. Sandstones with and without crossbedding. 9. Deepening upward succession. 10. Shallowing upward succession. 11. Sequence boundaries. 12. Sequences: 1) Volgino sequence; 2) Kirensk sequence; 3) Kudrino sequence; 4) Chertovskaya sequence; 5) Baksa sequence; 13. First appearance of sedimentary phosphate in the section; 14. Peaks of phosphate accumulation (2nd type accumulation); 15–18 – Phosphate distribution in the section: 15. Interval of continuous phosphate (Ph.) accumulation; 16. 1st type Ph. accumulation in limestones; 17. 3rd type Ph. accumulation in sandstones; 18. 4th type Ph. accumulation in limestones, aleurolites and argillites. TST – Transgressive Systems Tract; mfs – maximum flooding surface; HST – Highstand Systems Tract.

The Kirensko-Kudrinian regional stage is clearly divided into two parts separated by a regional erosional unconformity which corresponds to the Middle/Upper Ordovician boundary (Figure 2). It consists of the two depositional sequences: Kirensk and Kudrino [Dronov, 2013]. The lower Kirensk sequence is represented by the intercalation of violet and red lagoonal quartz aleurolites with a carbonate matrix and light-gray limestones. The types of limestones vary throughout the section. At the lower part of the section limestones are represented by bioclastic grainstones with calcite peloids. Upwards the section they pass into oolitic grainstones, above which lie calcimicrobe–stromatoporoid bioherms (the 3rd limestone layer of the Kirensk depositional sequence on Figure 2). At the top of these deposits, corresponding to the end of the Darriwilian, phosphatic grains appear in bioclastic limestones (the 4th limestone layer of the Kirensk depositional sequence on Figure 2 and Figure 4A). Those grains are represented by peloids and ooids of phosphatic

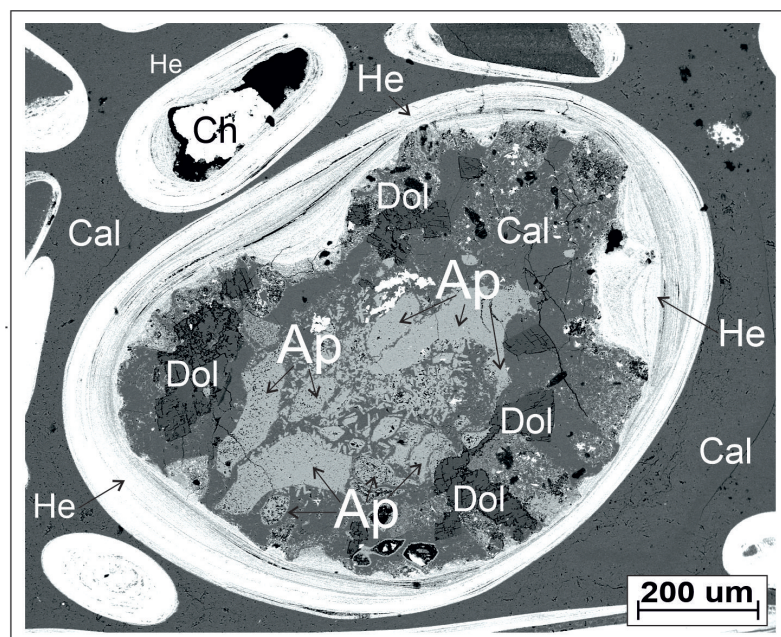


Figure 3. SEM image of the iron ooid from the transgressive lag at the base of the Volgino sequence. Ap – fluorapatite, He – hematite, Cal – calcite, Dol – dolomite, Ch – chalcopyrite.

composition. The content of phosphate matter in carbonates increases to 5–10%, in contrast to the sediments of the Volgino sequence. The Kirensk sequence is represented only by a Transgressive Systems Tract bounded by unconformities at the base and at the top.

At the base of the next Kudrino depositional sequence, there is a thin (20 cm) layer of phosphate conglomerate and/or granular phosphorite, which is interpreted as a transgressive lag deposit at the base of a Transgressive Systems Tract of this sequence (Figure 4B). That is the first maximum of the phosphate accumulation in the Moyero river section. An optical study showed that the phosphorite is gray-colored and non-layered. Grain sizes vary from silty to small-pebble size. The most common grain size is 0.15–0.35 mm. The rock is composed of 85% of phosphate material sometimes with bioclastic components (phosphatic brachiopods). The remaining 15% consists of subrounded quartz and feldspar grains of silt and sand size. The intraclasts are fragments of reworked sediments, composed of phosphatic material with or without clastic admixture, as well as phosphatic ooids and quartz pebbles. This phosphorite is cemented by clearly crystalline calcite (sparite).

The Kudrino depositional sequence is represented by quartz sandstones. In the lower two meters of the sequence, interpreted as a Transgressive Systems Tract, sandstone beds (from 2 to 7 cm thick) are intercalated with thin layers of aleurolites. The top surfaces of sandstones layers demonstrate ripple marks, while the base of the layers reveals trace fossils *Cruziana* and *Rusophycus*. In thin sections of these sandstones there are numerous phosphate ooids, peloids and fragments of phosphatic brachiopods. (Figure 4C). The upper seven meters of the sequence is represented by relatively thick (20–30 cm) layers of quartz sandstone with horizontal and/or cross-stratification and vertical *Skolithos* burrows. It is interpreted as a Highstand Systems Tract of the Kudrino depositional sequence. The change in the ichnofossil association indicates a shallowing upwards the section. The sandstones in this part of the section contain phosphate grains and phosphatized ostracod shells (Figure 4D).

In the next Chertovskaya depositional sequence despite a prominent shift in sedimentary environment from a shallow-water near-shore to relatively deep-water off-shore [Dronov, 2013] phosphate accumulation persists. The base of the Chertovskaya depositional sequence is represented by an unconformity which marks the sequence boundary coinciding with the transgressive surface. Lithologically, it is marked by an abrupt change from fine-grained shallow-water quartz sandstones (the underlying Kirensko-Kudrinian

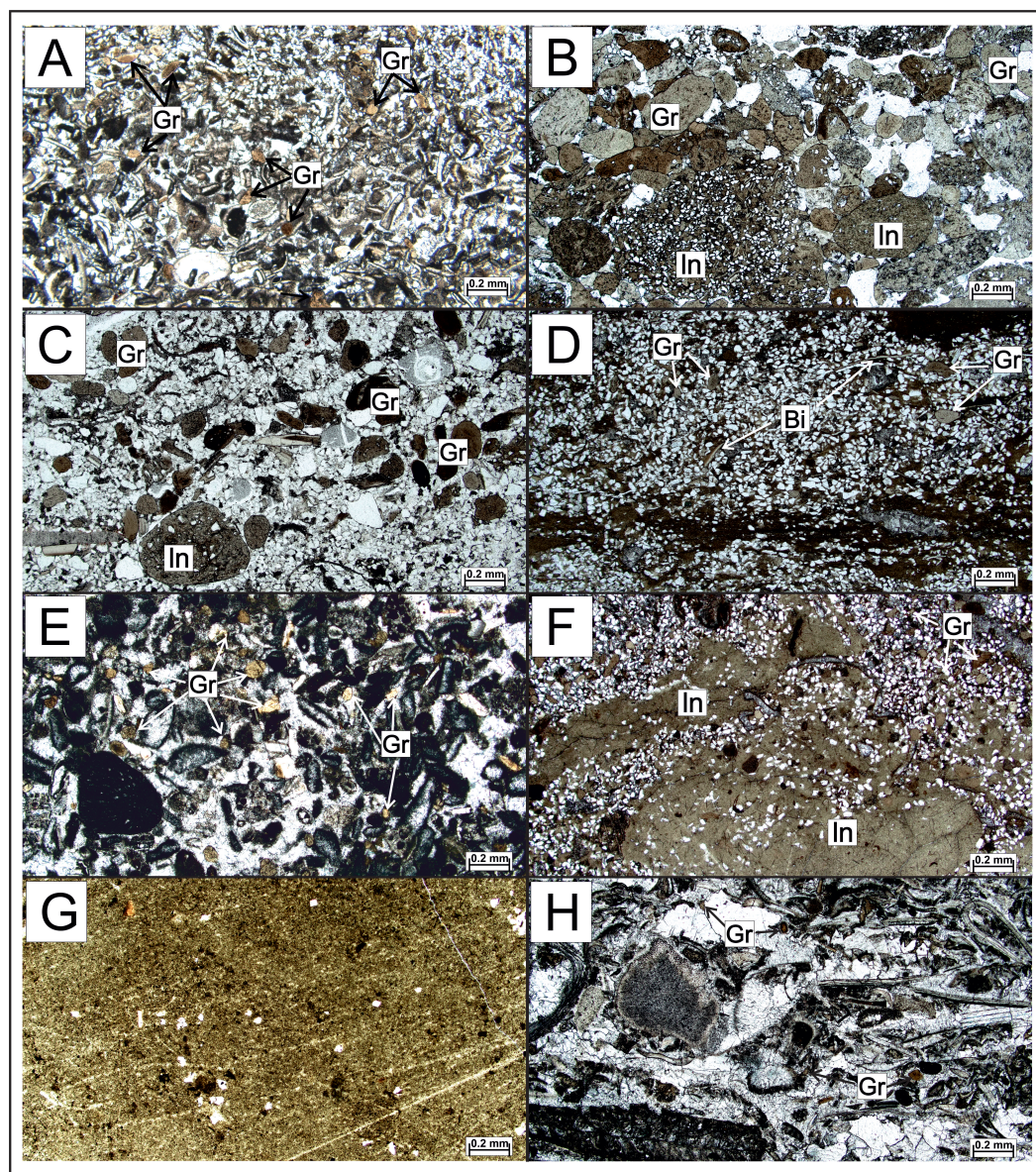


Figure 4. Phosphate materials in the studied deposits. Photos of the thin sections without an analyzer: In – intraclasts; Gr – grains; Bi – bioclasts. A – phosphatic grains in bioclastic limestone; B – granular phosphorite (Ph1); C – sandstones with phosphatic grains; D – sandstones with phosphatic grains and phosphatised ostracod shells; E – limestone with phosphatic grains; F – aleurolites with phosphatic grains and intraclasts; G – argillites with cryptocrystalline phosphate material and phosphatic grains; H – limestone with phosphate grains.

regional stage) to cherry-brown relatively deep-water argillites. This part of the sequence is interpreted as a Transgressive Systems Tract. The upper part of the sequence, interpreted as a Highstand Systems Tract is composed of green argillite and aleurolite with carbonate cement intercalated with interlayers of bioclastic wackestone or packstone (Figure 4E). Bioclastic limestone contains phosphatic grains (Figure 4F). In the argillites was found an admixture (according to an X-ray phase analysis) of phosphatic matter, the content of which could reach up to 15%. Phosphatic matter is represented by cryptocrystalline material (Figure 4G) dispersed in the clay matrix. The number of carbonate layers increase upwards the section.

A layer (15 cm) with lenses of hematitized granular phosphorites (thickness ranging from 2 to 8 cm) is observed at the base of the next Baksa depositional sequence and

interpreted as transgressive lag deposits. It represents the second peak of phosphate accumulation (Figure 2). Optical microscopy studies (Figure 5A) show that the phosphorite bed consists of phosphate grains represented by ooids, fragments of inarticulate brachiopods and intraclasts within a clear-crystalline (sparite) calcite cement. In addition, the rock contains sand-sized grains of quartz and calcareous biogenic components. The phosphorite also contains secondary dolomite, barite, and chalcopryrite. Phosphate grains (mainly ooids) are partially or completely covered with hematite films (Figure 5B).

Overlying deposits of the Baksa depositional sequence are similar to the underlying Highstand Systems Tract deposits of the Chertovskaya sequence (Figure 4H). Phosphate matter from bioclastic limestones layers disappears in the middle part of the Baksonian regional stage. According to the X-ray diffraction analyses and the X-ray spectral microanalyses the studied phosphate material is represented by fluorapatite.

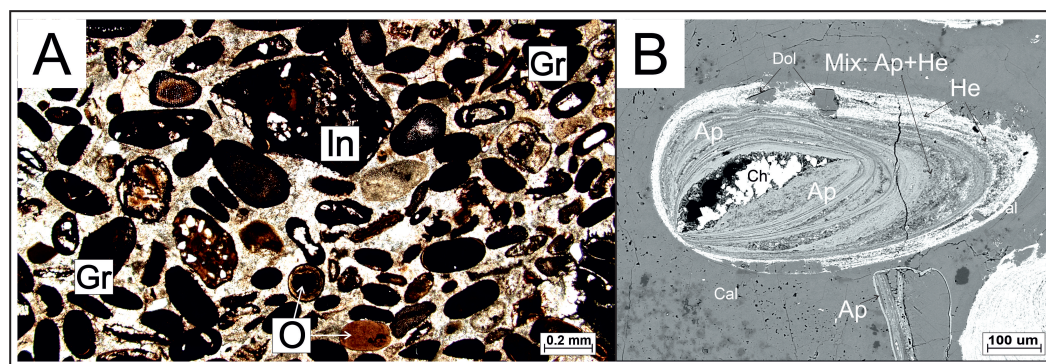


Figure 5. Hematitized granular phosphorite (Ph2) from the base of the Baksa depositional sequence. A) Thin section: Gr – phosphate grains, O – hematitized phosphate ooids, In – phosphate intraclasts. B) SEM image: Ap – fluorapatite, He – hematite, Cal – calcite, Dol – dolomite, Ch – chalcopryrite, Mix – mixture of fluorapatite and hematite.

The layer with hematitized phosphate ooids at the base of the Baksa depositional sequence is similar to the layer of iron ooids (transgressive lag deposits) at the base of the Volgino depositional sequence where the first appearance of phosphate matter was recorded (Figure 2), [Markov, 1969]. However, A continuous interval (45 m) with an increased amount of phosphate matter (“Phosphate Accumulation zone”) started only in the middle of the Kirensk depositional sequence and terminated in the middle of the Baksa depositional sequence during the Middle-Upper Ordovician transition (Figure 2). This zone can be divided into several types of phosphate accumulations in rocks (relative to facies variability)

The 1st type representing the onset of the “Phosphate Accumulation Zone”, is characterized by the initial appearance of phosphatic grains as an admixture within the limestone layers. The 2nd type represents the peaks of phosphate accumulation: Ph1 and Ph2. A phosphorite layer (Ph1) composed of reworked phosphate material. It represents a transgressive lag deposit of the Kudrino depositional sequence and rests directly on its erosional lower boundary. The next 3rd type of phosphate accumulation is associated with the Highstand Systems Tract deposit of the Kudrino depositional sequence and is represented by quartz sandstone containing phosphate grains and phosphatized ostracod shells. During the next Chertovskaya sequence of phosphate accumulation due to the sea-level rise and change in the sedimentation regime, clays enriched with cryptocrystalline phosphate material and individual layers of limestones and aleurolites with phosphate grains, were deposited – 4th type. The second peak of phosphate accumulation (2nd type), like the first, represented by a phosphorite layer (Ph2) with an erosional lower boundary, composed of repeatedly reworked phosphate material. It represents a transgressive lag deposit at the base of the Baksa depositional sequence. Upwards the section the accumulation of phosphates (1st type) gradually decreases and terminates in the first half of the Baksa sequence. Phosphate material here is in the form of phosphate grains and bioclasts in limestone layers.

It should be noted that the peaks of phosphate accumulation are associated with the formation of layers of granular phosphorites at the sequence boundaries coinciding with transgressive surfaces [Kanygin *et al.*, 2010]. Thus, the highest enrichment of sediments with phosphate material coincides with a relative rise in sea level.

Discussion

Marine upwelling is one of the major physical processes responsible for the marine primary productivity rise. That is why its distribution in the Ordovician is so important for understanding the “Great Ordovician Biodiversification Event”. There were several attempts to reconstruct possible oceanic circulation patterns, surface water currents and upwelling zones in the Ordovician [Christiansen and Stouge, 1999; Servais *et al.*, 2014; Wild, 1991]. The most reliable reconstruction was first introduced by Christiansen and Stouge [Christiansen and Stouge, 1999] and later modified by Rasmussen *et al.*, [Rasmussen *et al.*, 2016] (Figure 6). This reconstruction based on modern analogues demonstrates an upwelling zone on the Siberian margin. Our regional data supports this reconstruction.

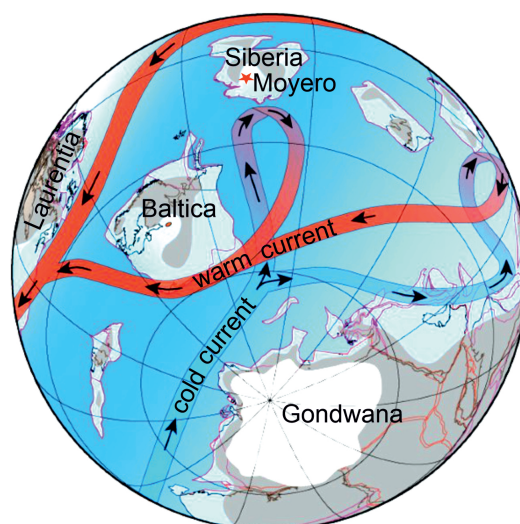


Figure 6. Simplified ocean current circulation model for the Middle Ordovician Southern Hemisphere based on Rasmussen *et al.* [2016]. Blue belt in the Iapetus Ocean (left) shows proposed Middle Ordovician cool, deep-water countercurrent the inflow toward north along Siberia, with an upwelling along the shelf and around the intra-Iapetus Ocean Island arcs. Red bands – warm surface water circulation; blue bands – cold deep ocean water circulation; red borders – continental shelf-ocean boundaries; black border – outline of the present-day Scandinavian and Baltic land-sea boundaries; light blue – the Middle Ordovician shallow sea; dark blue – Middle Ordovician deep ocean; gray – the Middle Ordovician exposed land areas; white – the Gondwana continent ice-covered south pole region.

The Siberian platform was situated in low latitudes, gradually migrating from the Southern Hemisphere during the Early Ordovician to the Northern Hemisphere by the Late Ordovician [Cocks and Torsvik, 2007]. However, despite its closer proximity to the equator, the platform exhibits evidence of cooling which starts already in the Middle Ordovician and reaches its maximum in the Upper Ordovician, which is represented by a series of cool-water carbonates [Dronov, 2013]. The most reliable explanation for this cooling is the invasion of cold deep oceanic waters into the tropical epicontinental basin of Siberia as a result of upwelling [Dronov, 2009, 2013]. Appearance of phosphorites in the upper Darriwilian – lower Sandbian interval of the Tungus basin in Siberia is one of the possible indicators of such an upwelling event. Like in East Siberia, the phosphate accumulation during the Middle-Late Ordovician transition is also observed in the Baltic region [Küpli *et al.*, 2010] in the same stratigraphic interval.

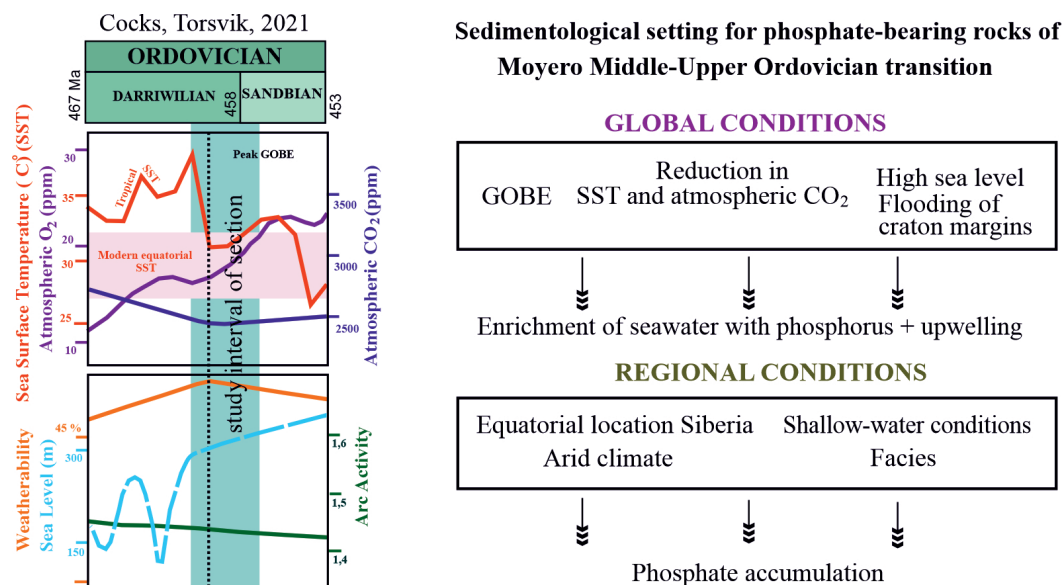


Figure 7. Sedimentological setting for phosphate-bearing rocks of the Moyero Middle-Upper Ordovician transition. GOBE – Great Ordovician Biodiversification Event, SST – sea surface temperature at the equator. The global conditions for the Middle-Late Ordovician transition are presented according to [Cocks and Torsvik \[2021\]](#).

The structural features of the studied phosphate-bearing rocks indicate the multi-stage and long-term nature of their formation. Granular phosphorites were deposited under conditions of redeposition and condensation of phosphate matter in the transgressive lag deposit above the sequence boundaries at the base of Kudrino and Baksa depositional sequences. Accumulation of granular phosphorites is obviously linked to abrupt sea level changes [[Kanygin et al., 2010](#)]. The first appearance of phosphate in the section is also localized in the transgressive lag deposit of the Volgino depositional sequence when the relative sea level was rapidly rising. The whole “Phosphate Accumulation Zone” coincides with a long-term eustatic rise of the global sea level ([Figure 7](#)) [[Haq and Schutter, 2008](#)]. The coastal upwelling on the Siberian margins seems to start earlier already in the Dapingian and ends later, probably in Hirnantian or the Early Silurian. However, “Phosphate Accumulation Zone” possibly reflects maximum invasion of the cold and phosphate-rich deep oceanic waters into the Tungus epicontinental basin. This invasion seems to coincide with the maximum of relative sea level rise in the basin.

The large-scale coastal upwelling during the Late Ordovician affected the shallow margins of a number of cratons [[Challands et al., 2009](#); [Pope and Steffen, 2003](#); [Saltzman and Young, 2005](#); [Young et al., 2008](#)]. Comparative analysis of the Ordovician successions of Siberia and Laurentia demonstrates a striking similarity in the long-term lithologic changes. On both palaeocontinents the Ordovician succession starts with tropical stromatolite-bearing carbonates which abruptly changes to siliciclastic deposits and terminates with cool-water carbonates [[Dronov, 2013](#); [Ettensohn, 2010](#)].

Similar to Laurentia the Siberian palaeocontinent was located in the tropical zone during the Cambrian, Ordovician and Silurian [[Cocks and Torsvik, 2007, 2021](#)]. Therefore, similar to Laurentia [[Dronov et al., 2015](#); [Holland and Patzkowsky, 1996](#); [Pope and Steffen, 2003](#); [Saltzman and Young, 2005](#)] the shift from tropical-type to temperate-type carbonates in the Middle and Late Ordovician of Siberia can be explained by an upwelling of cold oceanic waters into the intracratonic basin. The onset of cooling marked by the distribution of cool-water carbonates and phosphate-rich deposits starts earlier in Siberia (later Darriwilian – early Sandbian) than in Laurentia (early Katian). This observation demonstrates the importance of regional factors in the long-term global climate changes ([Figure 7](#)).

Phosphate accumulation relates to the upwelling, but its causes are a combination of both global and regional conditions. According to [Cocks and Torsvik \[2021\]](#) several global events occurred at the turn of the late Darriwilian and early Sandbian: the pick of GOBE, the reduction in sea surface temperature (SST) and atmospheric CO₂ ([Figure 7](#)). A combination of these global factors resulted in the enrichment of seawater with phosphorus. The reduction of SST caused the rise of CO₂ dissolving in the ocean, which also favored the rise in P₂O₅ enrichment in the ocean deep water. At the same time, due to regional conditions (equatorial location of Siberia, arid climate and facies), the cold, phosphate-rich waters of the World Ocean could have warmed as they ascended to the shallow settings of craton margins ([Figure 6](#)), contributing to the intensive accumulation of phosphates.

Conclusion

A 45 m interval of phosphorite accumulation has been found and studied in the Moyero river section. Based on forms of phosphatic matter manifestation and associated sediments we distinguish 4 types of phosphatic accumulations in the studied stratigraphic interval. This interval of intensive phosphate accumulation reflects the general patterns of climatic and oceanographic changes during the Ordovician period. The widespread phosphate-bearing rocks (phosphate rocks and phosphorites) in the Middle-Upper Ordovician transition suggest that the upwelling had a significant impact on this part of the Siberian platform during this time, against the background of favorable regional conditions of phosphorite accumulation.

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