A new paleotemperature method from biotic proxy indices - An example from the Upper Paleozoic paleogeographic and paleotectonics reconstructions of Siberia

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Research Article

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Abstract

A new method for quantitatively assessing paleotemperatures in the Upper Paleozoic of Siberia based on the taxonomic composition of biota is proposed. This method utilizes a large data set on the geographic distribution and ecology of various biotas in Siberia and surrounding regions from the newly developed PaleoSib database. We developed new tools to analyze the paleotemperatures of the Siberian Platform (Angarida) shallow-water deposits during the Late Paleozoic. The obtained results clarified the dynamics of the paleoclimate and paleo-tectonics of this time in the region. Some lithological indexes were integrated with biotic ones to strengthen the paleotemperature analyses. A wide geologic community dealing with sedimentary geology and paleo-tectonics can utilize the method and the tools. The method can be used by anyone regardless of his or her skill level from students to professionals. We plan to integrate this method into the Paleobiology Database.

1. Introduction

The climate is an important component of the Earth's system that directly affects the development of the system's sedimentary stratisphere, hydrosphere, atmosphere, and biosphere. Therefore, studies of the climate and its dynamics over time are essential, both for a general understanding of the history of the Earth and the individual episodes, including the evolution of numerous groups of fauna and flora, the processes of weathering, the different compositions of sediments and minerals associated with sedimentary processes (coals, evaporites, laterites, etc.).

The main methods for reconstructing paleoclimates have been the study of the composition of sediments and sedimentological indices indicating cold (dropstones, diamictites, glendonites), arid (calcarenites, evaporites, laterites), and humid climates (coals, peat) (Boucot et al. 2013; National Research Council 2006). In recent years, climate parameters have been generally established using the so-called geochemical weathering indices (Baumgardner et al. 2014; Rasmussen et al. 2011). Oxygen and carbon isotopes and Ca/Mg ratios in biogenic carbonates provide the general mean of the oceanic water temperature as well (Berlin and Khabakov 1960; Epstein et al. 1951; Lebrato et al. 2020; Veizer and Prokoph 2015). The improvement of modern mass spectrometers has provided very accurate data on Sea Surface Temperatures (SST) in the past while studying biogenic phosphates (Joachimski et al. 2004). However, all geochemical methods of paleotemperature recovery require a complex and expensive instrumental base and are carried out for a long time. For example, the SST data in the Late Paleozoic are available in only one region (Southern China), where the climate, hydrography, physiography, and paleogeography are quite specific.

A recently proposed approach to modeling paleotemperatures by estimating the level of carbon dioxide in the atmosphere was exploited in several studies (Marcilly et al. 2022; Niezgodzki et al. 2017; Upchurch et al. 2015). Paleotemperatures are estimated from the position of the studied objects relative to climatic zones created with the climatic modeling based on carbon dioxide content in the atmosphere (Roeckner et al. 2003). The level of carbon dioxide is determined by studying stable isotopes of paleosols, and by the stomata index (stomata index) of plant leaves (Royer 2001).

Lithological indices of climate are widely used in geology, but at the same time, a huge amount of information on paleotemperatures, which reflect the living environments of biota in various ecological settings, remains largely beyond the view of the most of geological community. Diverse groups of flora and fauna alone can indicate, sometimes quite accurately, general climatic conditions in terrestrial as well as marine environments (Gosling 2015; Landman et al. 2015; Murray 2006; Oskina et al. 2019; Scrutton 2020; Sessa et al. 2015; Sweet 1988; Tanabe et al. 1996; Williams et al. 1997–2007). Paleontologists who study biotas in different climatic zones usually understand the general climatic parameters for a certain taxonomic group (corals, ammonoids, planktonic foraminifers, radiolarians, etc.). At the same time, sedimentological indices can sometimes accurately and quantitatively assess the temperature range or environment (gledonites, laterites, and others), but the biotic taxonomies are not consistently used for the quantitative appraisal of paleotemperatures. The fact that famous classification and map of the modern climatic zones is largely based on the distribution of terrestrial biota (mainly flora) (Köppen 1923; Köppen and Wegener 1924; Kottek et al. 2006) (Fig. 1), has not yet been found the adequate response among paleontologists. However, Kappen's attempts to utilize the biotic and sedimentologic indices to develop the Phanerozoic paleoclimatic models provide only a general view of the deep-time climate (Köppen and Wegener 2015).

Here we propose the prototype of the paleoclimate model developed with the biotic paleotemperature proxies in Siberia and the Russian Far East during the Late Paleozoic. The climate dynamics in connection with global climate change and tectonic activity of various levels within Siberia are analyzed as well. The proposed approach somewhat mirrors the principles of determining temperatures from sedimentologic indices used in Boucot et al. (2013), especially since some taxa (palms and crocodiles) are already used in their work. Biotic paleotemperatures were employed in the earlier publication to solve paleotectonic problems in the Arctic (Davydov 2016). This work is an in-depth development of these principles. This paper discusses the methodology we developed and employed to analyze the distribution of paleotemperatures in time and space exemplified by the data from Siberia. The PaleoSib database and the time-slices data sets and newly developed tools to analyze and recognize the reliable biotic paleotemperature indices to understand the Late Paleozoic climate of Siberia in depth. Obviously, not all the biotic paleotemperature indices proposed here accurately show the real temperatures in different parts of the region. This is the first attempt of this kind and, of course, we expect some shortcomings or even errors in the proposed model. We are aware of the imperfection of the approach and developed model, once we are at the very beginning of the journey. We also expect that paleontologists who study various taxonomic groups will join the work on refining biotic paleotemperature indices so that over time this database will become an available tool for constructing and refining paleobiogeographic, paleogeographic, and paleotectonic maps and models. The proposed database and tools can also be employed as a reference and verification tool for the non-paleo geological community. If the work proposed here arouses the interest and support of geologists, we plan to expand both the set of faunal groups and the age ranges with which they are associated.

2. Materials and Methods

The PaleoSib database (https://doi.org/10.5281/zenodo.8286567) is the backbone of our project and was primarily compiled during the implementation of the project "Paleogeography of the Siberian continent in the Late Paleozoic era and the global bipolarity of glaciations: Carboniferous-Permian glacial and interglacial events in Verkhoyansk" (Davydov et al. 2022). The data were collected from stratigraphic correlation charts across various areas of Siberia, spanning the Devonian to the Triassic (a list of references can be found in **Appendix S1**). In Russia, these charts are commonly used to summarize sedimentologic, biostratigraphic, and chronostratigraphic data from key geologic basins such as the Siberian Platform and its surrounding areas. The main basin is further divided into sub-basins, where stratigraphic successions are separated into chronostratigraphic units at least at the stage level. Among paleontological remains that we collected for this project, we focused only on taxa with reliable quantitative assessments of paleotemperature (e.g., smaller benthic foraminifera, marine bivalves, some brachiopods, ammonoids, conodonts) or those whose temperature gradient in Siberia changes distinctly upon transitioning from warm to cold climates (e.g., corals, fusulinids). Furthermore, we included some data from the Paleobiology Database (https://paleobiodb.org), mainly from the Permian-Triassic deposits of Siberia.

We selected and compiled data from 170 published sources (S1), which occur in sub-basins (structurally controlled facies zones in Russian literature [SFZ]) or specific locations mentioned in the literature. The PaleoSib database covers all the SFZs from the Upper Paleozoic and Triassic of the Siberian Platform (including Western Siberia) and northeastern Russia. The number and size of sub-basins vary from geologic system to system, depending on how they are designated in the correlation charts. The database includes 23,580 stratigraphic records of taxa with assessed average paleotemperatures from 5,229 collections throughout Siberia. The data are chronologically subdivided according to the stages accepted in the International Geological Time Scale (Gradstein et al. 2020). Figure 4 shows the statistics of the taxonomic data and the number of collections in the database.

3. Estimates of paleotemperatures of taxa

The following principles were employed for the assessment of paleotemperatures in our project. First, modern up-to-date data on several biotas (at the level of families or even orders, mainly for the Triassic and younger) make it possible to accurately estimate the ranges of habitats of certain taxa at various taxonomic levels (Bevilacqua et al. 2021).

Second, we considered the latitudinal biodiversity gradient, which indicates that biotic diversity is greater in warm-water environments than in cold water (Davydov 2014; Pianka 1966; Willig et al. 2003). An increase in biodiversity in similar facies and bathymetric settings within the different paleolatitudes indicates the warming of the basin waters and vice versa (Figure 5).

Third, we considered the facies, environments, and bathymetry of the biotas. Shallow-water environments realistically reflect the temperatures of surface waters, while transitional deep-water settings have permanent or intermediate temperatures. For the analysis of paleotemperatures in Siberia, we assessed only groups that occur in shallow water conditions at depths of no more than 250–300 m. Accordingly, the shallow water faunas indicate higher temperatures than those of deeper water. This criterion is valid for all benthic organisms, but

nektonic and planktonic faunas (ammonoids, conodonts, radiolarians, and some others). The temperature estimation of the latter required more skills and integrative sedimentological, geochemical, and other types of data.

The bathymetry of biotas is of critical importance in determining paleotemperatures, since at considerable depths (>300 m) the water temperature is very weakly or in no way related to the climate and, accordingly, to surface water temperature. Therefore, for the analysis of paleotemperatures in Siberia, only groups that occur in shallow water conditions at depths of no more than 250–300 m or less were assessed (Figure 3).

The evaluation of paleotemperatures from the taxonomic composition in Siberia was carried out according to several parameters. First, the position of taxa relative to the climatic zones: (1) equatorial, (2) subtropics (3) warm temperate, (4) cool temperate, and (5) polar (Figure 1). That is, if migrants from a warm-water climatic zone (for example, corals among cold-water faunas) are found in the studied assemblages' characteristic of high latitudes, this gives grounds to associate this stratigraphic level in a given place with warmer, albeit short-term, conditions. Conversely, the appearance of cold-water conditions indices in warm-water taxa assemblages may indicate possible trends toward cooling.

In addition, we also used the following methodological approach. First, the taxa characteristics of warm-water and cold-water habitats were separated. All deep-sea taxa living at depths of more than 250-300 m can be classified as cold water (Hohenegger 2004; Murray 2006; Pinet 2019). Warm-water taxa live at depths of 250-300 m or shallower in tropical and subtropical zones. In the other climatic zones, they occur at much shallower depths (Figure 3). All other taxa of middle and high latitudes (>50-55°N-S) are categorized as cold water. We implement the search query "taxon name" + cold-water for cold-water taxa on the Internet web search and subsequent analysis of the obtained publications from the search results. A selected taxon that occurs in shallow water realistically shows surface water temperatures. Forms that are found only in deep-sea conditions are excluded from the analysis. These forms may appear at any latitude and therefore not directly document the SST (Sea Surface Temperature). The insertion of such data in the database will distort the results.

Since global and regional climate conditions change dynamically over time, multidirectional migrations of taxa occur because of these changes. For example, warm-water taxa can occur in middle and even higher latitudes together with cold-water forms, since the latter usually have a wide range of thermal tolerance and better adapt to warming environments (Dorey et al. 2019). In this case, there is a mutual overlap of taxa of different habitat conditions (warm and cool-cold water). Provisionally, we resolved this issue simply by excluding them from consideration. These rare exotic taxa had little effect on the average temperatures established for certain geographic areas and chronostratigraphic times. Such taxa must be evaluated separately in each specific case, which requires a lot of time and special knowledge.

In this paper, we explain how to determine paleotemperatures employing biota and focus only on the primary trends in surface water temperature changes. We apply this method to study the Late Paleozoic paleoclimate in Siberia. Shallow-water species living in the tropical zone (≤ 300 m depth) have average habitat temperatures ranging from approximately 20-35°C, while species in the subtropics range from 18-25°C. In middle latitudes, temperatures range from 12-20°C, and in high latitudes, they range from 4-10°C, while in polar regions, temperatures range from 0-4°C (see Figures 1 and 2b) (Pinet 2019; Segar and Segar 2018). Under deep-water conditions below 250-300 meters, but up to around 500 meters, habitat temperatures in the tropics fall below ~ 10-12°C, in mid-latitudes, they range from 5-7°C, and in high latitudes above 60° (N - S) temperature varies by about 1-4 degrees even in shallow water (Figures 2b-3) (Miller and Wheeler 2012). All these factors are also influenced by the climatic season, sea-ocean currents, and local and regional settings (such as the presence of large rivers, mountain ranges of glaciers, anomalous salinity of deep-water depressions, underwater volcanism, etc.)) (Pinet 2019; Segar and Segar 2018). We have not considered these parameters in our project yet.

For more than a century, the concept of "biomes" has existed (Clements 1916), and was originally used to describe ecological communities in continental settings and construct climate maps (Archibold 1995). Biomes represent the second-to-last stage in the organization of life, ranging from a single cell to the biosphere (van der Maarel 2005), and are characterized by ecological and evolutionary traits under specific climatic and physiographic conditions. The biome is a crucial concept in ecology and biogeography (Goldstein and DellaSala 2020; Mucina 2019). Biomes are large-scale ecosystems of biotic assemblages of species associated with specific abiotic environments that interact within and between these assemblages and the physical space in which they function (Faber-Langendoen et al. 2020). The term "biome" in marine settings possessed controversial meaning since it was proposed (Clements and Shelpord 1939; Hedgpeth 1957). Nowadays, marine biomes are classified into hierarchical categories based on the level of organization, taxonomic composition, and scale of distribution, each with specific characteristics, including temperature: ecoregion, ecosystem, ecozone, ecoformation, and others (Costello and Chaudhary 2017; Goldstein and DellaSala 2020; Woodward 2008). Each of these categories is found in specific climatic and temperature conditions and physiography (Costello 2020; Fay and McKinley 2014). By establishing these categories for the sedimentary basins in Siberia, researchers can create reliable paleoclimate maps and identify areas with exotic biomes, the appearance of which can be explained by paleotectonic or other geological reasons.

Since temperature variations (temperature gradient) for the same taxon can be quite large (Dorey et al. 2019; Goldstein and DellaSala 2020; Nati et al. 2021; Williams et al. 1997-2007), the temperature distribution of different taxa can significantly overlap in one not only stratigraphic unit and region but also even in one locality (Figure 6). To solve this problem and establish a temperature close to the existing values, we divided all taxa into several classes according to the degree of reliability and narrowness of variations in their average habitat temperatures (Williams et al. 1997-2007):

1. Reliable - temperature variations do not go beyond ± 2-3 ° C

2. Slightly varying - temperature varies ± 3-5 ° C

3. Wide temperature variations within ± 5-10 °C

4. Extreme temperature variations within ±10-15 °C

The first two gradations can be confidently used in paleotemperature assessments. The third category is also placed on the graphs for the overall framework. The fourth category was excluded from the analysis of paleotemperatures.

4. The algorithm for calculating average biotic paleotemperatures

The average biotic paleotemperatures for paleolatitudes in Siberia were determined using a 10-degree palaeolatitudinal bin for all 29 studied stages. Here we describe the algorithm for obtaining average temperatures, using the Pragian Stage as an example (Figure 5, Table 1).

First, data from the Pragian Stage in the database (DB) is compiled, and only taxa with an average thermal temperature tolerance of less than 5 °C are selected. This results in 448 records of taxa found in the studies sections (Figure 5). Taxa are then classified based on the degree of reliability and narrowness of variation in their average habitat temperatures (see Chapter 3). Of the 448 records, 347 taxa demonstrated reliable temperatures (variations ≤ 3 °C) and 101 taxa with slightly varying average temperatures (variations 3-5 °C). The average between the maximum and minimum temperatures is calculated for each record. All taxa are grouped according to paleolatitudes with a 10° bin. The resulting data can be visualized in the box plots (Figure 5a). Taxa with identical temperature variations are then grouped. To improve sampling reliability, outliers are excluded using the Tukey method (Tukey 1977) (Figure 5b). Next, the main statistical characteristics (Table 1) are obtained using the non-parametric Hodges-Lehman estimate (Hodges and Lehmann 1963; Wilcox 2021), yields, and average temperature value for each paleolatitude since our data on temperature variations have an abnormal distribution. The final temperature estimate for each paleolatitude is shown in Figure 5c, where the red line shows the trend of seawater temperature variation depending on the latitudinal position of collection within Siberia.

Table 1. Main statistical characteristics for paleolatitudes in the Pragian stage. Columns in the table: ***n*** is the number of records on temperature variations of taxa; ***n.int*** is the number of unique temperature intervals; ***HLM*** is the value of the temperature estimate for the corresponding paleolatitude using the Hodges-Lehman metric; ***Q1, Q3*** are the first and third quartiles; ***IQR*** - interquartile range.

Stage	Paleolatitude	n	n.int	HLM	Q1	Q3	IQR
Pragian	10	21	4	22.625	22.3	23.1	0.88
Pragian	20	181	11	19.625	17.5	22.0	4.50
Pragian	30	226	10	19	17.3	21.4	4.13
Pragian	40	20	3	19	18.0	20.0	2.00

5. Taxonomic level assessment of biotic paleotemperatures.

The main question at the start of the project was: At what taxonomic level can one accurately determine paleotemperatures? While this issue has been discussed for many years in modern marine invertebrates (Heip et al. 1988; Warwick 1993), it has never been addressed in paleobiology to our knowledge. We acknowledge that taxa at different taxonomic levels, such as species, genus, and family, typically occupy similar ecological niches due to their shared evolutionary history and ecological responses under certain conditions (Clarke and Warwick 1998). Hence, higher taxonomic levels can be used to quantify ecological communities (Olsgard and Somerfield 2000), a concept known as taxonomic sufficiency (Ellis 1985). Recent studies on taxonomic sufficiency in modern ecological communities have focused on various large ecological units, including marine, freshwater, and terrestrial habitats (Bevilacqua et al. 2021). The results indicate that regardless of the habitat type, genus or family-level identification is sufficient to detect changes in communities in response to natural sources of ecological variability (Fig. 6). Species-level analysis is only necessary for local and regional studies (Fig. 6) (Jones 2008; Olsgard and Somerfield 2000; Terlizzi et al. 2014). Furthermore, it is worth noting that taxa of higher rank, such as families, are less precise in determining ecological parameters and may differ significantly from parameters established by species and genera within their distribution areas (Fig. 4) (Carranza et al. 2011; Losos 2008).

6. PaleoSib DB Visualization Tools

For better accessibility and convenience in analyzing data from PaleoSib, a visualization tool was created to see all taxa paleotemperatures distributions relative to paleolatitude within the chronostratigraphic framework (Fig. 7). The core of the tool for the data analysis is the PBTV service (Paleo-Biota-Temperature-Vision). PBTV is a web application written in the R language based on the Shiny Apps web service (https://mironcat.shinyapps.io/pbtv**).** The main windows of the service is an interactive chart that shows the distribution of all established biota temperatures relative to paleolatitude (Fig. 7a). The latitudes for the Siberian Platform are shown according to the palinspastic model from the PaleoAtlas for GPlates and the PaleoData Plotter Program (Scotese 2015). The service allows the creation of two independent sample sets (red and blue) using temperature ranges that meet the selected temperature ranges. These scales are convenient for selecting and displaying warm-water (red grades) and cold-water (blue grades) taxa in the PBTV service (Fig. 7B). There is another scale to the right (Fig. 7C), which allows for setting the boundaries of thermal tolerance within the sample. In other words, the scale allows for limiting the width of the temperature range in which a particular taxon can exist. Red and blue squares on the chart display the position of the corresponding taxa. There are two checkboxes (Fig. 7D) that allow control of the display of the red and blue samples on the chart, making it possible to see where the taxa samples overlap, dominate, or are absent. The overlap area is very important for understanding the validity of the temperatures we have established since such overlap allows identifying taxa with conflicting temperatures, and establishing and resolving which of our paleotemperature data for specific taxa require clarification. It is also possible that some of these taxa have a significantly wider level of thermal tolerance to habitat temperatures than is usually considered. Two other checkboxes (Fig. 7D) allow you to see global temperatures established using lithologic indices (Scotese et al. 2021) and the presence of collections in different parts of the chronological scale. The next block (Fig. 7E) displays the main statistics of the sample (the number of selected records in the database, taxa, collections, and temperature range).

The PBTV service also enables interactive selection of specific points on the graph (Fig. 8A) so that their position is immediately displayed on the map below the distribution graph of taxa over timescale (Fig. 8C-8D). On the left side of the map (Fig. 8B-8C), a list of all selected taxa is automatically generated with their main attributes (belonging to the red or blue group of taxa, collection age where the taxon is found, absolute age in millions of years, name of the subbasins (SFZ), full stratigraphic distribution of the taxon and its associated formation, taxon's Latin name, mean temperature of its habitat (min.-max.), modern and paleo-coordinates, and the temperature range of each highlighted taxon (Fig. 8C). By selecting (clicking on) any taxon or group of taxa, its taxonomy and paleotemperature indices for each taxon, as well as its real position on the map (blue and red dots), can be immediately viewed (Fig. 8B-D) All of these capabilities help to assess problems with conflicting paleotemperatures and paleotectonics.

An example from the southeastern periphery of the Siberian platform helps to illustrate the use of the tool. Here, the so-called Tukhinsky sub-basin is distinguished (Ruzhentsev and Nekrasov 2009). The existing geodynamic models for the formation of this sub-basin are contradictory (Khanchuk et al. 2015; Parfenov et al. 2001; Safonova and Santosh 2014). On the paleogeographic map of Scotese (Scotese et al. 2021), it is shown as part of the Siberian platform terrains, i.e., located in the Permian period at least in mid-latitudes or higher. However, the taxa encountered in this sub-basin indicate that this structure during Permian was in a tropical zone (mean temperatures ~ 20–22° C) (Fig. 9), i.e., at a significant distance to the south of the Siberian platform and have not been a part of the platform. This example demonstrates that when the PaleoSib BD project is fully implemented, some paleotectonic problems can be practically solved by anyone who needs this, including a wide range of geologists of different specialties. This opportunity will not require special knowledge of paleontology, taxonomy, and ecology of the fossils, just their names, locations, and bathymetry.

7. Biotic paleotemperature indices and the position of the Siberian Platform in time and space during the Upper Paleozoic and Lower-Middle Triassic

The established biota average temperature estimations reveal the main climate trends within Siberia through the Late Paleozoic time. The two largest factors that affect the paleotemperature change in the region: are paleo-tectonics and global-regional paleoclimate fluctuations. When large plates move laterally, especially the large ones such as the Siberian Platform, they might cross several climatic zones and, accordingly, paleotemperatures in shallow water basins are changing within the platform. At the same time, the borders of climatic zones on the earth vary depending on the global climate. During global warming, the boundaries of all climatic zones shift towards the poles. During global cooling, the zone boundaries shift towards the equator (Brito-Morales et al. 2020; Burrows et al. 2011). The Late Paleozoic epoch is precisely characterized by a contrasting change in the global climate (Fig. 10), often referred to as the "Late Paleozoic Ice Age (LPIA)" (Fielding et al. 2008). At the same time, however, glaciations occurred in pulsations and the climate during interglacial periods could be quite warm (Davydov et al. 2013; Davydov 2014; Fielding et al. 2023; Montanez and Poulsen 2013; Montañez 2022). Both factors should be taken into account when interpreting

paleotemperatures, especially in the case of the Siberian Platform, where the significant influence of both tectonics and global climate is obvious (Boucot et al. 2013).

According to the paleomagnetic data, at the beginning of the Devonian, the southern part of the Siberian Platform was located at paleolatitudes from 20° N (modern northern part of the platform) to ~ 40° N in the north (modern southeastern part of the platform) (Domeier and Torsvik 2014; Metelkin et al. 2015). The obtained average paleotemperature in Siberia at this time varies from 22 to 17°C (Fig. 10), depending on the latitudinal location of the data on the platform (paleo-north – paleo-south). According to these data, the Siberian platform in general was located in the subtropics (~ 20–25° N), but its northern margin probably also extended into the warm-temperate zone (Fig. 1). Starting from the Eifelian to the Frasnian, there is a slight temperature drop of about 1–2°C (Fig. 10–11), which is most likely associated with a slight northward migration of the Siberian Platform. This assumption, in addition to the temperature drop on the Siberian platform, is substantiated by the significant increase in global temperatures at this time, the trend of which is rising in the opposite direction (significant warming at the global scale) than on the platform (Fig. 10b) (Joachimski et al. 2004; Scotese et al. 2021). This trend of falling paleotemperatures persists to the end of the Devonian and into the beginning of the Carboniferous, although the overall fall in paleotemperatures in the Siberian Platform is small. In Visean time, a significant decrease in paleotemperatures by ~ 3–5°C was observed (Fig. 10A). At the same time, significant warming and extensive reef development (Hoenisch et al. 2012; Kiessling et al. 2002) characterize the global Visean climate. All this speaks in favor of the fact that the speed of the Siberian Platform movement to the north at the beginning of the Visean approximately doubled (Fig. 10).

During the Serpukhovian-Bashkirian, there is a sharp drop of the average temperatures in the Siberian Platform basins by ~ 7–8°C, which is associated with a series of global glacial episodes, which are well documented in the Southern Hemisphere (Fig. 10) (Fielding et al. 2023; Griffis et al. 2023; Rosa and Isbell 2021). In the Serpukhovian and Bashkirian, the trends in the distribution of paleotemperatures to latitudes within the Siberian Platform are especially clear. In the paleo-north of the platform, temperatures are much lower than in its paleo-south (Fig. 10A). All this indicates that the Siberian Platform at that time was still in the middle latitudes (~ 45–50°), and glacial deposits could hardly have formed here (Banzon et al. 2014; Dowsett et al. 2009; Dowsett et al. 2012; Maturi et al. 2017).

During the Moscovian of Pennsylvania and up to the Capitanian of the Middle Permian, that is, during ~ 37 Myrs, the paleotemperatures in the Siberian Platform basins vary slightly, being in the range from 4 to 10 ° C (Fig. 10). The temperature at all latitudes in the Siberian Platform differs very little. They decreased slightly during the proposed glacial episodes (P1-P3) and increased slightly during the interglacial times documented in the Southern Hemisphere (Fig. 10). All this means that the Siberian Platform was located approximately at the same latitudes, possibly very slowly migrating northward. The biota diversity at this time remains unchanged (Fig. 11).

The development of glacial deposits in Pennsylvania and Early Permian in the absence of high mountains is not to be expected on the Siberian Platform, which was in the middle latitudes at that time. Nevertheless, some studies suggest the development of glacial deposits in the Moscovian and Sakmarian in various regions of Siberia and Novaya Zemlya (Povysheva and Ustritsky 1988; Ustritsky et al. 1971). The sediments of the diamictite type in Novaya Zemlya have been studied superficially. A thorough study of these Sakmarian diamictites of Novaya Zemlya revealed that they are turbidites, and not glacial deposits (Povysheva and Ustritsky 1996). The presence of the glacial deposits on the Siberian platform in Pennsylvania and early Permian still needs to be studied and verified.

During the Middle Permian, the climate on the Siberian Platform displays reasonably constant paleotemperatures and the platform possesses a position a high middle latitude. Despite this, typical glacial-marine deposits have been discovered there recently (Davydov et al. 2022). These deposits are distributed in the most paleo-northern part of the platform (Fig. 12). Glacial-marine deposits are found at three stratigraphic levels: (1) late Roadian-early Wordian; (2) early Wuchiapingian and (3) middle Changhsingian (Davydov et al. 2022). At the very end of the Changhsingian and during Induan, there was a sharp and noticeable increase in paleotemperatures from ~ 5°C to 12–13°C (Fig. 10B). Paleotemperatures during the rest of the Triassic period remain approximately at the level of 12–14°C and their values do not change during this time. Simultaneously with the Late Permian-Triassic warming, a sharp diversification of Siberian biota occurred, and the diversity increased by about 2–3 times (Fig. 11). In terms of global paleotemperatures, it is assumed that at the end of the Early Permian and during the rest of the Permian, paleotemperatures increased sharply from ~ 12°C in the Kungurian to 25°C in the Changhsingian (Fig. 10B) (Scotese et al. 2021). Apparently, at that time, the SP migrated to the north, but it is unlikely to be higher than ~ 60–65° N (Fig. 12), since thick coals continued to form on the platform at that time (Cherepovskiy 2001, 2003). Under modern interglacial conditions, the accumulation of peat, which subsequently transforms into coal, mainly occurs at latitudes south of the Arctic Circle at 66.5° N (Kopansky et al. 2022).

8. Conclusion

This article proposes a new method for estimating paleotemperatures from the proxy of paleontological taxa of generic to family levels in various paleoecological settings. We are at the very beginning of creating a reliable basis for estimating biotic paleotemperatures, but our goal is to develop a tool that will help solve various kinds of geological problems. The approach to the database and tools presented here is not limited to any particular stratigraphic interval or taxonomic group. If this work attracts the attention of paleontologists studying a wide array of taxonomic groups, then the proposed database can become a reliable tool for both paleontologists and geologists of different specialties. With the improvement of the taxa estimates that we proposed here and a more complete database from various regions, a wide range of problems in geology, including paleoclimatology, paleogeography, paleooceanology, paleobiogeography, paleotectonics, and possibly several others could be addressed. Until now, paleoclimates of various epochs have been reconstructed from indirect proxies—the composition texture, and geochemistry of sedimentary rocks. Paleo-biotas, their spatial distribution, and taxonomic composition undoubtedly play a significant role in this respect. Up-to-date data and models of modern ecology, climatology, meteorology, geography, geochemistry, geophysics, and astronomy are of great importance for the further developments of the method of biotic paleotemperature establishment. The approach proposed in this article significantly complements all the methods listed above.

Declarations

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The PaleoSib relational database consists of seven tables with raw data that are uploaded in CSV

format to the Zenodo repository and can be accessed at: https://doi.org/10.5281/zenodo.8286567, 2023 (Davydov et al. 2023). The Zenodo repository also contains several tables that contain prepared data for the PBTV Shiny Application. The source code of the PBTV. The source code of the PBTV Shiny

Application is available under a CC BY 4.0 license on GitHub (Karasev, 2023; https://github.com/mironcat/pbtv, last access: 10 September 2023)

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Figures

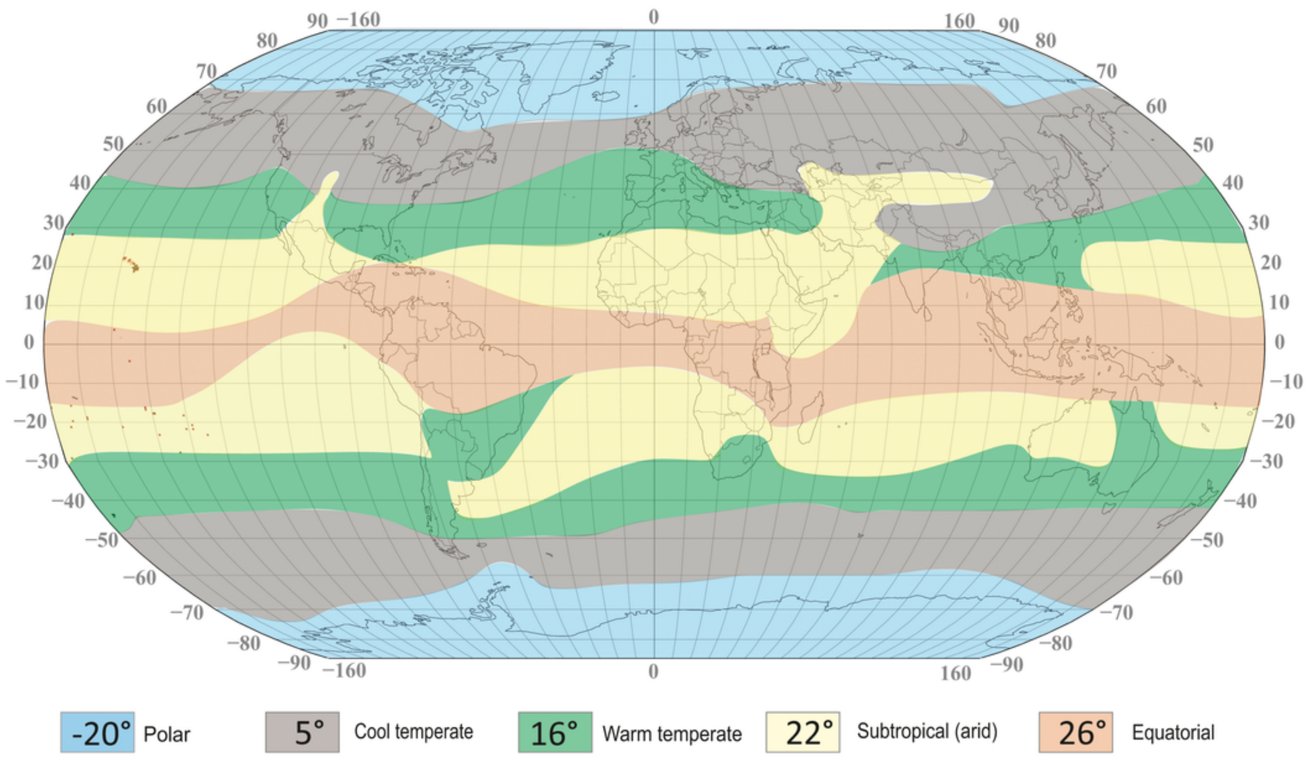


Figure 1

Simplified model of climatic zones of the Köppen model (1923) and average temperatures in each zone (map modified from Scotese et al. 2021).

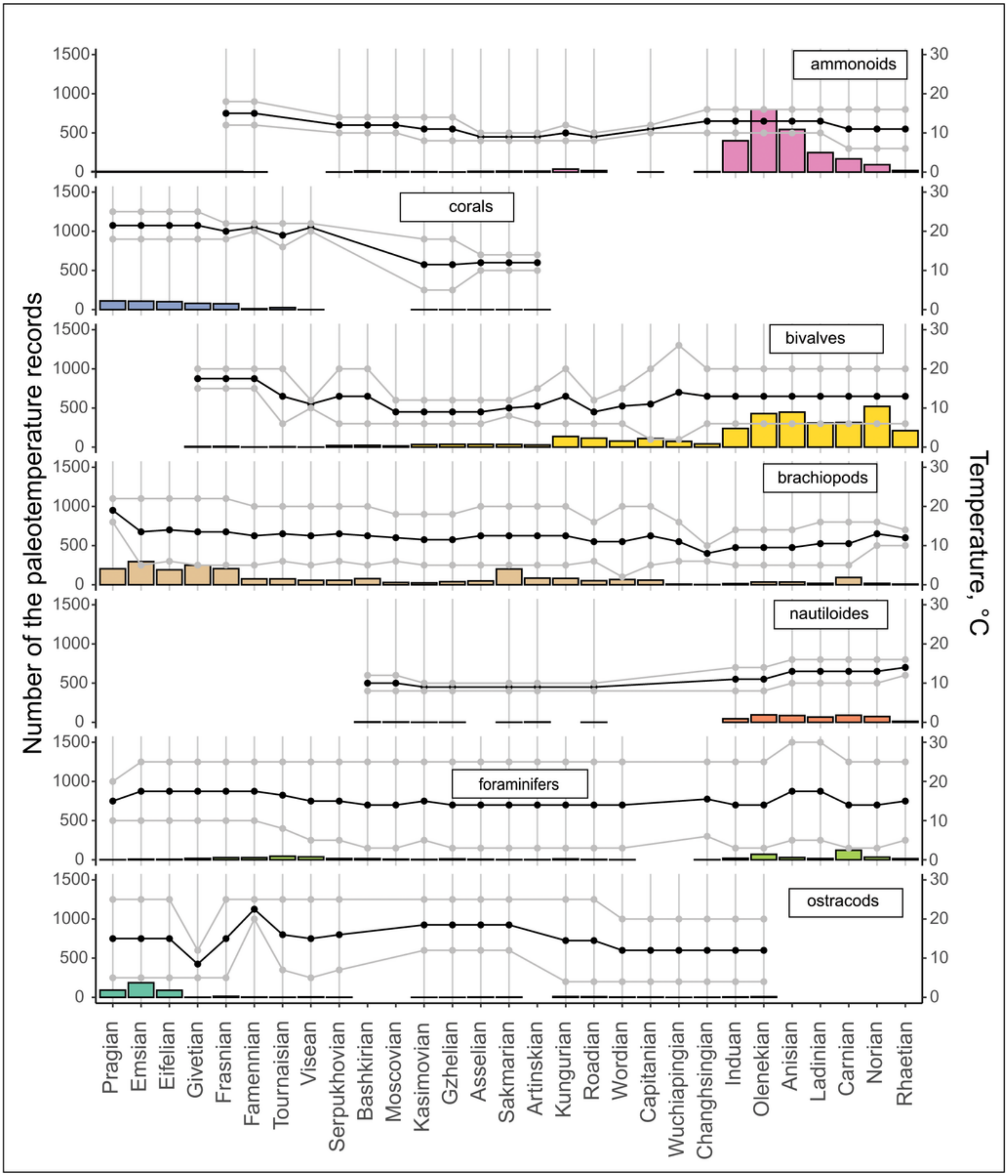


Figure 2

Maps of taxonomic diversity of species in the oceans (A) and average ocean surface temperatures (B). Taxonomic diversity is calculated as the number of species in 50 random samples in each 5° latitude-longitude cell (51,670 species) (Costello and Chaudhary 2017). The greatest biodiversity is observed in the tropical and subtropical zones. Diversity decreases towards the poles. Distribution of mean annual ocean surface temperatures according to (Banzon et al., 2014). In the tropics and subtropics, as well as in the polar latitudes, the isotherms are at a considerable distance from each other and there are many taxa with a narrow thermal tolerance. At middle and high latitudes, isotherms are very concentrated, and taxa are adapted to exist within a wider thermal tolerance. At latitudes above 60°, tolerance decreases sharply (Deutsch et al. 2020; Dorey et al. 2019; Stuart-Smith et al. 2017; Sunday et al. 2011).

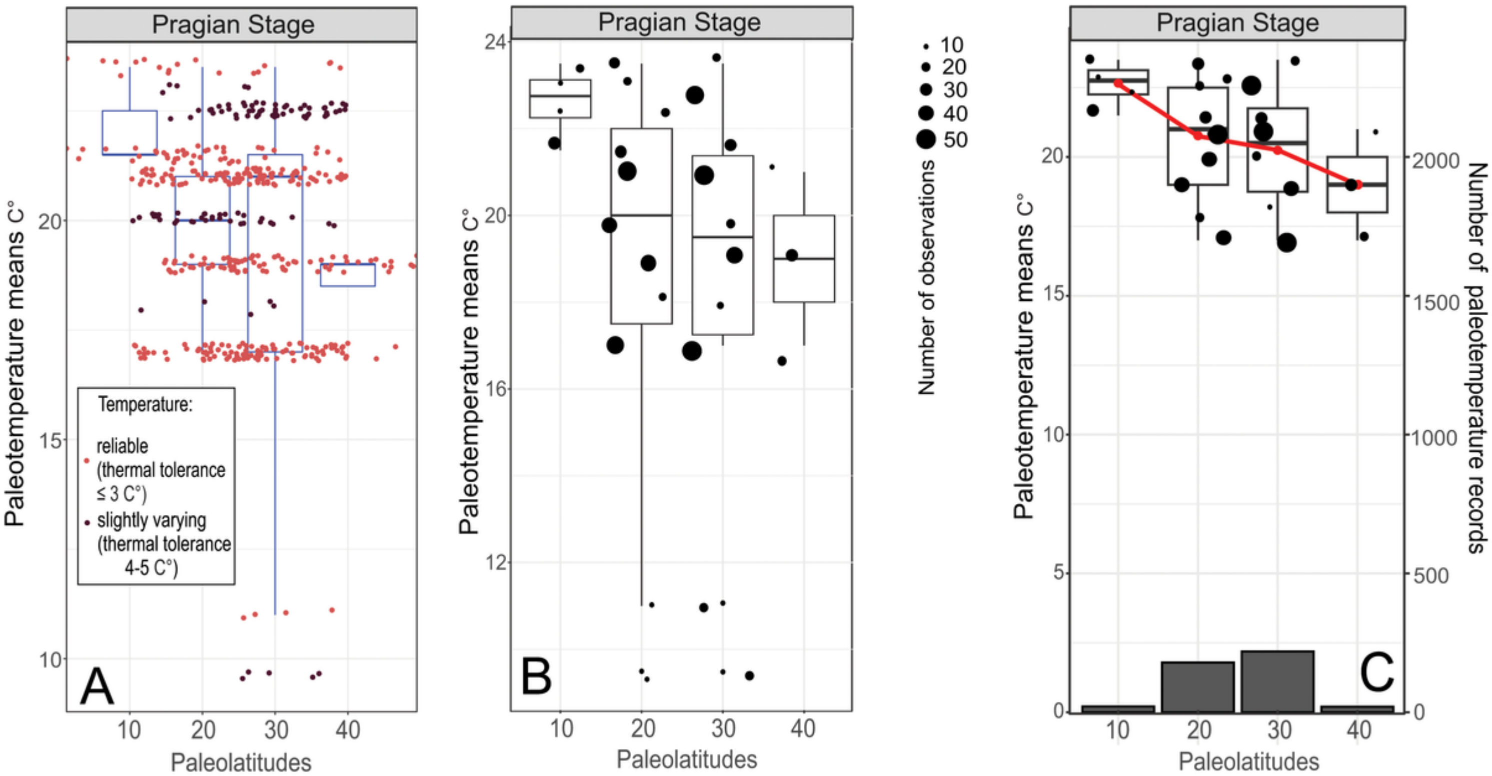


Figure 3

Temperature distribution in the central part of the Pacific Ocean. **A**, the vertical temperature cross-section at depths. The thermocline between warm and cold water is located at a depth of ~ 1000 m. **B**, the longitudinal cross-section of the distribution of temperature isotherms over the latitudes. Most ocean water is colder than 4°C (modified from Pinet 2019, p.560).

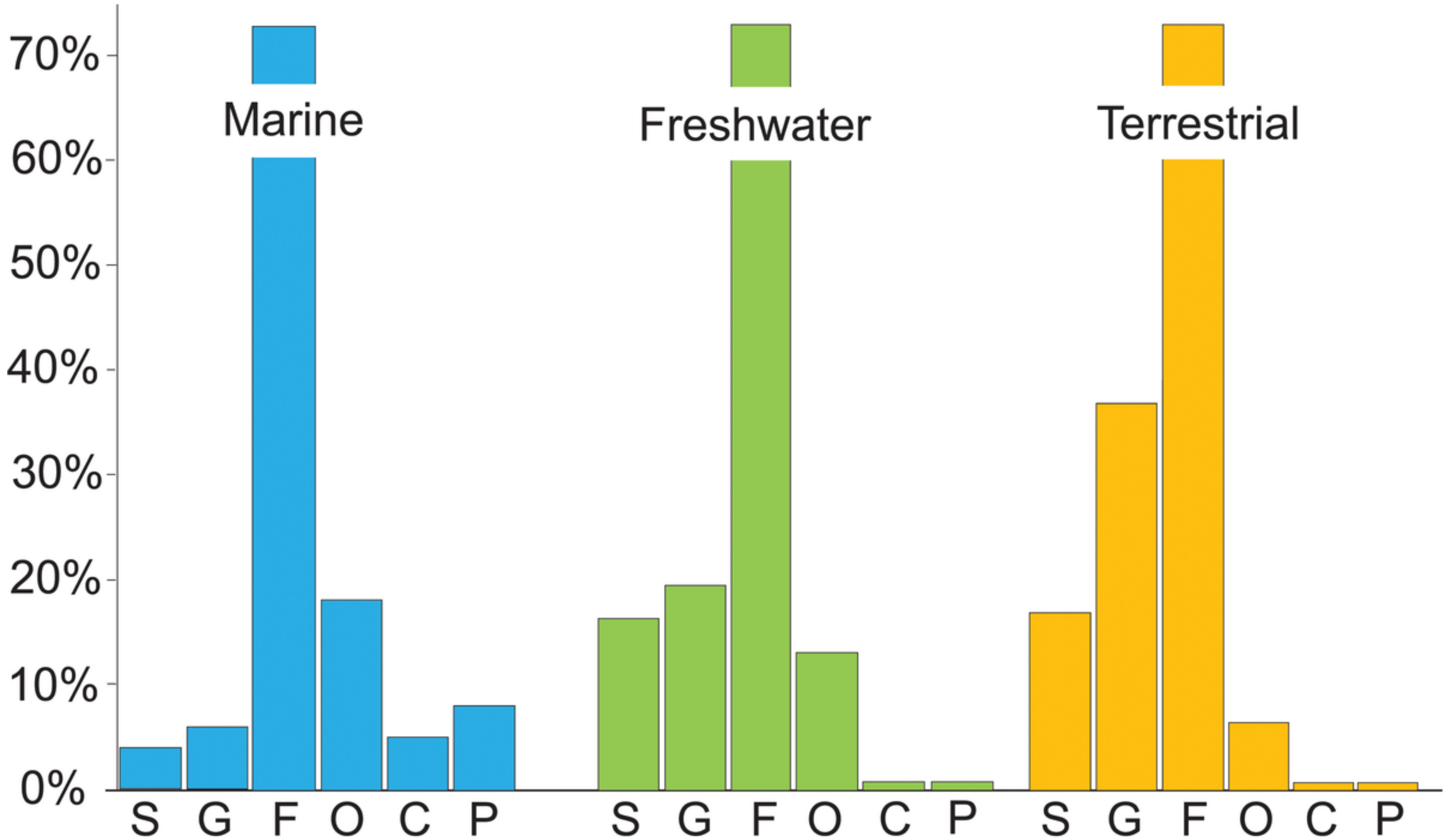


Figure 4

Taxonomic composition, number of observations, paleotemperatures, and distribution of taxa in the PaleoSib database by age. The number of collections is shown as a histogram, whereas the paleotemperatures - the means (solid line), minimal, and maximum values for the respective latitudes and climate zones.

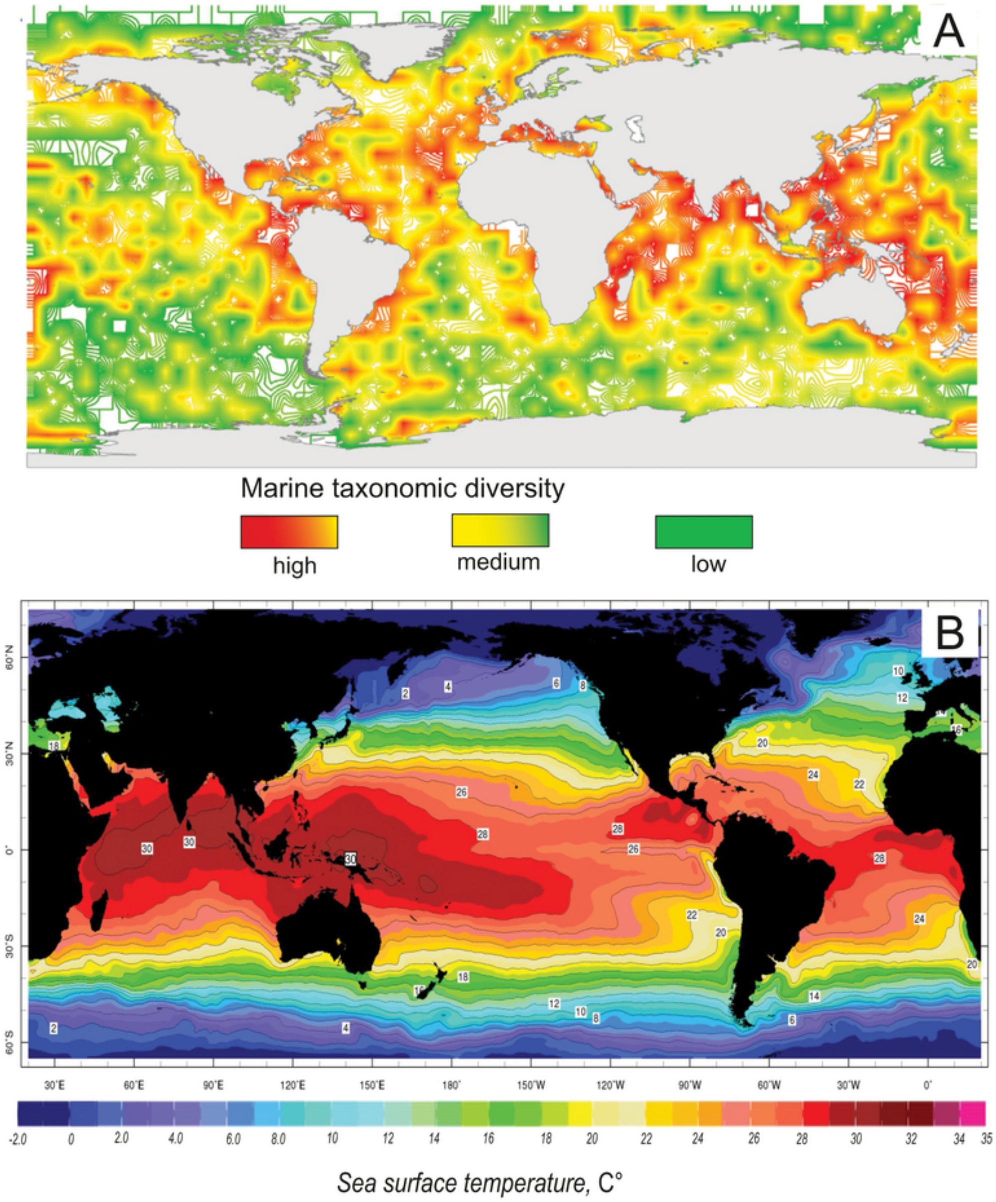
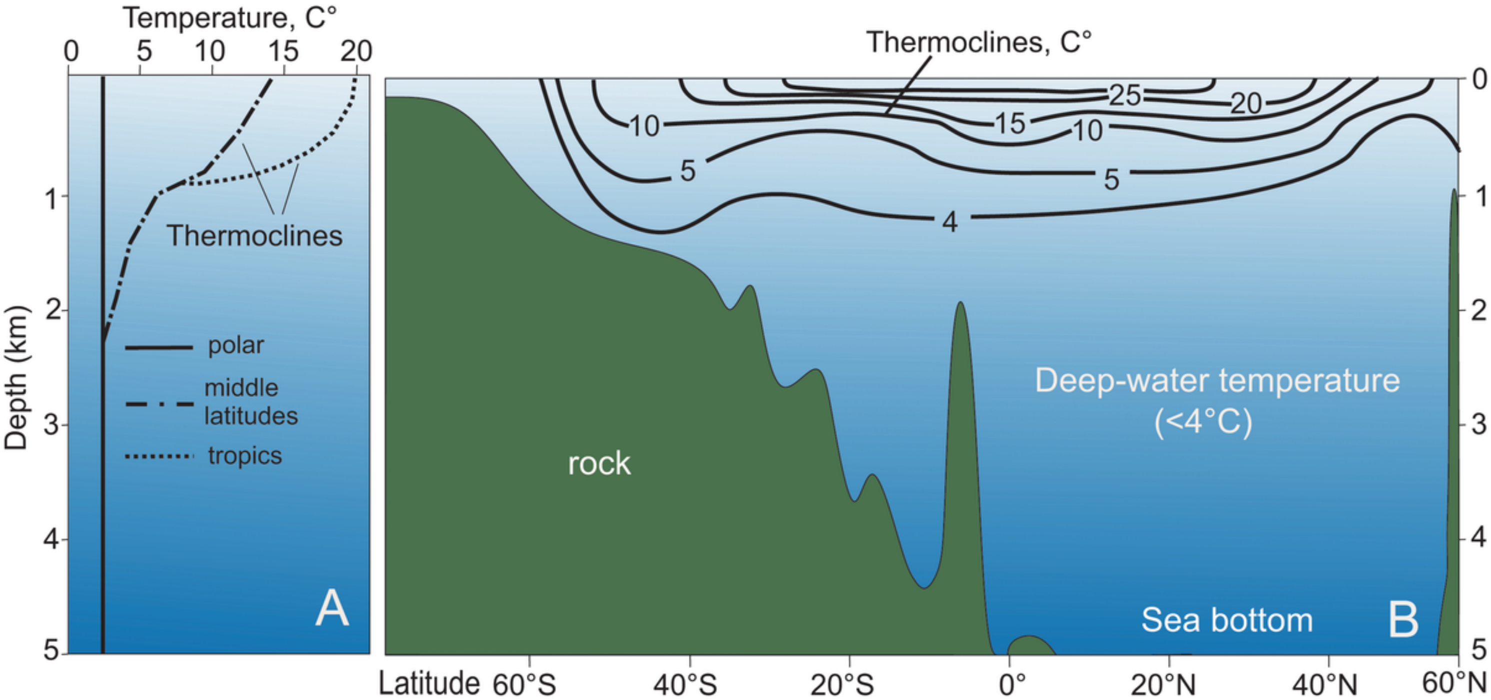


Figure 5

The sequence of data filtering with statistical methods to obtain the Pragian data analyzed the dynamics of the paleotemperatures over time in Siberia. See the explanations in the text. **A** - Visualization of the obtained values for the average biotic paleotemperatures in different paleolatitudes. **B** - Visualization of the obtained values of identical temperature variations; the size of the dots shows the number of records of the corresponding interval. **C** – the final result of temperature estimation for each paleolatitude; the red line shows the trend of change obtained with Hodges-Lehman statistics (Hodges and Lehmann 1963) paleotemperature estimate depending on paleolatitude. The bar charts at the bottom - the quantity of the data.



A, Temperature profiles; B, Temperature distribution (°C) in central Pacific Ocean

Figure 6

The percentage of taxa at different taxonomic levels for marine, freshwater, and terrestrial community types, and the proportion of taxa at different taxonomic levels that is sufficient to define ecological patterns (including temperature) in general terms; **C**, class; **G**, genus; **F**, family; **O**, order; **P**, phylum; **S**, species. (After Bevilacqua et al. 2021). The figure shows that for reliable estimates of ecological conditions for marine communities over large areas, it is best to use data at the level of families and, to a lesser extent, orders; for freshwater and terrestrial communities - at the level of families, genera, and species.

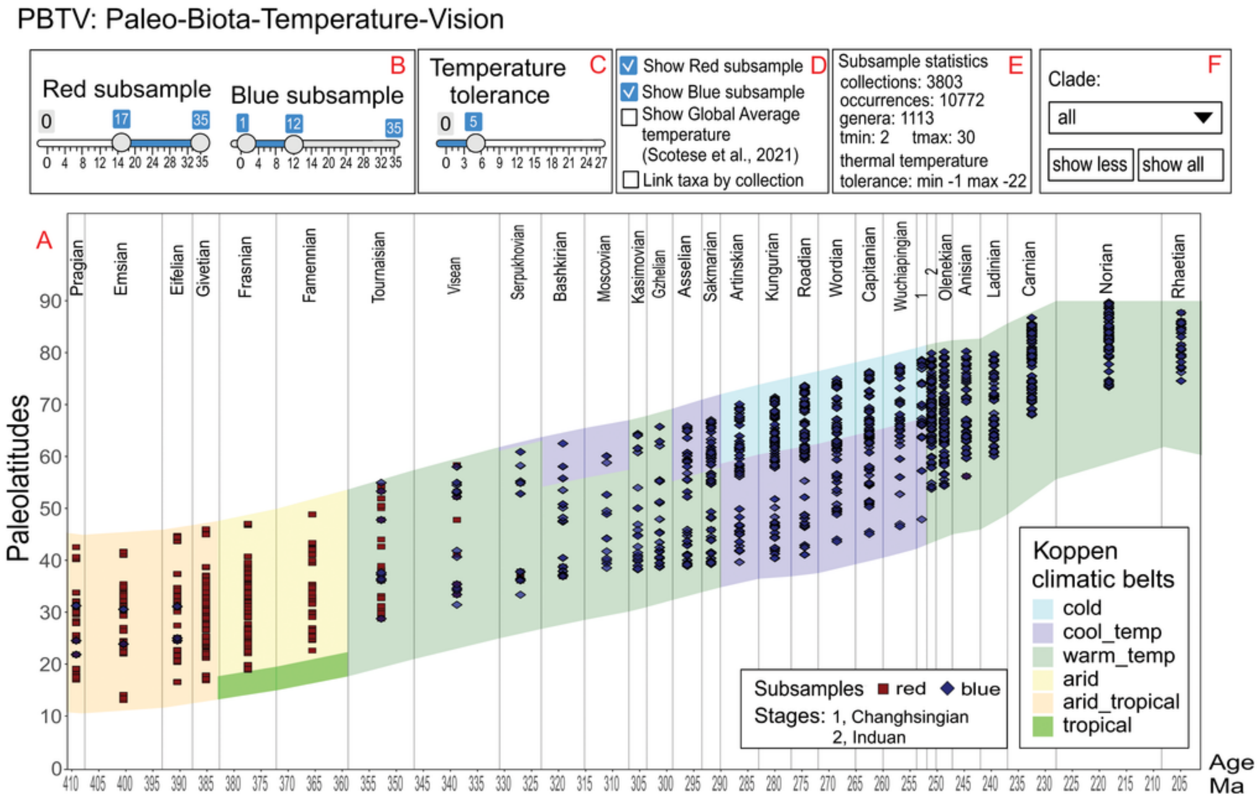
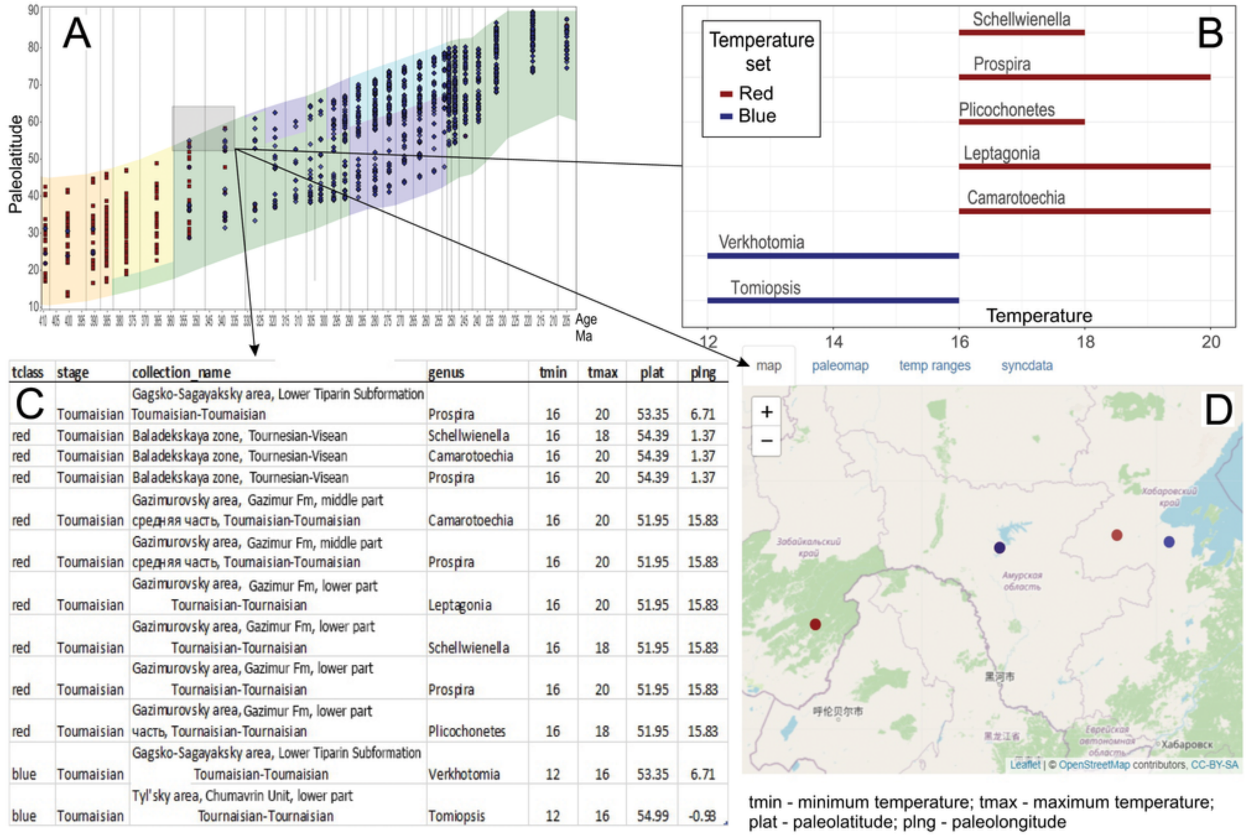


Figure 7

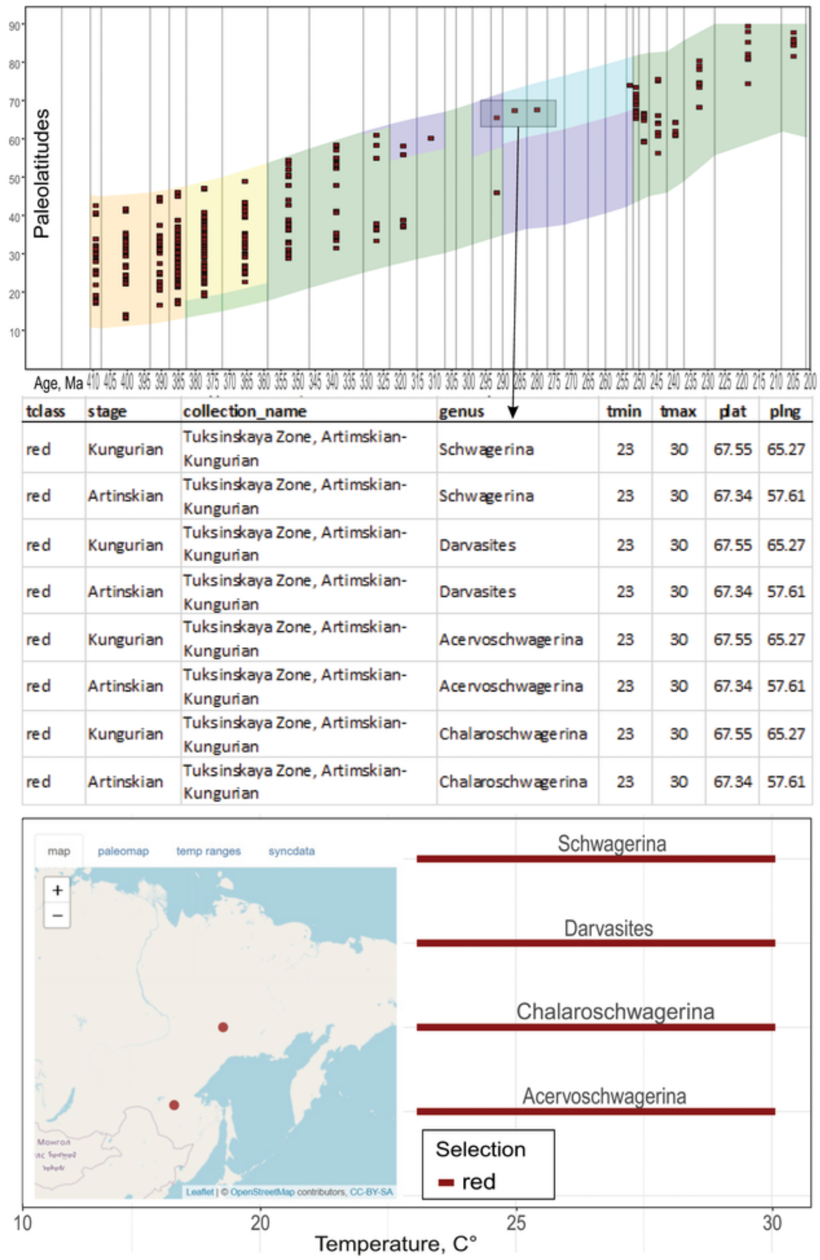
Interactive graphic of the distribution of taxa with given paleotemperatures in time and space in the Siberian Platform during the Upper Paleozoic. The color in the center shows the climatic zones according to Boucot et al. (2013) divided into tiers by vertical lines. Other explanations are in the text.



tclass	stage	collection_name	genus	tmin	tmax	plat	plng
	Toumaisian	Gagsko-Sagayaksky area, Lower Tiparin Subformation Toumaisian-Toumaisian	Prospira	16	20	53.35	6.71
red	Toumaisian	Baladekskaya zone, Tournesian-Visean	Schellwienella	16	18	54.39	1.37
red	Toumaisian	Baladekskaya zone, Tournesian-Visean	Camarotoechia	16	20	54.39	1.37
red	Toumaisian	Baladekskaya zone, Tournesian-Visean	Prospira	16	20	54.39	1.37
red	Toumaisian	Gazimurovsky area, Gazimur Fm, middle part средняя часть, Toumaisian-Toumaisian	Camarotoechia	16	20	51.95	15.83
red	Toumaisian	Gazimurovsky area, Gazimur Fm, middle part средняя часть, Toumaisian-Toumaisian	Prospira	16	20	51.95	15.83
red	Toumaisian	Gazimurovsky area, Gazimur Fm, lower part Tournaisian-Tournaisian	Leptagonia	16	20	51.95	15.83
red	Toumaisian	Gazimurovsky area, Gazimur Fm, lower part Tournaisian-Tournaisian	Schellwienella	16	18	51.95	15.83
red	Toumaisian	Gazimurovsky area, Gazimur Fm, lower part Tournaisian-Tournaisian	Prospira	16	20	51.95	15.83
red	Toumaisian	Gazimurovsky area, Gazimur Fm, lower part часть, Tournaisian-Tournaisian	Plicochonetes	16	18	51.95	15.83
blue	Toumaisian	Gagsko-Sagayaksky area, Lower Tiparin Subformation Toumaisian-Toumaisian	Verkhotomia	12	16	53.35	6.71
blue	Toumaisian	Tyl'sky area, Chumavrin Unit, lower part Tournaisian-Tournaisian	Tomiopsis	12	16	54.99	-0.98

Figure 8

Visualization tool for paleotemperature and biotic data in the Siberian platform through time. A, the distribution of temperatures relative to paleolatitude on the Siberian platform. The paleolatitude data were obtained from GPlates (Boucot et al. 2013). Each point on the graph represents a temperature from a specific collection in a particular sub-basin; B, the second window with the list of all taxa at the selected point, and their thermal tolerance; C, a list of collections from different sub-basins; D, the position of the selected collections on a modern geographical map. If necessary, the paleogeographic map projection can be selected to show the selected points in paleo-projection.



tclass	stage	collection_name	genus	tmin	tmax	plat	plng
red	Kungurian	Tuksinskaya Zone, Artimskian-Kungurian	Schwagerina	23	30	67.55	65.27
red	Artinskian	Tuksinskaya Zone, Artimskian-Kungurian	Schwagerina	23	30	67.34	57.61
red	Kungurian	Tuksinskaya Zone, Artimskian-Kungurian	Darvasites	23	30	67.55	65.27
red	Artinskian	Tuksinskaya Zone, Artimskian-Kungurian	Darvasites	23	30	67.34	57.61
red	Kungurian	Tuksinskaya Zone, Artimskian-Kungurian	Acervoschwagerina	23	30	67.55	65.27
red	Artinskian	Tuksinskaya Zone, Artimskian-Kungurian	Acervoschwagerina	23	30	67.34	57.61
red	Kungurian	Tuksinskaya Zone, Artimskian-Kungurian	Chalaroschwagerina	23	30	67.55	65.27
red	Artinskian	Tuksinskaya Zone, Artimskian-Kungurian	Chalaroschwagerina	23	30	67.34	57.61

Figure 9

The PBTV service provides the immediate visualization of temperature deviations from the overall trend. In this case, it is shown that in the Tuksynskaya SFZ, paleotemperatures are characteristic of a tropical belt. This means that during the Permian period, this SFZ was located far to the south of the Siberian Platform and other terrains with cold-water fauna. The square and arrows indicate the position of the

Tuksynskaya zone's biota, the location of this zone on the map, and the range of paleotemperatures for each taxon.

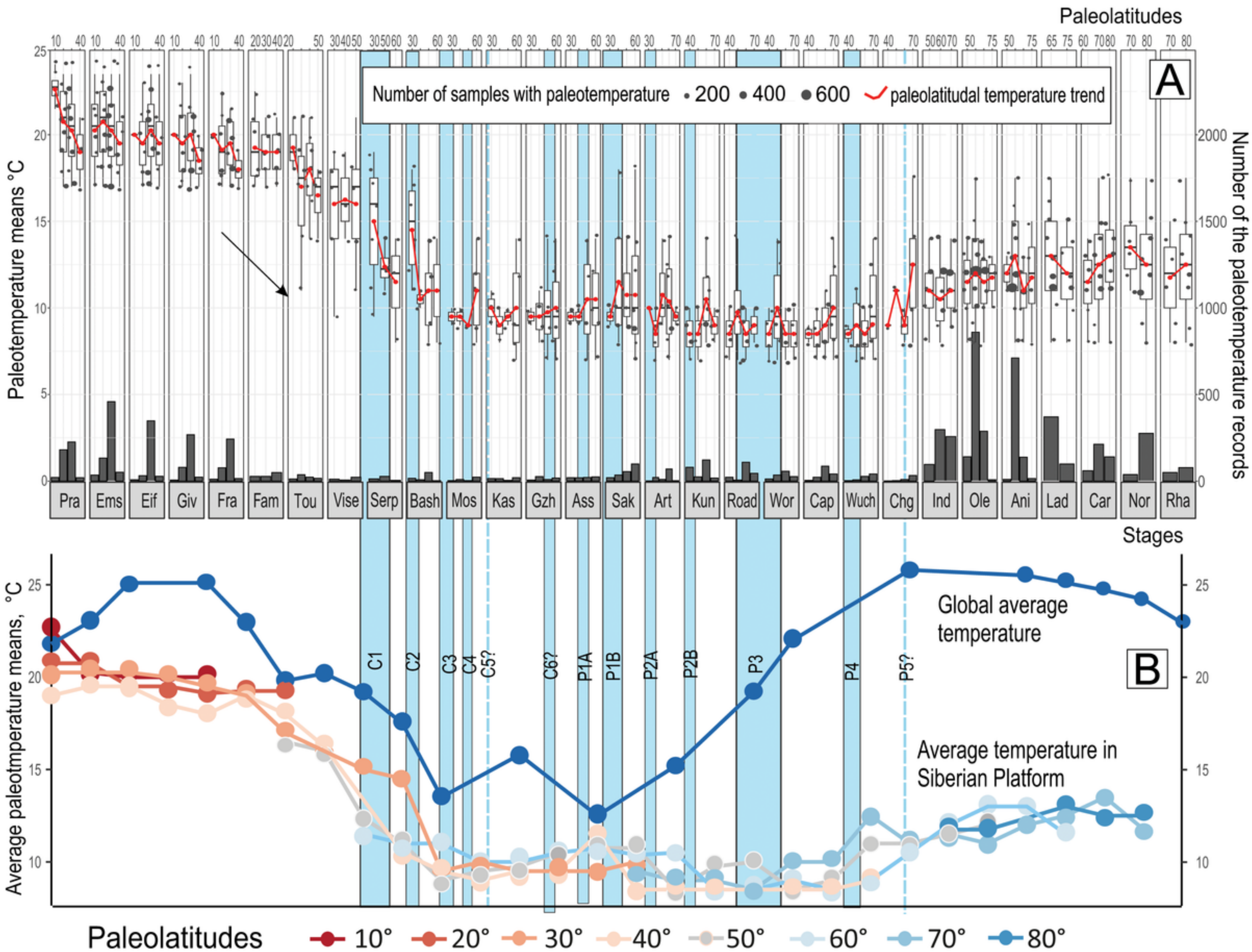


Figure 10

Distribution of paleotemperatures on the Siberian Platform during the Devonian-Triassic. **A,**Mean biotic paleotemperatures and their distribution relative to the latitudinal position on the Siberian Platform. Dots show the value of the thermal tolerance of taxa. Below - is the occurrence of all taxa in different sub-basins and separate outcrops. Blue-shaded zones are glacial episodes in Gondwana and Siberia. The arrow on the left in Figure 10a shows the moment of the sharp tectonic displacement of the Siberian Platform towards the north. **B**, Trends of average paleotemperatures on the Siberian Platform relative to the latitudes of the Siberian Platform proposed by (Boucot et al. 2013), and their comparison with global average paleotemperatures from (Scotese et al. 2021).

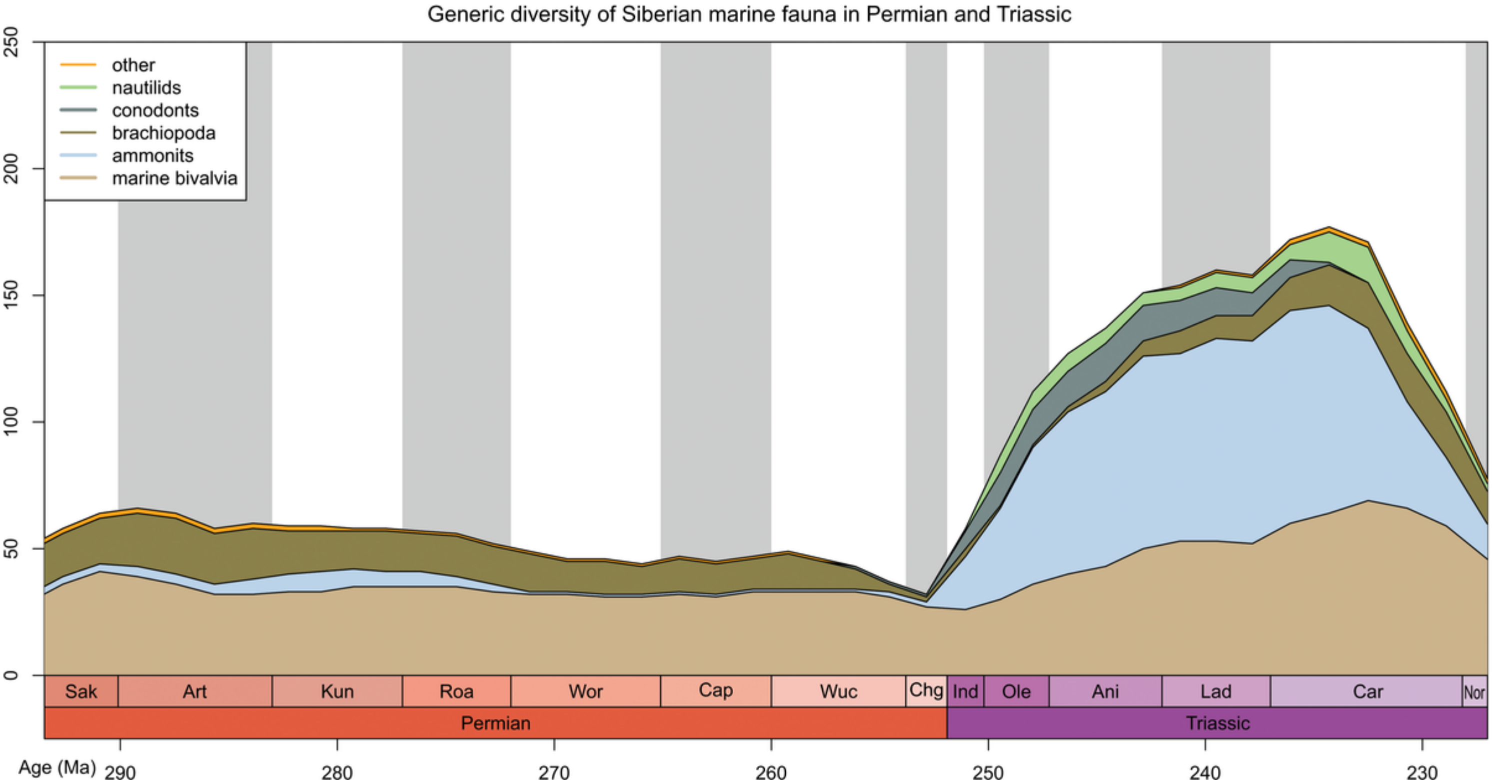


Figure 11

Generic diversity of Siberian marine fauna in the Permian and Triassic (Davydov 2021). It can be seen that the climate changed little during the Permian, while a sharp warming occurred in the Triassic, which led to an increase in diversity.

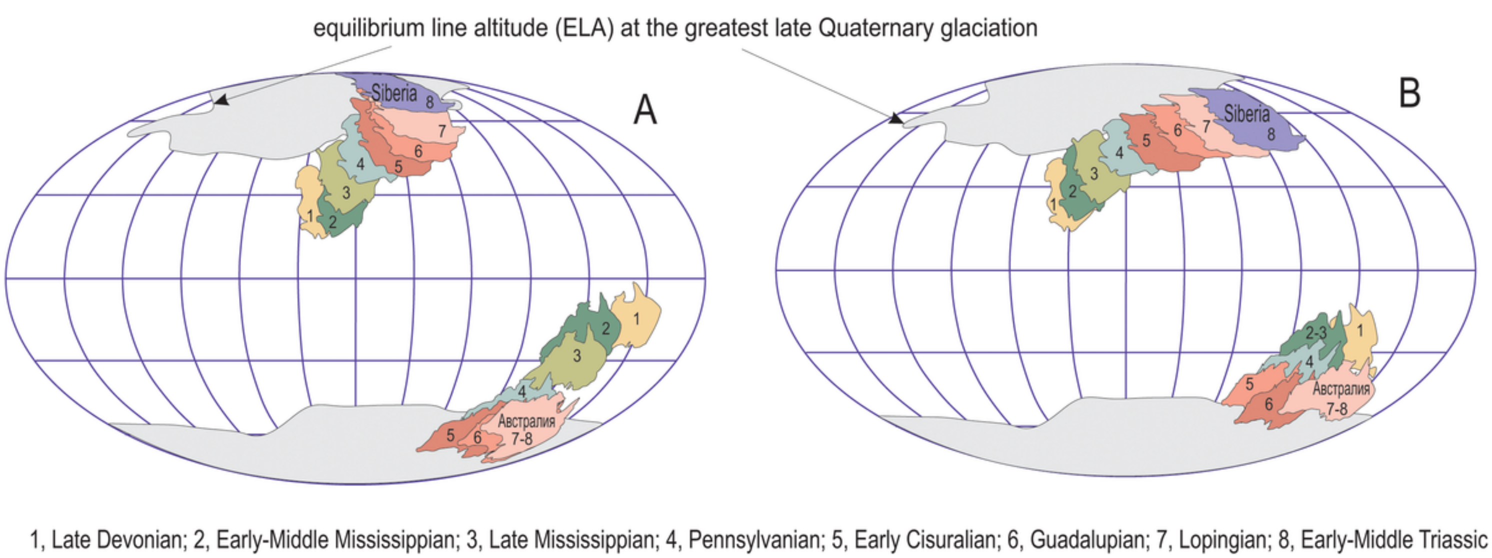


Figure 12

Paleogeographic reconstructions of the position of the Siberian and Australian cratons within climatic zones during the Late Paleozoic. A – according to paleomagnetic and data on detrital zircons (Ershova et al. 2016; Ershova et al. 2022; Khudoley et al. 2018; Miller et al. 2008); B – estimated from paleotemperature biotic data from PaleoSib DB.