Palaeoceanography and biogeography in the Early Jurassic Panthalassa and Tethys Oceans

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Abstract

A first conceptual palaeoceanographic model for the Early Jurassic Panthalassa and Tethys Oceans is outlined in the present paper. The new palaeoceanographic model uses fundamental physic oceanographic principles known from the modern world and a global palaeogeographic reconstruction for the Early Jurassic to examine the long-term response of the Panthalassic and Tethyan fossil invertebrate faunas to the proposed surface ocean circulation. Analysis of palaeobiogeographical data (ostracods, ammonites, brachiopods and bivalves) has enabled circulation changes to be reconstructed over the studied period in some detail. Panthalassic circulation pattern shows an almost hemispherical symmetric pattern, with the development of the two large subtropical gyres that rotates clockwise in the northern hemisphere and anti-clockwise in the southern hemisphere. Surface circulation in the Tethyan Ocean is dominated by monsoonal westerly-directed equatorial surface currents that reached its western corner and droved them off to the north, along the northern side of the Tethys Ocean, during summer and in opposite direction during the winter.

Keywords: Early Jurassic; The Panthalassa Ocean; The Tethys Ocean; Ocean currents; Climate models

1. Introduction

Palaeoceanographic models play a very important role in paleoclimate and palaeobiogeographic studies. It is difficult to reconstruct Early Jurassic palaeoceanography on global scales from the paleontological record because the data tend to be scattered and unevenly distributed. In light of existing work on paleoclimate models, and in accord with the aim of this paper, the study of the pattern of surface currents and its implications in the palaeobiogeography of the main Early Jurassic fossil groups, a new conceptual circulation model for the Early Jurassic has been proposed. The conceptual palaeoceanographic approach presented here elaborates on the similar procedure used by Stehli (1965), Berggren and Hollister (1977), Lloyd (1982), Parrish (1982), Parrish and Curtis (1982), Wilde (1991), Christiansen and Stouge (1999) using primary oceanographic circulation principles to hypothesize on the major current pattern. This new model is simple in concept and is based on atmospheric circulations patterns and consequently, on major wind belts, and takes also into account the influence of large mountain ranges and the distribution of landmasses.

Three types of oceanic circulations models have been formulated (Kutzbach et al., 1990; Winguth et al., 2002; Smith et al., 2004), for simulating oceanic circulation patterns over an idealized Panthalassa Ocean for the Permian–Triassic. They used numerical models of atmospheric circulation (GCM simulations), but since they utilized a very simple basin configuration, essentially a single rectangular one, their results were a dynamic, hemispherically symmetric overturning with standard gyres and western boundary currents, which are difficult to test against the geological and fossil record.

General features of this type of conceptual models are modified according to the specifics of the Early Jurassic palaeogeography. Until recently, it was not possible to consider the Early Jurassic global surface ocean circulation in the context of a more integrated palaeogeography (Ziegler, 1988, 1992; Scotese and Golonka, 1992; Golonka et al., 1994, 2006; Roy, 2001,

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2004; Takagi and Arai, 2003; Ziegler et al., 2001; Scotese, 2002; Golonka, 2004, 2007; Harris, 2006). The Early Jurassic palaeogeography shows all continents assembled in a large landmass, the Pangaea, centred over the Equator (from 80°N to 80°S), surrounded by a huge world-wide Panthalassa Ocean and with a wedge shaped sea into its eastern margin, the Tethys Ocean (Dewey et al., 1973; Smith et al., 1973; Bju-Duval et al., 1977; Owen, 1983; Dercourt et al., 1985; Ziegler, 1988; Van der Voo, 1993, Acharyya, 1999, 2001; Scotese, 2002; Golonka and Kiessling, 2002; Golonka, 2007). Pangaea comprised two large landmasses: the Laurasia (North America and the majority of Eurasian) and the Gondwana (South America, India, Australia and Antarctica) continents (Fig. 1).

The palaeogeographic base map for this model, including land–sea distribution, bathymetry and land surface elevation has been taken from the Palaeogeographic Atlas Project of the University of Chicago (Ziegler et al., 1997). Therefore, the Early Jurassic palaeogeography is reasonably well known, except for the position of islands in the Tethys Ocean that at the present time fit in Southeast Asia. The altitude data of Pangaean mountain chains, which has a relevant impact on the climate simulations (such as the intensification of low-pressure zones by the elevation heat effect), are based on Pliensbachian palaeotopographical reconstructions (Ziegler et al., 1983; Scotese, 2002). A consensus has emerged in recent years that much of the eastern Tethys consist of terrenes drifted from the northern margin of southeast Gondwana (Dewey, 1988; Golonka, 2007). With regard to the western part of the Tethys Ocean it is generally assumed that a series of microcontinents existed within the tropical Tethys, which subsequently drifted away from Gondwana (Sengör and Natalin, 1996; Golonka et al., 2006).

Period	Epoch (sub-period)	Age	When began
Jurassic	Early Jurassic (Lias) 24 My	Toarcian	183
		Pliensbachian	194
		Sinemurian	201
		Hettangian	210

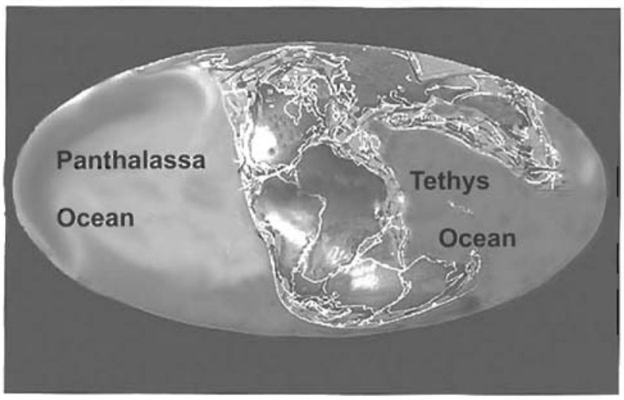


Fig. 1. The world of the Early Jurassic. Present-day continents are shown in outline: in the Southern Hemisphere (left to right), South America lies against Africa, with India to the right. Below are Antarctica, and to its right, Australia. Together these pieces (South America, Africa, India, Antarctica, and Australia) form Gondwana (Vaughan and Pankhurst, 2008). In the Northern Hemisphere, North America is adjacent to Western Europe, though much of Europe is covered by the European Epicontinental Sea. Together, they (North America, Europe, Siberia) form Laurasia. Pangaea includes both Gondwana and Laurasia and they obstruct and enclose the Tethys Ocean; surrounding Pangaea is Panthalassa, the world ocean (after Scotese, C.R., 2002, http://www.scotese.com, PALEOMAP website, Golonka, 2007).

This paper is the first attempt to reconstruct the Early Jurassic surface ocean circulation by means of a new conceptual model that uses basic principles of modern oceanography and atmospheric circulation, without being a computerised parametric approach. An additional purpose of this model is to explain several aspects of the distributional pattern of Tethyan and Panthalassic fossil groups that had resisted previous interpretations, such as, displaced faunas in North American marginal terranes or stepping-stone dispersal.

2. The Early Jurassic simulation: Theoretical atmospheric and surface oceanic circulation pattern

In attempts to reconstruct the Early Jurassic atmospheric circulation two type of information have been considered. Initially, the basis for the present model was the distribution of average zonal sea-level pressure for each season, which was based on analogies with the present general atmospheric circulation pattern, following the conceptual approach of Parrish and Curtis (1982) and Parrish et al. (1982). In addition, average zonal pressure derived from climate simulations of Scotese and Summerhayes (1986); Crowley et al. (1989); Kutzbach and Gallimore (1989); Kutzbach et al. (1990); Chandler (1994) have been also considered (see Appendix A, Fig. 2A, B). The present simulation is based, as much as possible, on fundamental principles of physics, thus the results that they generate are only partly based on boundary conditions. This is the main reason for using a conceptual approach to simulate the global atmospheric circulation.

Most of Early Jurassic atmospheric simulations show the dominance of monsoonal circulation conditions along the eastern part of Pangaea (Scotese and Summerhayes, 1986; Crowley et al., 1989, Kutzbach and Gallimore, 1989; Kutzbach et al., 1990; Fawcettt et al., 1994; Barron and Fawcett, 1995). The major features of this simulated Early Jurassic model include warm surface air temperatures, extreme continentally in the low and mid-latitudes, and monsoons, which dominate along the mid-latitude coasts of Tethys and Panthalassa Oceans.

The simulated global distribution of Early Jurassic sea-level pressures (Fig. 3A, B) show that winter high-pressure cells alternate with summer low-pressure cells over the continent. Subpolar low-pressure cells develop over the ocean and the subtropical high-pressure zone is present. Despite the similarity between the hemispheric patterns, a substantial degree of asymmetry caused by land–sea distribution and topographic differences has to be considered.

During the summer, the faint insolation and the strong heat loss over the part of Pangaea situated in the southern hemisphere caused a decrease of the temperature over the interior of the Pangaea (predominantly on the southern hemisphere) and consequently, the sinking cooled air could create a high-pressure belt over the Gondwana continent, southern Pangaea. The warm temperatures can also generate an extensive low-pressure zone over central Laurasia, northeastern Pangaea (between 10

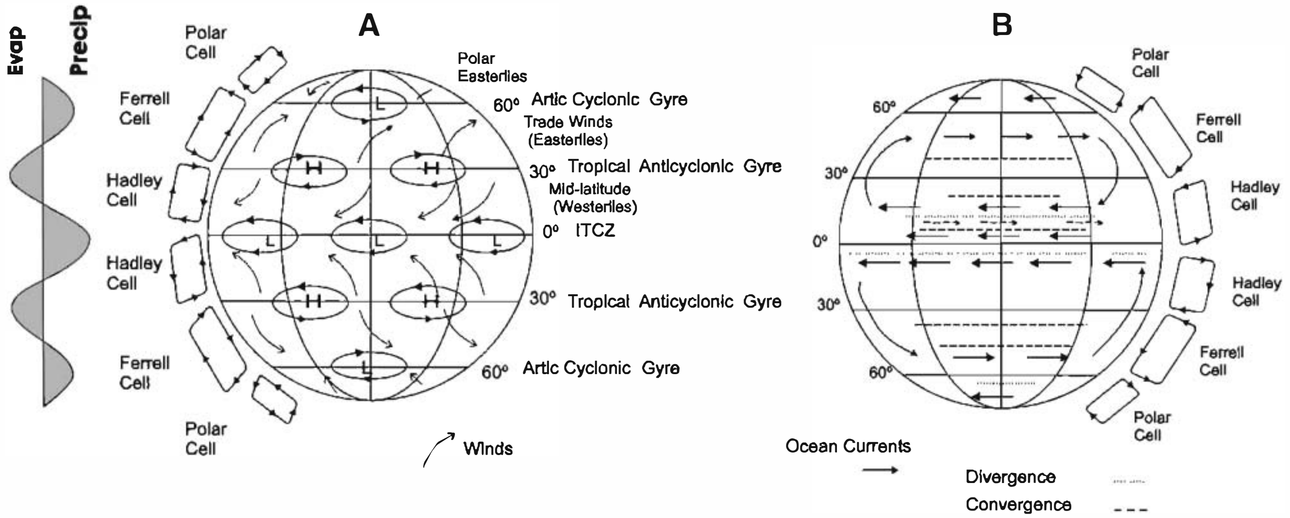


Fig. 2. (A) General circulation of the atmosphere and wind belt of the modern world (right); and precipitation versus evaporation (left); (B) Wind-driven ocean surface pattern. Grey arrows represent wind patterns and black arrows ocean currents.

and 30°N latitude) that deepens above the higher elevations in the eastern part of the continent (Fig. 3A). The situation during the winter was exactly the reverse. During the winter, strong solar heating over the Pangaea located in the southern hemisphere caused heated air to rise over the land and the development of a strong low-pressure zone positioned over the southern part of Gondwana and eastern part of the Tethys Ocean. In the northern hemisphere, the reduced seasonal insolation, the high elevations, and the extensive landmass could have generate extremely cold temperatures (colder than −30 °C) north of 35° latitude in both continents, stabilising the continental air masses and generating a high-pressure cells belt across the northern hemisphere, over the Laurasia continental masses (Fig. 3B).

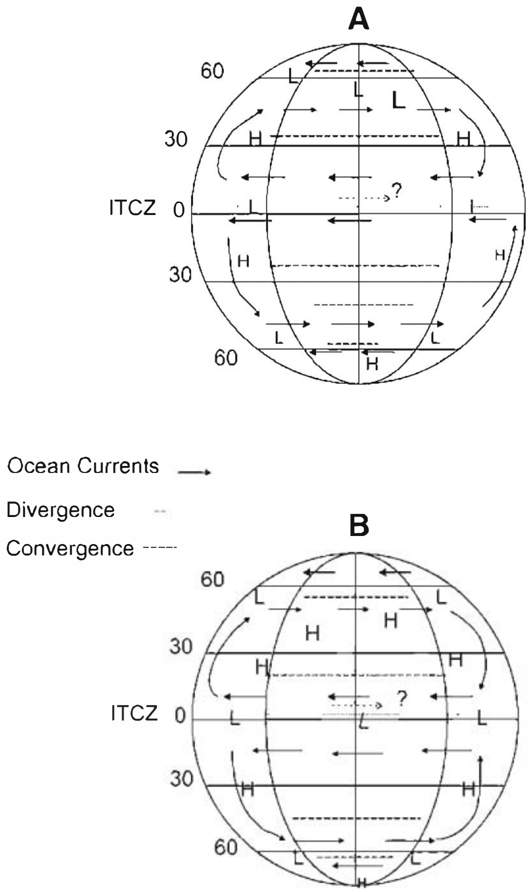


Fig. 3. Schematic pattern of the simulated Early Jurassic general atmospheric and oceanic circulations for the northern hemisphere summer (A) and winter (B). Black arrows represent ocean currents.

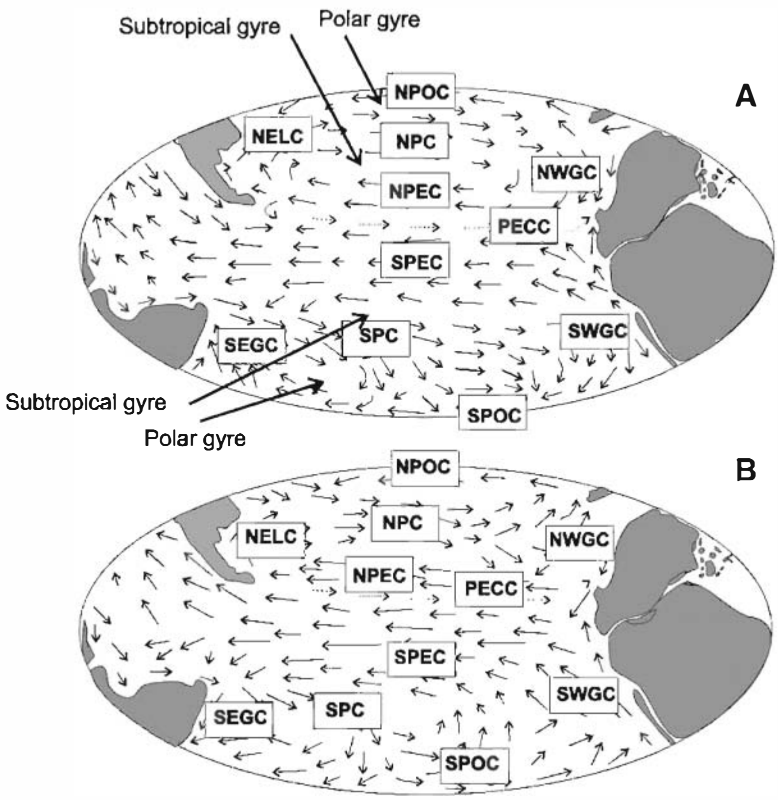
3. The Panthalassa Ocean

A hemisphere-sized ocean, larger than today's Pacific, the Panthalassa, surrounded the Pangaean supercontinent (Fig. 1). Initially it was postulated that, because of the large size of Panthalassa, surface oceanic circulation patterns would have been relatively simple, consisting of an enormous single gyre in each hemisphere (Kennet, 1977; Enay, 1980). Some paleoceanographers interpret Panthalassa as a stagnant and highly stratified ocean (Winguth et al., 2002). Modelling studies indicate that an east–west sea surface temperature (SST) gradient, with the coldest water delivered by upwelling in the east, with warmest water in the west extending into the Tethys Sea, seem to be almost a certain feature of the Panthalassa Ocean (Chandler et al., 1992, Winguth et al., 2002).

From the present proposed conceptual oceanic model, several subtropical gyres seem to have dominated the circulation pattern in the Panthalassa Ocean. The wind forcing for northern Panthalassa Ocean consists of mid-latitude westerlies (at latitudes north of about 60°N) and trades or tropical easterlies winds between 60°N and the equator. Between the two hemispherical belts of tropical trades there is a convergence zone, the Intertropical Convergence Zone (ITCZ). This zone could move seasonally north and south away of the equator, and is located in lower latitudes (around 20°N). The dominant pattern of atmospheric circulation north of 30°N is associated with the North Panthalassa High. The wind stress would create Ekman convergence between 15°N and 50°N, and Ekman divergence between 5°N and 10°N. These patterns force Sverdrup transport, northward in Ekman divergence regions and southward in Ekman convergence regions. Because the return flow in this ocean transport is by means of western boundary currents, an anticyclonic circulation at mid-latitudes (subtropical North Panthalassa gyre), and a meridional narrow anticyclonic circulation centred at 20°N are created (North Panthalassa gyre) (Fig. 4A, B).

In the northern Panthalassa Ocean (Fig. 4A, B), the trade winds would be responsible for westward horizontal Ekman flows in the tropical Panthalassa, and the westerlies would cause the equatorward flows at high latitudes. Consequently, the trade winds would move the water away from the Gondwana continent and pile it up against Laurasia to form the *northern Panthalassa Equatorial Current* until the upper layers reach the western boundaries of the ocean which divert the flows poleward in an intense western boundary currents (the *North-eastern Laurasia Current*). After moving poleward the mean currents turns eastward driven by the westerly winds of the middle latitudes forming the *North Panthalassa Current*. These gyral circulations are closed to the east by much weaker eastern boundary current (*the North-western Gondwana Current*).

Because the North Panthalassa gyral circulations (Fig. 4A, B) are concentrated in the west (this phenomenon is known as



North-eastern Laurasia Current (ELC)
North polar Current (NPOC)
North-western Gondwana Current (NWGC)
North Panthalassa Current (NPC)
North Panthalassa Equatorial Current (NPEC)
Panthalassa Equatorial Counter Current (PECC)
South Panthalassa Equatorial Current (SPEC)
South Panthalassa Current (SPC),
South-eastern Gondwana Current (SEGC)
South-Western Gondwana Current (SWGC)
South polar Current (SPOC)

Fig. 4. Schematic representation of the surface oceanic circulation in the Panthalassa Ocean during (A) the winter monsoon and (B) the summer monsoon. A clockwise circulation of water, known as the North Panthalassa Gyre generally dominates the North Panthalassa. This pattern of circulation is comprised of several currents: the North-eastern Laurasia Current (ELC), North polar Current (NPOC), the North-western Gondwana Current (NEGC), the North Panthalassa Current (NPC) and the North Panthalassa Equatorial Current (NPEC). The Panthalassa Equatorial Counter Current (PECC) lies between 3° and 10°N and is considered to roughly serve as the northern boundary for the South Panthalassa Equatorial Current (SPEC). The South Panthalassa Ocean is dominated by the counter clockwise-moving South Central Gyre. South of the latitude 30°S, the prevalent westerly winds result in an eastward flow of the tropical waters, via the South Panthalassa Current (SPC), which is an extension of the South eastern Gondwana Current (SEGC). Farther south, starting at latitudes below 60°S, is the region containing the South polar Current (SPOC) approaches the South Gondwana continent, part of the water mass is deviated northwards and goes to form the South-west Gondwana Current (SWGC) which enters the equatorial zone after making a detour to the west.

the "westward intensification" of currents and raised from the fact that the Coriolis effect increases with latitude (Stommel, 1948, 1957; Pond and Pickard, 1997), the equator return flows distributed over much of the rest of the Panthalassa Ocean. Since the *northern and southern Panthalassa Equatorial currents* piled up a large volume of water in the western portions of the Panthalassa Ocean, and because the Coriolis effect would be minimal near the equator, a large accumulation of water that would flow under the gravity could be originated, creating as a result, a *Panthalassa Equatorial Counter Current*.

In southern Panthalassa Ocean (Fig. 4A, B) the prevailing easterly winds in conjunction with the westerlies created other circular-moving gyres of water. This subtropical gyre, the South Panthalassa gyre, has rotated counter clockwise and would have been composed of four main currents: the *South Equatorial Panthalassa Current*, which has flowed westward (between the equator and 10°S) into the western intensified *South Panthalassa Current*. From there, it joins the *South Polar Current*, and completes the gyre as a *Southwestern Gondwana Current*. When surface currents, moving eastward as a result of prevailing westerlies, come near subpolar latitudes, they are driven westward by the polar easterlies producing a subpolar gyre that rotates opposite to the adjacent subtropical Panthalassa gyre. Subpolar gyres are smaller and better developed in the northern hemisphere than in the southern hemisphere. In addition, the northeastern corner of the Laurasia and southeastern corner of the Gondwana continent could have altered the general model and the situation of the subpolar gyre, which would have been deviated westward.

Another dynamic feature associated with the Coriolis effect, which could affect the distribution of water properties, is the presence of divergences and convergences at the boundary between oppositely directed currents, e.g. there is a surface divergence at about 30°N between the northern Panthalassa Equatorial Current and the Panthalassa Equatorial Counter Current, and a convergence at about 30°N between the North Panthalassa Current and northern Panthalassa Equatorial Current in the northern hemisphere and another at about 30°–60°S between the southern Panthalassa Equatorial Current and the South Panthalassa Current in the southern hemisphere (Figs. 3 and 4).

The results of this model indicate that the general features of the eastern Panthalassic circulation can be comparable to the modern Pacific, although the present model shows significant differences about the number of gyres in each hemisphere. In contrast to the previous ocean simulations with idealized symmetrical land–sea distribution, such as, Kutzbach's model (Kutzbach et al., 1990), this model shows the occurrence of two strong subtropical and two polar gyres centred on 30° and 60° latitude respectively, in each hemisphere (Fig. 4) as a consequence of the wind system and the asymmetrical distribution of land areas and sea in relation to the equator.

4. The Tethys Ocean

As already indicated, Pangaea had become established, at the Early Jurassic, as a large supercontinent; uncertainties remain, especially in relation to some Tethyan and northwest North American terrenes (Engebretson et al., 1985; Debiche et al., 1987; Sengör and Natalin, 1996; Keppie and Dostal, 2001; Metcalfe, 2001a,b, 2006; Golonka, 2007). In the Early Jurassic, the Tethys Ocean was rimmed by the landmasses of Pangaea, particularly Laurasia in the north and Gondwana in the south, with numerous continental blocks drifted from the southern margin of Gondwana northward across the Tethys crossing almost the equator. Sedimentological studies in the Tibetan Himalayas and Nepal areas seem to indicate the Triassic rifting of the Lhasa microplate from northern Gondwanaland. This plate, sited in the middle of central Tethys, could have had an effect on the ocean current pattern in this area (Dewey, 1988; Sengör and Natalin, 1996; Metcalfe, 2006; Golonka, 2007).

The Tethys Ocean, with just a few relatively narrow passages connecting it to the Panthalassa Ocean to the west, may have had a more restricted circulation, although today's Mediterranean, with only a single passage (the Strait of Gibraltar), exchanges large quantities of water with the adjoining Atlantic Ocean.

Kutzbach and Gallimore (1989) and Kutzbach et al., (1990) provided the first ocean general circulation model for an idealized Tethys Ocean. This model showed an important westward flow at the equator area, both boundary currents along the northern and southern margins of the Tethys Ocean and an eastward flow at higher latitudes. A series of experiments, designed to examine the Cretaceous ocean circulation, has been carried out by Barron and Petersen, which used GCM models (Barron and Petersen, 1990). They proposed a clockwise circulation within the Tethys, with an eastward-flowing current along the northern margin of the Tethys Ocean. However, these results are generally inconsistent with the geological and paleontological record.

Many authors proposed the existence of monsoonal circulation (Parrish and Curtis, 1982; Parrish et al., 1982; Chandler et al., 1992). In winter, when the air over the Laurasia is colder than over the Panthalassa, a large high-pressure cell is created, which forces atmospheric masses of the continent and out over the ocean. These northeast trade winds flow over the Tethys Ocean. During the summer, the winds reverse. Because of the lower heat capacity of land compared with water, the Laurasia continent warm faster than the ocean creating low-pressure cells over the Laurasia continent. This event forces air over the Tethys Ocean onto the Laurasia continent, which may be thought of as continuation of the southeast trade wind across the Equator.

A wind-driven equatorial ocean current circulation mainly characterizes the Tethys Ocean. Surface circulation in the northern Tethyan Ocean is not a simple prolongation of the West Panthalassa Ocean circulation pattern. During the summer, in the northern margin of the Tethys, the south-west monsoon winds and the Ekman effect creates a clockwise gyre, with an eastward-flowing *Monsoon Tethys Current* and from the equator 20°S there is the eastward-flowing *South Panthalassa Equatorial Current* (Fig. 5A). During the winter, the northeast monsoon wind produces a westward-flowing *South Panthalassa Equatorial Current* (Fig. 5B), which is a continuation of the Panthalassa circulation. The dominant feature of the southern hemisphere ocean circulation is the subtropical anticyclonic (counter clockwise) gyre, which comprises the westward-flowing *South Equatorial*

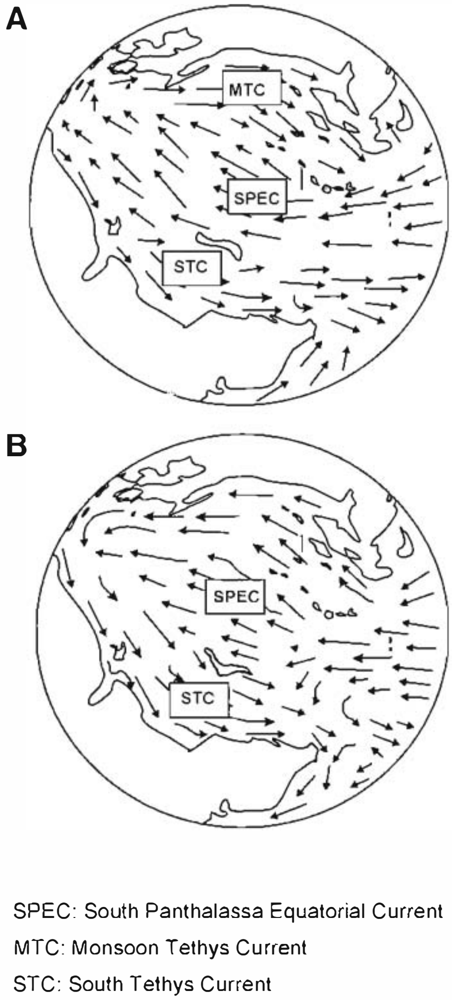


Fig. 5. Schematic representation of the circulation in the Tethys Ocean during (A) summer monsoon and (B) winter monsoon. The abbreviations are as follows: SPEC, South Panthalassa Equatorial Current; MTC, Monsoon Tethys Current and SET South Tethys Current.

Panthalassa Current and the eastern flowing *South Tethys Current* along the southern margin of the Tethys Ocean. This gyre is the response of the ocean to the mean basin-wide wind stress curl distribution and exhibits most of the features of a classical mid-latitude gyre, modified by the large seasonal variability in the wind directions (Woodberry et al., 1989). Because of the great size of Pangaea, it is probable that the monsoon winds were proportionately greater than today's. In order not to invite any erroneous conception with regard to the Tethyan currents, it maybe added that the ocean currents of the central regions of the Tethys Ocean, which is characterized by the occurrence of several microplates, would be losing their predominantly eastside direction (Golonka and Kiessling, 2002).

5. Palaeobiogeographic evidence

In our effort to understand the meaning of Early Jurassic faunal distributions, it has focused on genetic similarity of these faunas in the context of the known palaeogeographic constrains and the limit placed on the knowledge of the palaeogeography of some fossil groups. The present paper has been done on the richest and most diverse invertebrate groups in the Early Jurassic, ammonites, brachiopods and bivalves.

In the earliest Early Jurassic there was no direct communication between the western area of the Tethys Ocean and the Panthalassa Ocean via the Hispanic Corridor. Because the presence of many fossils of Tethyan affinities in the American Cordillera (mainly bivalves and ammonites), several authors indicated the possibility that they could have been transported long distances by some current dispersal, rejecting the option of that cordilleran terranes have migrated from west Panthalassa (Enay, 1980; Westermann, 1981; Kristan-Tollmann and Tollmann, 1983; Hallam, 1983, 1994; Newton, 1988; Damborenea and Manceñido, 1992; Nishihara and Yao, 2001; Krobicki and Golonka, 2007; Aljinovic et al., 2008). They sustained pantropical distributions and they supported this hypothesis by the Jurassic faunal distribution, with many Tethyan taxa appeared over a wide area between the Alps and South America. The opening of the Hispanic Corridor, which was a continuous seaway through the Central America, at least since the Early Pliensbachian, allowed free migration of boreal and Tethyan faunas into eastern Panthalassa (Arias, 2006).

Ammonites can be especially useful in showing this circum-Panthalassa distribution (Riccardi, 1991). The influence of the eastern and western boundary currents would clarify the common presence of Western Tethyan and European ammonites, such as, *Protogrammoceras*, *Arieticeras*, *Dactylioceras*, *Palpartites* and *Fanninoceras* (~*Radstockiceras*) in North and South America during the Pliensbachian (Donovan, 1967; von Hillebrandt, 1970; Howarth, 1973; Westermann, 1981, 1993; Smith and Tipper, 1986; Riccardi, 1991), or the presence of Mexican ammonites later described in the Toarcian of Australia and Antarctica (Elmi, 1993).

Hallam (1983, 1994) described the presence of Hettangian–Sinemurian bivalves of North America (*Plagiostroma*, *Jaworskiella* and *Homomya*) in the Pliensbachian of South America, and North American bivalves of the Pliensbachian (*Plicatostylus*, *Opisoma-Lithiotis*, *Vaugoni*) in the Toarcian of South America. Other examples repeatedly cited are *Actinostreon*, a well known genus from the Sinemurian of Chile and Pliensbachian of Mexico; *Posidonotis* from the Early Sinemurian of North America and the Early Pliensbachian of South America; *Weyla* from the Hettangian–Sinemurian of Canada and United States and the Pliensbachian of Alaska and Chile and Toarcian of Madagascar and the Himalayas (Damborenea and Manceñido, 1979; Damborenea, 1987, 1993; Liu et al., 1998); *Lithiotis-Opistoma* from the Pliensbachian of Oregon, North America and Toarcian of Chile and Argentina, South America (Du Dresnay, 1977; Nauss and Smith, 1988; Leinfelder et al., 2002). This observed connection can be attributed either to the seasonally enhanced eastern boundary currents, events that periodically push water along the eastern margin this open ocean.

Faunal dispersal across Panthalassa is more difficult to verify. Larval transport across the mid-Panthalassa Ocean would require entrainment in one of these major currents, however, the thermal cooling associated with the North and South Atlantic

Gyres may prohibit higher latitude larval transport for many invertebrates species. If dispersal from the west is responsible for the colonization of the eastern Panthalassa, what route achieved this? The three possible routes are: (1) the North Panthalassa Gyre; (2) the Equatorial Undercurrent; or (3) the South Panthalassa Gyre (Fig. 4). The most possible connection links the western Panthalassa–Tethys area (for example Timor) with the western North America. This network indicates that either the North Panthalassa Gyre or the Equatorial Undercurrent could have been used, as the western North America lies in the path of the former, and is also likely affected by both current systems, e.g. Pliensbachian genus *Plicatostylus* which is present on western North America and then, on Chile, Peru and Timor (Hallam, 1983; Smith and Tipper, 1986).

On the western side of the Tethyan Ocean, the scarcity of paleontological data makes more difficult to corroborate the present proposal of ocean circulation pattern. The majority of authors distinguished dispersal by means of filters bridges and sweepstakes along the southern margin of Tethys, from Australia to the European Epicontinental Sea (Frakes, 1979; Hallam, 1983; Smith and Tipper, 1986; Frakes and Francis, 1988; Kutzbach and Gallimore, 1989; Riccardi, 1991, Chandler et al., 1992; Damborenea and Manceñido, 1992 and Frakes et al., 1992). *Bouliceras*, a very well studied ammonite described originally from Madagascar and lately recorded in Kenya, Somalia, Arabia, East Africa, Morocco, Portugal and Spain, would move easily along this route (Mouterde, 1953; Goy and M tinez, 1990). Another ammonite genus, *Nejdia*, which was initially recorded from the lowest Upper Pliensbachian sediments of Madagascar, was later described in the latest Upper Pliensbachian of the Cordillera Ibérica and the Vasco-Cantabrian basin of northern Spain (Rulleau et al., 2003).

A more complicated pattern is derived from the palaeobiogeography of Tethyan ostracods. The Early Jurassic ostracod faunas of western Australian have a high similarity with North and Central Europe as they do with Northern Africa. Initially, when considered as a whole, the majority of ostracod species have their first records in Australia, suggesting a northward faunal migration along the southern margin of Tethys. However, the description of a similar fauna of healdioids from the Himalayan area (Lord, 1988), would also suggest the existence of another Tethyan source area, one along the southeastern margin of Laurasia, and would demonstrate the existence of a northern subtropical gyre as it was described in the present proposal (Arias, 2006).

Nevertheless, the Southern Gyre is the least likely route, based on these findings as well as oceanographic considerations; this current system is colder and slower than the other routes and the distance between Australia and South America is the largest trans-Panthalassa gap, e.g. Jurassic inoceramids bivalve described in Argentina are remarkably similar to inoceramids of the same age in New Zealand (Damborenea and Manceñido, 1992). Damborenea (1987, 2000) used two main groups of similarity coefficients to assess affinities and palaeogeographic distribution of Jurassic bivalve assemblages from North America, South America and Japan. The highest similarity among these assemblages was established between North and South American assemblages during the Pliensbachian, meanwhile across the Pacific, between Japanese and the American faunas, the similarity was very low during the Sinemurian and Pliensbachian.

These examples show that dispersal gives some species the opportunity to invade distant shore merely by being passengers on the ocean's transport system of currents. We rarely can verify this process in the past, but several species have invaded new coasts during the Early Jurassic, and their spread can be documented.

6. Conclusions

A new conceptual palaeoceanographic model as an innovative tool for palaeobiogeographic reconstructions is outlined in this paper. During the Early Jurassic, the Panthalassic circulation was characterized by the development of the two large subtropical gyres rotating clockwise in the northern hemisphere and anti-clockwise in the southern hemisphere (Fig. 4A, B). The Tethys Ocean is very different from the Panthalassa Ocean; the most striking difference is the seasonal reversal of the monsoon winds and its effect on ocean currents in the northern hemisphere (Fig. 5A, B). In the summer winds blew Tethyan surface water eastward, whereas in the winter they blew it westward. During the northeast monsoonal season (winter) the current system resembled closely those of the Panthalassa Oceans. During the summer, conversely, the direction of the currents along the northern margin of the Tethys was the reverse; the westward currents were replaced by eastward flow. The result was a northern hemisphere gyre, which rotated in an opposite direction of the southern hemisphere subtropical gyre. Another dissimilarity, which affected to the South Tethys circulation, is due to the effect of the southeastern corner of the Gondwana continent and the presence of several microplates in central Tethys. As a consequence of the existence of this corner, the oceanic circulation pattern is modified, developing a new subpolar gyre, which displacing the southern Panthalassic gyre eastward.

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Appendix A. Palaeoceanographic reconstruction (P. Wilde)

General circulation patterns applicable to palaeoceanography studies using palaeogeographic reconstructions are derived in a series of steps with increasing complexities (time scales). Basic global assumptions: (1) Earth is basically spherical of the same dimensions as today with an axis of rotation essentially perpendicular to the plane of the ecliptic and with the direction of rotation the same as modern (West to East). (2) As a consequence of the orientation of the axis of rotation, incoming solar radiation is concentrated in the Equatorial regions and heat is transferred from the Equator towards the poles. (3) The size of the Earth requires the heat transfer to occur in three atmospheric cells mirrored at the Equator: a tropical cell (Hadley), a temperate cell (Ferrel) and a polar cell. The tropical cell is driven by rising air at the Equator, which moves poleward and sinks about 30° and returns along the surface towards the Equator. The polar cell is driven by sinking air at the poles moving along the surface Equatorward and rises at about 60°. The driven cells entrain the temperate cell. (4) The rotation of the Earth from West to East produces surface winds deflected to the West (Easterly winds) with Equatorward movement and to the East (Westerly winds) with poleward movement (Fig. 2A, B).

Case I: World ocean (no land)

The zonal planetary surface winds will shape the water in the surface ocean into a series of longitudinal mounds (high pressure in the ocean) and troughs (low pressure in the ocean) corresponding geographically to the atmospheric cells. This is caused by Ekman transport producing divergence (upwelling) at 60° and the Equator and convergence along 30°.

Case II: Ocean and land (meridional boundaries)

Significant land (30%) would cause the longitudinal oceanic pressure systems to convert to gyres at the ocean–land boundaries. Governed by the rotation of the Earth, ocean circulation about these gyres will be geostrophic (deflected to the right in the direction of the pressure gradient in the northern hemisphere and to the left in the southern hemisphere). Thus knowledge of the palaeogeography and the location of any land boundaries are crucial to interpreting paleocean currents. The Coriolis effect produces two oceanic low-pressure gyres with water advecting away from the Eastern side of the tropical ocean and piling up on the Western side. The Equatorial Currents are the poleward side of these gyres. The western pile up is partially relieved by the Equatorial Counter Current flowing as the return gyre of the two lows. Much of the water in the pile up is advecting into the western gyre of the located at latitudes on about 30° oceanic Highs, for example, this rotational western intensification (Stommel, 1948) produces the modern Kuroshio and the Gulf Stream currents in the northern hemisphere and the Tasman and Brazil currents in the southern hemisphere.

Case III: Seasonal effects

Monsoons. With significant land area over a wide latitudinal extent, seasonal monsoons can develop, which can influence ocean currents. This is caused by the large difference in heat capacity between water and land, with the land heating and cooling much faster than the oceans. In the hemispherical winter, rapid cooling of the large landmasses generates a persistent high atmospheric pressure and correspondingly relative low pressure over the equatorial waters. In the hemispheric summer, however, atmospheric pressure over the land caused by increased solar heating and rising air is lower than atmospheric pressure over the oceans. If these pressure differences are sufficiently strong, seasonal geostrophic winds will override the annual circulation described in Case II and oceanic currents will also be reversed. The strength of these monsoonal currents depends on whether they enhance or impede the annual circulation. Such potential reversals could have great significance in the migration of non-swimming flora and faunas depending on their 'bloom' times.

Slope currents. Another overprint of the annual current regime due to the presence of landmasses may be due to seasonal rains. Fresher, lighter winds in coastal region will produce a wedge of less saline water away from the coast until dissipated and mixed with open ocean water. This wedge slopes away from the coast and will produce a geostrophic current that overlies the underlying annual currents. For example, the modern winter Davidson Current of the west coast of the United States flows north, was along the coast over the southward flowing California Current, which is the return gyre of the North Pacific High. As these slope currents are thin surface currents they also may have seasonal influence on biotic migration of surface floras and fauna.

References

Acharyya, S.K., 1999. The role of India–Asia collision in the amalgamation of the Gondwana-derived blocks and deep-seated magmatism during the Paleogene at the Himalayan foreland basin and around the Gongha syntaxis in the South China block. Gondwana Research 2 (4), 510–512.

Acharyya, S.K., 2001. The role of India–Asia collision in the amalgamation of the Gondwana-derived blocks and deep-seated magmatism during the Paleogene at the Himalayan foreland basin and around the Gongh syntaxis in the South China block. Gondwana Research 4 (1), 61–74.

Aljinovic, D., Isozaki, Y., Sremac, J., 2008. The occurrence of giant bivalve Alatoconchidae from the *Yabeina* zone (Upper Guadalupian, Permian) in European Tethys. Gondwana Research 13 (3), 275–287.

Arias, C., 2006. Northern and Southern Hemispheres ostracod palaeobiogeography during the Early Jurassic: possible migration routes. Palaeogeography, Palaeoclimatology, Palaeoecology 233 (1–2), 63–95.

Barron, E.J., Fawcett, P.J., 1995. The climate of Pangaea: a review of climate model simulations of the Permian. In: Scholle, P.A., et al. (Ed.), The Permian of Northern Pangaea. . Paleogeography, Paleoclimates, Stratigraphy, vol. 1. Springer, New York, pp. 37–52.

Barron, E.J., Petersen, W.H., 1990. Model simulation of the Cretaceous ocean circulation. Science 244, 684–686.

Berggren, W.A., Hollister, C.D., 1977. Plate tectonics and paleocirculation, commotion in the ocean. Tectonophysics 38 (1–2), 11–48.

Bju-Duval, B., Dercourt, J., Le Pichon, X., 1977. From the Tethys ocean to the Mediterranean sea: a plate tectonic model of the evolution of the western alpine system. International Symposium of Structure Historian of Mediterranean basins, Split, 1976. Technip édit, Paris, pp. 134–162.

Chandler, M.A., 1994. Depiction of modern and Pangaean desert: evaluation of GCM hydrological diagnostics for paleoclimates studies. In: Klein, G.D. (Ed.), Pangaea: Paleoclimate, Tectonics and Sedimentation during Accretion, zenith and break-up of a Supercontinent. Geological Society of America Special Paper, vol. 288, pp. 117–137.

Chandler, M.A., Rind, D., Ruedy, R., 1992. Pangaean climate during the Early Jurassic: GGCM simulations and the sedimentary record of paleoclimate. Geological Society of American Bulletin 194, 543–559.

Christiansen, J.L., Stouge, S., 1999. Oceanic circulation as an element in paleogeographical reconstruction: the Arenig, Early Ordovician as an example. Terra Nova 11, 73–78.

Crowley, T.J., Hyde, W.T., Short, D.A., 1989. Seasonal cycle variations on the supercontinent of Pangaea: implications for Early Permian vertebrate extinctions. Geology 17, 457–460.
Damborenea, S.E., 1987. Early Jurassic Bivalvia of Argentina, Part 2: Superfamilies Pteriacea, Buchiacea, and part of Pectinacea. Palaeontographica Abteilung A 199, 113–216.
Damborenea, S.E., 1993. Early Jurassic South American pectinaceans and circum-Pacific; palaeobiogeography. Palaeogeography, Palaeoclimatolology, Palaeoecolology 100, 109–123.
Damborenea, S.E., 2000. Hispanic Corridor: its evolution and the Biogeography of Bivalve Molluscs. GeoResearch Forum 6, 369–380.
Damborenea, S.E., Manceñido, M.O., 1979. On the palaeogeographic distribution of the pectinid genus Weyla Bivalvia, Lower Jurassic. Palaeogeography, Palaeoclimatology, Palaeoecology 27 (1/2), 85–102.
Damborenea, S.E., Manceñido, M.O., 1992. A comparison of Jurassic marine benthonic faunas from South America and New Zealand. Journal of the Royal Society of New Zealand 22 (2), 131–157.
Debiche, M.G., Cox, A., Engebretson, D., 1987. The motion of allochthonous terranes across the North Pacific basin. Geological Society of America Special Paper 207, 1–49.
Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sorokhtin, O., Geyssant, J., Lepvrier, C., Sborshschikov, I.V., Boulin, J., Biju-Duval, B., Sibuet, J.C., Savostin, L.A., Westphal, M., Laver, J.P., 1985. Présentation de 9 cartes paléogéographiques au 1/20.000.000 s´étendant de`l Atlantique au par mir pour la période der Lias a l´actuel. Bulletin de la Société Géologique de France 8 (5), 637–652.
Dewey, J.F., 1988. Extensional collapse of orogens. Tectonics 7, 1123–1139.
Dewey, J.F., Pitman, W.B.F., Ryan, J., Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine system. Geological Society of America Bulletin 84, 3137–3180.
Donovan, D.T., 1967. The geographical distribution of Lower Jurassic ammonites in Europe and adjacent areas. In: Adams, C.G., Ager, D.V. (Eds.), Aspects of Tethyan Biogeography. Systematic Association Publication, London, vol. 7, pp. 111–134.
Du Dresnay, R., 1977. Le milieu récifal fossile du Jurassique inférieur (Lias) dans le domaine des chaînes atlasiques du Maroc. 2eme` Symp. Intern. Coraux et récifs coralliens fossiles, Paris 1975. Mém. Bureau du Recherches Géologiques et Minies, Mémoires 89, 296–312.
Elmi, S., 1993. Les voies d'échange faunique entre l' Amérique du Sud et la Tethys alpine pendant le Jurassique Inférieur et Moyen. Documents des Laboratoires de Géologie 125, 139–149.
Enay, R., 1980. Paléobiogéographie et Ammonites jurassiques: "Rythmes fauniques" et variations du niveau marin; voies d'échanges, migrations et domaines biogéographiques. Livre Jubilaire de la Société Géologique de France, 1830–1980. Mémoires historique série de la Société Géologique de France, Paris 10, 261–281.
Engebretson, D.C., Cox, A., Gordon, R.G., 1985. Relative motions between oceanic and continental plate in the Pacific basin. Geological Society of America, Special Paper 206, 1–59.
Fawcettt, P.C., Barron, E.J., Robinson, V.D., Katz, B.J., 1994. The climate evolution of India and Australia from the Late Permian to mid-Jurassic; a comparison of climate model results with the geological record. Geological Society of America Special Paper 228, 139–157.
Frakes, L.A., 1979. Climates Throughout Geologic Time. Elsevier, Amsterdam, pp. 1–310.
Frakes, L.A., Francis, J.E., 1988. A guide to Phanerozoic cold polar climates from high-latitude ice rafting in the Cretaceous. Nature 333, 547–549.
Frakes, L.A., Francis, J.E., Syktus, J.I., 1992. Climate Modes of the Phanerozoic. Cambridge University Press, pp. 1–274.
Golonka, J., 2004. Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic. Tectonophysics 381, 235–273.
Golonka, J., 2007. Late Triassic and Early Jurassic paleogeography of the world. Palaeogeography, Palaeoclimatology, Palaeoecology 244, 297–307.
Golonka, J., Kiessling, W., 2002. Phanerozoic time scale and definition of time slices. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), Phanerozoic Reef Patterns. SEPM Special Publication, vol. 72, pp. 1–20.
Golonka, J., Ross, M.I., Scotese, C.R., 1994. Phanerozoic Paleogeographic and Paleoclimatic Modeling maps. In: Embry, A., Beauchamp, F., Glass, D.J. (Eds.), Pangea: Global Environments and Resources. Memoir, Calgary, vol. 17. Canadian Society of Petroleum Geologists, pp. 1–47.
Golonka, J., Krobicki, M., Pajak, J., Nguyen Van, G., Zuchiewicz, W., 2006. Global plate tectonics and paleogeography of Southeast Asia. Faculty of Geology, Geophysics and Environmental Protection. AGH University of Science and Technology, Arkadia, pp. 1–128.
Goy, A., Martínez, G., 1990. Biozonación del Toarciense en el área de la Almunia de Doña Godina-Ricla sector central de la Cordillera Ibérica. Cuadernos de Geología Ibérica 14, 11–53.
Hallam, A., 1983. Early and mid-Jurassic molluscan biogeography and the establishment of the central-Atlantic seaway. Palaeogeography, Palaeoclimatolology, Palaeoecolology 43, 181–193.
Hallam, A., 1994. An Outline of Phanerozoic Biogeography. Oxford University Press, Oxford, pp. 1–246.
Harris, A., 2006. Rise and fall of the Eastern Great Indonesian arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor. Gondwana Research 10 (3–4), 207–231.
Howarth, M.K., 1973. Lower Jurassic Pliensbachian and Toarcian ammonites. In: Hallam, A. (Ed.), Atlas of Palaeobiography. Amsterdam, Elsevier, pp. 275–282.
Kennet, J.P., 1977. Cenozoic evolution and Antarctic glaciations, the circum-Antarctic Ocean and their impact on global Palaeoceanography. Journal of Geophysical Research 82, 3843–3860.
Keppie, J.D., Dostal, J., 2001. Evaluation of the Baja controversy using paleomagnetic and faunal data, plume magmatism, and piercing points. Tectonophysics 339, 427–442.
Kristan- Tollmann, E., Tollmann, A., 1983. Tethys-faunenelemente in der Trias der USA. Mitteilungen der Österreichischen geologischen Gesellschaft 76, 213–272.
Krobicki, M., Golonka, J., 2007. Latest Triassic/earliest Jurassic geodynamic evolution of the Pangea-bivalve migration pattern and mass extinction. IGCP Programme 506 - Jurassic marine: non-marine correlation; Abstract book; Bristol, 4–8 July 2007, pp. 26–28.
Kutzbach, J.E., Gallimore, R.G., 1989. Pangaean climates: megamonsoons of the megacontinent. Journal of Geophysical Research 94, 3341–3357.
Kutzbach, J.E., Guetter, P.J., Washington, W.M., 1990. Simulated circulation of an idealized ocean for Pangaean time. Paleoceanography 5, 299–317.
Leinfelder, R.R., Schmid, D.U., Nose, M., Werner, W., 2002. Jurassic reef patterns the expression of a changing globe. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), Phanerozoic Reef Patterns. SEPM (Society for Sedimentary Geology) Special Publication, 72, pp. 465–520.
Liu, Ch., Heinze, M., Fürsich, F.T., 1998. Bivalve provinces in the Proto Atlantic and along the southern margin of the Tethys. Palaeogeography, Palaeoclimatolology, Palaeoecolology 137, 127–151.
Lloyd, C., 1982. The mid Cretaceous Earth: Palaeogeography; ocean circulation and temperature; atmospheric circulation. Journal of Geology 90, 393–413.
Lord, A., 1988. Ostracoda of the Early Jurassic Tethyan Ocean. In: Hanai, T., Ikeya, N., Ishizaki, K. (Eds.), Biology of Ostracoda: Its Fundamental and Applications. Proceeding of the Ninth International Symposium on Ostracoda, Shizouoka, Japan. Developments in Paleontology and Stratigraphy, vol. 11. Elsevier, pp. 855–867.
Metcalfe, I., 2001a. The Bentong-Raub Suture Zone, Permo-Triassic orogenesis and amalgamation of the Sibumasu and Indochina terranes. Gondwana Research 4 (4), 700–701.
Metcalfe, I., 2001b. Phanerozoic continental growth of east and southeast Asia: timings of amalgamation and accretion. Gondwana Research 4 (4), 701–702.
Metcalfe, I., 2006. Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: the Korean Peninsula in context. Gondwana Research 9, 24–46.
Mouterde, R., 1953. Faunes à affinités italiennes et marocaines dans le Lias moyen portugais. Les Comptes rendus de l'Académie des sciences 236, 1980–1982.
Nauss, A.L., Smith, P.L., 1988. *Lithiotis* Bivalvia bioherm in the Lower Jurassic of east–central Oregon, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 65 (3–4), 253–268.
Newton, C., 1988. Significance of "Tethyan" fossils in the American Cordillera. Science 242, 385–391.
Nishihara, C., Yao, A., 2001. Environmental change of the western Panthalassa in view of Jurassic radiolarian. Gondwana Research 4 (4), 717–718.

Owen, H.G., 1983. Atlas of Continental Displacement, 200 Million Years to the Present. Cambridge University Press, Cambridge, pp. 1–159.
Parrish, J.T., 1982. Upwelling and petroleum source with reference to the Palaeozoic. American Association of Petroleum Geology Bulletin 66, 750–774.
Parrish, J.T., Curtis, R.L., 1982. Atmospheric circulation, upwelling and organic rich rocks in the Mesozoic and Cenozoic eras. Palaeogeography, Palaeoclimatolology, Palaeoecolology 40, 31–66.
Parrish, J.T., Ziegler, A.M., Scotese, C.R., 1982. Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. Palaeogeography, Palaeoclimatolology, Palaeoecolology 40, 67–101.
Pond, S., Pickard, G.L., 1997. Introductory Dynamical Oceanography, 2nd Edition. Butterworth-Heinemann Ltd., Oxford, pp. 1–329.
Riccardi, A.C., 1991. Jurassic and Cretaceous marine connections between the Southeast Pacific and Tethys. Palaeogeography, Palaeoclimatolology, Palaeoecolology 87, 155–189.
Roy, A.B., 2001. Phanerozoic reconstitution of Indian shield as aftermath of Gondwana break-up. Gondwana Research 4 (4), 757–758.
Roy, A.B., 2004. The Phanerozoic reconstitution of Indian shield as the aftermath of break-up of the Gondwanaland. Gondwana Research 7 (2), 387–406.
Rulleau, L.M., Bzcaud, P., Neige, P., 2003. Ammonites generally classified in the Bouleiceratinae sub-family Hildoceratidae, Toarcian: phylogenetic, biogeographic and systematic perspective. Geobios 36, 317–348.
Scotese, C.R., 2002. Plate Tectonic animation, Jurassic to Quaternary. http://www.scotese.com, PALEOMAP website.
Scotese, C.R., Golonka, J., 1992. PALEOMAP Paleogeographic Atlas, PALEOMAP Progress Report no. 20, Department of Geology, University of Texas at Arlington, Arlington, Texas, pp. 1–34.
Scotese, C.R., Summerhayes, C.P., 1986. Computer model of Paleoclimate predict coastal upwelling in the Mesozoic and Cenozoic. Geobyte 28–42.
Sengör, A.M.C., Natalin, B.A., 1996. Paleotectonics of Asia: fragment of a synthesis. In: Yin, A., Harrison, T.M. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 486–640.
Smith, A.G., Briden, J.C., Drewry, G.F., 1973. Phanerozoic world maps. In: Hugues, N.F. (Ed.), Organism and Continent Through Time. Special Paper in Paleontology, vol. 12, pp. 1–39.
Smith, P.L., Tipper, H.W., 1986. Plate tectonics and paleobiogeography: Early Pliensbachian endemism and diversity. Palaios 399–412.
Smith, R.S., Dubois, C., Marotzke, J., 2004. Ocean circulation and climate in an idealised Pangean OAGCM. Geophysical Research Letters 31, 1–18.
Stehli, F.G., 1965. Palaeontological technique for defining ancient oceans currents. Science 148, 943–946.
Stommel, H., 1948. The westward intensification of wind-driven ocean currents. Transactions of the American Geophysical Union 29, 202–206.
Stommel, H., 1957. A survey of ocean current theory. Deep-Sea Research 4, 149–184.
Takagi, H., Arai, H., 2003. Restoration of exotic terranes along the median tectonic line, Japanese Islands: overview. Gondwana Research 6 (4), 657–668.
Van der Voo, R., 1993. Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans. Cambridge University Press, Cambridge, pp. 1–411.
Vaughan, A.P.M., Pankhurst, R.J., 2008. Tectonic overview of the West Gondwana margin. Gondwana Research 13, 150–162.
von Hillebrandt, A., 1970. Zur Biostratigraphie und Ammoniten Fauna des sudamerikanischen Jura Karaibe, Chile. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen 136 (2), 166–211.
Westermann, G.E.C., 1981. Ammonite biochronology and biogeography of the circum-Pacific middle Jurassic. In: House, M.R., Senior, J.R. (Eds.), The Ammonoidea. Systematical Association Special Paper, London, 18, pp. 459–498.
Westermann, G.E.C., 1993. On alleged negative buoyancy of ammonoids. Lethaia 26, 246.
Wilde, P., 1991. Oceanography in the Ordovician. In: Barnes, C.R., Williams, S.H. (Eds.), Advances in Ordovician Geology. Canadian Geological Survey Paper, vol. 90–99, pp. 283–298.
Winguth, A.M.E., Heinze, C., Kutzbach, J.E., Maier-Reimer, E., Mikolajewicz, U., Rowley, D., Rees, A., Ziegler, A.M., 2002. Simulated warm polar currents during the middle Permian. Paleoceanography 17 (4), 9.1–9.18.
Woodberry, K.E., Luther, M., O'Brien, J.J., 1989. The wind-driven seasonal circulation in the southern tropical Indian Ocean. Journal of Geophysical Research 94, 17 985–18 002.
Ziegler, P.A., 1988. Post-Hercynian plate reorganization in the Tethys and Arctic–North Atlantic domains. Chapter. 30. In: Manspeizer, W. (Ed.), Triassic–Jurassic Rifting. Continental Break-up and Origin of the Atlantic Ocean and Passive Margin, Part B. Elsevier, Amsterdam, pp. 711–755.
Ziegler, P.A., 1992. Geological Atlas of Western and Central Europe. Elsevier, Amsterdam, pp. 1–130.
Ziegler, P.A., Cloetingh, R., Guiraud, R., Stampfli, G.M., 2001. Peri-Tethyan platform. dynamics of rifting and basin inversion. In: Cavazza, W., Robertson, A.H., Ziegler, P.A. (Eds.), Peritethyan rift/wrench basins and passive margins. IGCP 369. Bulletin du Muséum National d'Histoire Naturelle du Paris. Peri-Tethys Memorie, vol. 6, pp. 9–49.
Ziegler, A.M., Hulver, M.L., Rowley, D.B., 1997. Permian world topography and climate. In: Martini, P. (Ed.), Late Glacial and Postglacial Environmental Changes—Quaternary. Oxford University Press, New York, pp. 111–146.
Ziegler, A.M., Scotese, C.R., Barrett, S.F., 1983. Mesozoic and Cenozoic paleogeographic maps. In: Brosche, P., Sündermann, J. (Eds.), Tidal Friction and the Earth's Rotation II. Springer-Verlag, Berlin, pp. 240–252.