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Permian to earliest Cretaceous climatic oscillations in the eastern Asian continental margin (Sikhote-Alin area), as indicated by fossils and isotope data

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Abstract: Palaeozoological, palaeobotanical and geochemical analyses of Lower Permian to the lowermost Cretaceous sediments exposed in the southern Russian Far East (Bureya–Jiamusi–Khanka superterrane and the Sergeevka terrane), and higher latitude areas (northern Russian Far East and Spitsbergen) suggest a direct relationship with global climatic events defined by the data from oxygen-isotopic palaeotemperatures. Several positive carbon-isotopic anomalies discovered within the uppermost Cisuralian, Guadalupian, early Lopingian and Aalenian–Bajocian intervals are possibly connected to strong hydrological intermixing of oceanic waters under the influence of considerable thermal gradients.

Keywords: Permian, Triassic, Jurassic, Cretaceous, fossils, palaeotemperatures, carbon-isotope anomalies, Russian Far East, Spitsbergen.

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Introduction

The interpretation of climatic change seen in the late Paleozoic to middle Mesozoic deposits remains a matter for extensive discussion (Francis 1994; Golonka et al. 1994; Larsson et al. 2000; Mei & Henderson 2001; Vajda 2001; Chumakov 2004; Chen et al. 2005; Korte et al. 2005a, 2005b; Hyde et al. 2006; Shen et al. 2006; Galfetti et al. 2007; Yin et al. 2007; Jansson et al. 2008). The southern Russian Far East (South Primorye, or Ussuri region, and Lesser Hingan, Fig. 1) offers a highly favourable area for palaeoclimatological investigation of Permian to Early Cretaceous marine and terrestrial sequences, yielding diverse fossil fauna and flora.

The main aim of this study is to show the evidence of climatic changes seen in the Sakmarian to Berriasian sediments of the southern Russian Far East using articulate brachiopod, mollusc and floral successions, correlated with global oxygen and carbon-isotope events on the basis of published and original data.

Materials and methods

Invertebrate and plant remains, which compose the traditional basis for marine and non-marine Permian to Lower Cretaceous biostratigraphy, as well as original data from the isotopic composition of some Permian organogenic carbonates are used in this study for palaeoclimatic reconstruction. Certain data on Permian plants and brachiopods and Late Triassic bivalve molluscs of South Primorye were taken from Kiparisova (1972), Burago & Kotlyar (1974), Burago (1979, 1983, 1986, 1990), Kotlyar et al. (1989, 2006) and Okuneva (2002), respectively. However, herein we have investigated Permian to Early Cretaceous fossils, and analysed the carbon and oxygen isotopic composition of Permian organogenic carbonates from the north Far East Russia and Spitsbergen.

The following methods were used to determine diagenetic alterations in the calcite: (1) visual signs; (2) degree of integrity of microstructure under a SEM; (3) preliminary luminescent test using a JXA–8200 (JEOL, Tokyo, Japan) microanalyser and (4) preliminary metallic-element measurements. Results obtained show that the analysed invertebrate shell material fulfils diagenetic screening criteria and the samples were therefore considered suitable for both carbon-isotope and, in some cases,

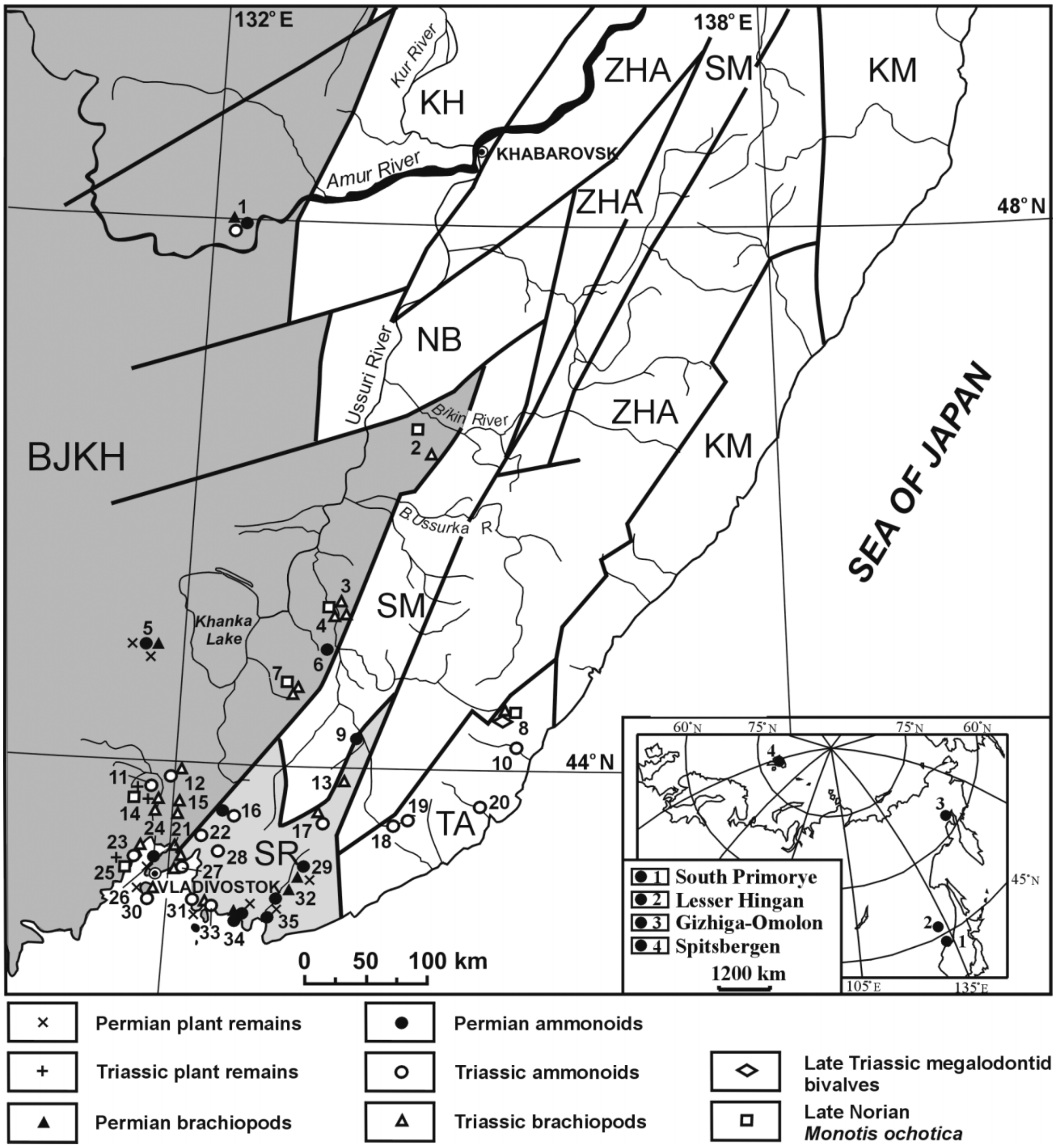

Fig. 1. Distribution of Permian and Triassic macrofossils in different terranes of the Sikhote-Alin area, southern Russian Far East, showing southeastern, eastern and northeastern configuration of the shallow-water sea basin, named the Ussuri-Lesser Hingan Sea, within the bounds of the BJKH and the SR. Other terranes include: SM, Samarka; ZHA, Zhuravlevka-Amur; KM, Kema; NB, Nadanhada-Bikin; KH, Khabarovsk (based on terrane maps of Golozubov (2006) and Kemkin (2006)). Localities: 1, Lesser Hingan, Bolshiye Churki; 2, Bikin River basin (Marevka and Ulyanovka); 3, Malinovka River basin; 4, Krylovka River basin (Krylovka and Gornaya); 5, Pogranichnyj village; 6, Arsenyevka River basin (Lagernyj); 7, Yakovlevka and Andreevka villages; 8, Dalnegorsk area (Nezhdanka); 9, Pavlovka River basin (Levaya Antonovka); 10, Kavalerovsky Creek; 11, Razdolnaya River basin; 12, Ussurijsk town area (Komarovka and Rakovka); 13, Ussuri River headstream (Arkhipovka village); 14, Perevoznaya River basin; 15, villages in the Razdolnoye area (Popovka, Kiparisovka, Alekseevka and Knevichanka); 16, Artyomovka River basin; 17, Sergeevka River basin (Imalinovskaya, Tekhnichesky); 18, Kievka River basin; 19, Chernaya River basin; 20, Avvakumovka River basin (Novonikolaevka village); 21, Peschanka River basin; 22, Artyom town area; 23, Western Amur Gulf (Atlasov); 24, Bogataya River basin; 25, Amba River basin; 26, SE part of Vladivostok City (Pervaya Rechka and Groznyj); 27, Western Ussuri Gulf area (Tri Kamnya and Basargin); 28, Smolyaninovo village; 29, Pilnikov Creek; 30, Russian Island; 31, E. Ussuri Gulf (Dunai and Golyj); 32, Senkina Shapka Cliff; 33, Abrek Bay area; 34, Nakhodka area (Nakhodka Reef, Tungus and Neizvestnaya bays); 35, Mount Sestra.

oxygen-isotope analysis. In Kungurian brachiopod shells (Spitsbergen) with excellently-preserved fibrous microstructure, some siliceous parcels were recognised in SEM (JSM–6300) and these were excluded from the isotope analysis.

Oxygen and carbon isotope measurements were made by using a Finnigan MAT-252 mass spectrometer at the Analytical Center of the Far Eastern Geological Institute (FEGI), Vladivostok. The laboratory gas standard was calibrated relative to calcite National Bureau of Standards (NBS) 19 and equals $1.8 \pm 0.10‰$ for oxygen relative to the Vienna Pee Dee Belemnite (VPDB) and $-0.75 \pm 0.10‰$ for carbon. Reproducibility of replicate standards was always better than 0.10‰.

In calculating temperatures a $\delta^{18}O$ of −1.2‰ VPDB (equivalent to −1.0‰ SMOW) was thought to be appropriate (Savin 1977), since we assume that icecaps were not present during Permian times. Anderson & Artur's (1983) scale was used for palaeotemperature calculation from calcitic material.

Cathodoluminescence studies were carried out with a JXA-8100 microanalyser (JEOL) coupled with SEM. Elemental concentrations during preliminary measurements were determined by energy-dispersion X-ray spectrometer INCA Energy 350 (Oxford) at FEGI.

Observations and results

Geological setting

The main area of investigation was the Bureya–Jiamusi–Khanka superterrane (BJKH) and Sergeevka terrane (SR, Fig. 1) located between the Sino–Korean craton to the south and the Sikhote–Alin fold belt to the east (Khanchuk et al. 1995; Golozubov 2006; Kemkin 2006). A detailed description of Permian to Jurassic facies and biostratigraphical units has been presented elsewhere (Burago 1973, 1986; Zimina 1977, 1997a, 1997b; Kotlyar et al. 1989; Zakharov & Oleinikov 1994; Markevich & Zakharov 2004; Markevich et al. 2005; V.A. Zakharov et al. 2005; Kotlyar et al. 2006).

The Lower Permian (Sakmarian–Artinskian) plant-bearing Dunai Village Formation in South Primorye comprises volcanic-terrigenous strata, 1100–3900 m thickness. The overlying Kungurian plant, brachiopod and ammonoid-bearing Abrek Bay and Pospelov Cape formations (several hundred metres thick) and the Pilnikov Creek beds (180–1000 m thick) are composed of terrigenous and volcanic (small portion) deposits of continental, lagoonal and nearshore origin. The Roadian–Wordian plant, brachiopod and ammonoid-bearing Vladivostok City Formation (570–1600 m thick) is dominated by volcanic rocks and volcanoclastic and siliciclastic sediments of nearshore and non-marine origin. The latest Wordian–Capitanian Chadalaz Ridge Formation (900–1200 m thickness) mainly comprises siliciclastic and carbonate shallow-water deposits with abundant marine invertebrates. The Wuchiapingian–Changhsingian Lyudyanza Bay (about 720 m thickness) and Yastrebovka River formations (about 30 m thickness) and the latest Changhsingian Kapreevka Village beds (about 150 m thickness) mainly consist of siliciclastic and volcanoclastic sediments, containing large carbonate build-ups with abundant and diverse marine invertebrate fossils.

The Lower Triassic (Induan) Lazurnaya Bay Formation (105 m thickness), found everywhere in the south Far East is represented by coarse-grained clastics and sandstones with lenses of coquina yielding numerous molluscan remains. The early Olenekian formations (Tobizin and Schmidt Cape, about 130 and 40 m thick, respectively) in the BJKH superterrane are comprised mainly of shallow-water marine sandy facies with lenses of coquina, yielding abundant ammonoids. These sequences are overlain by silty-pelitic facies of the Zhitkov Cape Formation (82 m thickness) with numerous calcareous concretions, yielding abundant and diverse cephalopod faunas. A similar silty-pelitic facies is common for both the lower Olenekian and the upper Olenekian in the SR. The Anisian Karazin Cape Formation (not less than 129 m thickness) in the southern Russian Far East composed mainly of fucoid sandstones with large septarian concretions, yielding abundant ammonoids. Ladinian deposits in the southern Far East (Sputnik Station, Tractorny Creek and, apparently, Akhlestyshev Cape formations), resting unconformably on the erosion surface of the Anisian, are composed of siltstones, quartz sandstones and some intercalating mudstones, yielding rare mollusc and amphibian remains. Late Triassic deposits lie unconformably upon the Permian or Ladinian in the BJKH superterrane. The early Carnian Kiparisovo Village Formation is represented by lagoonal sediments with halobiid bivalves and rare brachiopods and is conformably overlain by late Carnian non-marine deposits of the coal-bearing Sadgorod Station Formation. Marine Carnian siltstones with rare ammonoids are known only in exotic blocks of terrigenous rocks in the SR and Taukha terranes. The Norian in the BJKH superterrane is represented by intercalation of marine and non-marine terrigenous sediments (early–middle Norian Peschanka River, middle Norian Amba River (coal-bearing) and late Norian Perevoznaya River formations), overlain by possible Rhaetian conglomerate and sandstone. Norian marine sediments in the SR are known as the Imalinov Creek Series.

The Lower Jurassic (Hettangian) Shitukhe River Formation, 250–300 m thickness, represented by non-marine and nearshore marine plant and mollusc-bearing terrigenous deposits in the SR occurs with an erosional and small angular non-conformity on Anisian marine sediments of the Shimeuza Village Series. The Triassic–Jurassic boundary is not exposed in the area. The Sinemurian mollusc-bearing beds, 175 m thickness, of the Trudny Peninsula Member in the SR are represented by conglomerate and siltstone. The 480 m thick Sinemurian–Pliensbachian Demidovo Village Formation in the SR terrane has been divided into lower and upper members. The lower member (300 m thickness) is represented by siltstones, greywackes with the Sinemurian ammonoid *Coronoceras*, acidic tuff and tuffite interbeds. The upper member (180 m thickness) occurs conformably upon the lower member and was transgressive over the Middle Triassic beds of the Shimeusa River Series. It consists mainly of sandstones and the Pliensbachian ammonoid *Arieticeras* has been identified in these successions. The Sinemurian–upper Toarcian plant and mollusc-bearing sequences (60–100 m thick) in the SR terrane, consisting essentially of submarine sandstones and occurs through erosional planar disconformity above the Shitukhe River Formation. The Pliensbachian–upper Toarcian bivalve-bearing Komarovka River Formation (about 90 m thickness), consisting of greywacks with thin interbeds of gravelstone, conglomerates and palitic tuffs, occurs with an erosional contact on top of the Triassic in the BJKH superterrane. The upper Toarcian–lower Bathonian Bonivur Creek Formation (30–400 m thick), represented by shallow-water bivalve-bearing marine terrigenous sequences occurs conformably upon the Komarovka River Formation, or transgressively on older formations, including the Upper Triassic in the BJKH superterrane. The upper Aalenian–Bathonian (600 m thickness) plant-bearing and coal-bearing non-marine and submarine sediments of the Ananyevka River series in the BJKH superterrane are represented mainly by sandstones, and rarer siltstones, tuffs, coaly-clayey schists, and coal; their contact with the underlying formation is unknown. The Bathonian Monakino Village plant-bearing series (more than 240 m thickness) is non-marine and occurs disconformably through angular unconformity on older formations in the BJKH superterrane. The series is divided into lower (rhyolitic) and upper (terrigenous-volcanic) members. The middle–upper

Bathonian Rakovka series (255–350 m thickness) in the BJKH superterrane consists of submarine greywackes. The middle Tithonian–lower Berriasian Chigan Cape Formation (252 m thickness) in the SR terrane consists mainly of shallow-water sediments (conglomerates, fucoid sandstones, siltstones and silty claystones with thin coal lenses), resting unconformably on older formations, including the middle Anisian. However, the lower Berriasian follows conformably on Tithonian sediments, within the same formation (Konovalova & Markevich 2004).

Palaeoclimatic evidence from Permian fossils

Sakmarian to Artinskian

Middle Early Permian sediments of the Dunai Peninsula Formation are characterised by the absence of coal. The Dunai flora consists of typical Siberian elements (*Paracalamites*, *Sphenopteris*, *Angaropteridium*, *Cordaites*, *Rufloria*, *Evenkiella*, *Gaussia*, *Krylovia* and *Xiphophyllums* (Eliseeva & Radchenko 1964; Meyen 1966; Taschi & Burago 1974; Zimina 1977, 1997a; Burago 1979). Thus, climatic evidence based on fossil plants and the lithology of the upper part of the formation suggests that South Primorye was warm-temperate and arid during the Sakmarian and much of the Artinskian (Fig. 2).

Kungurian

In the early to middle Kungurian, South Primorye continued to be located in the warm-temperate climatic zone based on the composition of the fossil plant assemblages encountered in the lower part of the Abrek Bay and the lower part of the Pospelov Cape formations in the Abrek Bay area and Russian Island (Fig. 1, loc. 30 and 33). The sediments yield an abundant and diverse Siberian floristic association (*Sphenophyllum*, *Paracalamites*, *Annularia*, *Annulina*, *Koretrophyllites*, *Tschernovia*, *Spheopteris*, *Zamiopteris*, *Cordaites*, *Rufloria*, *Crassinervia*, *Nephropsis*, *Vojnovskya*, *Gaussia*, *Wattia*, *Samaropsis*, *Cordaicarpus*, *Skokia, Sylvella*) (Burago & Kotlyar 1974; Burago 1979, 1983; Zimina 1997a). The paleoclimatic interpretation of a warm-temperate climatic zone for the early Kungurian is in good agreement with the presence of the Boreal type ammonoid (*Epijuresanites*) (Zakharov et al. 1999b) and brachiopods (*Rhynoleichus*, *Primorewia* and *Tomiopsis*) (Kotlyar et al. 2006) in the middle Kungurian Pilnikov beds of the Partizanskaya River Basin (Fig. 1, loc. 29).

The first appearance of Cathaysian elements (*Sphenopteris*, *Cladophlebis*, *Protoblechnum* and *Pterophyllum*) in South Primorye was documented for the late Kungurian portion of the Pospelov Cape Formation in the Tikhaya Bay, Mingorodok and Russian Island areas (Zimina 1997a; Kotlyar et al. 2006) and western Primorye (Burago & Kotlyar 1974; Burago 1979, 1983, 1986). These elements in the association constitute about 5%; other genera are represented by the Siberian elements; *Paracalamites*, *Koretrophyllites*, *Prynadaeopteris*, *Pecopteris*, "*Callipteris*", *Odontopteris*, *Comia*, *Cordaites*, *Rufloria* *Psygmophyllum*, *Samaropsis*, *Cardiocarpus*, *Sylvella* and others. This suggests a short-term climatic optimum during the late Kungurian. However, more research is needed to define the position of the Kungurian–Roadian boundary in the South Primorye region.

Roadian to Wordian

Up to 34% of the Cathaysian macroflora (*Lobatannularia, Annularia, Schizoneura, Sphenophyllostachus, Pecopteris, Neuropteridium, Taeniopteris, Pterophyllum, Bicoemplectopteridium* and *Rhipidopsis*) has been documented in the Vladivostok floristic assemblage (Burago 1983, 1986, 1990) in the Vladivostok City Formation and sequences corresponding to the lowermost part of the Chadalaz Range Formation. Other components in the floral assemblage found in the Pervaya Rechka (Fig. 1, loc. 26) and Shevelevka Village sections and in some localities of south-western Primorye are *Prynadaeopteris, Callipteris, Comia, Compsopteris, Protoblechnum, Rufloria, Crassinervia, Nephropsis, Psygmophyllum, Dicranophyllum, Mengrammia?* and others (Burago 1983, 1986; Zimina 1997a). This would support an almost subtropical climate in the southern Russian Far East during the Roadian–Wordian, with the exception of the very end of the Wordian (*Monodiexodina sutschanica–Neomisellina dutkevichi* Zone), characterised by domination of Boreal-type brachiopods in the marine realm (Kotlyar et al. 2006).

Latest Wordian to early late Capitanian

The Sitsa Flora of the Chandalaz Range Formation of the Partizanskaya River basin is considered to be of a Midian (latest Wordian to Capitanian) age (Burago 1983, 1986; Kotlyar et al. 1989, 2006) based on the macroflora such as *Annularia*, *Asterotheca*, *Prynadaeopteris*, *Peltaspermum*, *Pursongia*, "*Callipteris*", *Comia*, *Cordaites*, *Rufloria*, *Psygmophyllum*, *Ginkgophytopis* and some others. The Capitanian climate has been interpreted as cool-temperate and humid as the Sitsa assemblage yields only 14–22% of Cathaysian elements, e.g. *Taeniopteris*, *Lobatannularia* and as it is further characterised by the appearance of the Siberian elements; *Annularia*? *jeruunakovensis* Neuburg, *A.*? *sibirica* Radczenko, *Psygmophyllum sibiricum* (Zalessky), *Cordaites insignis* (Radczenko). Additionally, some coal layers are present in the Sitsa plant-bearing beds. However, Zimina (1997b) interpreted a somewhat older age for the Sitsa flora based on its taxonomic composition. Abundant Capitanian marine fossils (foraminifera, brachiopods and ammonoids) from South Primorye and the Bolshiye Churki area (Fig. 1, loc. 1) provide evidence for the Tethyan connection of both the South Primorye and Amur River areas (Kotlyar et al. 1997, 2006).

Wuchiapingian to Changhsingian

Late Permian continental sediments are unknown in the South Primorye SR terrane; only rare plant remains (*Taeniopteris*) have been reported from marine sediments in the area (Burago 1986). Judging from these traces of the *Taeniopteris* flora in the Lyudyanza Bay Formation and the lack of *Cordaites*, Burago (1986) interpreted a warm climate with increasing humidity in South Primorye during the Late Permian.

Analysing the marine fossils, we also discern minor temperature fluctuations in the southern Far East during most of the Wuchiapingian to early late Changhsingian, because the *Stacheoceras orientale* and *Xenodiscus subcarbonarius* beds, early Wuchiapingian limestones of the Nakhodka Reef (Fig. 1, loc. 34) yield the typical Tethyan-type ammonoids *Neogeoceras*, *Stacheoceras* and *Xenodiscus* (Zakharov & Pavlov 1986a), as well as brachiopods (Kotlyar et al. 2006) and diverse

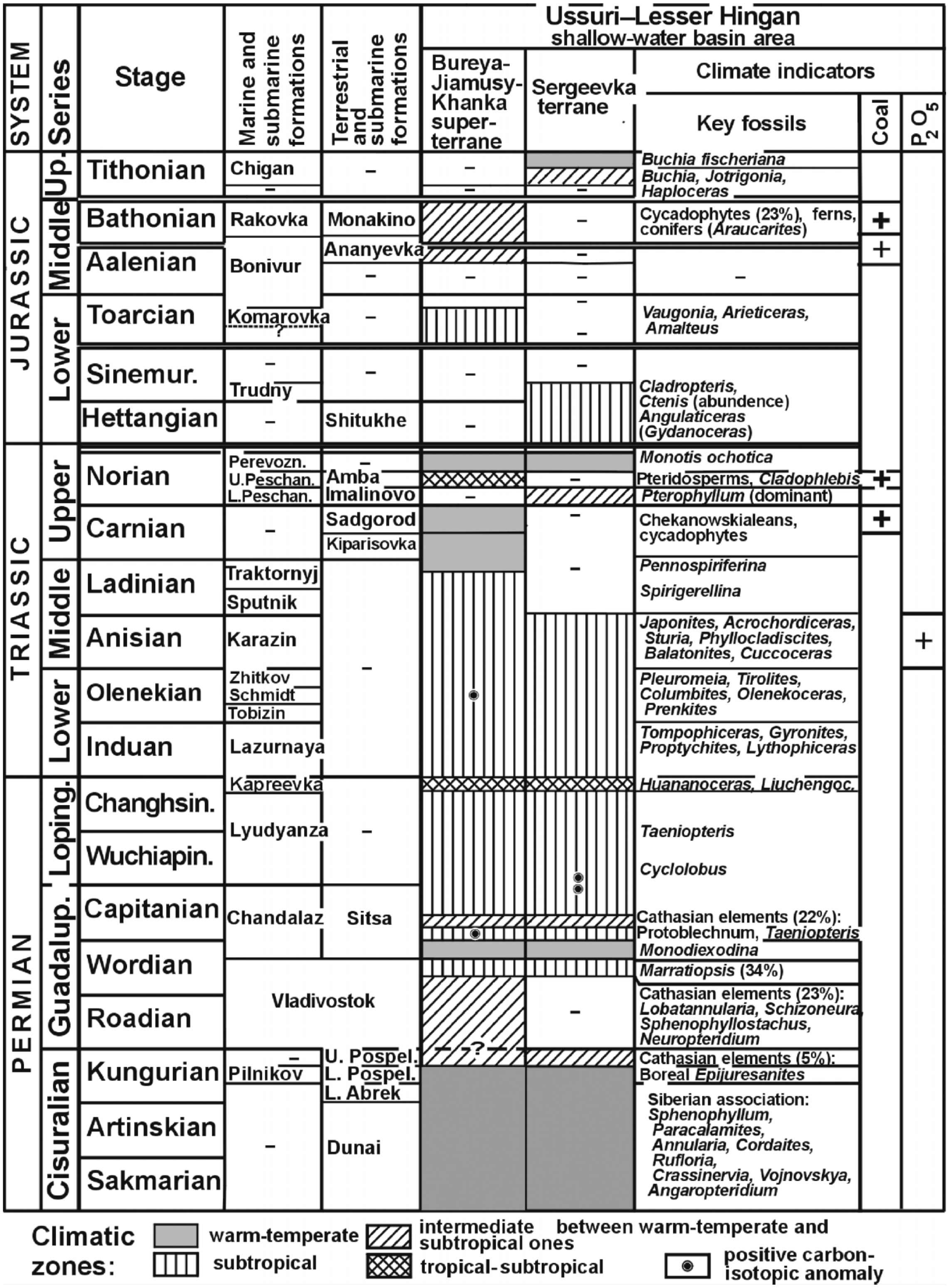

Fig. 2. Reconstruction of Permian–Triassic climatic changes in the shallow-water Ussuri-Lesser Hingan Sea area (BJKH and SR area): evidence from paleofloral, brachiopod, ammonoid, bivalve and carbon-isotope data.

tropical-subtropical sphinctozoans (Boiko et al. 1991). The middle Wuchiapingian *Cyclolobus kiselevae* Zone in South Primorye and the late Wuchiapingian *Eusanyangites bandoi* beds are also characterised by typical Tethyan fossils comprising ammonoids, including araxoceratids (Zakharov 1983; Zakharov & Pavlov 1986a, 1986b), and small foraminifera (Vuks & Chedia 1986).

The warmest Permian interval of the Southern Russian Far East seems to have been the latest Changhsingian based on the warm climate-loving ammonoid assemblage including

Changhsingoceras, *Huananoceras*, *Liuchengoceras* and *Sinoceltites*). This assemblage is similar to that of the Cathaysian Province, as discovered in both the *Huananoceras qianjiangense* Zone of the Partizanskaya River Basin and the Pleuronodoceratidae-*Liuchengoceras* beds of the Artymovka River Basin (Zakharov & Oleinikov 1994). This conclusion is supported by the discovery of brachiopod species (*Crurithyris flabelliformis* Liao and *Araxathyris minor* Grunt), common for the uppermost Changhsingian in South China, in the *Huananoceras qianjiangense* Zone of the Partizanskaya River Basin (Zakharov & Oleinikov 1994; Zakharov et al. 1997a).

Palaeoclimatic evidence from Triassic fossils

Induan to Olenekian

On the Russian Island, South Primorye, Triassic basal conglomerates overlay Roadian plant-bearing sediment of the Lower Vladivostok City Formation. Erosion of several middle–late Permian sediments (Upper Vladivostok, Chandalaz and Lyudyanza) seems to be one of the events coeval to the largest end-Permian regression and widespread extensive volcanism (Yin et al. 2007), which led mainly to significant aridity and climate warming during the Early Triassic.

A common, Early Triassic plant adapted to arid conditions from the Southern Russian Far East is *Pleuromeia* encountered in the lower part of the upper Olenekian (*Neocolumbites insignis* Zone of the Zhitkov Cape Formation (Krassilov & Zakharov 1975). According to rare palaeobotanical evidence (*Cladophlebis gracilis* Sze, V.I. Burago's determination, personal communication), obtained from the upper part of the upper Olenekian (*Subfengshanites multiformis* Zone), a change in climatic conditions from arid to humid took place in the Southern Far East by the end of the Olenekian.

Induan and Olenekian ammonoids from the Southern Far East are represented by Tethyan (*Glyptophiceras*, *Owenites*, *Prosphingitoides*, *Tirolites*, *Columbites*, *Arnautoceltites*, *Prenkites* and some others) and cosmopolitan (e.g. *Hedenstroemia*, *Euflemingites*, *Arctoceras*, *Wasatchites*) elements, although some Boreal-type elements (*Olenekoceras*, *Northophiceras* and *Svalbardiceras*) are reported from the lower part of the upper Olenekian (Zakharov 1997a). Early Triassic articulate brachiopods *Abrekia*, *Paranorellina*, *Hustedtiella*, "*Fletcherithyris*", *Lepismatina* (Bittner 1899; Dagys 1974), *Piarorhynchella*? and *Lissorhynchia* (A.M. Popov, unpublished data) reported for South Primorye are also common in Tethyan areas but among them, only *Hustedtiella spitsbergensis* has been found at higher latitudes in Spitsbergen (Dagys 1974). This assemblage may reflect a position of the Southern Russian Far East in the subtropical climatic zone during the Early Triassic.

Anisian to Ladinian

Based on data of phosphate distribution in the Far East and in Arctic Siberia, the Early Triassic arid-climate was replaced by a humid one in this extensive territory during the middle Anisian, possibly in relation to a sea level rise (Zakharov & Shkolnik 1994). Most of the cosmopolitan elements in the southern Far East, as well as in Arctic Siberia, have been documented in the lowermost Anisian *Ussuriphyllites amurensis* Zone of the Karazin Cape Formation, which is characterised by the presence of the ammonite genera *Parasageceras*, *Ussuriphyllites*, *Megaphyllites*, *Leiophyllites*, *Ussurites*, *Paradanubites*, *Paracrochordiceras*, *Prohungarites*, *Arctohungarites*, *Salterites* and *Tropigastrites*. We interpret this assemblage as reflecting a warm and uniform climate for the beginning of the Anisian. The earliest Anisian sediments of Russian Island contain abundant shark teeth, which additionally confirm our assumption.

Early and mid-Triassic cephalopod assemblages, ammonoids of the BJKH superterrane and SR terrane areas, mainly exhibit Tethyan-type genera or cosmopolitan ones. This interpretation is in agreement with data from early Anisian brachiopods from South Primorye (*Spirigerellina* cf. *stoliczkai* (Bittner), *Lepismatina tsinghaiensis* (Yang and Yin) and *Costinorella zharnikovae* Dagys) and the early Ladinian (*Spirigerellina stoliczkai* (Bittner), *Schwagerispira* ex gr. *schwageri* (Bittner), *Plectoconcha variabilis* Dagys, *Piarorhynchella* cf. *trinodosi* (Bittner), *Costirhynchopsis tienchungensis* (Yang and Yin), *C.* cf. *breviplicata* (Yang and Yin), *Lepismatina* cf. *pauciplicata* (Yang and Yin) and *L. tsinghaiensis* (Yang and Yin) (Dagys 1974; Popov 2008). All of them, with the exception of representatives of the cosmopolitan genus *Lepismatina*, are common Tethyan elements.

On the contrary, during the late Ladinian, water temperatures of the Ussiri-Lesser Hingan basin apparently dropped sharply, based on the presence of the typical Boreal brachiopod genus *Pennospiriferina* that has been reported from the upper part of the upper Ladinian in South Primorye (Dagys 1965). The basin was apparently located within the warm-temperate climatic zone during late late Ladinian time.

Carnian

The early Carnian floral assemblage of the Kiparisovo Village Formation of South Primorye (southern part of the BJKH superterrane) yields diverse cycadophytes (*Otozamites*, *Ctenozamites*, *Pseudoctenis*, *Anomozamites*, *Nilssonia* and *Taeniopteris*), ferns (*Todites*, *Clathropteris* and *Cladophlebis*), equisetaceans (*Equisetum* and *Neocalamites*), conifers (*Podozamites* and *Cycadocarpidium*) and ginkgoaleans (*Baierella*; Shorochova 1997; Volynets & Shorochova 2006, 2007).

The investigated flora is derived from the coal-bearing Sadgorod Station Formation of South Primorye (southern part of the BJKH superterrane and the SR terrane) and consists of mainly bryophytes, ferns (*Dictyophyllum* and *Hausmannia*), ginkgoales (*Baiera*, *Glossophyllum* and *Desmiophyllum*) czekanowskiales and diverse coniferales (*Podozamites* and *Pityophyllum*) (Shorochova 1997; Volynets & Shorochova 2006, 2007).

The great abundance of coniferales and ginkgoales and the presence of cycadophytes in the early Carnian sediments of the Kiparisovo Village Formation indicate a warm-temperate and arid climate at the beginning of the Carnian in South Primorye (Volynets & Shorochova 2006, 2007). However, the predominance of czekanowskiales and coniferales (Pinaceae), abundant large-stemmed *Neocalamites* and subordinate cycadophytes and ferns (Camptopteridacea) in the late Carnian floral assemblage of the region are consistent with a warm-temperate and humid climate (the latter also in line with the commercial Sadgorod Station Formation coal resources).

Early Norian

The floral association from the early Norian Imalinov Creek Series of the SR terrane in South Primorye is characterised by a high diversity of cycadophytes (*Pterophyllum*, *Nilssonia*, *Ctenis*, *Pseudoctenis* and *Taeniopteris*), an abundance of coniferales (*Elatocladus* and *Podosamites*), presence of rare coniferale Cheirolepidiaceae, as well as ferns, ginkgoales, czekanowskiales (*Phoenicopsis*, *Leptostrobus* and *Ixostrobus*), horsetails and pteridosperms (Volynets & Shorochova 2006; Volynets et al. 2006). This assemblage is indicative of a warm-temperate to subtropical and more or less humid climate; further supported by the presence of thin coal-beds in the Imalinov Creek Series (Volynets & Shorochova 2006, 2007; Volynets et al. 2006, 2008).

The rare early Norian ammonoids *Norosirenites* and *Yanotrachiceras* found in the SR terrane (Sergeevka River Basin) are typical Borea1 genera; *Paratrachyceras* from the Levaya Antonovka River of the same terrane is, however, common for the Tethys (Zakharov 1997b). Brachiopods from the early to middle Norian (lower to middle part of the Peschanka River Formation of the southern part of the BJKH superterrane) include, e.g. *Laevithyris*, *Kolymithyris* and *Spondylospiriferina* and are typical Boreal elements, while the genus *Piarorhynchella* is common for the Tethys.

Based on plant, brachiopod and ammonoid data, we assume that South Primorye was located between the warm-temperate and subtropical climatic zones during the early Norian.

Middle Norian

The Amba flora, characterised by having the highest taxonomic diversity among the Triassic assemblages, was discovered in the middle Norian Amba River Formation of the southern part of the BJKH superterrane (Amba, Razdolnaya, Komarovka, Bystraya, Malinovka, Marevka and Bikin River basins; Fig. 1, loc. 25). In the middle Norian sediments czekanowskiales are replaced by ginkgoales *Sphenobaiera* and pteridosperms (*Thinnfeldia*, *Imania* and *Tudovakia*). Ferns and cycadophytes, including *Clathropteris*, *Camptopteris* and *Dictyophyllum, Pterophyllum*, *Williamsoniella*, *Ctenis*, *Nilssonia* and *Taeniopteris*, became the dominating elements (Shorochova 1997; Volynets & Shorochova 2006, 2007). This indicates that the coal-bearing Amba River Formation was formed in humid conditions in a tropical-subtropical climate.

Late Norian

All the known late Norian brachiopods (*Orientospira gregaria* (Dagys), *Viligella rotunda* (Tuchkov), *Kolymithyris kolymensis* (Moisseev), *Laballa suessi* (Moisseiev), *Laevithyris rossochae* (Dagys), *Ochotathyris ochotica* (Dagys), *Spondylospiriferina* sp. and *Rhaetina pyriformis* (Suess) from the Perevoznaya River Formation of the south part of the BJKH superterrane, with the exception of the latter (Rhaetina – a Tethyan element), are typical representatives of the Boreal realm (Popov 2008). They are everywhere, in the large area of the Southern Russian Far East (Fig. 1, loc. 11, 14 and 15), associated with *Monotis ochotica* (Keyserling) and some other bivalves common for the Boreal realm. Data from both brachiopods and bivalves show that significant cooling took place at the very end of the Norian, when the analysed basin was located in the warm-temperate climatic zone (Boreal realm).

The Rhaetian portion of the Upper Triassic has not been investigated palaeontologically in either the BJKH superterrane or the SR terrane, but only in the reef facies of the adjacent Taukhe terrane (Fig. 1, loc. 8; Punina 1999).

Palaeoclimatic evidence from Jurassic–Early Cretaceous fossils

Liassic

In the Hettangian–earliest Sinemurian floras, 39 taxa have been identified in an area including the Shitukhe River Formation of the Petrovka and Litovka River basins, SR terrane (Krassilov & Shorochova 1975; Volynets 2008) and a small portion of the lower part of the Petrovka River Formation of the Dushkino Passage, SR terrane (Konovalova & Markevich 2004). The macrofloral assemblage consists of ferns (*Cladophlebis*, 6 spp.; *Marattiopsis*, 1 sp.; *Phlebopteris*, 1 sp.; *Clathropteris*, 1 sp.; *Hausmannia*, 1 sp. and *Todites*, 1 sp.), cycadophytes (*Pterophyllum*, *Ctenis*, *Nilssonia* and *Taeniopteris*), coniferales (*Podozamites*, *Cycadocarpidium*, *Pityophyllum* and *Elatocladus*), ginkgoales (*Ginkgoites*, *Baiera* and *Sphenobaiera*), czekanowskiales (*Czekanowskia* and *Phoenicopsis*). The presence of Hettangian tropical-subtropical taxa such as *Clathropteris*, *Phlebopteris*, *Marratiopsis*, *Podozamites* and *Cycadocarpidium* and abundant *Ctenis* and *Pterophyllum* reflect paleoecological conditions close to the humid subtropics during the Hettangian to probably the earliest Sinemurian.

By contrast, early Sinemurian sediments of the Trudny Peninsula Formation in the Neizvestnaya Bay section, SR terrane are characterised by the presence of the sub-boreal and boreal ammonoid *Angulaticeras* (*Gydanoceras*) and the bivalve *Pseudomytiloides rassochaensis* Polubotko, common in the upper Sinemurian *Otapiria limaeformis* Beds of the Boreal realm (Sey & Kalacheva 1980; Konovalova & Markevich 2004).

Late Pliensbachian sediments of the Okrainka Village Formation (lower part) exposed in the Izvilika River basin, SR terrane, are characterised by the mixed Tethyan-Boreal ammonoid fauna. Among Tethyan ammonoids, *Arieticeras*, *Fontanelliceras* and *Paltarpites* can be recognised, while *Protogrammoceras* represents a cosmopolitan species. Ammonoid species, common for the Boreal realm include *Amaltheus stokesi* (Sowerby) in the mentioned assemblage. A similar, but more restricted assemblage (*Arieticeras*, *Fontanelliceras* and *Protogrammoceras*) has been documented in contemporaneous sediments of the Petrovka River Formation of the Litovka River, SR terrane (Sey & Kalacheva 1980).

Subtropical conditions are presumed also during the Toarcian in South Primorye based on the abundance of the thermophilous trigoniid bivalve *Vaugonia* in sediments of the Komarovka River and Bonivur Creek formations of the Komarovka River basin (Konovalova & Markevich 2004) and the occurrence of the Tethyan ammonoid *Arieticeras* in coeval deposits of the Izvilinka River, both in the SR terrane (Sey & Kalacheva 1980).

Aalenian to Bathonian

Data on the Aalenian to Bathonian fossil flora of the Alexeevka River (BJKH superterrane), Ananyevka River (upper part) and Monakino Village (lower part) series are accounted for in Volynets (1999, 2008). The macrofloral assemblage is represented by 81 taxa (Volynets 2008), represented by; ferns 28 spp. (*Sphenopteris*, *Cladophlebis*, *Klukia*, *Cyathea*, *Osmundopsis*, *Phlebopteris*, *Ruffordia*, *Dicksonia*, *Coniopteris*, *Onychiopsis*, *Adiantopteris* and *Acrostichopteris*); coniferales, 17 spp. (*Podozamites*, *Araucarites*, *Cunninghamia*, *Pityophyllum*, *Brachyphyllum*, *Elatocladus*, *Coniferites* and *Conites*); cycadophytes, 17 spp. (*Otozamites*, *Dictyozamites*, *Cycadolepis*, *Anomozamites*, *Ptilophyllum*, *Zamites*, *Nilssonia* and *Pseudoctenis*); pteridosperms, a single species of *Thinnfeldia*; Caytoniales, four species of *Caytonia* and *Sagenopteris*; ginkgoales, two species of *Baiera* and *Pseudotorellia*; czekanowskiales, three species of *genera Czekanowskia* and *Leptostrobus*; and some others.

The macrofloral assemblages are indicative of warm and medium humid paleoecological conditions for the Bathonian of the BJKH superterrane. Additional paleoclimatological evidence for a warm-temperate to subtropical Middle Jurassic in this area is provided by the presence of the Aalenian–Bajocian Boreal inoceramid bivalves *Retroceramus jurensis* (Koschelkina), *Retroceramus* cf. *lucifer* (Eichwald) and *Retroceramus* aff. *elegans* (Koschelkina) (Konovalova & Markevich 2004) in the Bonivur Creek Formation of Strelkovaya Mouth, SR terrane, in association with the cosmopolitan ammonites (*Holcophylloceras* and *Lytoceras*) and rare Tethyan trigoniid bivalves (*Vaugonia*) (Sey & Kalacheva 1980, 1981; Konovalova & Markevich 2004).

Upper Jurassic to lowermost Cretaceous

Callovian to Kimmeridgian marine faunas from South Primorye are absent with only a continental regime during the Callovian, and intensive erosion starting from the Oxfordian in this region; only restricted evidence on Callovian plant fossils (*Pseudocycas* sp.) has been reported (Markevich et al. 2008). The Oxfordian–Kimmeridgian part of the marine Dongrong Formation in the neighbour area of northeast China is characterised by the Boreal *Buchia* cf. *concentrica-B. tenuistriata* assemblage (Sha 2007).

There is no palaeontological evidence from the lower part of the lower Tithonian portion of the Chigan Cape Formation exposed at the eastern Ussuri Gulf, SR terrane. However, the lower–upper Tithonian part of the Dongrong Formation in eastern Heilongjiang Province, northeast China is characterised by the *Buchia* cf. *mosquensis-B*. cf. *rugosa* assemblage (Sha 2007). The middle Tithonian part of the Chigan Cape Formation in South Primorye is characterised by mixed Boreal-Tethyan bivalve fossils among which are buchias, common for the Boreal realm (*Buchia mosquensis* (Buch), *B. rugosa* (Fisch.) and others); thermophilose trigoniid bivalves (*Jotrigonia*) are dominant. This part additionally yields ammonoids regarded as Tethyan taxa (*Semiformiceras*, *Glochiceras*?, *Pseudolissoceras*, *Haploceras*, *Parapallasiceras*, *Sublithacoceras*, *Corongoceras*, etc.) and cosmopolitan (*Lithacoceras*, *Subplanitoides*, "*Partschiceras*", *Aulacosphinctoides, Torquatishinctes*?, *Aulacosphinctes*, *Himalayites*, *Holcophylloceras*, *Virgatosphictes*, *Subplanites* and "*Metahaploceras*") (Sey & Kalacheva 1980, 1981; Konovalova & Markevich 2004).

Presumed cooler conditions prevailed in South Primorye at the very end of the Jurassic, because in the latest Tithonian portion of the Chigan Cape Formation only *Buchia "piachii"* Gabb, *B. fischeriana* (Orbigny), and *B.* ex gr. *fischeriana* (Orbigny), common for the Boreal realm have been found (Konovalova & Markevich 2004). A similar Boreal assemblage (*Buchia russiensis–B. firscheriana*) has been recently discovered in the lower part of the Dong'anchen Formation of the adjacent area (eastern Heilongjiang Province, northeastern China; Sha 2007).

However, this was followed by warmer, more likely subtropical conditions at the beginning of the Cretaceous, because the lower Berriasian portion of the Chigan Cape Formation yields only Tethyan (*Pseudosubplanites* and *Dalmasiceras*) and cosmopolitan (*Berriasella*) cephalopods (Zakharov et al. 1996; Sey & Kalacheva 1999).

Carbon-isotope composition of Permian–Triassic organogenic carbonates

Some variation in the $^{13}C/^{12}C$ ratio in marine organogenic carbonates is related to variations of different environmental factors, such as the carbon cycle balance, upwelling and primary productivity, and therefore it is usually difficult to separate the effect of each of these factors, especially for deep-water conditions. However, when worldwide carbon isotope shifts are observed only in shallow-water carbonates, they are generally attributed to change in primary productivity (Alcala-Herrara et al. 1992). Contrary to Isozaki's et al. (2007) conclusion, our own results (Zakharov et al. 2000, 2001; Y.D. Zakharov et al. 2005) show that Permian positive carbon-isotopic anomalies seem to be contemporised with climatic optima and perhaps with transgressions. We personally have recorded the abnormally high $\delta^{13}C$ values in organogenic carbonates obtained from 22 levels of the Kungurian, Roadian, Wordian, Capitanian, Wuchiapingian, Changhsingian, Induan, Olenekian and Anisian of different regions of the former USSR, including the Russian Far East (Zakharov & Biakov 2008, Fig. 32). Recently, we obtained additional information on isotopic composition of organogenic carbonates from the lower Capitanian (*Parafusulina stricta* Zone) of the Barabash area, Induan (*Abrekia* beds) of Abrek Bay (Fig. 1, loc. 33), and the lower Ladinian (Sputnik Formation) of the Atlasov Cape area (Fig. 1, loc. 23). The positive carbon-isotopic anomaly discovered in the *Tirolites-Amphistephanites* Zone in Russian Island (Zakharov et al. 2001, Fig. 14) is interpreted by us as connected with the middle Olenekian transgression and thermal optimum. Positive anomalies from the same level were discovered also in the North Caucasus (Belaya–Rufabgo, Kapustina and Svinyachia; Zakharov et al. 2001, Figs. 9 and 10) and South China (Tong & Zhao 2005). Tong & Zhao (2005) have remarked that the above-mentioned middle Olenekian event was followed by a gentle decrease in $\delta^{13}C$ values, which might have resulted from the local tectonic setting combined with a regression in the region.

Figs. 3–6 (see $\delta^{13}C$ anomaly column) show the highly irregular location of the positive carbon-isotopic anomalies discovered within the Sakmarian–Rhaetian interval. They are located most frequently in the upper Kungurian, upper Wordian, Capitanian, Wuchiapingian and also in the Induan–lowest Anisian interval. By contrast, the Sakmarian–middle Kungurian, Roadian–middle Wordian, middle–upper Changhsingian intervals and major parts of the Middle and Upper Triassic are characterised by comparatively rarer positive carbon-isotopic anomalies.

Correlation of oxygen-isotope (palaeotemperature) events

Gzhelian to middle Kungurian interval

Comparatively cool temperature conditions calculated for the latest Carboniferous, Gzhelian, of the South Urals (Zakharov et al.

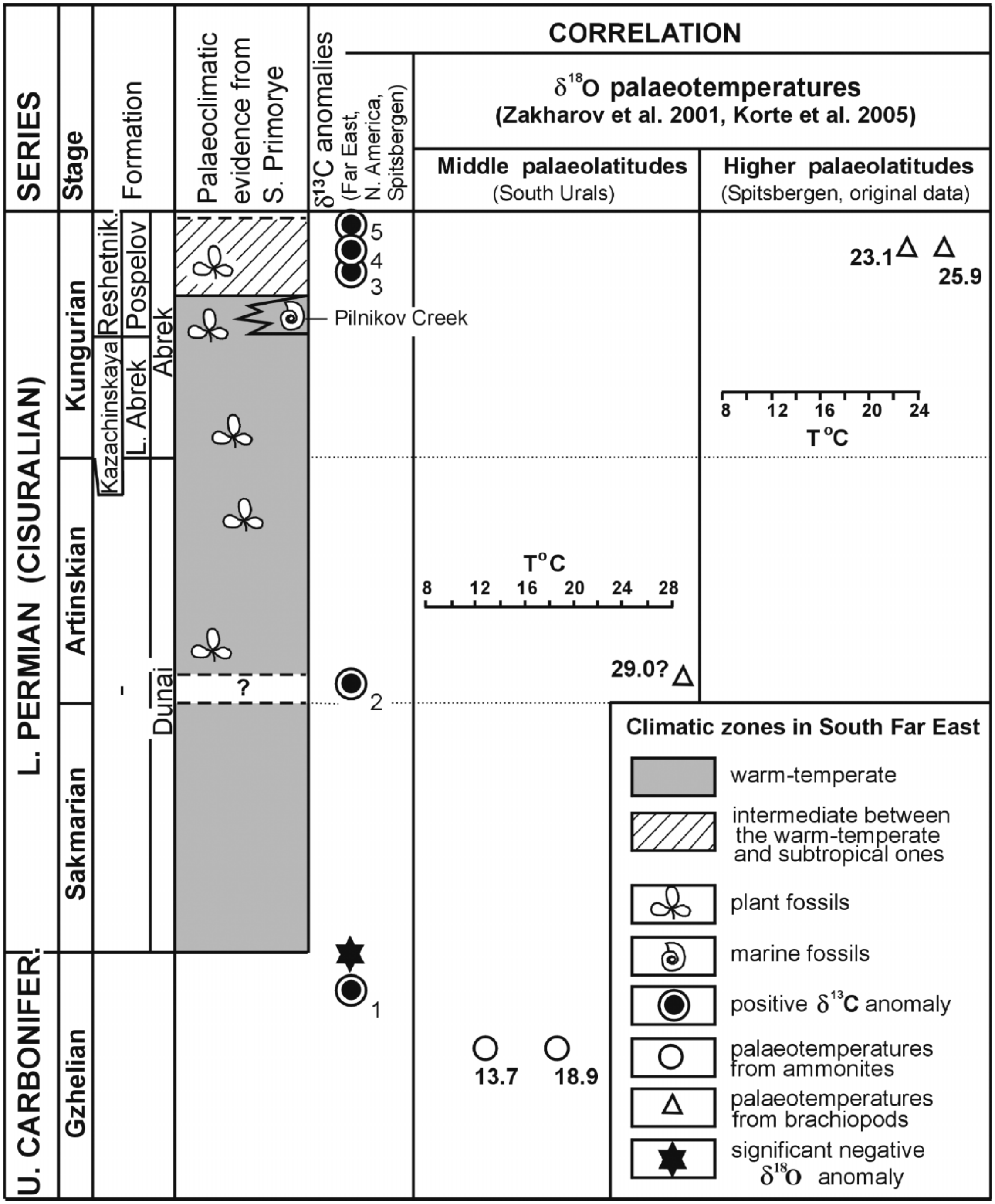

Fig. 3. Correlation of the Lower Permian of the southern Russian Far East using available oxygen and carbon-isotope data. Positive carbon-isotopic anomalies: 1, Gzhelian (Grossman et al. 1991); 2, Early Permian (Artinskian) (Rao 1988; Zakharov et al. 1997b); 3, late Kungurian (Korte et al. 2005a, 2005b); 4–5, late and the latest Kungurian (original data from Spitsbergen and the northern Russian Far East).

2001; 13.7–18.9°C) (Fig. 3) continued in middle latitudes mainly until the late Kungurian, with the potential exception of some Artinskian intervals (Korte et al. 2005a). This is coincident with the development of Boreal floral associations of the Dunai and Lower Abrek formations in South Primorye, as well as the Boreal marine assemblage of middle Kungurian Pilnikov Beds in the same area.

Late Kungurian interval

During the excursion on the Festingen section in Spitsbergen (Fig. 1), organised for the Boreal Triassic Conference (Longyearbyen, August 2006), one of the authors (Y. Zakharov) collected a few brachiopod (athyridid and *Rhombospirifer*? sp.) shells with excellently preserved microstructure (Fig. 7) from the Vøringen Member of the Kungurian to Capitanian? Wuchiapingian Tempelfjorden Group exposed at Starostin Cape (Worsley 2006). The age of the brachiopod shells analysed is considered to be late Kungurian (G.V. Kotlyar, personal communication).

The excellently-preserved fibres of the secondary layer, combined with Mg (1400–3300 mg/kg) and Na

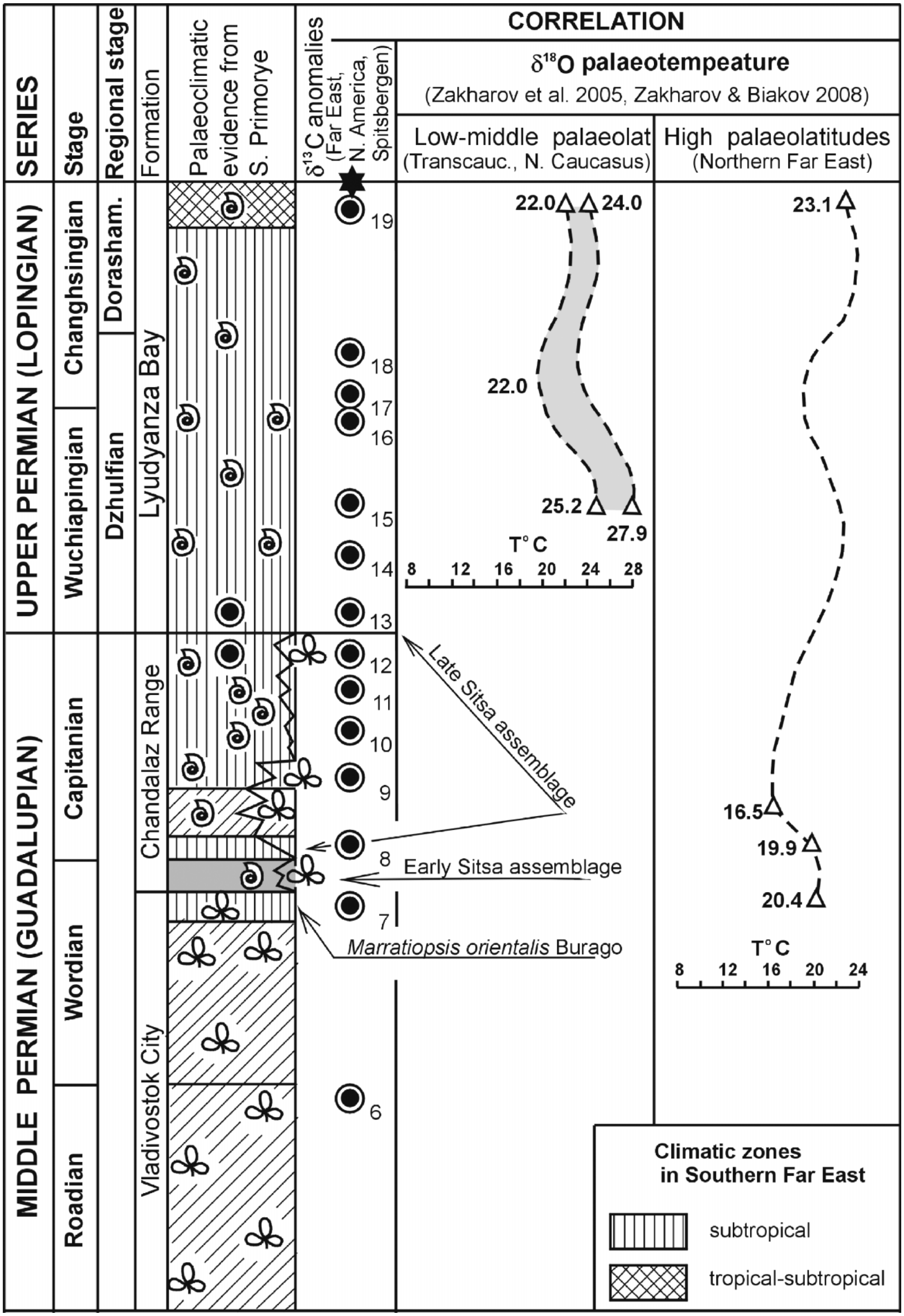

Fig. 4. Correlation of Middle–Upper Permian of the southern Russian Far East with available oxygen and carbon-isotope data. Positive carbon-isotopic anomalies: 6, late Roadian (original data from northern Russian Far East); 7, late Wordian (Korte et al. 2005a, 2005b and original data from northern Russian Far East); 8–12, Capitanian (original data from northern Russian Far East); 13–15, Early Wuchiapingian (Y.D. Zakharov et al. 2005 and original data from northern Russian Far East); 16, late Wuchiapingian (Y.D. Zakharov et al. 2005); 17–19, Changhsingian (Y.D. Zakharov et al. 2005 and original data from northern Russian Far East). Additional designations as in Fig. 3.

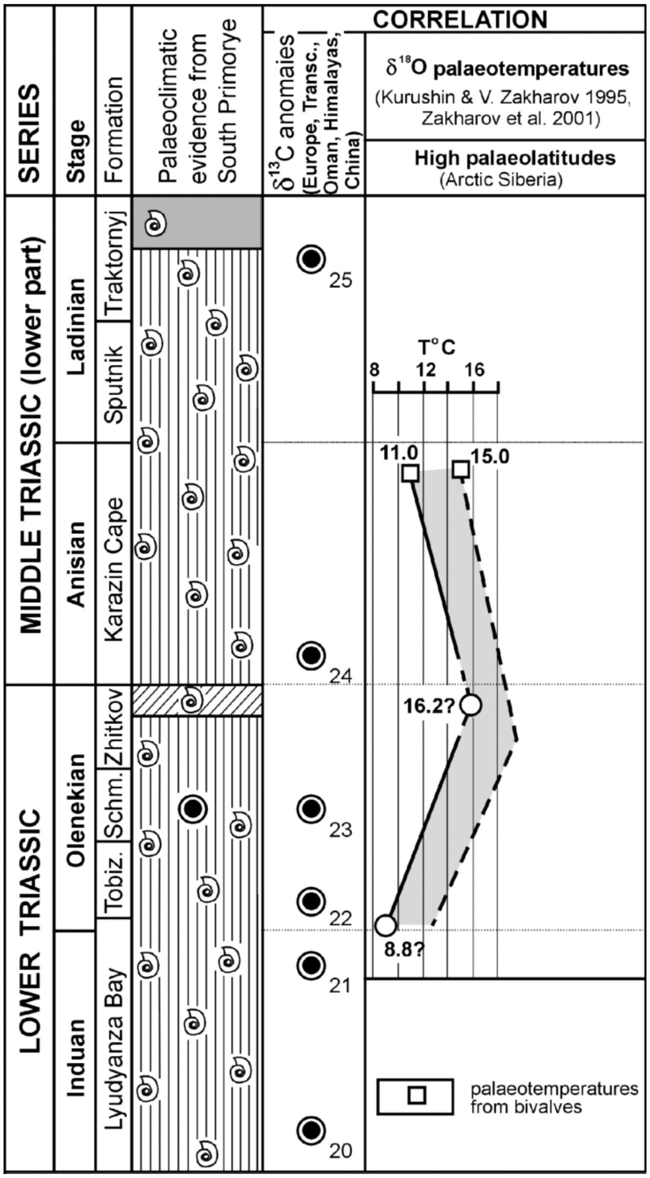

Fig. 5. Correlation of Lower–Middle Triassic of the southern Russian Far East with the available oxygen and carbon-isotope data. Positive carbon-isotopic anomalies: 20, early Induan (Y.D. Zakharov et al. 2005; Richoz 2006); 21, late Induan (Altudorei 1999; Zakharov et al. 2000); 22, early Olenekian (Richoz 2006); 23, middle Olenekian (Altudorei 1999; Zakharov et al. 2000; Payne et al. 2004; Galfetti et al. 2007; Horacek et al. 2007); 24, early Anisian (Altudorei 1999; Zakharov et al. 2000); 25, late Ladinian (Altudorei 1999; Zakharov et al. 2000). Additional designations as in Figs. 3 and 4.

(2200–2900 mg/kg) content (Fig. 8), confirm the unusually good preservation of the investigated shell because these concentrations are within the range of modern terebratulid brachiopods (Brand et al. 2003). A relatively high value for Fe (10,900 mg/kg) was found in the carbonates by the dispersion energy X-ray spectrometer at only one point (Fig. 7D, point 2, Fig. 8, spectrum 4) out of 32, indicating only local diagenetic alteration.

The oxygen isotope data derived from the excellently preserved parts of the brachiopod shells display a range of values from −3.1 to −2.6‰ (V–PDB), showing shallow-water palaeotemperatures not lower than 23.1–25.9°C (Table 1). Incidentally, we would like to note that abnormally high $\delta^{13}C$ values (6.5–7.2‰) were discovered in all five samples collected from the best preserved areas of the brachiopod shells, which might have been biased by high-biological productivity of the seas of that time. If such high temperatures existed in the higher latitude Spitsbergen area, it was caused by short-term warming at the very end of the Cisuralian, which agrees with palaeobotanical records from the upper part of the Pospelov Cape Formation in South Primorye, but seems to be in contradiction with the oxygen-isotope data from the middle Kungurian to middle Wordian of the Sydney Basin in Australia (Korte et al. 2008), which reflects a cooling phase during the late Kungurian to Roadian in the Southern Hemisphere. Correlation of this event is still uncertain.

Roadian to Capitanian interval

We have recently calculated Wordian to Capitanian palaeotemperatures from oxygen-isotopic composition of well-preserved brachiopods, collected from the late Wordian upper Omolon Formation (Y.D. Zakharov et al. 2005) and early Capitanian lower Gizhiga Formation of the Gizhiga–Omolon area, Northern Russian Far East (Fig. 1). Comparatively high temperatures during the late Wordian (20.4°C, Fig. 4) and the main trend for temperature drop in the early Capitanian (from 19 to 16.5°C) (Zakharov & Biakov 2008) were documented for this high-latitude area, which seems to be in accordance with the floristic data (Fig. 4) from the Roadian–Wordian Vladivostok Formation, including late Wordian *Marratiopsis orientalis* Beds, and latest Wordian–Capitanian Sitsa Formation (Kotlyar et al. 1989) in South Primorye. However, the major part of Capitanian marine faunas from the southern Russian Far East is thermophilous (Kotlyar et al. 1997, 2006), in contrast with the latest Wordian fauna from the *Monodiexodina sutchanica–Metadoliolina dutkevichi* Zone.

Wuchiapingin to Changhsingian interval

Two maxima in palaeowater temperatures seem to occur during the Late Permian, that is during the early Wuchiapingian (with 25.2–27.9°C calculated for middle palaeolatitudes of Transcaucasia (Zakharov et al. 2001)), and the late Changhsingian (present in both middle and high palaeolatitudes and characterised by somewhat lower palaeotemperatures, 22–24.2 and 23.1°C, respectively (Y.D. Zakharov et al. 2005)), which is in agreement with the data from thermophilous marine faunas from South Primorye (Fig. 4). Very high palaeotemperatures for the Lopingian-aged Joulfa section in Iran (23–34°C) and the Meishan section in South China (26–32°C) were similarly obtained by Korte et al. (2005a). However, some of these data seem to be in disagreement with Beauchamp and Baud's (2002) hypothesis, according to which the northwest margin of Pangaea was under the influence of cold to very cold waters for nearly 30 m.y. in the post-Sakmarian Permian, the time of chert accumulation in this area.

Permian–Triassic boundary (PTB) transition

Many hypotheses for processes to explain PTB events have been offered, recently reviewed by Berner (2002), Kidder & Worsley (2004), Richoz (2006) and Vajda & McLoughlin (2007); a question that remains is the temperature impact.

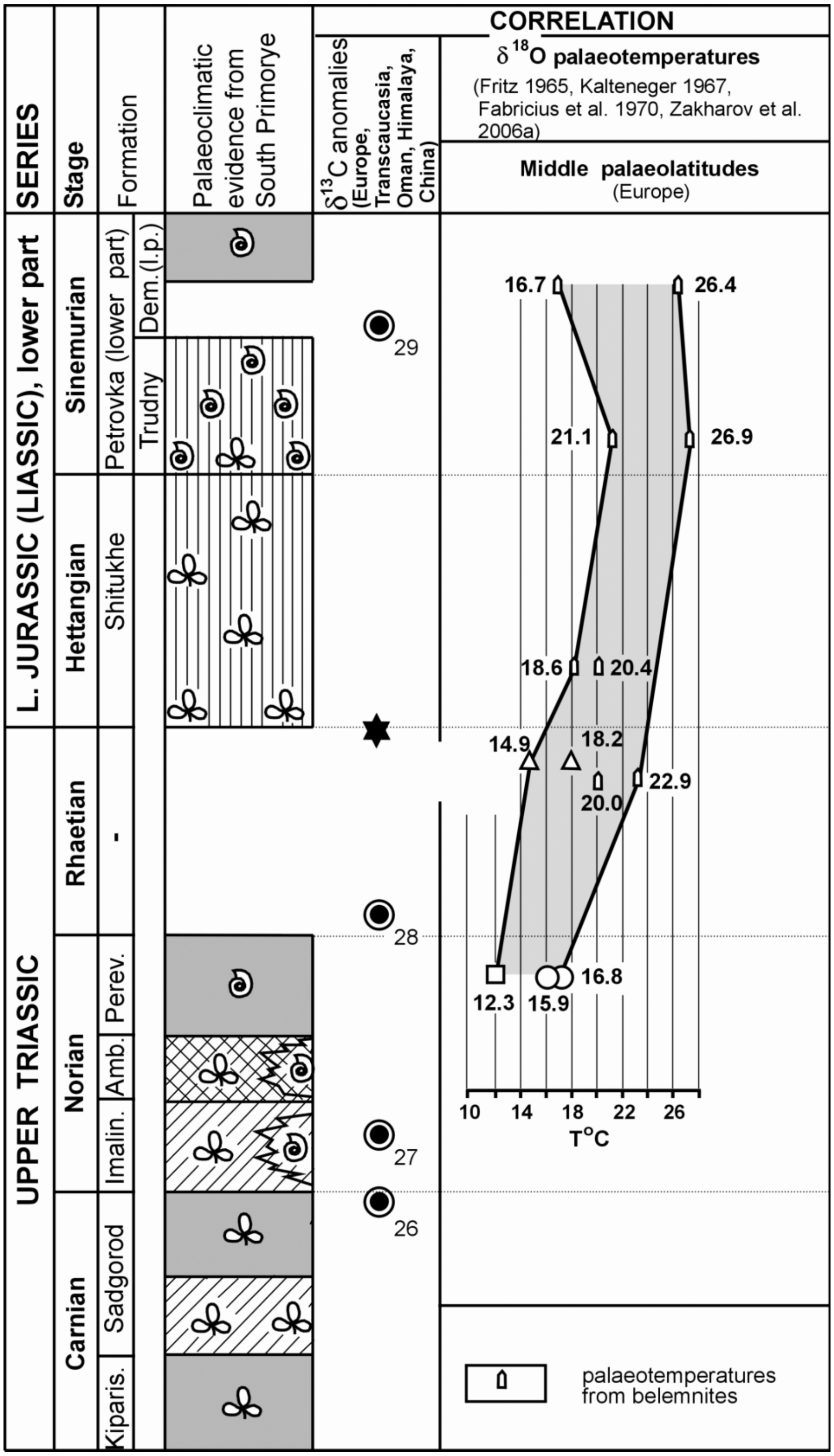

Fig. 6. Correlation of Upper Triassic to lower Liassic of the southern Russian Far East with the available oxygen and carbon-isotope data. Positive carbon-isotopic anomalies: 26, late Carnian (Altudorei 1999; Zakharov et al. 2000); 27, early Norian (Zakharov et al. 2000); 28, early Rhaetian (Morante & Hallam 1996); 29, middle Sinemurian (Jenkyns et al. 2002). Additional designations as in Figs. 3–5.

There is no information on isotopic palaeo-seawater temperatures for PTB beds (no well-preserved fossils, suitable for oxygen-isotopic investigation, have been discovered within this interval). However, information on the main trends in temperature change has been obtained, using the Ca–Mg ratio method for carbonate sequences (Zakharov et al. 2001). We interpret the lowest magnesium content in the uppermost Permian carbonates of Transcaucasia as a short-term fall of palaeo-seawater temperature at the very end of the Changhsingian, following the thermal maximum of the late Changhsingian *Paratirolites kittli* Zone, and particularly at the beginning of the Induan (FAD *Hindeodus parvus*), just after a significant negative carbon-isotope excursion (Baud et al. 1989; Y.D. Zakharov et al. 2005). It is known that prominent negative carbon-isotope excursions along with the Permo–Triassic one, mentioned above (Baud et al. 1989; Magaritz 1989; Holser et al. 1991; Yin & Zhang 1996; Zakharov et al. 2001; Berner 2002), were discovered in the Carboniferous–Permian (Magaritz 1989), Triassic–Jurassic (Guex et al. 2004; Kuerschner et al. 2007) and Jurassic–Cretaceous (Guex et al. 2004) boundary

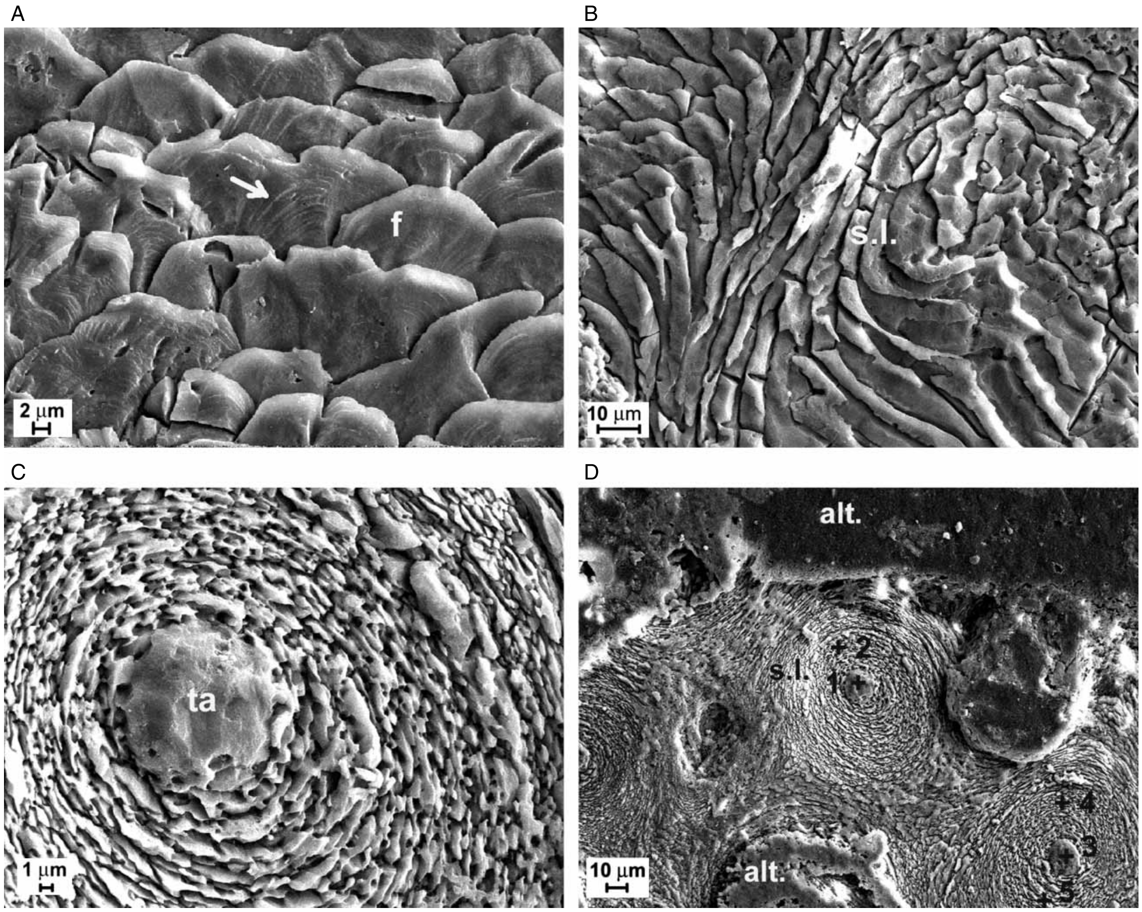

Fig. 7. Microphotograph of the shell structure in late Kungurian brachiopods from the Kapp Starostin Formation (Vøringen Member) in West Spitsbergen: A. athyridid brachiopod, sample Sp2–1; fibres of the secondary layer (shell transect, slightly oblique section of the pedicle valve); the arrow indicates an area with clear daily growth lines, showing their excellent preservation. B–D. *Rhombospirifer*? sp., sample Sp1–1 – pseudopunctae-like structure of the secondary layer (shell transection, slightly oblique section of the brachial valve) and some diagenetically altered parcels. Abbreviations: s.l., secondary layer; f, fibre of the secondary layer, ta, taleola (pseudopuncta), alt., siliceous parcel (combined with Al (4100—10,100 mg/kg), Fe (2200 mg/kg), Cl (15,700 mg/kg), Yb (700 mg/kg) and K (2100 mg/kg); location of some geochemical spectra (1–5) indicated by crosses.

transitions, which, following Wignall & Twitchett (2002) and Kidder & Worsley (2004), were mainly the result of volcanic activity and related methane poisoning.

Another possible reason to explain the fact of the lowest magnesium content in the uppermost Permian carbonates of Transcaucasia seems to be a fundamental change in PTB sedimentation, noted by Baud et al. (2007). However, Kozur (2007) discovered a cool-water conodont fauna in the *Pleuronodoceras occidentale-Xenodiscus jubilaearis* Zone of Transcaucasia and Iran and volcanic microsphaerulites at this level in Iran and the Germanic Basin. These palaeontological and volcanological patterns are consistent with our version.

Induan to Ladinian interval

According to our oxygen-isotope temperature determinations (Zakharov et al. 1999a), late Olenekian and late Anisian climates in Arctic Siberia seem to be about 7.4 and 6.6°C warmer, respectively, than early Olenekian temperatures (Fig. 5). The calculated middle to late Anisian isotopic palaeo-seawater temperatures of about 15°C for Arctic Siberia (Kurushin & Zakharov 1995; Zakharov et al. 1999a), approach those of the late Olenekian (about 16.2°C; Zakharov et al. 1999a).

No oxygen-isotopic palaeotemperature data have been obtained for other levels of the Lower–Middle Triassic, including the Ladinian. Furthermore, the temperatures estimated now from oxygen isotopic analyses on Lower to Middle Triassic biogenic carbonates on the whole are preliminary and restricted only to the Boreal realm, and therefore it seems to be especially difficult to use this information for global correlation.

Carnian to Rhaetian interval

There is no information on oxygen-isotopic composition of well-preseved Carnian fossils. Recalculating Fabricius et al.'s (1970) oxygen-isotopic data from late Norian invertebrate shells of the northern Alps shows comparatively low palaeotemperatures: 15.9–16.8°C from cephalopods *Arcestes* and Nautilidae, and 12.3°C from the bivalve *Halobia* (Fig. 6). The revised oxygen-isotopic palaeotemperatures for aragonitic shells here, and below, were obtained by us using the method proposed by Grossman & Ku (1986); for calcitic shells, as was mentioned

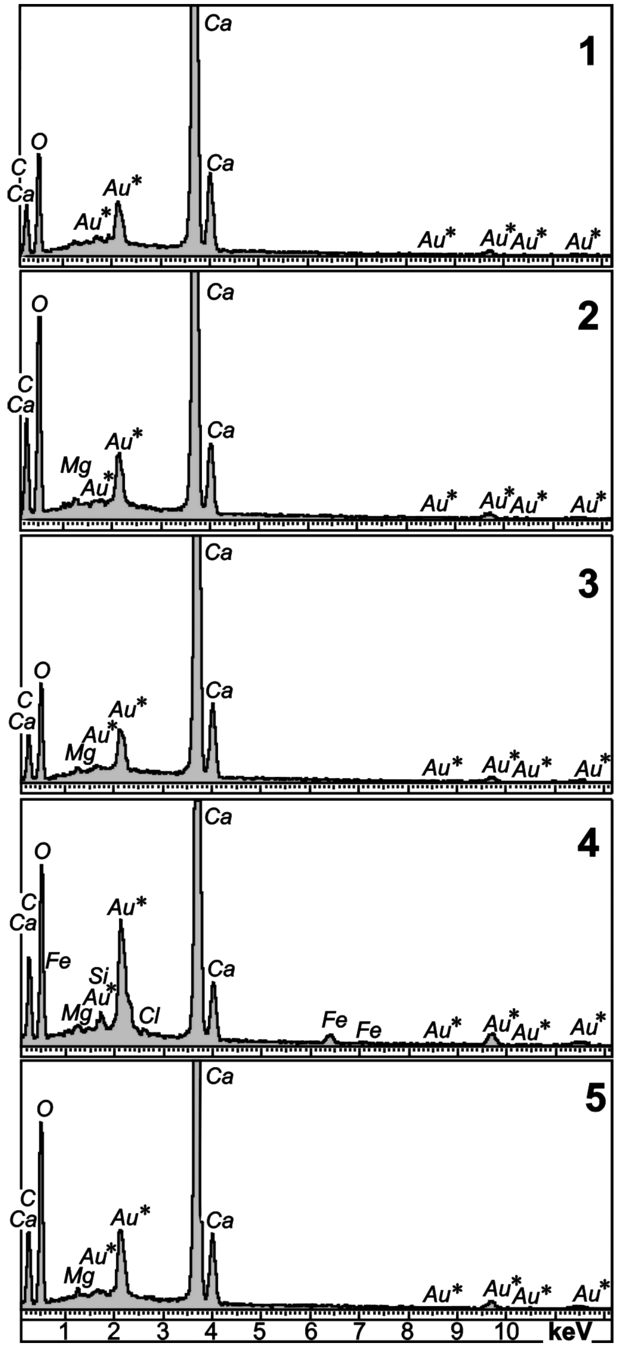

Fig. 8. Geochemical profiles from shell of *Rhombospirifer*? sp., sample Sp1–1. Location of the spectra 1–5 are shown in Fig. 7D. The asterisk near Au indicates that this Au value should not be taken into account because the surface of the sample was covered by gold before scanning. Figure 7C, D cross-sections of pseudopunctae-like structure of secondary layer. Designations as in Figs. 3–6.

above, we used the form proposed by Anderson & Arthur (1983). Data on comparatively low late Norian palaeotemperatures are in good agreement with evidence from South Primorye concerning latitudinal reduction of the tropical-subtropical climatic zone during the late Norian. Somewhat higher credible palaeotemperatures for the Alps were recalculated from data on the late Rhaetian brachiopods (14.9–18.2°C, Fabricius et al. 1970) and some well-preserved belemnites (16.6–22.9°C; Kaltenegger 1967), which is in accordance with the palaeofloral records from Triassic–Jurassic boundary strata in Greenland (Hesselbo et al. 2003a).

Hettangian to Sinemurian interval

The Jurassic is generally characterised as a period with greenhouse conditions (Vajda & Wigforss-Lange 2009, Mehlqvist et al. 2009, this volume). Again, using Fabricius et al.'s (1970) oxygen-isotopic data from Hettangian belemnites of the Alps we can see comparatively high-recalculated palaeotemperatures (>18.6–20.4°C), similar to those obtained for the late Rhaetian (Kaltenegger 1967) in this area (Fig. 6).

Contradictory isotopic information has been obtained for Sinemurian palaeotemperatures. High palaeotemperatures came from ammonoids in Europe: those from the lower Sinemurian show palaeotemperatures of 26.9°C and those from the upper Sinemurian 26.4°C (Fritz 1965; Zakharov et al. 2006b). However, recalculated palaeotemperatures, obtained from a Sinemurian brachiopod (15.1°C) and belemnites (13.1–17.4°C) from the Alps are significantly lower, showing possible cooling in some parts of the Sinemurian (Fabricius et al. 1970). Palaeotemperature data, obtained from Sinemurian ammonoid (Zakharov et al. 2006b), brachiopod and belemnite (Fabricius et al. 1970) faunas from Europe are consistent with palaeobotanical and palaeozoological evidence from South Primorye, showing the expansion of the tropical-subtropical climatic zone during the Hettangian to early Sinemurian. Short-term cooling, recognised from palaeontological data for the very end of the Sinemurian in South Primorye has not yet been confirmed by oxygen-isotopic data (because of a lack of information on this topic).

Pliensbachian to Toarcian interval

Our recent isotopic data from Liassic ammonoids of Europe (Zakharov et al. 2006b) show a drop in temperature from the early Pliensbachian (23.1–24.2°C) to the late Pliensbachian (20.7°C), using aragonitic ammonoid shells from England and Germany, respectively (Zakharov et al. 2006b). Similar evidence has been obtained earlier from European belemnites: 15–27°C for the early Pliensbachian (Fritz 1965; Fabricius et al. 1970; Rosales et al. 2004) and 10–22°C for the late Pliensbachian (Fabricius et al. 1970; Rosales et al. 2004). A distinct Toarcian climatic optimum (20–28.8°C) has been recorded on the basis of isotopic data from Western Europe (Pearson 1978; Rosales et al. 2004) (Fig. 9). Palaeozoological records on latitudinal reduction of the tropical–subtropical climatic zone in the Russian Far East in the late Pliensbachian, when mixed Tethyan-Boreal ammonoid assemblages occurred in South Primorye, and subsequent latitudinal expansion at least during the late Toarcian, when abundant subtropical trigoniids appeared there are in accordance with the isotopic palaeotemperature estimations given above.

Aalenian to Bathonian interval

Late Bajocian–the earliest Bathonian palaeotemperatures are comparatively low for middle latitudes of western Europe (13.2–23.0°C), Greenland (19.1–20.3°C) and high-latitude Alaska (15.9°C) (Teiss & Naidin 1973). Higher palaeotemperatures for the Bajocian were calculated only for South America (19.7–28.6°C, Teiss & Naidin 1973).

Table 1. Carbon and oxygen isotope analyses of calcitic brachiopod and bivalve shells from the Permian of the northern Russian Far East and Spitsbergen.

Sample	$\delta^{13}C$ anomaly number (index for NE Russia)	Locality	Species	Stage	Zone	Formation	Location	Colour	Degree of the shell structure safety	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	*T* (°C)
10c-1	18 (XVI)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp.	Changhsingian	*Inoceramus costatum*	Rogachev	Prismatic layer (5 mm thick)	Dark grey	Well preserved	3.2	− 13.7	–
10c	–	Taskan River, left bank, above Vesely Creek mouth	*Intomodesma* sp.	Changhsingian	*Inoceramus costatum*	Rogachev	Prismatic layer (6 mm thick)	Light grey and grey	Well preserved	1.1	− 9.6	–
10b	13 (XI)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* cf *tenkensis* Biakov.	Wuchiapingian-Changhsingian	*Maitaia tenkensis*	Rogachev	Prismatic layer (1.6 mm thick)	Grey	Well preserved	4.2	− 10.9	–
8-2a-1	12 (X)	Levyj Vodopadnyj Creek, Khivach River basin	Athyridid brachiopod	Upper–upper Capitanian	*Maitaia tenkensis*	Lower Khivach	Middle area of the ventral shell	Light grey	Excellent preserved	5.5	− 3.1	25.4?
8-2a	12 (X)	Levyj Vodopadnyj Creek, Khivach River basin	*Maitaia* sp. indet.	Upper–upper Capitanian	*Maitaia bella*	Lower Khivach	Prismatic layer (1 mm thick)	Dark grey and grey	Well preserved	3.9	3.9	–
10a-6	12 (X)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp. indet.	Upper–upper Capitanian	*Maitaia bella*	Rogachev	Prismatic layer (1–1.2 mm thick)	Light grey and grey	Well preserved	4.6	10.5	–
10a-5	–	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp. indet.	Upper–upper Capitanian	*Maitaia bella*	Rogachev	Middle part of the shell (1 mm thick)	Dark grey and grey	Well preserved	2.9	− 10.3	–
10a-4	11 (IX)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp. indet.	Middle–upper Capitanian	*Maitaia bella*	Rogachev	Prismatic layer (2 mm thick)	Dark grey and grey	Well preserved	3.6	− 13.0	–
10a-3	–	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp. indet.	Lower–upper Capitanian	*Maitaia bella*	Rogachev	Prismatic layer (9 mm thick)	Dark grey and grey	Well preserved	0.8	− 13.2	–
10a-2	10 (VIII)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia bella* Biakov	Lower–upper Capitanian	*Maitaia bella*	Rogachev	Hing margin	Grey	Well preserved	3.5	− 8.9	–
10a	–	Taskan River, left bank, above Vesely Creek mouth	*Maitaia bella* Biakov	Upper–lower Capitanian	*Maitaia bella*	Rogachev	Prismatic layer (3 mm thick)	Grey	Well preserved	2.8	− 14.30	–
10a-1	9 (VII)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp. indet.	Middle–lower Capitanian	*Maitaia bella*	Rogachev	Area of ventral valve	Dark grey and grey	Well preserved	3.5	− 12.9	–
31-16	–	Russkaya-Omolons-kaya River	*Neospirifer* sp.	Lowermost Capitanian	*Maitaia bella*	Gizhiga	Hinge margin of the ventral valve	Brownish light grey	Excellent preserved	5.0	− 1.1	16.5
31-15	–	Russkaya-Omolons-kaya River	*Merismopteria* ex gr. *macroptera* (Morris)	Lowermost Capitanian	*Maitaia bella*	Gizhiga	Prismatic layer (1.5 mm thick)	Dark grey	Excellent preserved	5.5	− 1.7	19.0
10	8 (VI)	Taskan River, left bank, above Vesely Creek mouth	*Maitaia*? sp. indet.	Upper–upper Wordian	*Intomodes-ma costatum*	Turin	Prismatic layer (3–4 mm thick)	Light grey and grey	Well preserved	5.0	− 13.6	–

Table 1. (Contd.)

Sample	$\delta^{13}C$ anomaly number (index for NE Russia)	Locality	Species	Stage	Zone	Formation	Location	Colour	Degree of the shell structure safety	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T (°C)
6e	8 (VI)	Taskan River, right bank, Kharius	*Maitaia*? sp. indet.	Uppermost Wordian	*Kolymia multiformis*	Turin	Prismatic layer (3–4 mm thick)	Light grey and grey	Well preserved	4.8	–	–
6d	–	Taskan River, right bank, Kharius	*Maitaia*? sp. indet.	Upper–upper Wordian	*Kolymia multiformis*	Turin	Prismatic layer (3–4 mm thick)	Grey and dark grey	Well preserved	4.5	−13.29	–
2e	–	Taskan River, left bank, above Vesely Creek mouth	*Maitaia* sp. indet.	Upper–lower Wordian	*Kolymia plicata*	Turin	Prismatic layer (2 mm thick)	Light grey and grey	Well preserved	4.7	−9.8	–
2d	7 (V)	Taskan River, left bank, above Vesely Creek mouth	*Kolymia plicata* Biakov	Lower–lower Wordian	*Kolymia plicata*	Turin	Prismatic layer (1.5–2 mm thick)	Light grey and grey	Well preserved	5.1	−10.2	–
3-55	7 (V)	Levyj Vodopadnyj Creek, Khivach River basin	*Neospirifer subfasciger* (Licharev)	Upper–upper Wordian	*Maitaia tenkensis*	Lower Khivach	Middle area of the ventral shell	Light grey	Excellent preserved	5.7	−2.0	20.4
2c	–	Taskan River, left bank, above Vesely Creek mouth	*Aphanaia* ex gr. stepanovi (Muromzeva).	Middle–upper Roadian	*Kolymia inoceramiformis*	Turin	Prismatic layer (4 mm thick)	Light grey	Well preserved	4.6	−10.3	–
2b	–	Taskan River, left bank, above Vesely Creek mouth	*Aphanaia*? sp. indet.	Lower–upper Roadian	*Kolymia inoceramiformis*	Turin	Prismatic layer (about 10 mm thick)	Light grey and grey	Well preserved	4.6	10.0	–
2a	6 (IV)	Taskan River, left bank, above Vesely Creek mouth	*Aphanaia*? sp. indet.	Upper–lower Roadian	*Aphanaia dilata*	Turin	Prismatic layer (3–4 mm thick)	Light grey and grey	Well preserved	4.7	−10.9	–
3-17-2	6 (IV)	Levyj Vodopadnyj Creek, Khivach River basin	*Kolymia taskanica* Biakov.	Upper Roadian	*Kolymia inoceramiformis* Licharew	Lower Omolon	Prismatic layer (3–4 mm thick)	Grey	Well preserved	5.4	−4.4	–
6c	6 (IV)	Taskan River, right bank, Kharius	*Kolymia taskania* Biakov	Upper–upper Roadian	*Aphanaia dilata*	Turin	Prismatic layer (3–4 mm thick)	Light grey	Well preserved	6.5	–	–
6b	–	Taskan River, right bank, Kharius	*Kolymia* sp. indet.	Lower–upper Roadian	*Aphanaia dilatata*	Turin	Prismatic layer (1–1.5 mm thick)	Light grey and grey	Well preserved	6.0	12.3	–
6a	–	Taskan River, right bank, Kharius	*Kolymia inoceramiformis* Licharev	Upper–lower Roadian	*Aphanaia dilatata*	Turin	Prismatic layer (1.5 mm thick)	Light grey	Well preserved	5.7	−12.3	–
2	–	Taskan River, left bank, above Vesely Creek mouth	*Kolymiaa* sp. indet.	Lower–lower Roadian	*Aphanaia dilata*	Turin	Prismatic layer (2–3 mm thick)	Grey	Well preserved	2.8	−12.6	–
29-3	5 (III)	Levyj Vodopadnyj Creek, Khivach River basin	*Aphanaia*? sp. indet.	Uppermost Kungurian	*Kolymia inoceramiformis* Locharew	Lower Omolon	Prismatic layer (1.5–2 mm thick)	Light grey and grey	Well preserved	5.4	−4.2	–
9c	5 (III)	Taskan River, right bank, Kharius	*Aphanaia* vel. *Kolymia* sp. indet.	Uppermost Kungurian	*Aphanaia andrianovi*	Kiprei	Prismatic layer (1.5 mm thick)	Light grey and dark grey	Well preserved	3.5	−13.9	–
9b	–	Taskan River, right bank, Kharius Creek	*Kolymia* sp. indet.	Upper–upper Kungurian	*Aphanaia andrianovi*	Kiprei	Prismatic layer (1 mm thick)	Dark grey and light grey	Well preserved	1.8	−15.5	–
9a	4 (II)	Taskan River, right bank, Kharius Creek	*Aphanaia*? sp. indet.	Upper–upper Kungurian	*Aphanaia andrianovi*	Kiprei	Prismatic layer (1.5 mm thick)	Light grey and grey	Well preserved	4.3	−15.5	–
Sp1-1	4 (II)	Spitsbergen, Starostin Cape	Spiriferid brachiopod *Rhombospirifer*? sp.	Upper–upper Kungurian	–	Tempelfjorden Group, Voringen Member	Secondary layer (at *L*> 36 mm)	Silvery white	Fibrous microstructure	6.5	−2.7	23.5
Sp1-2	4 (II)	Spitsbergen, Starostin Cape	Same shell	Upper–upper Kungurian	–	Tempelfjorden Group, Voringen Member	Secondary layer (at *L*> 34 mm)	Silvery white	Fibrous microstructure	7.0	−2.8	23.8

Table 1. (Contd.)

Sample	$\delta^{13}C$ anomaly number (index for NE Russia)	Locality	Species	Stage	Zone	Formation	Location	Colour	Degree of the shell structure safety	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	*T* (°C)
Sp1-3	4 (II)	Spitsbergen, Starostin Cape	Same shell	Upper–upper Kungurian	–	Tempelfjorden Group, Voringen Member	Secondary layer (at *L*> 33 mm)	Silvery white	Fibrous microstructure	7.2	− 3.1	25.4
Sp1-4	4 (II)	Spitsbergen, Starostin Cape	Same shell	Upper–upper Kungurian	–	Tempelfjorden Group, Voringen Member	Secondary layer (at *L*> 32 mm)	Silvery white	Fibrous microstructure	7.1	− 3.2	25.9
Sp2-1	4 (II)	Spitsbergen, Starostin Cape	Athyridid brachiopod	Upper–upper Kungurian	–	Tempelfjorden Group, Voringen Member	Secondary layer (at *L*= 16 mm)	Silvery white	Fibrous microstructure	6.6	− 2.6	23.1
14	3 (I)	Munugudzhak River (Khivach River basin)	*Aphanaia* sp.	Lower–upper Kungurian	*Kolymaella-Bocharella*	Dzhigdalin	Prismatic layer (1.2 mm thick)	Grey, dark grey and light grey	Fibrous microstructure	4.2	− 6.5	–
3a	3 (I)	Taskan River, left bank, down-stream Rogach Creek mouth	*Aphanaia* cf. *andrusovi* (Muromzeva)	Lower–upper Kungurian	*Aphanaia andrianovi*	Kiprei	Prismatic layer (2 mm thick)	Light grey and grey	Well preserved	4.9	− 7.8	–
5b-1	–	Taskan River, left bank, down-stream Rogach Creek mouth	*Lissochonetes magnum* Afanasyeva.	Lower Kungurian	*Aphanaia lima*	Kiprei	Middle area of the ventral valve	Light grey	Well preserved	0.2	− 13.6	–

A general temperature drop in middle latitudes during at least the second portion of the Bajocian (comparing with the Toarcian) partly coincides with a reduction of the tropical-subtropical climatic zone in the Russian Far East. This trend is based on the existing climatic conditions intermediate between warm-temperate and subtropical ones in South Primorye (Fig. 9), using palaeobotanical data (Volynets 2008) and the distribution of Boreal inoceramid bivalves, when associated only with rare thermophilous trigoniid bivalves, in the Aalenian–Bajocian Bonivur Creek Formation (Sey & Kalacheva 1980, 1981).

Callovian to Kimmeridgian interval

The highest Jurassic isotopic palaeotemperature (29.4°C), obtained by us came from aragonitic ammonoid *Kossmoceras* sp. shells, discovered in the lower middle Callovian of England (Zakharov et al. 2006b, Table 4). Other Callovian to Kimmeridgian fossils from middle latitudes show the following significant palaeotemperature fluctuation (Fig. 10): (1) 14.5–20.8°C (belemnites; lower Callovian, Poland and Pechera River Basin in Russia; Teiss et al. 1968); (2) 11.9°C (palaeotemperature calculated by us from a belemnite rostrum; middle lower Callovian Black Clay, Kineshma area, Volga River, at 1 km N from Novoloki Village; Zakharov et al. 2006b, Table 4); (3) 13.3–20.7°C (palaeotemperatures calculated by us from the ammonoid *Cadoceras elathmae* Nikitin and *Cadoceras* sp. shells; middle lower Callovian Black Clay, Kineshma area, Volga River, at 1 km N from Novoloki Village; Zakharov et al. 2006b, Table 4); (4) 9.8–16.7°C (palaeotemperatures calculated by us from brachiopod shells; middle lower Callovian Black Clay, Kineshma area, Volga River, at 1 km N from Novoloki Village; Zakharov et al. 2006b; Table 4); (5) 10.3–18.4°C (belemnites; middle Callovian, Russian Platform, Urals and Kazakhstan (Teiss et al. 1968; Podlaha et al. 1998); (6) 10.8–19.4°C (belemnites; upper Callovian, Poland, Russian Platform; Teiss et al. 1968; Longinelli et al. 2003); (7) 9.8–14.1°C (bivalves; upper Callovian, Russian Platform; Zakharov et al. 2006b); (8) 17.2–21.0°C (*Quenstedttoceras* sp. and *Kossmoceras aculcatum* Michailow; upper Callovian, Poland and Russian Platform; Zakharov et al. 2006b; Table 4); (9) 16–28°C (Oxfordian, England and Madagascar, Anderson et al. 1994; Lécuyer & Bucher 2006) (Fig. 10); (10) 11–13°C (belemnites; early Oxfordian, (lower Oxfordian, Polish); Longinelli et al. 2003); (11) 15.8–16.9°C (bivalves; lower Oxfordian, England; Anderson et al. 1994); (12) 13.5–26.7°C (belemnites; middle Oxfordian, England; Longinelli et al. 2003); (13) 12°C (belemnites; upper Oxfordian, England; Longinelli et al. 2003); (14) 16–17°C (belemnites; lower Kimmeridgian, Germany; Bowen 1961) and (15) 12–20°C (belemnites; upper Kimmeridgian, Greenland; Bowen 1969; Price & Sellwood 1994). It is important to note that palaeotemperatures calculated from some Callovian belemnites of the Russian Platform, as well as some Albian belemnites of North France, are lower than those from ammonite shells, found in the same calcareous nodule (Zakharov et al. 2006b). This evidence suggests that belemnites engaged in significant short-term vertical migrations in the water column, reaching colder upper bathyal waters.

Kimmeridgian high-latitude palaeotemperatures, calculated from belemnites and brachiopods collected in the Falkland Islands (Price & Sellwood 1994), New Zealand, Antarctica (Ditchfield et al. 1994; Podlaha et al. 1998), and the subpolar Urals (Teiss et al. 1968; Gröcke et al. 2003; V.A. Zakharov et al. 2005)

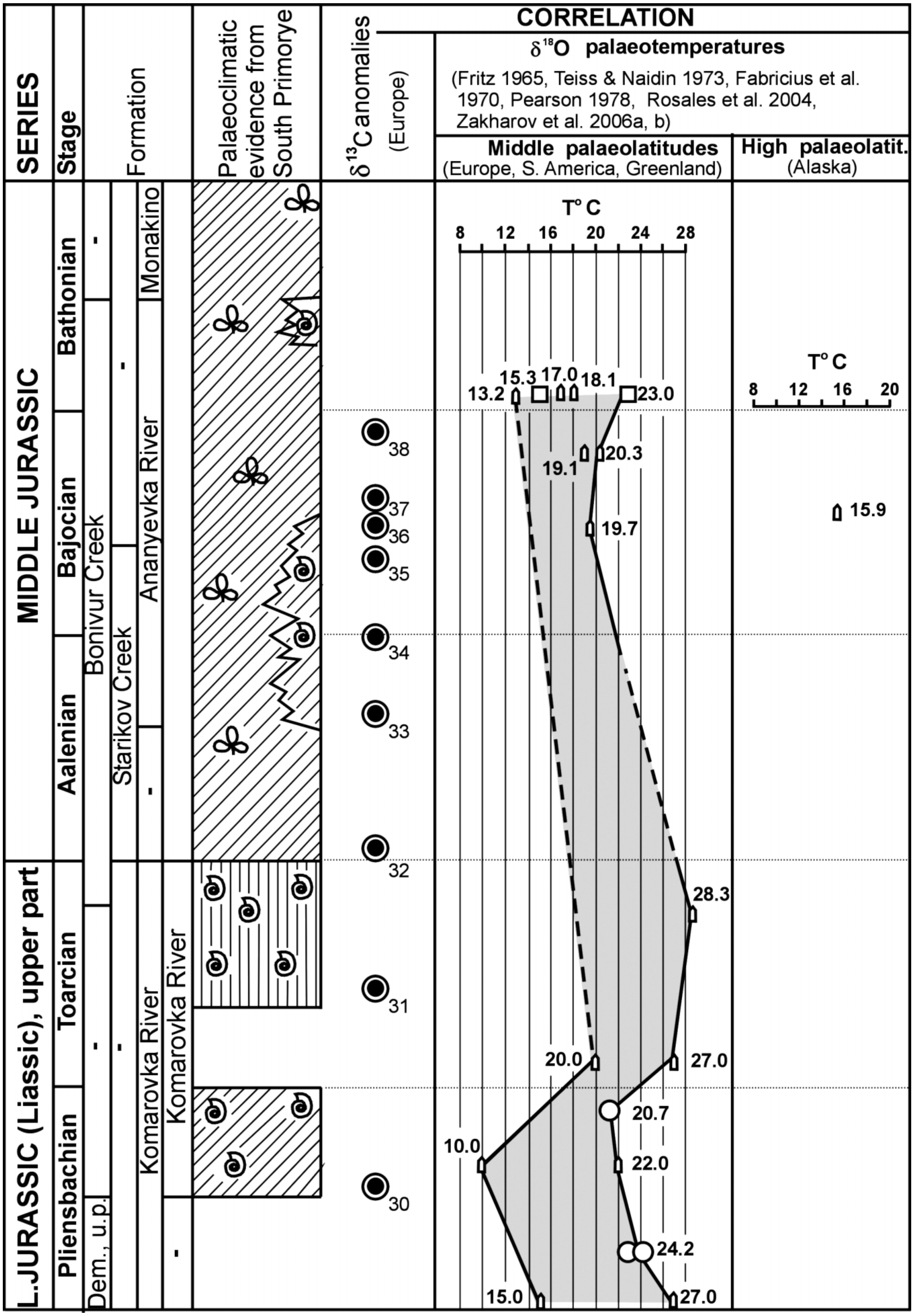

Fig. 9. Correlation of upper Liassic to Middle Jurassic of the southern Russian Far East with the available oxygen and carbon-isotope data. Positive carbon-isotopic anomalies: 30, middle Pliensbachian (Hesselbo et al. 2000; Jenkyns et al. 2002); 31, middle Toarcian (Ignatiev et al. 1982; Jenkyns et al. 2002); 32, early Aalenian (Jenkyns et al. 2002; Hesselbo et al. 2003b); 33, early late Aalenian (O'Dogherty et al. 2006); 34, earliest Bajocian (Ditchfield 1997); 35–38, Bajocian (Jenkyns et al. 2002; Hesselbo et al. 2003b; O'Dogherty et al. 2006). Additional designations as in Figs. 3–6.

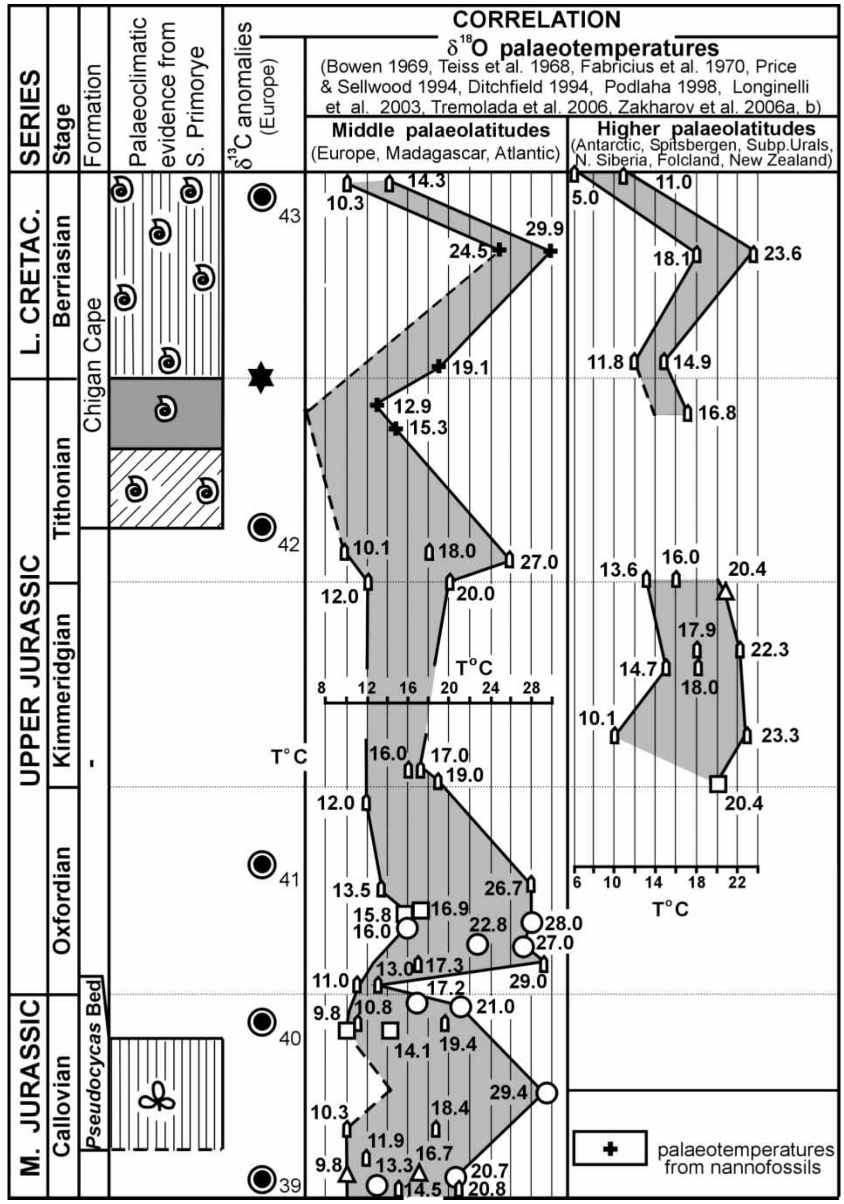

Fig. 10. Correlation of Upper Jurassic to Lower Cretaceous (Berriasian) of the southern Russian Far East using available oxygen- and carbon-isotope data. Positive carbon-isotopic anomalies: 39, early Callovian (Jenkyns et al. 2002; O'Dogherty et al. 2006); 40, late Callovian (Barskov & Kiyashko 2000); 41, late Oxfordian (Anderson et al. 1994); 42, early Tithonian (Tremolada et al. 2006); 43, late Berriasian (Price et al. 2000). Additional designations as in Figs. 3–6.

vary between 10.1 and 23.3°C. The most negative δ^{18}O value representing the most elevated 'temperature' (abnormal temperature, 25°C) recorded in the lowermost Kimmeridgian of the Falkland area, was considered by Sellwood et al. (2000) and Gröcke et al. (2003) to indicate fresh-water input resulting from a reduction in ice and/or snow-sheet and associated increased runoff.

A solitary piece of climatic evidence found in the Callovian–Kimmeridgian interval in South Primorye seems to be the discovery of the Callovian cycadean frond *Pseudocycas* sp., reflecting humid subtropical conditions or neighbouring subtropical areas. Therefore, we correlate the Callovian *Pseudocycas* Beds of South Primorye with the thermal lower middle Callovian maximum, determined on the basis of the oxygen-isotope data (Zakharov et al. 2006b).

Tithonian to Berriasian interval

Isotopic palaeotemperature data for the latest Jurassic (Tithonian) are incomplete and contradictory, but evidence from the Berriasian seem to be more complete (Fig. 10). Data on marine bivalves and ammonoids from South Primorye are in accordance with the oxygen-isotope evidence, according to which expansion of the tropical-subtropical climatic zone took place apparently in the early Tithonian (Berlin et al. 1967; Teiss et al. 1968; Price & Sellwood 1994; Tremolada et al. 2006) and early to middle Berriasian (Teiss et al. 1968; Ditchfield et al. 1994; Price & Mutterlose 2004) with a reduction in the late Tithonian (Tremolada et al. 2006; Zakharov et al. 2006b) and at the very end of the Berriasian (Ditchfield 1997; Price et al. 2000).

During the latest Jurassic palaeotemperature in middle latitudes dropped from about 27°C in the early Tithonian to 15.3°C in the late Tithonian, following warmer conditions (29.9°C) in Berriasian time (Fig. 10). The Tithonian to early Berriasian mollusc succession in South Primorye and the adjacent eastern Heilongjiang Province area, northeast China, provides evidence of the next stages: (1) early–middle Tithonian (mixed Boreal-Tethyan bivalve assemlage, represented by Boreal *Buchia* in Primorye and Heilongjiang and Tethyan *Jotrigonia* in Primorye; Tethyan and cosmopolitan ammonoids, *Semiformiceras*, *Pseudolissoceras*, *Haploceras*, *Pseudosubplanites* and *Dalmasiceras* in Primorye; Sey & Kalacheva 1980, 1981; Konovalova & Markevich 2004; Sha 2007); (2) latest Tithonian (Boreal *Buchia* assemblage with no thermophilous trigoniid bivalve elements in Primorye and Heilongjiang; Konovalova & Markevich 2004; Sha 2007); (3) earliest Berriasian (Tethyan and possibly mixed Boreal-Tethyan mollusc assemlages; in this stage of our knowledge of the earliest Berriasian Tethyan ammonoids, *Pseudosubplanites* and *Dalmasiceras* and cosmopolitan ammonoids has only been discovered in the South Primorye region, whereas the earliest Berriasian *Buchia volgenis-B.* cf. *subokensis-B.* cf. *okensis-B. unschensis* assemblage is now known only in Heilongjiang, with no latest Jurassic ammonoids found in notheastern China because of the facies conditions; Zakharov et al. 1996; Sey & Kalacheva 1999; Sha 2007).

Succession of carbon-isotope events

Additional important information on Early–Middle Triassic marine environments can be obtained from data from positive carbon-isotopic anomalies. As suggested by Alcala-Herrara et al. (1992), some variations in $\delta^{13}C/^{12}C$ ratios recorded in deep-water marine organic carbonates might be controlled by such environmental factors as the carbon budget, upwelling and primary productivity. It is difficult to separate the effect of each of these factors in deep-water conditions, but when worldwide carbon isotope shifts are observed in shallow-water carbonates, they are generally attributed to a change in primary biological productivity, first of all, as noted above, of phytoplankton. Phytoplankton is one of the main groups of organisms that utilise solar energy on the surface of the ocean and their main biomass is contained in an upper 100 m water mass, related to photosynthesis, but their location within the zone depends first of all on a degree of hydrological intermixing of water under the influence of thermal gradients and winds (Bogorov 1974). Phytoplankton productivity is great in areas characterised by an intensive vertical circulation, as in upwellings. The small amount of plankton in the Recent Arctic and Antarctic seems to be connected with the short vegetal period of phytoplankton at high latitudes. However, during times when polar ice was absent, the related hydrological conditions were probably considerably different from those of the present day, in that poleward transport of large equatorial warm-water masses and weaker vertical circulation of waters probably occurred in some climatic zones. Therefore, the actual method for investigation of Phanerzoic carbon-isotopic anomalies can be applied only with considerable care.

Much published material contains information on the carbon-isotope anomalies of the Late Carboniferous to Early Cretaceous interval (Baud et al. 1989; Holser et al. 1989; 1991; Magaritz 1989; Mii et al. 1997; Musashi et al. 2001; Zakharov et al. 2001; Berner 2002; Hesselbo et al. 2003a, 2003b; Longinelli et al. 2003; Guex et al. 2004; Krull et al. 2004; Payne et al. 2004; Rosales et al. 2004; V.A. Zakharov et al. 2005; O'Dogherty et al. 2006; Richoz 2006; Tremolada et al. 2006; Zakharov et al. 2006a; Galfetti et al. 2007; Horacek et al. 2007; Kuerschner et al. 2007; Payne & Kump 2007; Riccardi et al. 2007; Price & Page 2008). As was shown above, the most frequent Permian–Triassic positive carbon-isotopic anomalies occurred during the late Kungurian (Fig. 3) and late Wordian–early Changhsingian (Fig. 4), and somewhat less from the Induan into the earliest Anisian (Fig. 5). We suggest that a similar picture is apparent also for the late Aalenian–Bajocian time interval (Fig. 9). However, positive carbon-isotopic anomalies seem not to be so frequent during the Hettangian–early Aalenian (Figs. 6 and 9) and Bathonian–early Berriasian (Figs. 9 and 10) times.

Frequent positive carbon-isotopic anomalies of the latest Cisuralian (late Kungurian), Guadalupian, early Lopingian and early Middle Jurassic (late Aalenian to Bajocian) might have been biased by the very unstable biological productivity of the seas of that time, caused, apparently by repeated strong hydrological intermixing of oceanic waters under influence of considerable thermal gradients. Hydrological conditions in the latest Cisuralian (late Kungurian), Guadalupian and early Lopingian time probably differed considerably from most parts of the Cisuralian, late Lopingian, Middle and Late Triassic (somewhat less from the Induan into the earliest Anisian), Early Jurassic, late Middle and Late Jurassic and early Early Cretaceous ones (apparently mainly in a less stratified ocean).

Conclusions

1. Characteristics of Permian to the earliest Cretaceous macrofaunas from the BJKH and SR indicate that they inhabited a single marine basin (Ussiri–Lesser Hingan), located between middle and high latitudes in conditions of significant climatic change. Data obtained agree with the palaeobotanical results from this area, which show that the Permian to the earliest Cretaceous palaeoclimates in these terranes ranged mainly from warm-temperate to intermediate between warm-temperate and subtropical.
2. Judging from isotopic palaeotemperature data, various regional warmings seem to have followed the Permo–Carboniferous glaciation during later Permian to the earliest Cretaceous in the eastern Asian continental margin and these were most likely connected with the main global climatic changes, resulting in frequent expansions and reductions of the warm-temperate climatic zone of the Northern hemisphere.
3. The most frequent Permian to the earliest Cretaceous positive carbon-isotopic anomalies have been discovered within the intervals of the upper Kungurian, Capitanian, lower Changhsingian and upper Aalenian–Bajocian. Taking into account the known data on phytoplankton distribution in the present-day oceans, the location of which depends on a degree of hydrological intermixing of water, the post–Sakmarian conditions might have been related to global environmental changes biased by unstable hydrological conditions, which reached their zenith during the above-mentioned time intervals (in contrast to the Artiskian, Roadian, late Changhsingian to Toarcian and Bathonian to Berriasian times, when more or less stratified oceans seem to have been more common).

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