The Thermal Regime Dynamics in Callovian–Oxfordian Seas of Northwestern Eurasia: Implications of Relative Paleotemperature Data

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Abstract—Six paleothermal and paleohydrologic settings in Callovian–Oxfordian seas of northwestern Eurasia are modeled for six time intervals corresponding in duration to the substage. The modeling principle is based on the study of probabilistic relationships between various faunal elements from different paleobiogeographic provinces in a single species assemblage, ammonites in the considered case. The method opens a possibility to recognize periods of subglobal and local warming and cooling, to reconstruct currents in the entire sea system, and to specify paleotemperature distribution. Two periods of water mass warming (middle Callovian and middle Oxfordian) and three periods of their relative cooling (early Callovian, Callovian–Oxfordian boundary period, and late Oxfordian) are distinguished in the Callovian–Oxfordian. All paleobasins of northwestern Eurasia (Arctic, Central Russian, European, Peri-Tethyan, Tethyan) had autonomous circulation systems with different paleotemperature characteristics. Because of this, dynamics of the thermal regime in the Callovian–Oxfordian basins primarily reflects variations in the hydrological regime rather than paleoclimatic changes.

Key words: Callovian, Oxfordian, paleobiogeography, northwestern Eurasia, paleotemperatures, hydrological regime.

INTRODUCTION

During the Callovian–Oxfordian ages of the Middle–Late Jurassic, the territory of northwestern Eurasia was covered by vast epicontinental seas, which are traditionally subdivided into the European and Central Russian basins separated by the Scandinavian massif and Ukrainian land. In the north, the seas joined the Boreal (Arctic) basin via the Pechora seaway of the Central Russian sea and via a narrow strait between Greenland and Scandinavian massif (European sea). In the south, both basins, the boundary between which should probably be placed along the southern margin of epi-Hercynian massifs, were bordered by warm waters of the Tethys.

Although the Jurassic marine sequences in the territory of northwestern Eurasia are well studied, the paleotemperature characteristic of relevant seas remains poorly known so far. Until the appearance of paleothermometry methods, this aspect of paleobiogeographic studies was virtually ignored. The majority of authors, who were dealing with the problem of sea paleotemperatures, considered it as a problem of paleoclimatology and used the corresponding terminology and conceptual arsenal. Inasmuch as the methods of absolute paleothermometry are applicable only for determination of water paleotemperature, the relevant problems go however far beyond paleoclimatology and require the other,

at least paleohydrological conceptual basis. In his fundamental work *Jurassic Geology of the World*, Arkell (1961) does not use the notion "paleotemperature" at all and related aspects are discussed in small chapter dedicated to the Jurassic climate. He emphasized therewith that even this chapter could be excluded from the book because of absence of reliable data. Discussing paleotemperatures in Jurassic seas, Arkell used relative characteristics such as indicators of warm, tropical and subtropical seas. Among the mentioned indicators, there were reef-building corals, large mollusks, and prevalence of carbonate facies in studied lithofacies. He also compared data on marine sediments with observations in continents to reconstruct the Jurassic climate. This approach allowed him to arrive at the following conclusions: (1) the Jurassic climate was warmer than now; (2) equator was substantially closer to the north, approximately in the southern part of the modern Mediterranean region; (3) characteristic of the Jurassic were alternating cooling and warming periods with a maximal warming in the Oxfordian. The last inference was derived mainly from distribution of corals and thermophilic ammonite assemblages in marine sediments. Summarizing, Arkell assumed that solar radiation in the Jurassic was higher than now.

With the paleothermometry method proposed by H.C. Urey in the 1950s, absolute paleotemperatures can be estimated based on investigation of marine organo-

genic carbonates. During subsequent decades, numerous works, summarizing included, were dedicated to Jurassic paleotemperatures of northern Eurasia and other regions (Emiliani, 1967; Bowen, 1969; Stevens, 1971; Stevens and Clayton, 1971; Teis and Naidin, 1973; Riboulleau *et al.*, 1998; Rohl *et al.*, 2001; Gregory *et al.*, 2002; Poulsen *et al.*, in press; and others). According to these works with most complete data on the Oxfordian of Europe, paleotemperatures reflect primarily the latitudinal changes in this parameter. Temperatures fluctuations were substantial during the Jurassic, corresponding to three warming periods (Toarcian, middle Oxfordian, and Tithonian maximums) in Europe and Greenland (Bowen, 1969). The elucidated trend is complicated by insignificant deviations from average values in space and with time (early Kimmeridgian minimum). The asynchronous paleotemperature minimums and maximums in generalized curves compiled for various regions of the Boreal, Tethyan, and Notal provinces (Stevens, 1971; and others) created pessimistic attitude of some researchers to the absolute paleothermometry method (Hallam, 1978). In some works, there was admitted possibility of using oxygen isotopic ratios for paleotemperature reconstructions, although they are poorly correlative with data on carbon isotope ratios (Gruszczynski, 1998). Despite all the discrepancies in paleothermal studies, many of changes in absolute paleotemperatures estimated for Europe, general and particular, coincide however with changes in relative climatic characteristics based on distribution of corals (Arkell, 1933; Leinfelder, 1993; Bertling, 1993; Bertling and Insalaco, 1998; and others), dinoflagellates (Poulsen *et al.*, in press), and land flora (Vakhrameev, 1991; Abbink *et al.*, 1998, 2001; Rees *et al.*, unpublished data). The equator position proposed by Bowen is also compatible with that in the Arkell's reconstruction.

The available data on Jurassic paleotemperatures of Europe and adjacent regions are irregularly scattered. For instance, Bowen carried out his observations mainly in France and Germany and practically ignored other regions, except for England and Greenland. In terms of paleoclimatic approach, these data are sufficient to reveal succession of warming and cooling periods in different regions, although they give almost nothing for paleohydrological interpretation and can be even misleading in this aspect. It should be noted, that precisely paleoclimatic approach is a key objective of many interpretations.

In our country, paleotemperatures were estimated for the Russian platform and North Siberia (Saks, 1969; Teis and Naidin, 1973; and others). These observations within a wide stratigraphic interval are insufficiently accurate (stage intervals or greater). However, paleotemperature fluctuations defined in the Boreal Jurassic appeared to be synchronous with those in Europe. In the mentioned works, particular attention is paid to seasonal paleotemperature variations extremely valuable in terms of water mass characterization. The analysis of

these observations showed in particular that the northern part of Eurasia was in the Late Jurassic under influence of water masses with temperatures of 10–14°C, i.e., transitional between subtropical and temperate. Even lower paleotemperature values (7 to 10°C) were obtained for high-boreal areas based on analysis of Middle–Upper Jurassic belemnites from Spitsbergen (Ditchfield, 1997).

Based on a brief review of principal results obtained by paleothermal studies of Jurassic marine sediments in northwestern Europe, it is possible to outline several characteristic aspects in approaches of different researchers to paleotemperature data and their interpretation. First, the studied materials (mainly belemnites) are sampled from a limited number of localities in the geographical region under consideration, and inferable trends are incomplete therefore, elucidating only the latitudinal variations of paleotemperatures. Second, the analyzed samples characterize discrete levels within a wide stratigraphic interval so that the maximal resolution rarely exceeds the stage rank. Paleotemperature data for narrower ranges (zone, subzone, and biohorizon) have been published not long ago only (Anderson *et al.*, 1994; Riboulleau *et al.*, 1998; Barskov and Kiyashko, 2000). Third, the paleotemperature curves compiled for long time intervals (e.g., Stevens' curves) characterize particular regions, e.g., the Russian platform or Europe, being considered, nevertheless, as global in significance. These curves completely ignore regional fluctuations, sometimes opposite in sign. Fourth, the results of paleotemperature analysis are usually interpreted as paleoclimatic changes, and spectrum of possible causal effects is depleted therefore, capable to lead in a dead end, because the water temperature is not a climatic parameter.

The traditional paleoclimatic approach to interpretation of paleotemperature data often ignores azonal character and factors of temperature distribution. Therefore, the paleotemperature fluctuations within a given latitudinal zone have been frequently interpreted as "anomalies" or artifacts related to technology of the analysis (Hallam, 1978). The probable influence of currents on temperature distribution is also rarely taken into consideration in reconstructions of the Jurassic seas paleotemperatures. An event, which is commonly under discussion, is the influence of the warm Tethyan current that presumably penetrated via Europe far northward. For example, Arkell assumed influence of a warm current during the Portlandian in England based on coexistence of thermophilic marine and cryophilic continental faunas (Arkell, 1961). Bowen (1969), who noted strong paleotemperature variations (up to 6°C in range within area 200 km across) in the Parisian basin located slightly southward, explained this phenomenon by a local warm current. For the Late Jurassic, he also assumed influence of a warm current that crossed the North Sea and reached Greenland. This event was also discussed in reconstructions based on fossil floras (Abbink *et al.*, 2001). The origin of all these currents

has been considered in the work by Teis and Naidin (1973) who attributed them, based on additional data from Siberia, to a single warm current flowing from southern Europe via Greenland to Siberia. However, the general water circulation system in Jurassic basins has not been reconstructed because of fragmentary character of data used.

The paleobiogeographic data, if they are casually connected with paleotemperatures, are more informative than absolute temperature and better elucidate the hydrological regime in the given paleobasin estimates, being preferable because they are already available and need in a comprehensive analysis only. There are many works dedicated to this problem, and reconstructions of paleocurrents based on distribution of various faunal groups, e.g., ammonites, are of particular interest among them. In terms of methodology, these reconstructions are based on the assumption that migration paths of ammonites coincided with and were controlled by currents, being oriented away from the evolution center of this faunal group (Khudolei, 1976). The countercurrents in the strait between Greenland and Scandinavia (Enay, 1980; Khudolei, 1984, 1985, 1988, 1993; Abbink *et al.*, 2001) have been assumed for Jurassic seas in addition to the cold water discharge in the Pechora basin (Enay, 1980) and cold current of the Callovian time from the Central Russian sea to the Central Asian basin (Khudolei, 1985).

In this work, the main attention is focused on reconstruction of a general circulation system for the Callovian–Oxfordian seas of northwestern Eurasia based on ammonites. In my previous work (Kiselev, 1998), I considered the relative paleotemperatures only for the Central Russian sea. Main conclusions of that work were as follows. (1) In ammonite assemblages from two and more sections, proportions between taxa of different origin change in meridional direction even within geographically limited areas, i.e., these changes are consistent with the zonality principle. (2) Ammonites are mostly stenothermal organisms highly sensitive to water temperature gradients, and paleobiogeographic data on their distribution can be consequently used for detailed reconstructions of the thermal regime in sea basins. (3) Secular changes in relative paleotemperatures vary in different regions (Central Russian sea and adjacent areas of the Tethys, Europe, and the Arctic basin) and even subregions (western and eastern zones of the Central Russian sea), thus being dependent on regional circulation systems. In the Central Russian sea of the Callovian–Oxfordian time, there was a steady circulation system that included a permanent countercurrent crossing the entire basin from the north southward and several warm countercurrents of different origin.

METHODS

In this work, I used principle of the relative paleotemperature analysis applied to ammonite assemblages. This method of estimating relative paleotemperatures has been described earlier (Kiselev, 1998). Four assumptions are basic in the method.

(1) The thermal factor had decisive impact on geographic distribution of ammonite *species* within *intercommunicating epicontinental seas*. In oceanic basins, ammonites belonged to the other biome (in terms of Thierry, 1988), and their distribution was controlled therefore by shelf boundaries and by other factors of morphological–functional adaptation (Dommergues *et al.*, 1987; Thierry, 1988).

(2) The probability of species origin in a diversification center of a genus is maximal. The corresponding center coincides with the species radiation center. Migration paths are oriented away from the species radiation center (Khudolei, 1976).

(3) Four main centers of species radiation were characteristic of Jurassic seas: (a) the Arctic basin (Boreal Province, after Zeiss, 1968), (b) the Central Russian sea (Subboreal Province, ibid), (c) the European basin (Subboreal and Submediterranean provinces, after Ziegler, 1963), and (d) the Tethyan basin (Mediterranean and southerly provinces, ibid). The belonging of a species to a certain radiation center is determined by the assumption (2) regardless of its distribution. For widespread forms, the probability of origin in a radiation center is always maximal, though lesser than 1. An endemic species only can be considered as having probability of origin in a particular basin that is equal to 1 (until the established occurrence in the other basin).

(4) Each of four radiation centers was located at different paleolatitudes, in the following N–S succession: Arctic basin, Central Russian sea, European basin, Tethys ocean. This assumption leans upon paleogeographic reconstructions, the mobilistic included (Cariou *et al.*, 1985; Dommergues *et al.*, 1987; Golonka, 2002; Golonka and Bocharova, 2000; and others). In line with the principle of climatic zonality, the average temperature of water masses increased in the same direction.

The technical aspect of the method consists in calculation of exact proportions between species of different origin in each ammonite assemblage. Inasmuch as the origination center of any species, in particular cosmopolitan one, cannot be determined, in the absolute sense, the *probability* of its origin is calculated for each faunal province using the formula:

$$P_{species\ origin} = \frac{q}{\Sigma q}, \tag{1}$$

where q is a sum of species belonging to the particular genus in the relevant basin, Σq is a sum of q in all basins where the species occurs. The formula of species origin probability is based on the assumption (2). Four or less P values are calculated for each species depending on a number of basins, where it was found. For example,

four P values calculated for *Cardioceras cordatum* (Sow.), the cosmopolitan species within northwestern Eurasia, are 0.1, 0.44, 0.21, and 0.25 for the Tethyan, European, Central Russian, and Arctic basins, respectively. When the species is not cosmopolitan, three or less P values are calculated. For endemic species, P is equal to 1.

When calculating proportions of species originated from different radiation centers in a given ammonite assemblage, all P values are summed with subsequent averaging. In order to obtain parameters characterizing paleotemperatures, conventional coefficients 1, 2, 3, and 4 in order of the average water temperature rise are introduced into the next formula according to the above assumption (4):

$$RPC = \frac{4\Sigma Pt + 3\Sigma Pe + 2\Sigma Pc + 1\Sigma Pa}{\Sigma Pt + \Sigma Pe + \Sigma Pc + \Sigma Pa}, \quad (2)$$

where RPC is the relative paleotemperature coefficient, Pt, Pe, Pc, and Pa are probabilities of species originated in the Tethyan, European, Central Russian, and Arctic basins, respectively. Inasmuch as the probability of species origin for the entire system of basins is equal to 1, denominator $\Sigma(\Sigma P)$ in the formula (1) is consequently equal to the number of species in each assemblage, and the formula turns into the following:

$$RPC = \frac{\Sigma(Ca, c, e, t\Sigma Pa, c, e, t)}{N}, \quad (3)$$

where C is a conventional coefficient characterizing the average water temperature rise in different basins, and *N* is number of species in a given ammonite assemblage. Since the RPC is causally connected with variable temperature regimes in the system of basins under consideration according to assumptions (1) and (4), it can be referred to as "relative paleotemperature."

There are two stages of RPC calculation. The first stage includes compilation of a complete list of species occurring in all the basins within the particular stratigraphic interval and calculation of *q*, Σq, and *P* parameters for each genus separately. The second stage consists in the RPC calculation for the all species of different genera from the particular stratigraphic unit of the individual section or locality.

At the next stage, the calculated RPC values are to be plotted and outlined by isolines on the map. In total, six paleotemperature isoline schemes have been compiled for six time equivalents of the Callovian and Oxfordian substages. To fulfill this task, the necessary parameters have been calculated for 205 ammonite assemblages from 361 localities in 54 areas of the Arctic, European (Peri-Tethyan), Tethyan, and Central Russian basins of northwestern Eurasia (Table 1). The source materials have been collected from publications, museum and private collections in addition to original data obtained during field works in the Russian platform.

Despite the relative simplicity of this method, its application is associated with the following disadvantages.

(1) *Incompleteness of stratigraphic and paleontological data.* Ideally, the RPC should be calculated for the each outcrop, but a study area can frequently be characterized by a single site of several outcrops only because of incompleteness of other sections and fossil records (as is known, compilation of the complete list can take tens of years even in case of regular observations). Because of the same reason, the RPC calculation is problematic for narrow stratigraphic intervals (a zone and lesser subdivisions) in large territories, and therefore the substage scale is used in this work. By a general characterization of the substage time span, which are 1.5 to 2.0 m.y. long in the Jurassic System (Callomon, 1984), many fluctuations in the thermal regime of sea basins, which undoubtedly took place because of cyclic processes in the hydrosphere, remain obscure. Accordingly, any reconstruction for such a time interval depicts only most general trends the thermal regime evolution in a basin. In principle, the paleotemperature parameters and their changes can be inferred for any time interval, if configuration and disposition of the basins did not change. Within the greater time intervals, the calculated parameters become averaged, but their spatial distribution remains unchanged.

(2) *Subjective systematics.* As is known, researchers have different, even opposite views on taxonomy of fossils. Lists of taxa compiled by adherents of species unification and sexual dimorphism concept will be shorter than those of other paleontologists will, and calculated RPC values should be different therefore. Nevertheless, my own experience shows that different taxonomic approaches create an insignificant discrepancy. The erroneously identified close and endemic species almost do not affect the RPC value, because they occur usually in a single paleobiogeographic province (for endemic species this value is always equal to 1). For example, P_{origin} for *Cadoceras elatmae* (Nik.) in the Arctic, Central Russian, European, and Tethyan basins is 0.63, 0.25, 0.11 and 0.01, respectively. For *C. septentrionale* and *C. emelianzevi* Vor., the values are identical, equal to 1, 0, 0, 0 as both forms are unknown beyond the Boreal Province. The error in identification of close species with different geographic distribution is also insignificant, as it is usually concealed under the highest P value characterizing the province (basin), where the genus diversification center was. *Cadoceras tschernischevi* Sok. is known from the Central Russian and Arctic basins, therefore its P_{origin} is 0.69, 0.31, 0, and 0, i.e., insignificantly different in general as compared to above values calculated for *Cadoceras elatmae* (Nik.). The experience shows that the RPC value changes insignificantly and does not affect the general interpretation, if the sum of errors is 20% or less.

(3) *Taxonomic diversity increase*. The discovery of new species increases their lists for any locality. This should change unavoidably the RPC values, particularly when these species represent taxa untypical of the given biochore. Par example, the Callovian and Oxfordian families Oppelidae, Pachyceratide, and Reineckeidae represent taxa of this kind for the Boreal Province and the family Cardioceratidae for the Tethyan Realm. Therefore, it is necessary to estimate how sensitive is the method and how persistent will be conclusions after discovery of additional ammonite taxa, especially in poorly studied areas. I tested the issues using the cases of most critical increase in diversity of ammonite species from alternative biochores (Fig. 1). The RPC value depending on the species diversity changes as the power function, i.e., the rate of changes gradually decreases to reach a plateau. It is remarkable that the RPC change is insignificant even by substantial growth of the species list. The twofold increase in species number gives the enlargement factor of 1.35 only for the RPC parameter. Such an increase of species diversity is unreal for in any alternative biochores, particularly for those hosting tens of species (e.g., for well-studied Europe). Otherwise, it would be unreasonable to discriminate biochores. Most probable is the species diversity (species list) increase created by species of local origin or from a neighboring biochore. In this case, the rate of RPC changes is substantially lower, unaffecting the results. Thus, the available data on diversity of ammonites in the Callovian and Oxfordian sediments should be considered as representative and sufficient for solving the posed problems.

RESULTS

RPC changes in space. The distribution of RPC values over the territory of northwestern Eurasia can be presented in a form of paleotemperature charts of relative paleoisotherms (RPI), which illustrate zonal and regional aspects of the thermal regime evolution in the Callovian–Oxfordian seas (Figs. 2–7).

The azonal (regional) distribution of RPC values is detectable in isoline charts from bends of latitudinal and sublatitudinal isoline trends. In maps of present-day water temperatures, such bends outline the currents (Lednev and Muromtsev, 1953). The bend orientation southward and northward characterizes cold and warm currents, respectively, in the Northern Hemisphere. Therefore, despite their relative character and hypothetical relation with paleotemperature isolines, the observable RPI bends are interpreted here as hypothetical markers of paleocurrents.

The reconstructed paleocurrents characterize the general circulation system in basins of northwestern Eurasia and its evolution during the Callovian–Oxfordian.

For the *early Callovian* (Figs. 2, 8), there are traceable both the cold and warm currents. Two cold cur-
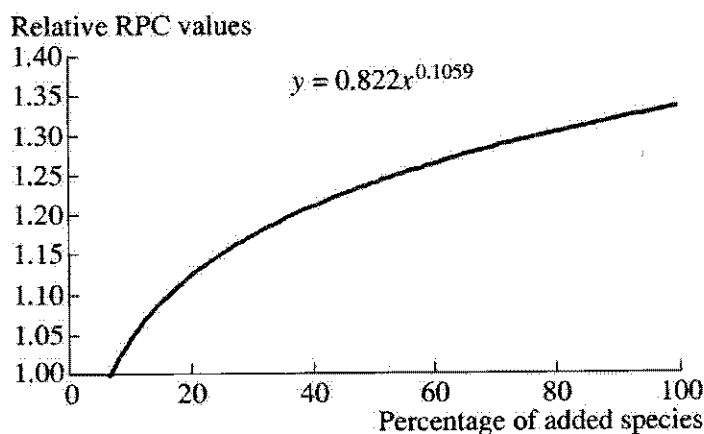
Relative RPC values

$$y = 0.822x^{0.1059}$$

Percentage of added species

Fig. 1. Changes of relative paleotemperature coefficients (RPC) as depending on species diversity increase in ammonite assemblage from alternative biochores (explanation in the text).

rents are distinguishable to the west and east off the Scandinavian massif. The eastern current penetrates into the Central Russian sea via the Pechora seaway. Previously (Kiselev, 1998), I regarded it as an effluent from northerly parts of the Boreal basin. In the Pechora basin or Middle Volga region, this current bifurcates into western and eastern branches: the Dnieper and Caspian seaways, respectively. The Dnieper cold current probably reached, via the Orekhovskii strait, the Crimean Tethys (the term of Sazonova and Sazonov, 1967), where it likely bifurcated again. According to mentioned authors, the Orekhovskii strait did not exist in the Callovian, although a significant percentage of Boreal forms in the Crimean ammonite assemblage and related RPI bend lead to an opposite conclusion. The eastern branch in the Caspian region probably flowed to Central Asia (Pamir Province, after Amanniyazov, 1971).

Another cold current bypassing the Scandinavian massif on the north was likely an effluent stream as well. In the north, it approached Greenland and then deviated eastward penetrating into Europe between England and Norway. Its fairway crossed southern Germany, where boreal species are particularly abundant, and then continued to the Tethys. Both cold currents served probably as main migration paths for boreal ammonites. This assumption is consistent with conclusions of Thierry (1976) who defined two migration paths for boreal ammonites in the Callovian.

Opposite northward-oriented bends of isolines outline warm currents in the European and Central Russian seas. The European warm current began in the Tethys and initially flowed to the Polish sea, being probably responsible for a wide development of carbonate facies there. Farther northward, the current should unavoidably deviate because of the Scandinavian massif, washed the latter on the south and flowed via the Pripyat strait to the Dnieper basin of the Central Russian sea. From the latter, the warm current followed along the Scandinavian massif up to the Pechora sea-

Table 1. Relative paleotemperature coeficients for 54 areas of northwestern Europe[1]

Area	NL	Callovian						Oxfordian					
		early		middle		late		early		middle		late	
		RPC	n	RPC	n	RPC	n	RPC	n	RPC	n	RPC	n
Scotland (Sky) P	5	–	–	–	–	–	–	–	–	2.56	18	2.22	22
England P	25	2.92	70	3.13	39	2.92	60	2.91	74	2.89	72	2.71	44
Germany (Swabia) P	6	3.06	93	3.27	61	3.11	33	3.02	47	2.9	56	2.91	36
Germany (Franconia) P	7	3.2	39	3.13	36	3.04	36	–	–	3.15	54	3.06	84
Northern Germany P	6	3.11	21	3.18	38	3.04	45	2.84	24	–	–	–	–
Poland, P, C	15	3.22	35	3.38	31	2.95	25	2.98	54	2.95	27	3.04	64
Spain (Pyrenees) P	2	3.46	19	3.79	10	–	–	3.66	8	3.49	24	3.54	28
Spain (Ricla) P	4	3.82	44	3.91	43	3.95	9	–	–	–	–	–	–
Southeastern Spain P	3	–	–	–	–	–	–	3.6	8	3.44	19	3.65	38
Portugal (Cap-Mondego) P	6	3.81	59	3.89	14	3.49	8	–	–	–	–	–	–
Central France P	8	3.29	41	3.38	61	3.15	114	2.79	56	–	–	2.83	9
Eastern France P	19	–	–	3.38	61	2.77	37	–	–	2.8	26	2.99	58
Southern France (Maritime Alps) P	3	3.62	21	3.73	25	–	–	–	–	–	–	–	–
Normandy P	8	–	–	–	–	–	–	2.68	13	2.85	12	2.71	8
Northern Jura (Herziah) P	1	–	–	3.25	40	3.08	62	3.11	56	3.15	23	3.05	52
Southern and Middle Jura P	7	3.44	8	–	–	3.37	35	2.91	33	3.05	84	3.1	66
Italy P	4	3.44	13	–	–	–	–	–	–	3.41	12	3.77	13
Sicily P	2	–	–	3.8	9	–	–	3.65	11	–	–	–	–
Moravia P	1	–	–	–	–	–	–	–	–	3.13	23	–	–
Romanian Carpathians P	2	3.64	13	3.85	9	–	–	3.36	6	3.51	6	3.65	10
Dniester, Prut P	5	–	–	–	–	3.35	5	–	–	–	–	3.77	9
Baltic region P	7	–	–	3.18	25	2.93	34	2.65	7	2.7	24	2.3	29
Pomor'e P	4	–	–	–	–	3.04	11	2.93	17	2.88	14	2.66	18
Donets Jurassic P,C	8	2.78	26	3.13	9	2.86	18	2.88	24	2.91	19	2.47	5
Zheleznogorsk C	1	2.32	13	2.92	8	–	–	–	–	–	–	–	–
Staryi Oskol C	1	–	–	–	–	–	–	–	–	2.63	20	–	–
Moscow region P, C, O	14	–	–	2.97	13	2.67	11	–	–	–	–	2.01	12
Rybinsk area O, P, C	9	2.26	7	2.5	16	2.62	15	2.59	12	2.4	26	2.19	12
Nizhnii Novgorod region (Prosek) O, C, P	3	2.02	31	3.1	–	–	–	–	–	–	–	2.1	10

Table 1. (Contd.)

Area	NL	Callovian						Oxfordian					
		early		middle		late		early		middle		late	
		RPC	n	RPC	n	RPC	n	RPC	n	RPC	n	RPC	n
Nizhni Novgorod region (Uzhovka) O, P	2	2.26	13	2.93	23	–	–	–	–	–	–	–	–
Oka River (Alpat'evo–Elat'ma) O, C, P	11	2.36	15	2.64	72	2.89	36	2.57	27	2.52	34	2.02	14
Mikhailov O, C	2	–	–	2.85	47	2.76	29	2.71	9	–	–	–	–
Unzha O, C, P	17	2.14	22	2.27	37	2.38	15	2.24	–	2.48	–	2.12	–
Sysola O, C, P	3	2.21	10	2.15	24	–	–	–	–	–	–	–	–
Orenburg P, C	4	–	–	2.92	7	2.56	13	2.52	12	2.33	11	2.13	7
Saratov Volga region P, C	8	2.47	16	2.75	22	2.76	55	2.57	27	2.69	28	–	–
Pechora River basin P, C, O	13	1.58	12	2.25	8	1.71	15	2.04	3	2.2	5	2	15
Eastern Greenland P	22	1.93	24	2.52	4	1.81	10	2.33	8	2.24	10	1.96	19
Novaya Zemlya P	4	–	–	–	–	1.78	8	–	–	–	–	–	–
Spitsbergen P	9	–	–	–	–	1.59	5	2.05	6	–	–	1.92	9
Mangyshlak P, C	6	3.34	28	3.29	21	3.26	26	2.88	18	–	–	2.68	8
Tuarkyr P	12	3.78	38	3.6	67	3.49	95	3.24	20	3.02	15	3.63	8
Kugitang-Tau P	6	3.69	30	3.66	30	3.58	32	3.09	14	3.55	14	–	–
Crimea P, C	2	3.27	13	3.63	7	3.42	10	3.33	10	3.32	4	3.53	6
Northern Caucasus P	14	3.49	69	3.62	91	3.45	55	3.25	12	3.22	9	3.85	11
Southern Caucasus	10	3.66	28	3.56	17	3.56	6	–	–	3.56	11	–	–
Negev P	3	–	–	3.91	13	3.79	18	–	–	–	–	–	–
Lebanon–Antilebanon P	5	–	–	3.72	7	3.72	4	3.82	41	3.63	4	–	–
Iran P	2	–	–	3.83	31	–	–	–	–	–	–	–	–
Kopetdag P	2	–	–	–	–	–	–	–	–	3.67	9	3.6	11
Western Gissar P	3	–	–	–	–	–	–	3.29	7	–	–	–	–
Morocco P	2	–	–	–	–	–	–	3.51	8	–	–	3.6	6
Algeria–Tunisia P	5	3.73	17	3.8	43	3.45	7	–	–	3.69	18	3.89	15
East Africa P	8	–	–	3.95	18	3.81	13	–	–	3.88	10	–	–

Letters designate sources of data used for compilation of ammonite species lists: (P) published (works are not listed because of their abundance); (C) collections; (O) original data; (NL) number of localities, which were used for compiling integral faunal lists for each region and for which relative paleotemperature coefficients (RPC) were calculated; (n) number of species in the ammonite assemblage. Dash indicates the absence of representative data for RPC calculation for the given time interval.
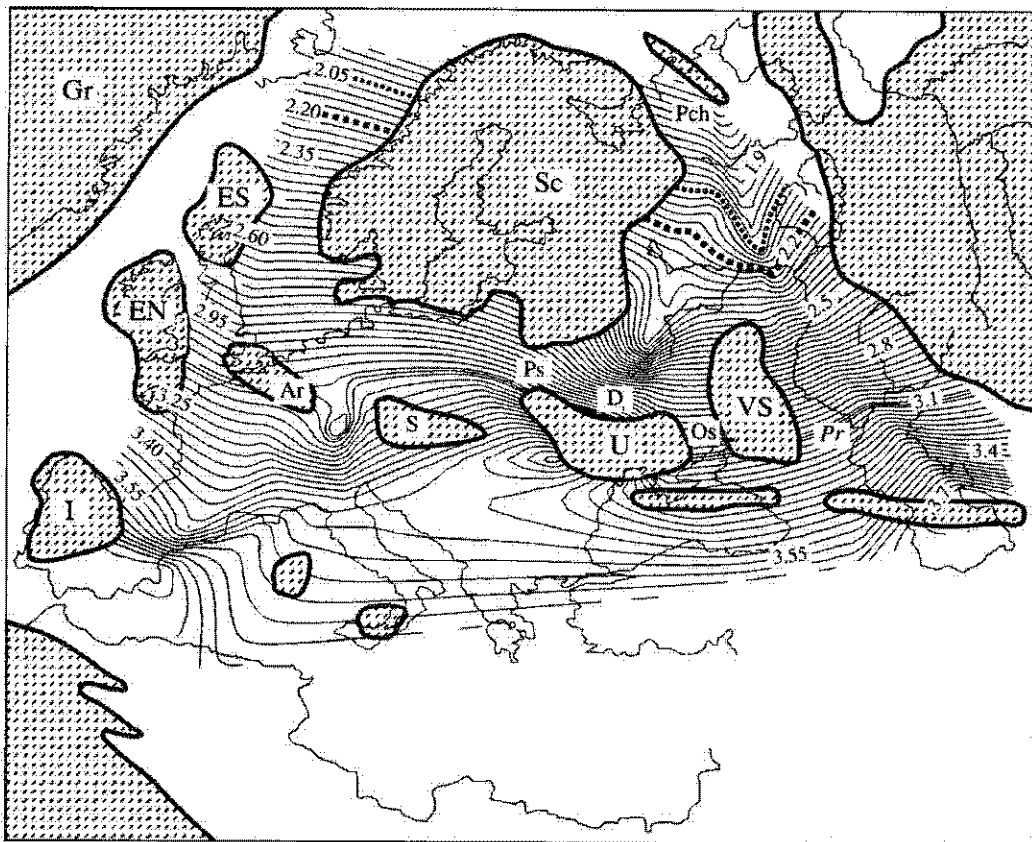
Fig. 2. Relative paleoisotherms (RPI), the early Callovian of northwestern Eurasia (processed data are from Sazonova and Sazonov, 1967; Thierry 1976, 1982; Cariou *et al.*, 1985; Dommergues *et al.*, 1987a, 1987b; Ziegler, 1990; Stampfli *et al.*, 1998). Geomorphological features: (EN) England–Normandy land; (Ar) Ardennes massif; (ES) England–Scotland land; (VS) Voronezh–Stavrolpol land; (Gr) Greenland; (I) Iberian massif; (Os) Orekhovskii strait; (Pr) Pripyat strait; (D) Dnieper basin; (NC) North Caspian basin; (Pch) Pechora basin; (S) Sudeten massif; (Sc) Scandinavian massif; (U) Ukrainian massif. In this and other charts, isolines are plotted by the Natural Neighbor triangulation method using the program Surfer 7. Dotted isoline 2.05 approximately corresponds to the thermal boundary between tropical and subtropical water masses (see text); thick isoline 2.2 approximates the thermal distribution boundary of the present-day of hermatypic corals (explanation in text).

way. This inference is supported by numerous finds of European faunal elements in the Dnieper basin, which implies the unidirectional migration via the Pripyat seaway already in the Callovian (Yanin, 1998, 1999). The warm current could be a decisive migratory factor.

In the *middle Callovian*, the RPI shift is oriented northward in all basins. This is indicative of substantial water warming in the entire region, which promoted the northward migration of thermophilic marine biota, the ammonites and other groups of marine invertebrates included (Yanin, 1998). The general circulation system was presumably the same as in the early Callovian, consisting of two cold effluent currents, the S–N trending European warm current, and the Dnieper warm countercurrent, the orientation and disposition of which remained unchanged (Figs. 3, 8). Simultaneously the system included some new elements. For example, there are several west-oriented RPI bends in the Tethys, which probably outline a latitudinal current that encircled the planet along the equator carrying waters westward (Hallam, 1978; Enay, 1980; Westermann, 1981). Its present day analogue, the north equatorial (tradewind) current, is located 5 to 10° (in equinox periods)

northward of the equator (Lednev and Muromtsev, 1953). Judging from the RPI bends, the presumable current turned northward at the latitude of Romania to meet the Ukrainian land, where it bifurcated into the main branch forwarded northward to the Polish sea and the other one that flowed along eastern coast of the Ukrainian land to meet the cold current from the Central Russian sea.

In the Tethys, there is distinguishable a presumable trace of another east-oriented warm current. According to the RPI bends, it passed between the Spanish (Iberian) archipelago and North Africa almost parallel to the above-mentioned equatorial current. The assumed current could reach Tethys via a long narrow strait (Hispanic Corridor, after Westermann, 1984, 1993) from the Caribbean basin, where there could (and most likely was) its own circulation system connected with additional water sources and specific discharge ways. Therefore, it could be an effluent stream from the Caribbean basin. Topologically, the current in question resembled the Gulf Stream, although it was not obligatory the genetic predecessor of the latter. The Gulf Stream is fed by autonomous trade-wind currents,
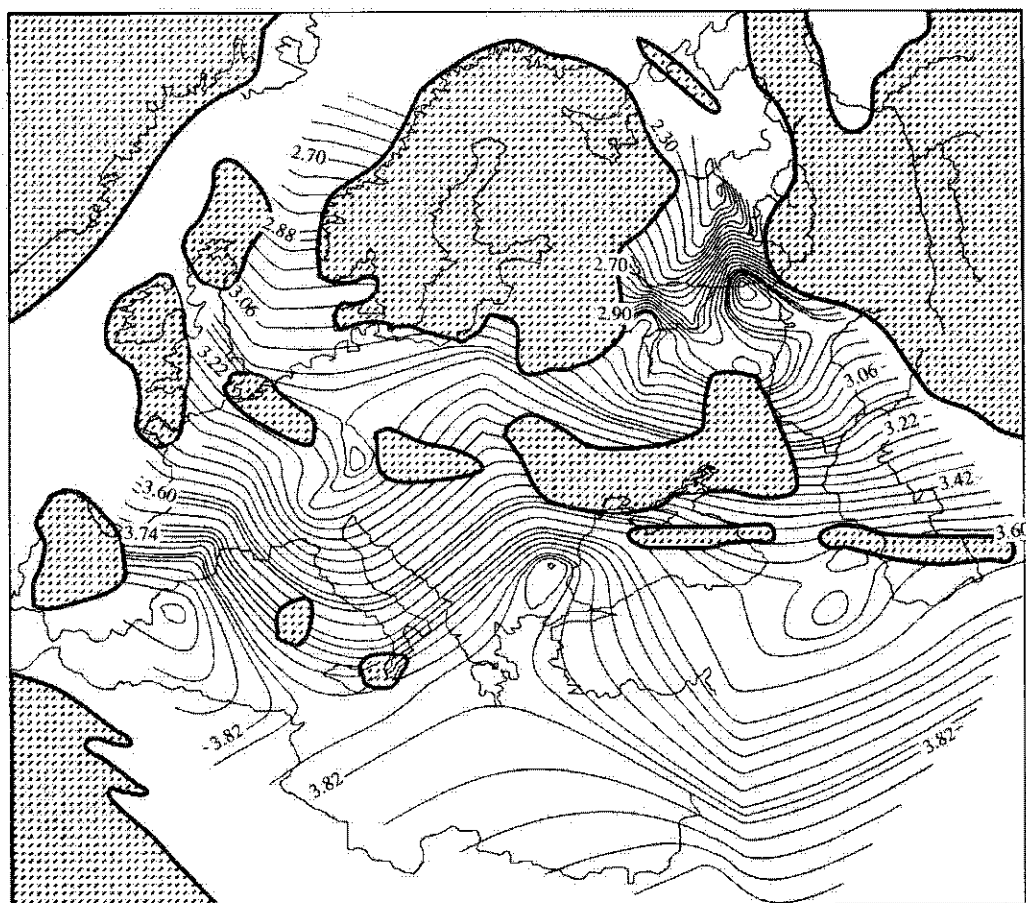
Fig. 3. Relative paleoisotherms (RPI), the middle Callovian of northwestern Eurasia.

being a warm current of the oceanic type, while the Hispanic Corridor, the early prototype of the Atlantic Ocean ("epicontinental Proto-Atlantic" after Thierry, 1982) was not an ocean in hydrological terms. The corridor was floored in the Callovian mainly by the continental crust (Westermann, 1981, 1993). Most likely, the proto-Caribbean Sea represented a large evaporation basin, as it follows from abundance of evaporites in that region (Hallam, 1978). The basin contained very warm hypersaline and heavy waters flowing to the Tethys via the Hispanic Corridor. There are grounds to believe that the system of Tethyan currents was of a similar type in the early Callovian as well (this is evident from the similar disposition of non-Tethyan currents), although it is impossible to test this assumption because of incomplete data on early Callovian ammonite assemblages of the Tethys.

In the middle Callovian, the circulation system of the Central Russian sea was slightly more intricate than that of the early Callovian time. The Boreal effluent current did not reach anymore the Tethys via the Crimea (Orekhovskii strait became closed, Sazonova and Sazonov, 1967). It met instead the Dnieper warm current that deviated as if under pressure of cold waters, as one can judge from the behavior of isotherms. The Dnieper current flowed, as in the early Callovian, along

the Scandinavian massif, where the convergence zone of warm and cold waters could be formed. In this area, the cold current sharply curved around the Voronezh paleoland and then flowed into the Tethys via the North Caspian basin. In the Tethys, the Central Russian cold current turned westward and met the warm Tethyan current.

In the *Late Callovian*, isolines in the northern part of the region are displaced southward to the latitude of England (to the RPI 2.95 in Fig. 4), while southerly isotherms remain in the same position as before. This change might reflect cooling northward of the England–Scotland massif. The total circulation system remained approximately unchanged, and all main currents occupied the same position (Fig. 8). Small transformations are as follows. (1) West Tethyan current penetrated the northern part of the European sea (north of the Ardennes massif) beginning from Germany, not from the Polish sea. It cannot be ruled out that this current behaved similarly in the early Callovian as well, although this is not reflected in isotherms. (2) The western branch of Boreal current in the Central Russian sea entered the Dnieper strait, followed slightly southward parallel to the warm current, and then flowed to the European basin via the Pripyat strait. These currents probably flowed at different depths. (3) Judging from
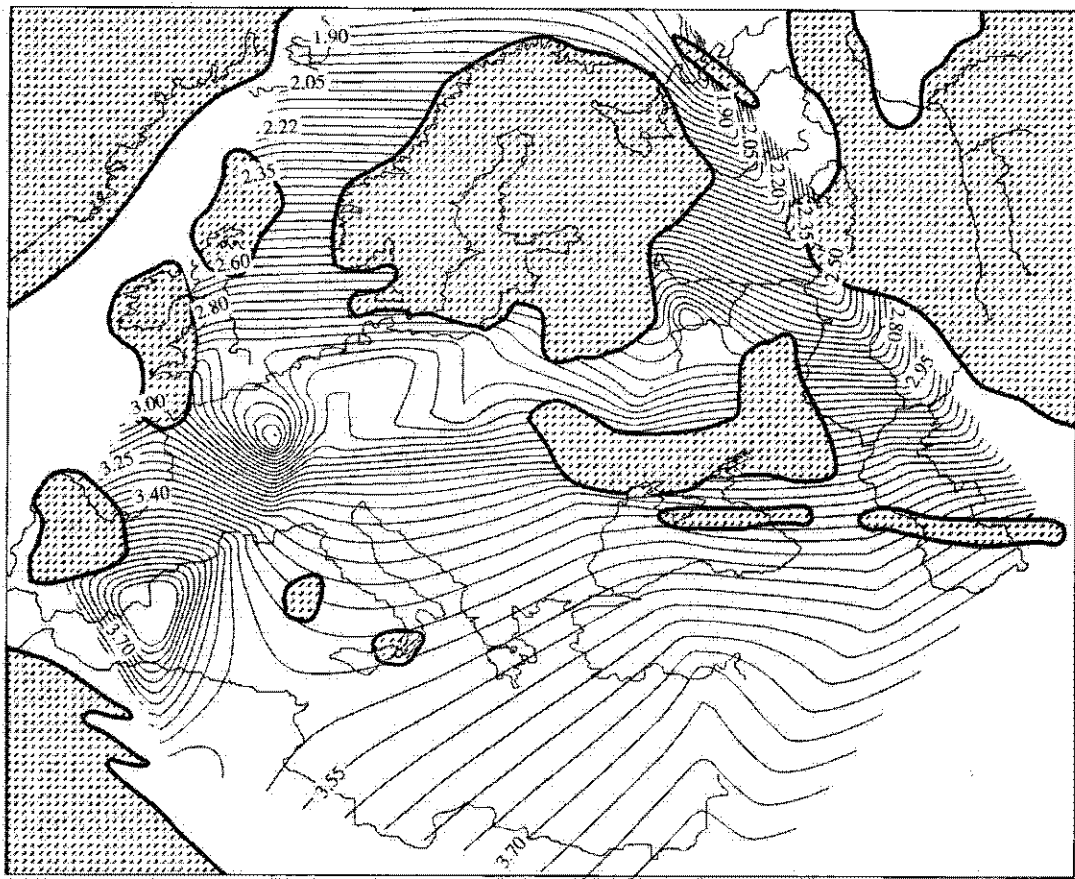
Fig. 4. Relative paleoisotherms (RPI), the late Callovian of northwestern Eurasia.

isotherms, the Central Russian convergence zone disappeared.

In the *early Oxfordian*, the presumable configuration of warm and cold currents did not change in general (Figs. 5, 8). In distinction from the middle Callovian epoch, the west effluent current of Boreal origin crossed Normandy, not Germany, and should pass west of the British Islands, although this is not reflected in isotherms. Simultaneously, the western Tethyan current avoided the Polish sea and flowed toward the England–Normandy massif. There, the warm and cold currents joined to form the convergence zone that is outlined in isotherms. The Central Russian sea received a lesser quantity of European waters than in the late Callovian epoch, being dominated by Boreal fauna that migrated via cold effluent currents.

In the *middle Oxfordian*, the system of detectable currents was the same in general as before (Figs. 6, 8). On global scale, the RPI contours are slightly displaced northward almost everywhere that may be indicative of warming in the entire region. This probably was a consequence of intensified Tethyan currents, since the northward-oriented RPI bends became more convex, particularly in the Central Russian sea.

In the *late Oxfordian* chart, isotherms are sharply displaced southward (Fig. 7), and a new RPI set corresponding to low RPC values appeared. This is particu-

larly well noticeable in areas northward of England and Normandy, like in the late Callovian. This shift likely reflects cooling and ingression of Boreal waters that was of a much higher amplitude than in previous epochs. The ingression was particularly significant in the Central Russian sea that was entirely occupied by Boreal waters (see RPI marked by low values in charts).

The general circulation system in the northwestern Eurasian seas retained its principal features, although some details changed (Fig. 8). The Central Russian sea was probably beyond the influence of warm Tethyan currents, which was characteristic of the middle Oxfordian. The Boreal effluent current significantly intensified was responsible for cooling in the entire Central Russian sea, the Dnieper basin and adjacent Tethyan areas (Mangyshlak, Kopetdag) included. The Dnieper basin was again influenced by the Boreal current at the time of the Orekhovskii strait wide opening (Sazonov and Sazonova, 1967). In the northern part of the Dnieper seaway, there was a convergence zone of warm and cold waters resembling that of the middle Callovian time. However, boreal waters more intensely invaded the Dnieper seaway west of the Voronezh land (Ryazan region), from where they flowed to the Orekhovskii strait. The Dnieper warm current moving northward met the Boreal countercurrent and deviated partly southward. As a result, a circular warm current
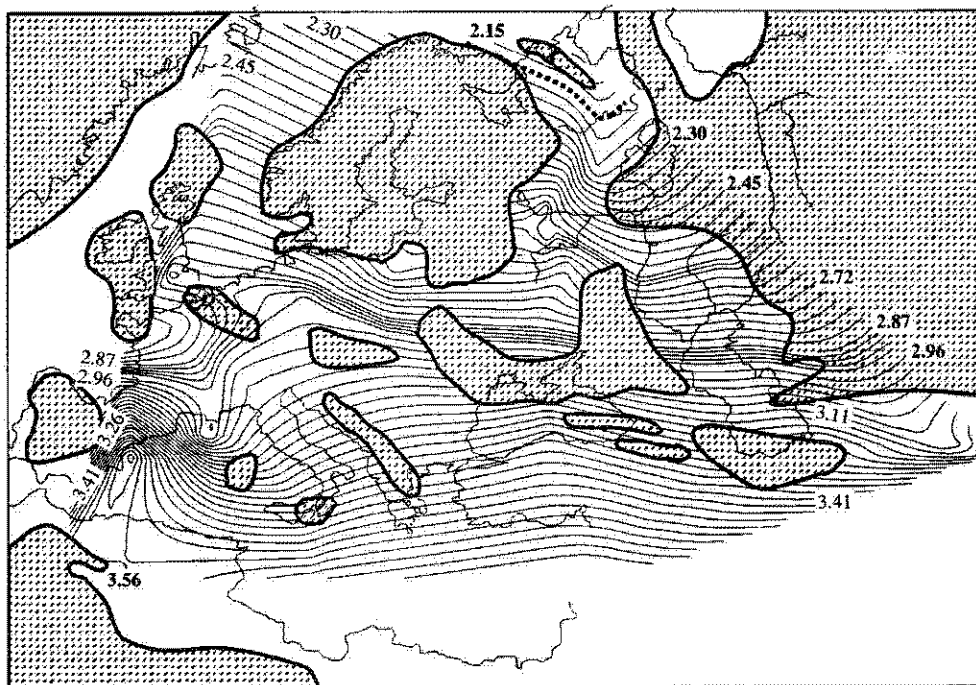
Fig. 5. Relative paleoisotherms (RPI), the early Oxfordian of northwestern Eurasia.

originated in the internal part of Central Russian sea during the late Oxfordian, like in the middle Callovian. Its influence is confirmed by finds of scleractinian corals in the axial part of "warm" isotherm bends (Fig. 10).

The cold current flowing out of the Orekhovskii strait met a powerful warm current from the Tethys in the chart area marked by blunt bends of "warm" isotherms and by wedging-in "cold" isotherms. Simultaneously, the higher density of isotherms is indicative of a convergence zone in that area.

The RPI zoning is distinct in all the charts displaying the regular decrease of RPC values from the south northward. This is a manifestation of the water cooling trend toward higher latitudes. According to widely accepted views, the Jurassic latitudes differed from the modern ones. The equator was located at that time approximately 30° northward of its present-day position and crossed the southern Mediterranean basin (Arkell, 1956; Bowen, 1969; Thierry, 1976; Cariou et al., 1985; Dommergues et al., 1987; Stampfli et al., 1998; and others). This is substantiated by absolute and relative paleotemperature data that characterize equatorial water masses.

The annual temperature variations represent an important characteristic of water masses. The amplitude of temperature fluctuations can also characterize the substantially longer time intervals, if positions of continents relative to the equator changed insignificantly. Moreover, they characterizes also the thermal zoning of a given water mass, as it is shown in previous work (Kiselev, 1998). Variations of the RPC values throughout the Callovian–Oxfordian period (Fig. 9)

show the regular dependence of their amplitude on the latitude, though with some regional deviations. In the southernmost part of the region under consideration corresponding to the northern Tethys, the RPC variations are almost negligible. The lowest temperature fluctuations in modern oceans are characteristic mainly of tropical water masses, where they are as low as 1 to 3°C (Zhizhchenko, 1974), corresponding to 3–12% of average annual variations. Almost all over the region under consideration, the RPI variations do not exceed 10%, and water basins were situated therefore in tropical zone, the northern boundary of which was probably located slightly northward of the Scandinavian massif, although its position undoubtedly migrated concurrently with changes in hydrological regime.

As was noted, the absolute paleotemperatures are calculated for a limited number of geographic sites and stratigraphic levels. In such a situation, it is impossible to reconstruct an adequate evolution of thermal regime in the basins. Nevertheless, extrapolating the absolute data to the relative ones we can, though with reservations, to draw absolute isotherms through different-size area based on calculated relative values. The calculated paleotemperatures of the late Oxfordian are published for eastern Greenland, France, and Switzerland (Bowen, 1969; Padden, in press), Scotland (Tan et al., 1970), Spitsbergen (Ditchfield, 1997), and European Russia (Riboulleau et al., 1998). Being compared with the late Oxfordian RPI chart, they elucidate some aspects of the generalized model discussed above. With due regard for discrepancy between data obtained by different methods of paleothermometry and for doubtful information on many time intervals, I consider here
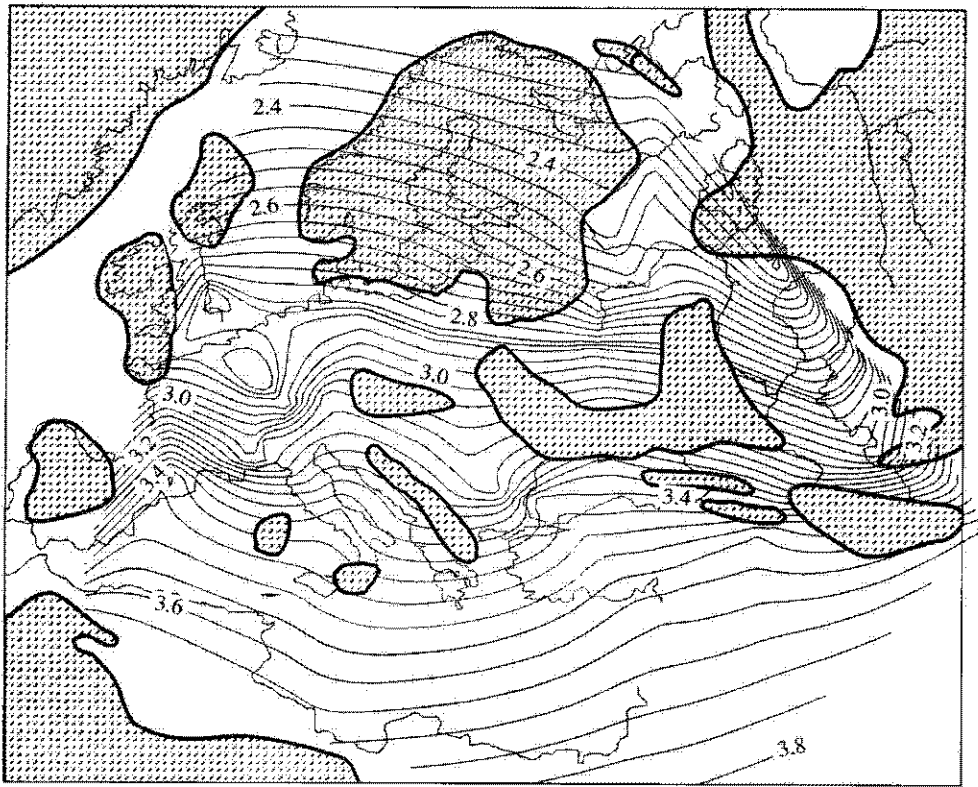
Fig. 6. Relative paleoisotherms (RPI), the middle Oxfordian of northwestern Eurasia.
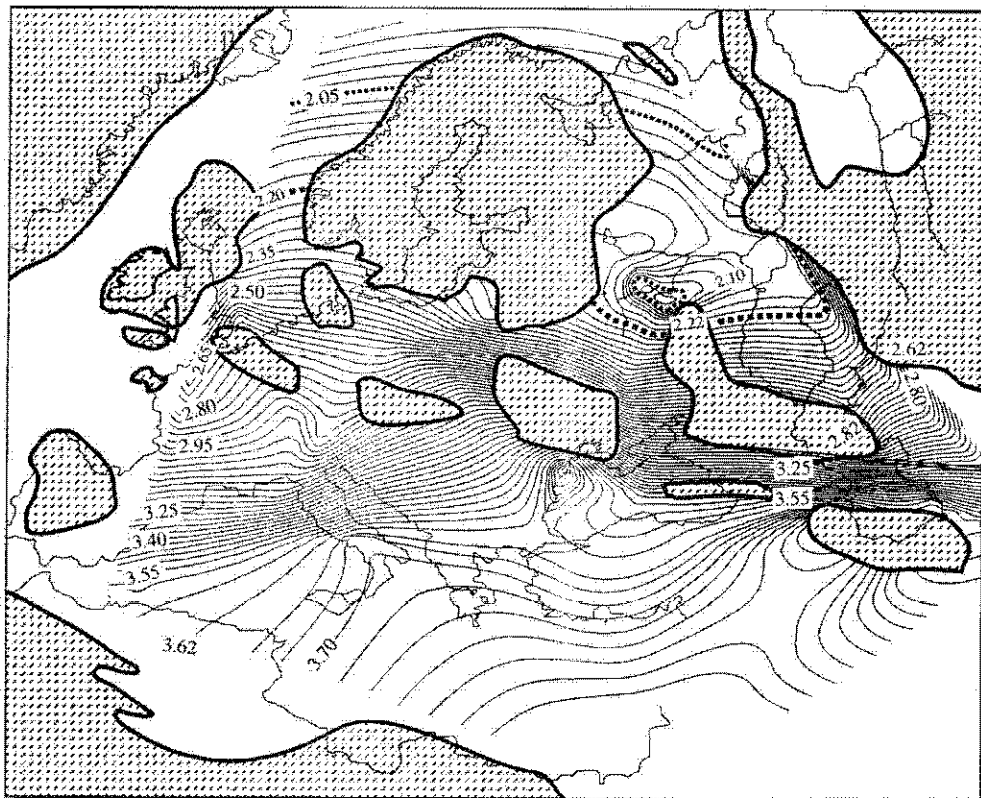

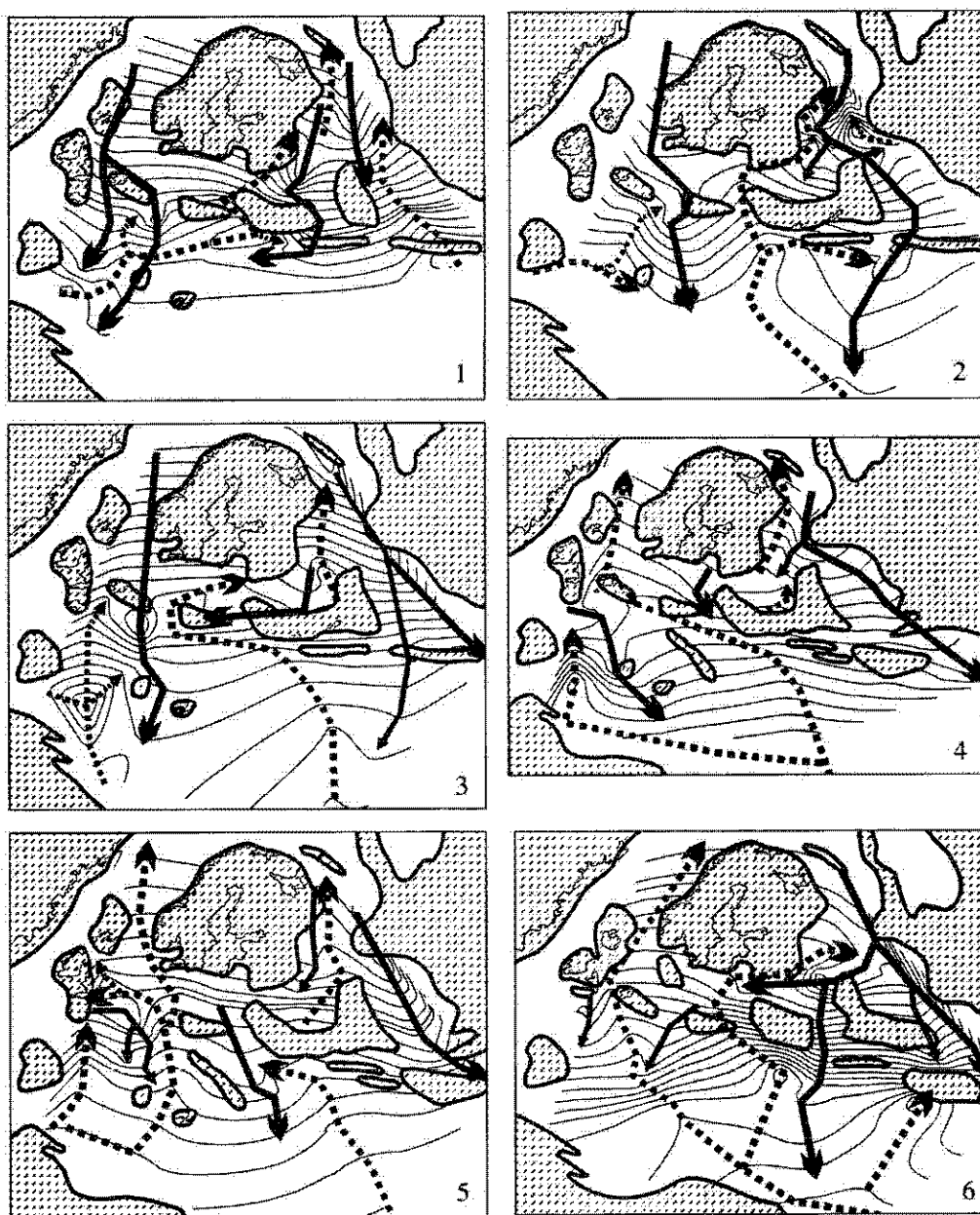Fig. 7. Relative paleoisotherms (RPI), the late Oxfordian of northwestern Eurasia.

Fig. 8. Reconstructed circulation systems in Callovian–Oxfordian seas of northwestern Eurasia; solid and dotted arrows connecting peaks of RPI bends show presumable directions of cold and warm currents. Because of deficient information on some areas and wide extrapolations, the arrow lines locally cross the land blocks unlike the real currents: (1) early Callovian; (2) middle Callovian; (3) late Callovian; (4) early Oxfordian; (5) middle Oxfordian; (6) late Oxfordian.

only a chart for the late Oxfordian (Fig. 10). The chart is based on the absolute paleotemperature analogues (APA) extrapolated to RPC values of the late Oxfordian as is shown in Table 2.

If this extrapolation is correct and we consider the entire system of the Callovian–Oxfordian basins, the maximal temperatures about 26°C were characteristic

in that system of the southern part of the Mediterranean Tethys (the present-day Egypt area). This indicated value is close to the present-day average annual water temperature near the equator. The minimal APA values (19.6°C) comparable with the temperature of warm subtropical waters would be then in the eastern Green-land area. According to accepted classification, the

Table 2. Extrapolated absolute paleotemperature analogues for the late Oxfordian

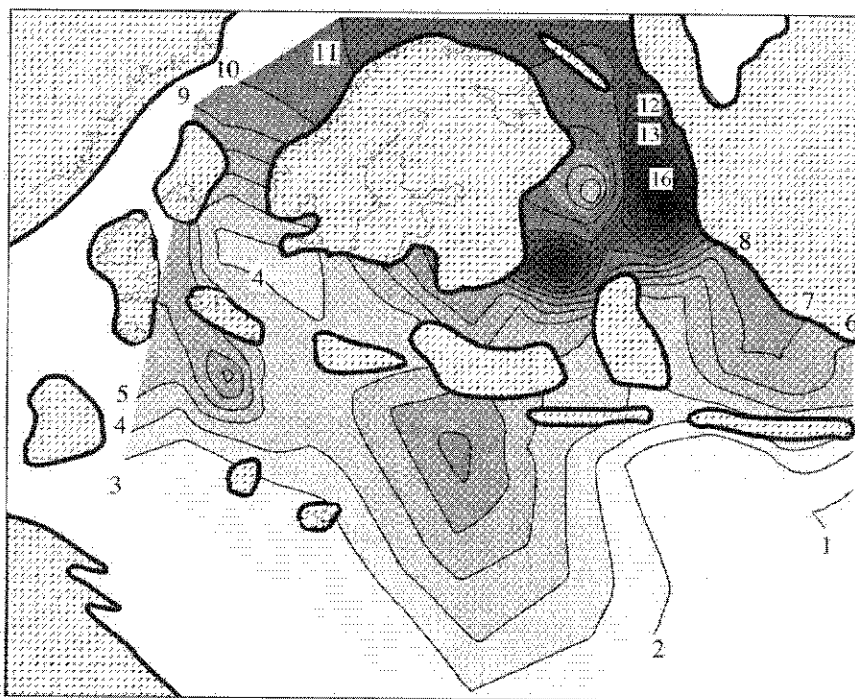| RTC	1.86	2.04	2.22	2.4	2.58	2.76	2.94	3.12	3.3	3.48	3.66	3.84
APA (°C)	19.2	19.8	20.5	21.2	21.9	22.5	23.2	23.9	24.5	25.2	25.9	26.5

Fig. 9. Amplitudes of RPC variations values in northwestern Eurasia during the Callovian–Oxfordian period shown as mean square deviations in percents (numerals attached to contours) from the average RPC value.

boundary between tropical and subtropical water masses corresponds to the isotherm 20°C (Zhizhchenko, 1974). In our case, this isotherm corresponds to the RPI value of 2.04. The variable southernmost position of this isotherm during the early and late Callovian and in the late Oxfordian is shown in presented charts (Figs. 2–7). As one can see in figures, the greater part of northwestern Eurasia was under influence of tropical water masses during the above periods. The southernmost areas of the Boreal basin (the eastern Greenland and Pechora sea) were beyond that influence. The internal part of the Central Russian sea appeared to be northward the isotherm in question only in the late Oxfordian (Fig. 11). These inferences are consistent with absolute paleotemperatures estimated for the early–middle Callovian of England (based on ammonites only, Anderson et al., 1994), being in disagreement with the data on the late Callovian–early Oxfordian basins of northwestern Europe, Greenland, European (Riboelleau et al., 1998) and Central Russia (Barskov and Kiyashko, 2000). In two last works, the isotopic paleotemperature values are substantially lower, equal to 8–17.8°C (first work, fig. 2) or to 6–12.5°C (last work, fig. 1). It is difficult to comment this discrepancy because of the well-known ambiguity of isotopic paleothermometry methods. For example, Gruszczynski (1998) repudiates the paleotemperature significance for changes in geochemical parameters, if there is a positive correlation between variations in $\delta^{18}O$ and $\delta^{13}C$ values. He interprets data of radiocarbon analysis as indicative only of water strati-fication degree (and anoxic/oxygenated state of bottom sediments) in paleobasins. In most publications, the mentioned inclusive, the positive correlation between secular variations of $\delta^{18}O$ and $\delta^{13}C$ parameters is actually observable. In work by Anderson et al. (1994), a significant scatter of isotopic paleotemperature values is noted only for taxonomic groups dwelling at different depth levels. The highest paleotemperatures are characteristic of ammonites that populated the upper water layer of sea basins (15–30°C with the normal distribution optimum close to 20–23°C). For Callovian belemnites, this value is 11–19°C with the optimum approaching 13–17°C. The discrepancy is explained in the work by a much deeper habitat zone of belemnites. This factor is also a good explanation to the discrepancy mentioned higher, because paleotemperature determinations in most works are based on belemnites.

Two kinds of paleotemperature parameters, the absolute and relative, reflect approximately the same situation (types of water masses, their boundaries and distribution) for the entire system of sea paleobasins in northwestern Eurasia. This suggests that they reflect some real trends. The outlined situation can be argued for by additional data on distribution of various temperature indicators, e.g., of hermatypic corals. In the late Oxfordian, scleractinian corals migrated far northward up to the Pomor'e region and Scotland (Fig. 10). In the last area, they formed massive, although small bioherms and biostromes (Krasnov, 1983). Plotting the localities of coral buildups on the RPI chart, one can see
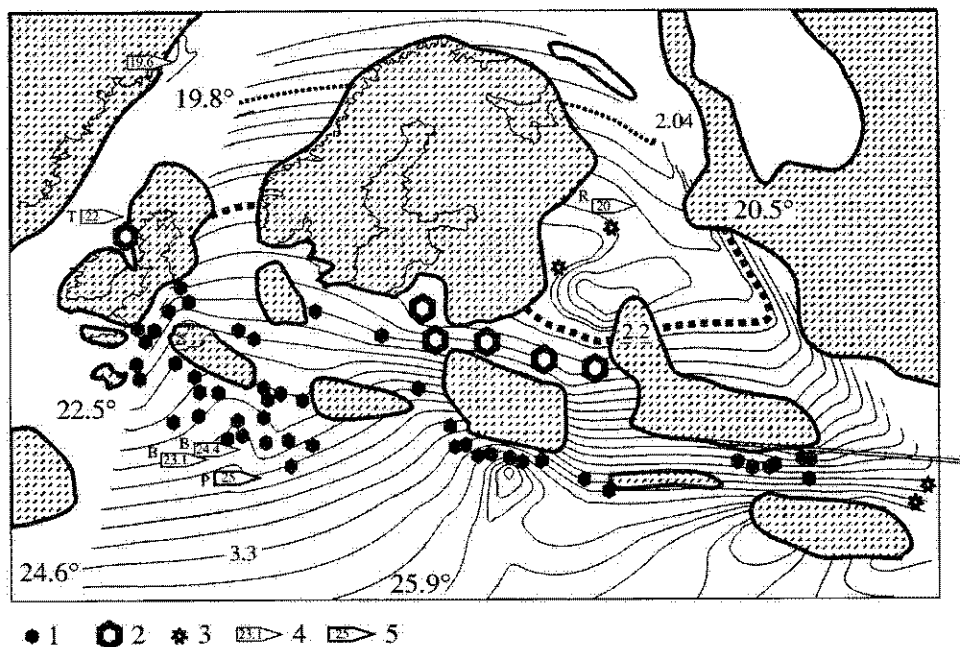
Fig. 10. The northern distribution limit of late Oxfordian scleractinian coral in northwestern Eurasia: (1) massive reefal buildings; (2) bioherms and biostromes; (3) solitary scleractinian corals or small coral meadows (after Arkell, 1933, 1961; Gerasimov, 1955; Sazonova and Sazonov, 1967; Krasnov, 1983; Leinfelder, 1993; Bertling, 1993; Bertling and Insalaco, 1998); (4) platform or periplatform and (5) Alpine thrust sites, where paleotemperatures have been estimated based on $\delta^{18}O$ in belemnites (in the last case, sampled sediments accumulated southward, and estimated values characterize southerly areas). The RPI contours are coordinated with absolute paleotemperatures in centigrade as explained in the text. Thick dotted isoline 2.2 approximately corresponds to thermal boundary (isotherm 20.5°C) that restrains the present-day distribution of hermatypic corals (see text). Thin dotted isoline 2.04 approximately corresponds to demarcation line between tropical and subtropical water masses (see text). Literal symbols designating publication and source areas of fossils: (B) Bowen, 1969 (Greenland, Miln Land; France, Deux; northern Switzerland, Aargo); (P) Padden *et al.*, in press (southern Switzerland, Montsalvens); (R) Riboulleau *et al.*, 1998 (European Russia, Makar'ev); (T) Tan *et al.*, 1970 (Scotland, Sky).

a remarkable fact: all the northernmost finds of hermatypic scleractinian corals are located near the relative paleotemperature isoline 2.22, which corresponds to the isotherm 20.5°C, the temperature boundary of the present-day distribution of reef-building corals. Moreover, almost all the buildups are located south of this isotherm, being distributed conformably to the entire isoline system. This is a distinct indication of the thermal control over distribution of the late Oxfordian corals. The observed boundary of hermatypic Scleractinia species seems to be real, because northward of the boundary, Subboreal coral assemblages are impoverished in taxonomy and ecologic aspects. In the northernmost localities (the RPI 2.7 approximately corresponding to the isotherm 22°C) of Scotland, the Pripyat trough, and Donets basin, corals form small bioherms, not reefal buildups, that is typical of suppressed corral communities. North of the isoline 2.22 (Moscow region, Unzha locality), there are known sporadic finds of corals, mainly of minute solitary but not hermatypic forms (Gerasimov, 1955). Suppressed assemblages of non-hermatypic corals are discovered also in Turkmenistan (Krasnov, 1983; Amanniayazov, 1971) at the latitude of mass occurrence of reef-building corals. It can be assumed that this regional advance southward of the suppressed coral assemblages is caused by influence of

a cold current. It is clear that considered data on distribution of corals cannot be taken for the undisputable argument in favor of the suggested model, because radiation of hermatypic scleractinian corals is also controlled by other factors in addition to the temperature (Leinfelder, 1993). The causes responsible for expansion of corals in the late Oxfordian are complex, requiring special analysis. Nevertheless, the outlined zoning in distribution of hermatypic corals suggests a significant temperature influence on this biotic group.

Secular RPC changes. During the Callovian and Oxfordian ages, secular changes of RPC values are quite regular, frequently rhythmical in most areas of 54 considered above (Figs. 11, 12). In the middle Callovian, the RPC values became elevated nearly in all the areas and attained their peak level in some of them. In Subboreal (European basin and Central Russian sea) and Arctic regions, a trend of gradual or stepwise RPC decrease from the middle Callovian to the late Oxfordian is established, and the last substage is marked by a sharp fall in this parameter. The relative paleotemperature minimum at the Callovian–Oxfordian boundary time is also distinguishable in many areas. In addition to global regularities, there were characteristic regional fluctuations. For example, secular RPC variations in the Arctic and Tethyan basins were different in principle,

Fig. 11. Secular RPC variations in 30 areas of northwestern Eurasia during the Callovian–Oxfordian (after Kiselev, 1998, Fig. 2, with additions and modifications). Thick, medium-thick and thin lines characterize variations in the Arctic basin, European areas and Central Russian sea, respectively; lines with circles characterize Tethyan areas.

particularly during the Oxfordian. Similarly, the late Oxfordian warming in the Crimean–Caucasian sector of the Tethys (the northward advance of Tethyan current) was concurrent to cooling in the Central Russian sea (intensification and bifurcation of Boreal currents). More features in common are characteristic of Subboreal regions, although numerous deviations are observable there as well. The highest similarity between secular variation curves is characteristic of *areas of the same region.* This fact implies that regional fluctuations of thermal regimes in the Callovian and Oxfordian basins prevailed over global changes. Warming or cooling events in common likely occurred as well, though periodically. The approximated variation trends exhibit three peaks in common: the early Callovian minimum, middle Callovian maximum, and Callovian–Oxfordian boundary minimum (Fig. 12). The correlation coefficients for these events are sufficiently high only for the Arctic basin, and global significance of corresponding changes in thermal regimes can be considered only as

conventional. Nevertheless, the mentioned and some other peaks detectable in general and regional variation curves are consistent with published data on oxygen isotope ratios in carbonates from several Callovian–Oxfordian sections of northwestern Europe and America. The thermal minimum of the Callovian–Oxfordian boundary time is recorded in England, Poland (Gruszczynski, 1998), and Central Russia (Riboulleau *et al.*, 1998; Barskov and Kiyashko, 2000). The late Oxfordian minimum and middle Oxfordian maximum (partly) are detected in the Peri-Tethys, western Cuba, and Central Russia (Riboulleau *et al.*, 1998; Barskov, private communication). The coincident rhythms of $\delta^{18}O$ and RPC variations seem to be not incidental and may be related to real paleotemperature fluctuations.

DISCUSSION

The considered data on circulation systems in the Callovian–Oxfordian seas of northwestern Eurasia sug-

gest that main detectable currents had stable position and did not change in quantity. These were the European and Central Russian cold effluent currents and the warm Tethyan and Dnieper currents. These currents were of approximately the same geographic position and direction.

Characteristic of the Callovian–Oxfordian time was the repeated formation of convergence zones of warm and cold currents with presumably vertical circulation and stable location. In the Central Russian sea, the convergence zone was always located in its internal part, at the junction site of three sea arms (middle Callovian to late Oxfordian). In the Tethys, the convergence zone was near the southwestern margin of the Ukrainian land, in the present-day Dniester River area (early Callovian, middle Callovian, late Oxfordian). The steady position of these elements in the circulation system implies that they characterize real events. Therefore, some deviations from the general trends should also be considered as real. The validity of suggested general model is also evident from unidirectional changes in the circulation system of Callovian–Oxfordian seas. For example, the Boreal European and warm Tethyan currents steadily migrated westward during the period under consideration. The outlined regional differences in the hydrological regime are consistent with available data on absolute paleotemperatures, which are discussed above.

The suggested circulation system is rather intricate, frequently inconsistent with factors that control the hydrological regime. For example, directions of some currents changed contrary to the Coriolis forces. To explain these deviations, I should remind that the region under consideration represented mainly a system of small epicontinental seas during the Jurassic. The direction of currents was controlled in this case by the gradient between low and high water levels in the basin. That gradient depends largely on disposition of drainage and discharge areas, on the latitude and configuration of the basin, its bottom morphology, and on location of river mouths, especially in small basins (Bowden, 1988). The Coriolis force is a factor of global circulation and affects the oceanic currents that is applicable to the Late Jurassic circulation system as well: the warm probably equatorial Tethyan current of the latter was west-oriented during the entire Callovian–Oxfordian, like in the present-day oceans. In the western terminal part of the Tethys, it met the land and deviated under the Coriolis force northward to reach Greenland, where it turned naturally eastward and probably reached Siberia (Teis and Naidin, 1973; Khudolei, 1984, 1985, 1988, 1993).

It is remarkable that practically all paleotemperature changes in the considered system of basins were of the regional, but not global character throughout the Callovian–Oxfordian time span. The relative paleotemperature variation curves plotted for separate small areas (Fig. 12) are cophasal only within a single region. The
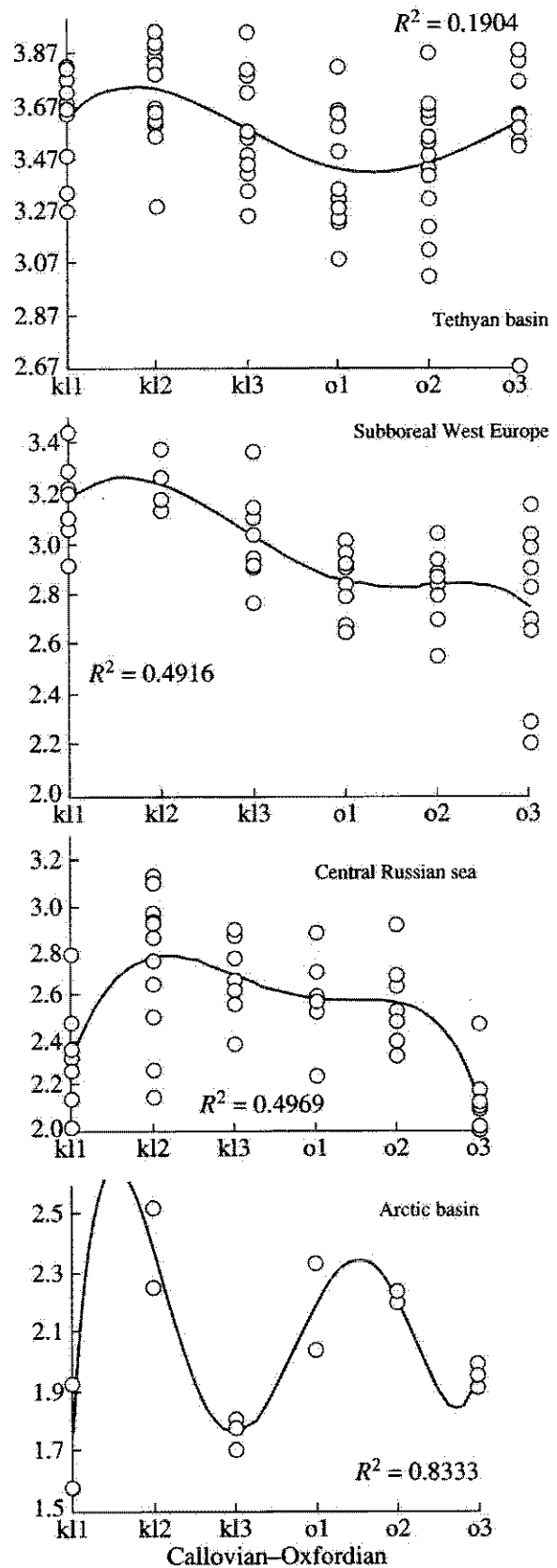

Fig. 12. Generalized trends (approximation lines correspond to polynomials risen to sixth power) characterizing secular RPC variations four Callovian–Oxfordian sea basins of northwestern Eurasia (approximated values for each region are presented in Table 1 and plotted in Fig. 11).

curves probably reflect changes in directions of warm and cold currents, which differed in various basins. Even the middle Callovian general warming of water masses was likely of a regional character, and climatic interpretation of the data obtained is hardly possible. The highest amplitudes of RPC value variations (Fig. 9) are established in areas with permanent fairways of presumable currents, and such a situation suggests that paleotemperatures primarily depend on the hydrological factor. Other factors that are able to influence directly the water temperature (solar constant, air temperature, and latitude) are almost imperceptible in the considered data. There are grounds to believe that in fact climatic changes followed the changes in the thermal regime of sea basins in question. The mutual character of thermal changes in the land climate and marine medium in the Jurassic is obvious for some regions, e.g., for the North Sea (Abbink *et al.*, 2001). Paleoclimatic curves based on palynological data from the former Scandinavian land (ibid) and entire northwestern Europe (Poulsen, *et al.*, in press) remarkably coincide with the relative paleotemperature variation curves based on ammonites from Subboreal and Boreal areas (Figs. 11, 12).

A similar dynamics of Callovian–Oxfordian transgressions and regressions in the considered system of sea basins is a probable explanation of more or less significant warming and cooling episodes. Indeed, the transgression peak that occurred in the middle Callovian (Sazonova and Sazonov, 1967; Hallam, 1988, 2001; Westermann, 1993) is correlative with the universal "warming" inferable from all paleotemperature indicators. The same situation is characteristic of the middle Oxfordian (Abbink *et al.*, 2001; Gruszczynski, 1998) that was the warmest age of the entire Jurassic period in opinion of Gruszczynski. The regression peaks of the Bathonian–Callovian and Oxfordian–Kimmeridgian boundary times were associated with decreasing paleotemperature parameters (Hallam, 1988, 2001; Norris and Hallam, 1995) that was untypical however of the regression recorded in the Callovian–Oxfordian boundary interval (Westermann, 1993; Sazonova and Sazonov, 1967). This situation can logically be explained by eustatic sea-level changes (Haq *et al.*, 1998), which are of a critical amplitude at the culmination time of transgressions and regressions.

The paleotemperature–paleohydrological situation under consideration slightly resembles the present-day thermal type of oceanic water exchange between high and low latitudes, the triggering mechanism of which is governed by sinking heavy cold waters in polar areas that form the psychrosphere. This circulation model was already referred to by consideration of the late Jurassic hydrological regime in the Viking Straits (Oshmann, 1987). In the alternative model proposed for the Jurassic and Cretaceous periods, there was suggested the other haline mechanism of water exchange (Krassilov, 1985; Miller 1991; Nesov, 1997 and others; Abbink *et al.*, 2001), when the triggering sinking of warm

hypersaline waters took place in low latitudes (S-downwelling after Nesov). Despite the prevalence of epicontinental seas in northwestern Eurasia of the Callovian–Oxfordian period, the region was lacking large evaporation basins necessary for launching the haline water circulation. It cannot be ruled out however that circulation in the basins under consideration was of the intermediate type, combining elements of both the haline and thermal water exchange.

Reviewers M. A. Zharkov and N. M. Chumakov

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