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A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons

G.M. Stampfli, G.D. Borel *

Institute of Geology and Paleontology, University of Lausanne, CH-1015 Lausanne, Switzerland

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Abstract

We developed a plate tectonic model for the Paleozoic and Mesozoic (Ordovician to Cretaceous) integrating dynamic plate boundaries, plate buoyancy, ocean spreading rates and major tectonic and magmatic events. Plates were constructed through time by adding/removing oceanic material, symbolized by synthetic isochrons, to major continents and terranes. Driving forces like slab pull and slab buoyancy were used to constrain the evolution of paleo-oceanic domains. This approach offers good control of sea-floor spreading and plate kinematics. This new method represents a distinct departure from classical continental drift reconstructions, which are not constrained, due to the lack of plate boundaries. This model allows a more comprehensive analysis of the development of the Tethyan realm in space and time. In particular, the relationship between the Variscan and the Cimmerian cycles in the Mediterranean–Alpine realm is clearly illustrated by numerous maps. For the Alpine cycle, the relationship between the Alpides senso stricto and the Tethysides is also explicable in terms of plate tectonic development of the Alpine Tethys–Atlantic domain versus the NeoTethys domain. © 2002 Published by Elsevier Science B.V.

Keywords: isochrons; plate boundaries; plate tectonics; models; Paleozoic; Mesozoic; paleo-oceanography

1. Introduction

Recent syntheses by IGCP and Tethys Group projects, in which we actively participated, provide an up-to-date framework for reassessing plate tectonic models for the Tethyan realm [1]. New plate tectonic concepts were also developed to integrate new data regarding the geodynamic evolution of pre-Variscan [2] and Variscan Europe [3–5] and of the Cimmerian orogenic cycle in the western Tethys [6,7]. These works followed plate tectonic models developed for the Alpine region [8,9] and for the Mediterranean region [10]. Our goal during the development of this model was to integrate geodynamic constraints (such as ocean spreading rates, plate buoyancy, dynamic plate boundaries and basin evolution), lithologic data (e.g. pelagic series and ophiolite occurrences) as well as the age and style of major tectonic and magmatic events.

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* Corresponding author.
Tel.: +41-21-692-4359; Fax: +41-21-692-4305.
E-mail addresses: gerard.stampfli@igp.unil.ch (G.M. Stampfli), gilles.borel@igp.unil.ch (G.D. Borel).

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2. Reconstructions parameters

Numerous parameters were integrated in the model in an iterative approach. It appeared that the most efficient procedure was to develop the final model forward in order to check its consistency step by step. The weight of the different parameters varies extremely from one reconstruction to another but also in the same reconstruction from one region to another (for details, see Sections 3 and 4).

2.1. Geological objects and tools

To define the size of continents, we digitized their present shape or geological boundaries where applicable. Where possible, we used a similar procedure for the terranes keeping their present shape for geographical identification. We systematically used tight fits in order not to underestimate widespread extension affecting continents and their margins. To use plates and not only continents, we developed the concept of a dynamic plate boundary (e.g. active spreading ridge, subduction zone, and transform fault) by adding to each continent its oceanic surface through time. Thus, paleo- synthetic oceanic isochrons have been constructed through time in order to define the location of the spreading ridges and to restore subducted ocean basins. To simplify the process we worked with symmetrical seafloor spreading for the main oceans (Paleo- and NeoTethys).

We combined stratigraphic, sedimentary and paleontological data to produce subsidence curves in some key areas. Subsidence analysis characterizes and constrains the timing of major geodynamic events, such as the onset of rifting, subduction of an active ridge or collision of continents, and consequently constrains spreading rates. Paleomagnetic (e.g.[11]) and paleobiogeographic information have also been incorporated, to the limit of our knowledge, to constrain the pre-Mesozoic location of older plates, whilst existing isochrons [12] were used to constrain younger reconstructions. Geological data, mainly regarding the age of accretion/collision, were compiled for most key areas (e.g. [13] and [14] for south-east Asia, [15] for the Tibetan back-arcs, etc.). Where possible, this multidisciplinary approach was applied to the entire globe in order to generate self-constrained reconstructions. However, little consideration was given to the PaleoPacific due to a lack of any information before the Jurassic. Despite this, most of the Paleozoic information could be gathered through investigation of cordillera construction/collapse around the Pacific (e.g. [16]).

2.2. Geodynamic forces and implications

Based on the fact that a continent is nearly always attached to a larger plate, continental drift has implications for its plate boundaries. Therefore, we consider that only models integrating plate boundaries can be compared to each other and that reconstructions based on continental drift as practised by everybody since Wegener should be abandoned. Continental drift models do not allow assessment of important geodynamic events such as the onset of subduction [17], mid-ocean ridge subduction (e.g. [18]) presence/absence of slab rollback and related plate motion (e.g. [19]) nor plate buoyancy criteria (e.g.[20]). Fig. 1 schematizes all these parameters and their influence on plate kinematics. Among other parameters, we assume that cordillera build-up (Fig. 1E) corresponds to subduction of young buoyant lithosphere, whereas cordillera collapse (Fig. 1F) and opening of back-arcs correspond to the subduction of heavier lithosphere producing slab rollback. In doing so we could relate, for example, the evolution of the Australian active margin (e.g. [21,22]) with the opening of the NeoTethys. Furthermore, two types of terranes can exist. The first one detached from the active margin by slab rollback and opening of back-arc, and has an active margin and a passive one (Fig. 1B), e.g. the European Hunic terranes. The other type, detached from a passive margin by slab pull, has two passive margins (Fig. 1G), e.g. the Cimmerian blocks. Slab pull becomes strong enough to detach a terrane only after the subduction of the active ridge. The sedimentary record of the terrane gives the timing of rifting for both oceans and consequently a good control on the spreading rate.

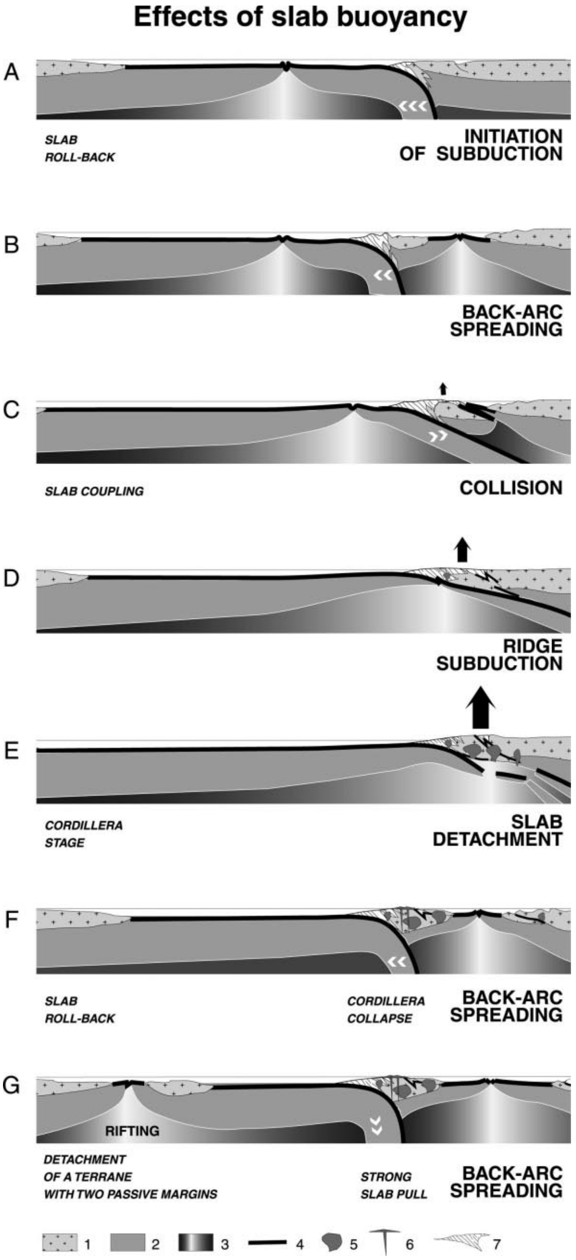

Fig. 1. Sketches showing the effect of the main driving forces (slab pull, slab buoyancy) on the evolution of oceanic margins. (A) Continental crust; (B) lithospheric mantle; (C) asthenosphere; (D) oceanic crust; (E) intrusives; (F) volcanism; (G) accretionary prism.

2.3. Technical tools and constraints

We develop our model using GMAP software package [23]. More than 100 continents and terranes were used to elaborate the reconstructions. In general, we always tried the simplest geometrical solution to move a plate.

The use of Euler poles to move plates has numerous consequences; one of them is the geometry of transform boundaries (small circle); where they are known (e.g. Levant transform) the chosen Euler pole has to conform to this geometry. The consequence is that the maximum spreading of a chosen pole lies along its equator. As a result, an acceptable spreading rate close to the Euler pole may be unacceptable a few thousands of kilometers away. We tried to keep sea-floor spreading at the Euler equator below 20 cm/yr. Spreading rates were calculated at the Euler equator of PaleoTethys and NeoTethys sensu stricto without taking in account the opening of back-arc basins along the Eurasian margin. To control the spreading rates we used the paleo-isochrons and the geological expression of the main geodynamic features, e.g. subduction of an active ridge, uplift of the active margin, implacement of batholites and increasing of slab pull (Fig. 1). The model implies spreading rates between 8 and 17 cm/yr for PaleoTethys. NeoTethyan values are generally lower, but the spreading rate increases from 7 cm/yr at 260 Ma to 20 cm/yr between 230 and 220 Ma. Although this rate is plausible due to the length of the subducted slab, such a spreading rate is very high. The spreading rate decreases to 6 cm/yr at 220 Ma (Carnian/Norian). This strong deceleration can be related to the Cimmerian orogenic collage [24,25], preceding the onset of subduction of NeoTethys under the recently accreted Cimmerian terranes.

We used the orthographic (orthogonal) projection to create the reconstructions because this projection deforms little the angles and allows a good visual control to choose between alternatives. The disadvantage of this projection is that only one hemisphere can be displayed. To work with a plate fixed as reference appeared as the best solution to easily check the geometrical consistency of a hypothesis. Thus, we worked with

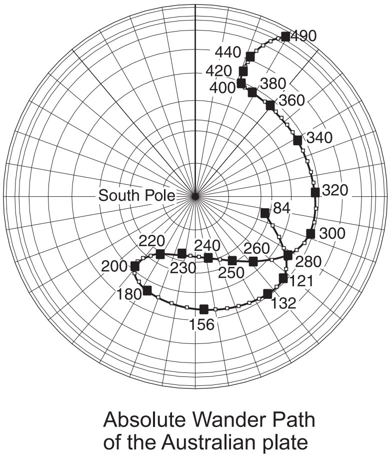

Fig. 2. Absolute polar wander path for the Australian plate related to Europe fixed in its present-day position using Baltica paleopoles.

Europe fixed in its present-day position and move the other plates relative to it.

We used Baltica paleopoles as global reference for paleolatitudes [23]. Baltica poles appeared to be the best constrained for the Paleozoic. Torsvik et al. [26] provide a new dataset for the Mesozoic adjusting the European poles with the North American ones. These datasets were checked against paleomagnetic data available in the literature for all relevant plates (e.g. [11,27]). Poles of continents situated at high latitudes generally come out in a cluster of 15° around the Baltica values.

In order to validate the choice of Baltica poles as reference, we constructed an absolute wander path of Australia, because we had non-consistent paleomagnetic poles locations for this plate in regard to Gondwana, due to its low-latitude situation. The result shows an acceptable absolute path also applicable to Gondwana (Fig. 2).

3. Tethyan realm: some of the main chosen alternatives

We focussed on the Tethyan realm for which numerous continental drifting reconstructions have been presented in the last 30 yr, in order to see if plate tectonic models, including dynamic plate boundaries, could solve some of the main geological issues. Alternative hypotheses were tested and choices were made. In the process, we discovered that dynamic plate boundaries, brought from one reconstruction to the next, provide greater constraints than the continental drift models proposed so far.

One of the main alternatives touches the evolution of PaleoTethys and the concept of the Hun superterrane [2]. This concept regards all Variscan and Avalonian terranes as derived from Gondwana in Paleozoic times, in a context of an active Gondwanan margin. Terranes were detached from Gondwana through the opening of back-arc oceans, following the subduction of the mid-ocean ridge of a former peri-Gondwana ocean – the ProtoTethys. Several stages of successful and aborted opening of back-arc basins can be recognized between late Neoproterozoic and Silurian times, giving birth first to the Rheic ocean, then to the PaleoTethys ocean (Figs. 3 and 4). The composite nature of the Hun superterrane implies the presence and amalgamation with the Cadomian and Serindia terranes (Figs. 3 and 4), and allowed us to find a satisfactory location for the Chinese blocks around Gondwana. A position which, in turn, allows a satisfactory location for these blocks to be determined later on, with a minimum of displacement (Figs. 4 and 5), but still within the limits of present paleomagnetic information on these blocks (e.g. [11]).

Our favored model is to group the Variscan terranes in two main terranes, the European Hunic terranes and the Asiatic Hunic terranes, until their collision with Laurussia and their subsequent lateral transfer and dismemberment along the Eurasian margin [5]. The terrane concept used for the Variscan domain is based on the present close and repeated juxtaposition of metamorphic and non-metamorphic units in the Variscan belt. A general mid-Devonian HP metamorphic event is recognized in most metamorphic units, whereas the non-metamorphic units do not record this event in term of flysch deposits or deformation. On the contrary, their geological evolution is generally towards a more mature passive margin stage characterized by pelagic sedimentation. Flysch deposits started only during the Early or

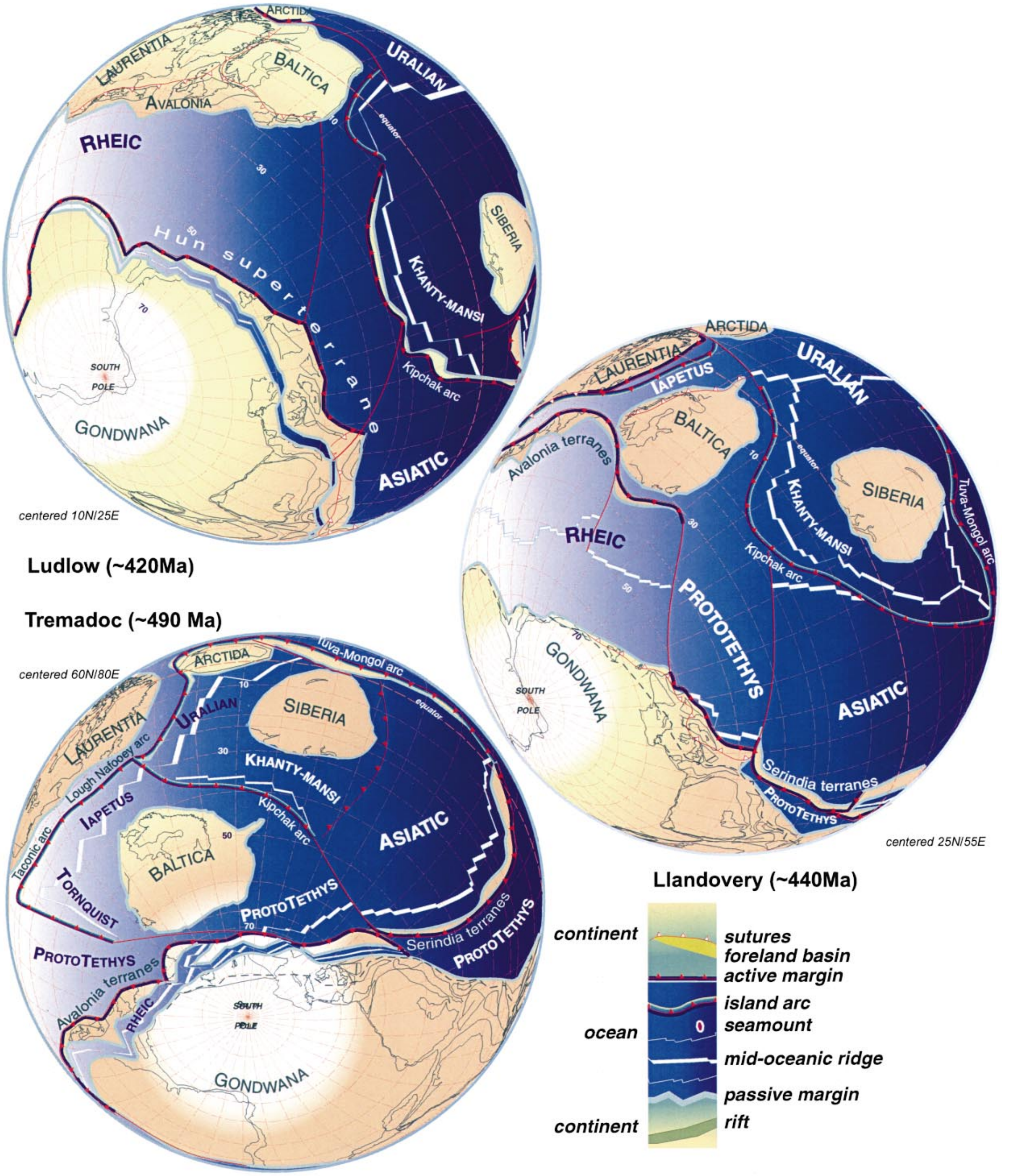

Fig. 3. Explanations in text. Orthographic projection with Europe fixed in its present-day position. Paleopoles of Baltica are used as reference for the paleolatitudes. A complete legend for selected key reconstructions (490 Ma, 360 Ma, 240 Ma, 155 Ma-M25 and 84 Ma-34) are available in the **EPSL Online Background Dataset**[1].

even Late Carboniferous on some blocks. To reconcile these present-day contradictory juxtapositions, we regard the metamorphic units as belonging to the leading edge (i.e. active margin) of a single, ribbon-like terrane in which HP metamorphism can be expected, whereas the other units represent the passive margin side of this terrane. This passive margin, in turn, became an active margin after the docking of the terrane against Laurussia. Recent paleomagnetic data confirm the drifting history of the European Hunic terrane [28–30], as well as the absence of collision between Gondwana and Laurasia before the Carboniferous [31], supporting the concept of a large Paleo-Tethys ocean in Devonian times, leading to a Pangea A collisional assembly of continent and terranes in Late Carboniferous times (Figs. 4 and 5).

The other main alternative concerns the NeoTethys and its prolongation into the east Mediterranean, Ionian Sea domain. Although the geodynamic evolution of NeoTethys is now relatively well constrained, mainly through recent studies of its Oman and Himalayan segment (e.g. [25]), its relationship with the east Mediterranean basin is more debatable. A new interpretation considers the east Mediterranean domain as part of the NeoTethyan oceanic system since the Late Paleozoic [24,25,32].

This is supported by:

1. The geophysical characteristics of the Ionian Sea and east Mediterranean Basin (isostatic equilibrium, seismic velocities, elastic thickness) which exclude an age of the sea floor younger than Early Jurassic.
2. The subsidence pattern of areas such as the Sinai margin, the Tunisian Jeffara rift, Sicily and Apulia sensu stricto, confirming a Late Permian onset of thermal subsidence for the east Mediterranean and Ionian Sea basins and the absence of younger thermal events.
3. The Triassic MORB found in Cyprus (Mamonia complex [33]), that is certainly derived from the east Mediterranean sea floor.
4. Late Permian Hallstatt-type pelagic limestone, similar to that found in Oman, where it commonly rests directly on MORB [34,35] has also been reported from the Sosio complex [36] in Sicily. This Late Permian pelagic macrofauna has affinities with both Oman and Timor and implies a Late Permian direct deep-water connection of the east Mediterranean Basin with the NeoTethys, also confirmed by microfaunal findings in Sicily.

This has also some bearings on the Apulian and Tauric plates dynamics and the opening of the Alpine Tethys:

1. Apulia sensu stricto (southern Italy) belonged to the Cimmerian blocks, and then to Gondwana after the cessation of spreading in the east Mediterranean domain in Late Triassic times. This implies that a Permian fit where the Adriatic plate (northern Italy) is left in its present-day position relative to Apulia is impossible, as it would bring Adria over the Iberic plate [10]. An alternative model [37], giving an even tighter fit than the one we propose for Iberia, placing Adria south of the French Pyrenees, is not supported by geological data from surrounding areas. We prefer a model where Italy is split in two, the Adriatic plate reaching its present-day position, with respect to Apulia, during the Late Cretaceous–Paleogene, in a west-directed extrusion process related to the formation of the western Alps.
2. The Tauric plate (southern Turkey) also became part of Gondwana in Late Triassic times until the east Mediterranean Ocean started to subduct under it in the Miocene. In the meantime, the Tauric plate was located 2000 km west of its present-day location with regard to the Pontides area (northern Turkey). This implies that elements found on both sides of the Izmir–Ankara suture zone had a quite different geological history before their Paleogene juxtaposition.
3. The opening of the Alpine Tethys is necessarily the eastward continuation of the central Atlan-

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[1] http://www.elsevier.nl/locate/epsl, mirror site http://www.elsevier.com/locate/epsl

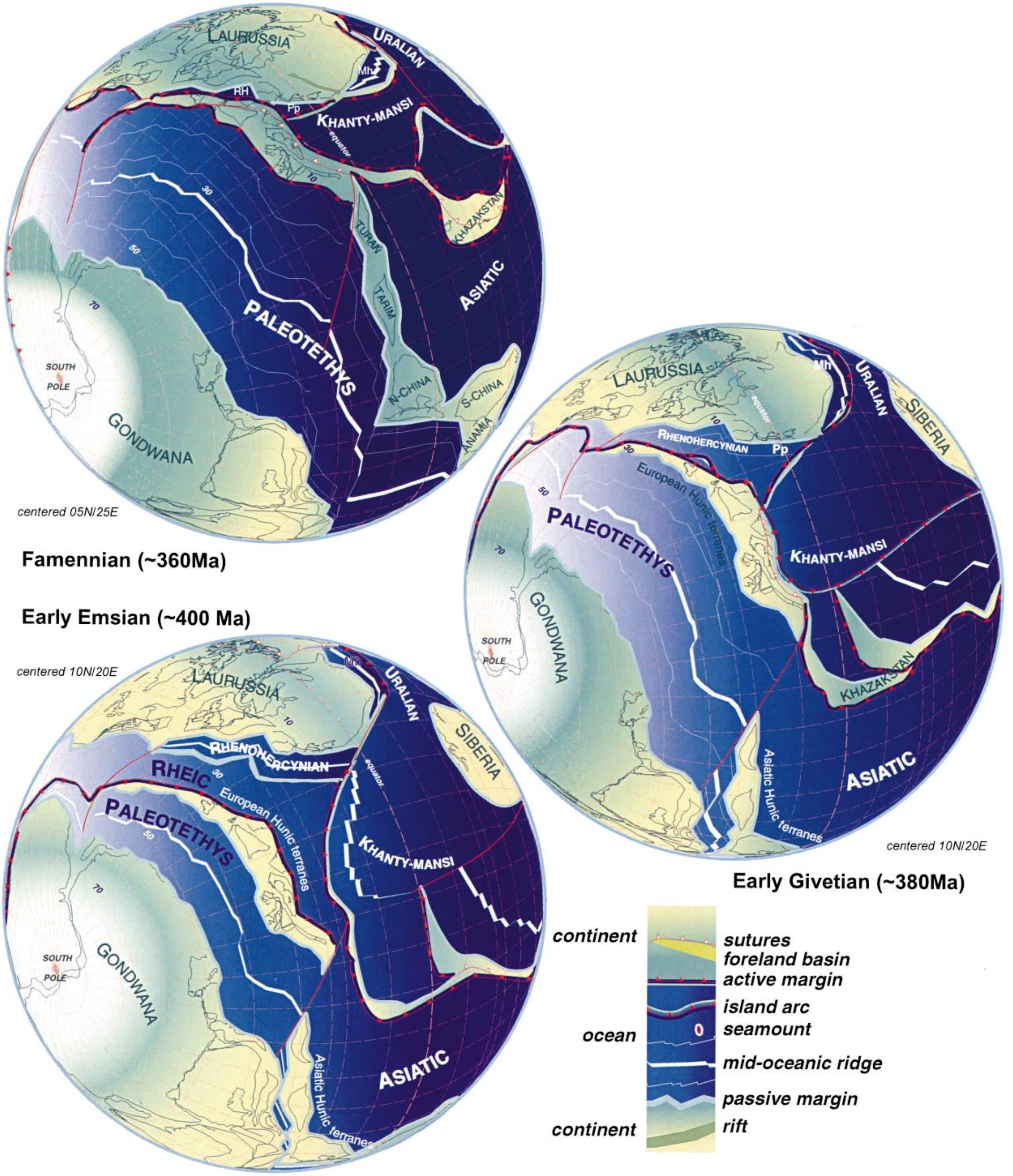


Fig. 4. See legend of Fig. 3.

tic, as no other oceanic domains opened between Africa and Europe during the Jurassic. This allows its width and average spreading rate to be determined with precision using magnetic anomalies in the Atlantic.

4. Dynamics of the Tethyan realm

Rheic ocean opening, separating Avalonia from Gondwana (Fig. 3), is constrained by subsidence analysis [38] as well as paleomagnetism (e.g. [39]), and its docking to Laurentia by deformation [40] and post-collisional deposits [41]. The extension eastward of Avalonia to Moesia and the Istanbul–Zonguldak terranes is supported by faunal affinities [42]. The Rheic ocean should have had, at its early stages, a lateral continuation in the former eastern prolongation of peri-Gondwanan microcontinents (e.g. Cadomia, Intra-Alpine Terrane). Subduction of oceanic ridge (ProtoTethys) triggered the break-off of Avalonia, whereas in the eastern prolongation, the presence of the ridge triggered the amalgamation of volcanic arcs and continental ribbons with Gondwana (Ordovician orogenic event [2]).

Renewed Gondwana-directed subduction led to the opening of the PaleoTethys (Fig. 3) associated with the detachment of the ribbon-like Hun superterrane along the northern margin of Gondwana. Diachronous subsidence patterns of Tethyan margins since the early Paleozoic [6] provide constraints for PaleoTethys opening during the Late Ordovician and the Silurian and the splitting of the Hun terranes in two parts, the European and Asiatic. The latter was affected by terranes amalgamation in Ordovician–Silurian times (Serindia terranes comprising parts of north China and Tarim, e.g. [43,44]).

The Variscan orogeny in Europe was not a continent–continent collision but a major accretion of peri-Gondwanan terranes, which took place mainly in Devonian times (Fig. 4). The main Variscan metamorphic events are then regarded as resulting from this collision, as well as from the subduction of the PaleoTethys mid-oceanic ridge in the Early Carboniferous. This led to the formation of the Variscan cordillera before the final collision of Gondwana with Laurasia in Late Carboniferous times.

The evolution of the Kipchak arc is taken from [45] and of the Asiatic ocean and Asiatic Hunic terranes from [46,47].

Gondwana collided with Laurasia in Late Carboniferous time, the event being well recorded by deformation of surrounding foreland basins, but the final closure of PaleoTethys in the Tethyan domain took place during the Cimmerian (Triassic to Jurassic) orogenic cycle (Fig. 5). The northward subduction of PaleoTethys is responsible for the widespread Late Carboniferous calc-alkaline intrusions and volcanism found in the Variscan Alpine–Mediterranean domain. Slab rollback also produced a general collapse of the pre-existing Variscan cordillera and large-scale lateral displacement of terranes took place, confirmed by paleomagnetic data [48]. A rift opened between Africa and East Gondwana in the Late Carboniferous, joining southward to the Karroo system. This rift was a future aborted branch of NeoTethys whereas another rift appeared in the east Mediterranean area (e.g. Jeffara basin of Tunisia).

NeoTethys opened from the Late Carboniferous to late Early Permian starting east of Australia and progressing to the east Mediterranean area (Fig. 6), as recorded from subsidence patterns of its southern margin [25]. This opening was associated with the drifting of the Cimmerian superterrane and the final closure of PaleoTethys in Middle Triassic times. The opening of NeoTethys and detachment of the Cimmerian blocks in Permian times was realized through increasing slab-pull forces in the PaleoTethys domain following the subduction of its mid-oceanic ridge below the Eurasian margin (e.g. accretion of Permian MORB in Iran [49]). At the same time, slab rollback of the PaleoTethys opened numerous back-arc basins along the Eurasian margin and resulted in the final collapse of the Variscan cordillera [7].

Between 240 and 220 Ma northward subduction of the PaleoTethys triggered the opening of back-arc oceans along the Eurasian margin from Austria to China (Fig. 7). The fate of these Permo-Triassic marginal basins is quite different from area to area. Some closed during the Cim-

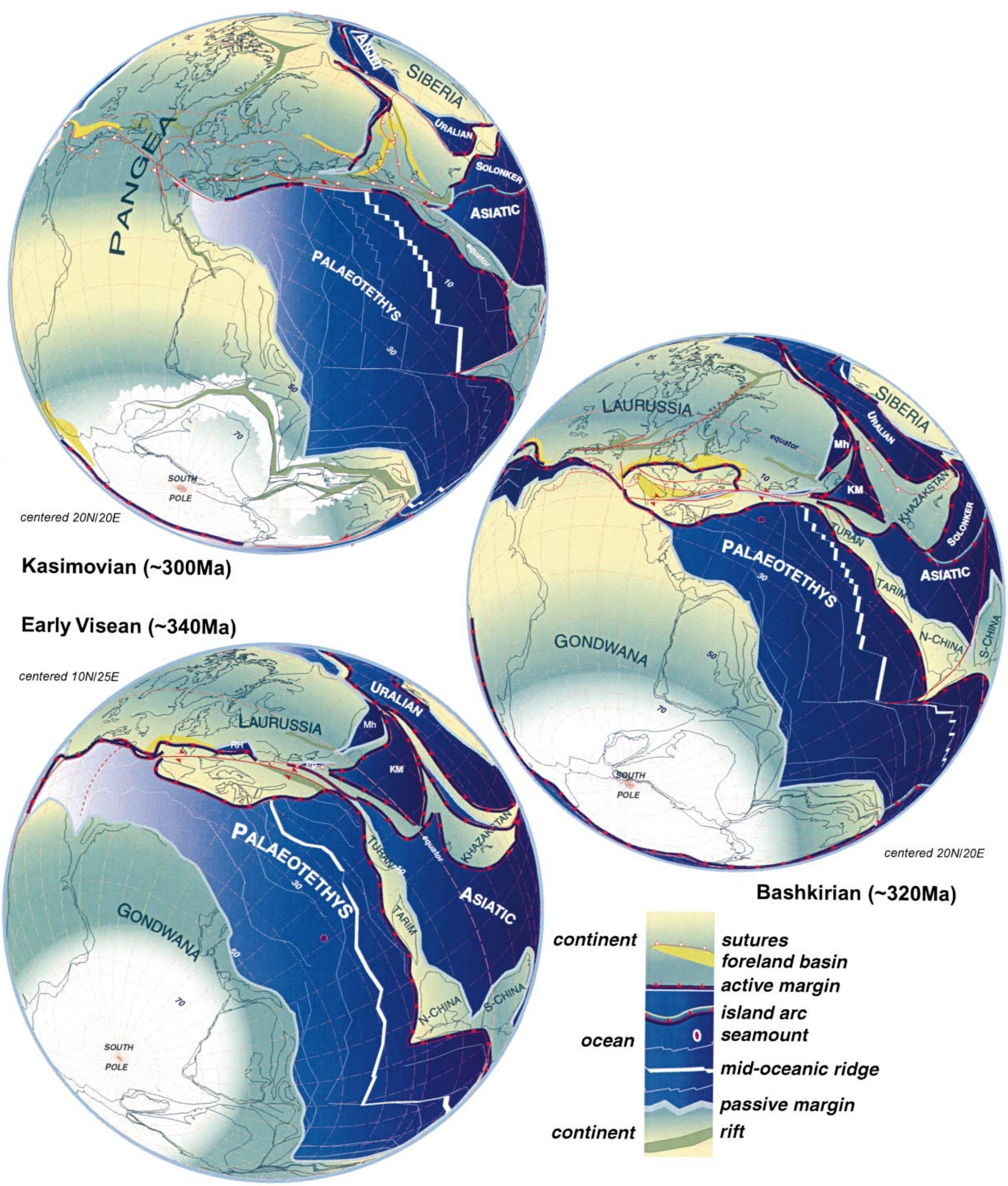
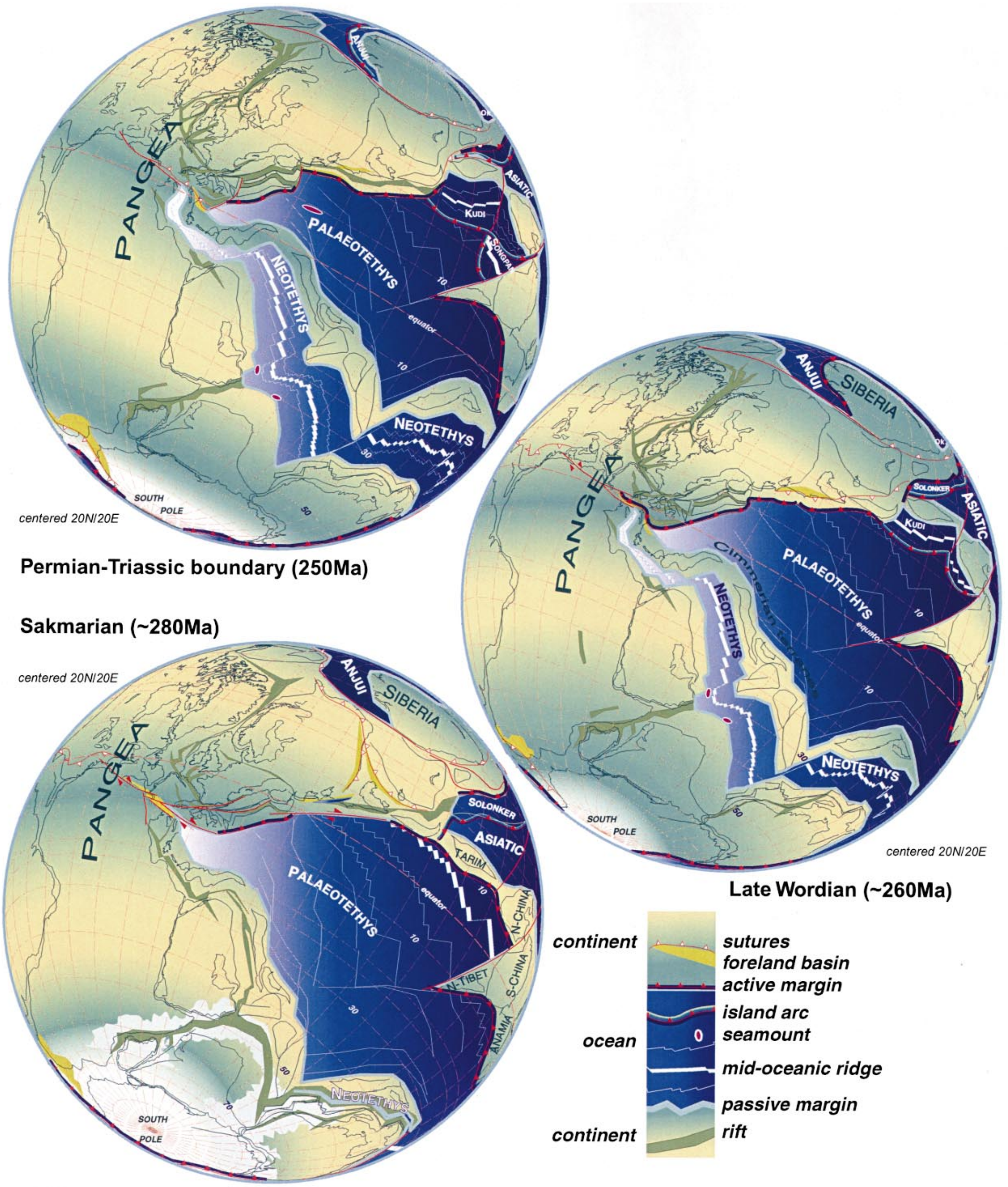


Fig. 5. See legend of Fig. 3.


Permian-Triassic boundary (250Ma)

Sakmarian (~280Ma)

Late Wordian (~260Ma)

Fig. 6. See legend of Fig. 3.

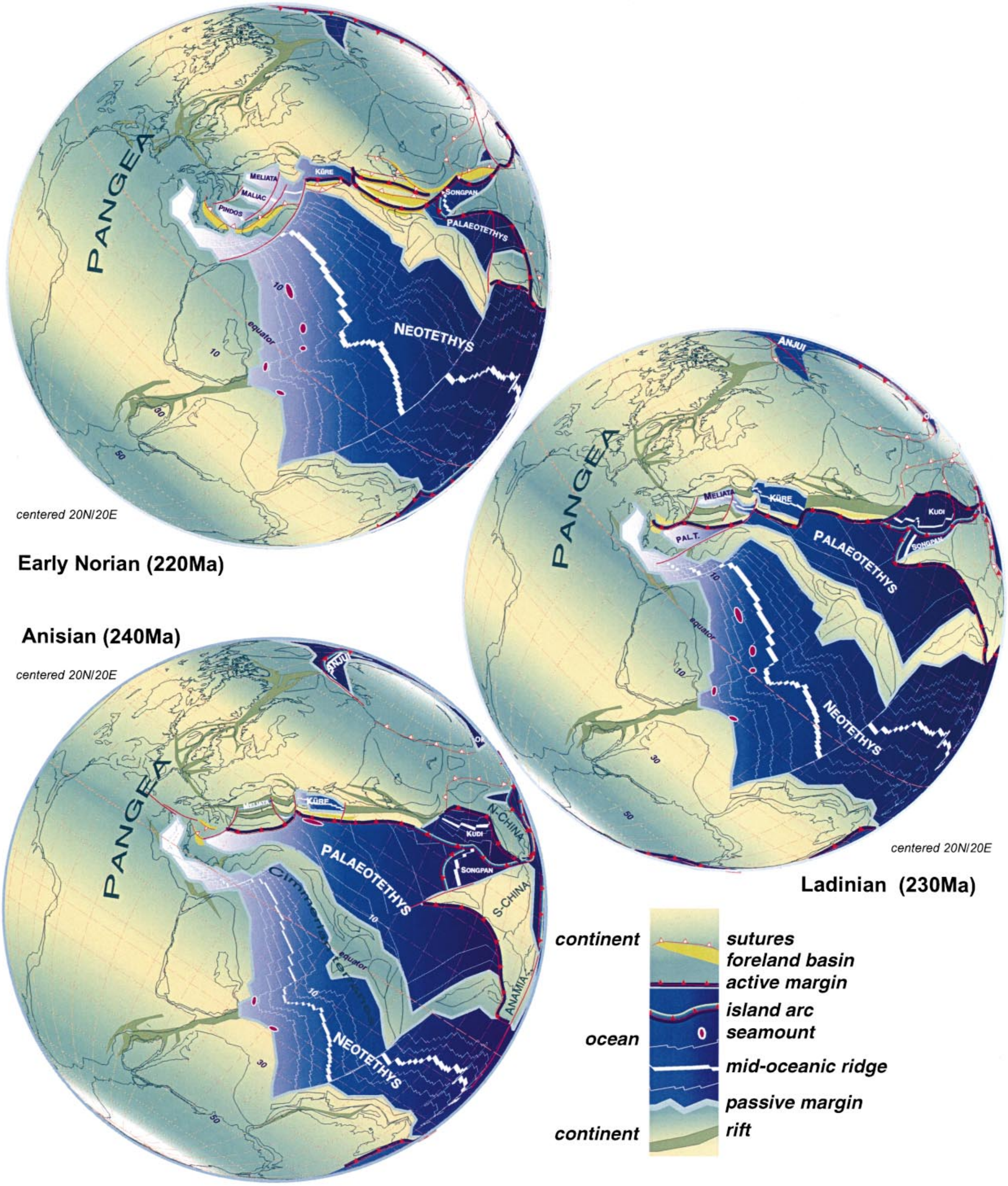


Fig. 7. See legend of Fig. 3.

merian collisional events (Karakaya, Agh-Darband, Küre), others (Meliata–Maliac–Pindos) remained open and their delayed subduction induced the opening of younger back-arc oceans (Vardar, Black Sea).

The evolution of the Tibetan marginal oceans is derived from the work of [15]. Concomitant Late Permian–Triassic opening of the marginal Meliata–Maliac–Pindos oceans (within the Eurasian margin) and NeoTethys (within the northern margin of Gondwana) accelerated the closure of PaleoTethys in the Dinaro–Hellenide region. Late Permian to Middle Triassic mélanges and fore-arc basin remnants found in the Dinarides, Hellenides and Taurides, indicate a final closure of this Paleozoic ocean at that time (Eocimmerian event). In northern Turkey and Iran, the collision of the Cimmerian terranes with the Eurasian margin was more complex due to the presence of oceanic plateaus and Marianna-type back-arc basins between the two domains (e.g.[50]).

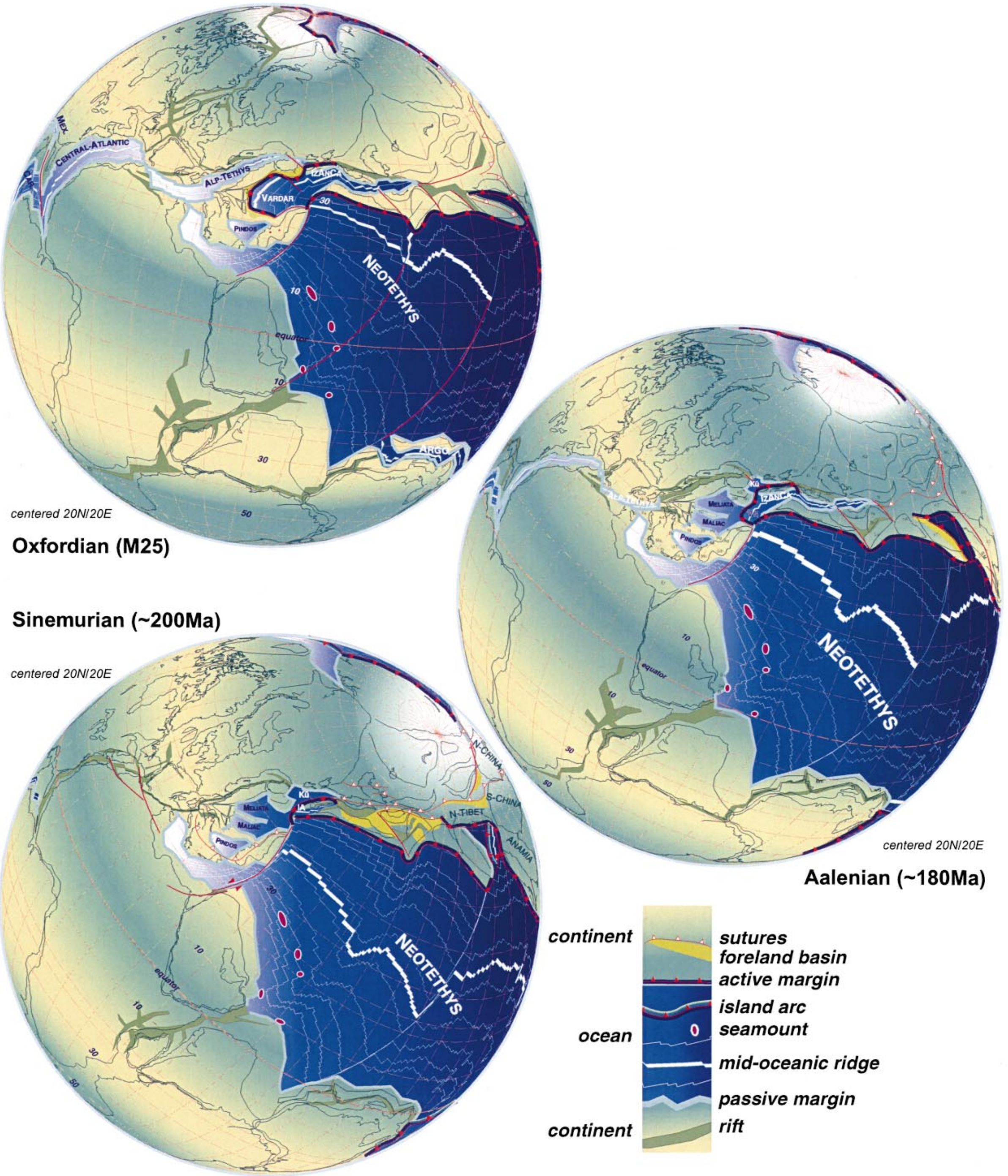
NeoTethys subduction (Fig. 8) recorded through the onset of magmatism along its northern Iranian margin, created a strong slab pull, which contributed to the break-up of Pangea and the opening of the central Atlantic Ocean in Early Jurassic time. This break-up extended eastward into the Alpine Tethys trying to link with new Eurasian back-arc oceans like the Izmir–Ankara and south Caspian Ocean. The diachronous subduction of the NeoTethys spreading ridge is held responsible for major changes in the Late Jurassic to Early Cretaceous plate tectonics and the final break-up of Gondwana, as well as the detachment of the Argo-Burma terrane off Australia, and the detachment of the Indian plate. If the collision of the Argo-Burma terrane with Malaysia can be placed before the Santonian, there are still some doubts about the timing of its separation from Australia. We adopted here a solution which does not fit rheological constraints but follows general views on a Late Jurassic drifting of Argoland. The problem is the necessity to develop a far too long transform to link up the new Argo mid-ocean ridge with the still-existing NeoTethys ridge north of the Indian plate. An Early Cretaceous drifting of Argoland together with India would be far less problematic.

Between the Valanginian and the Santonian, the subduction of the NeoTethyan mid-oceanic ridge south of Iran together with the subduction of the remnant Vardar–Izmir–Ankara oceans triggered a strong transtensional stress partly responsible for the break-up of Gondwana and the opening of a north–south oceanic realm from the Mozambique area up to the NeoTethys (Fig. 9). Changes in the subduction style in the Paleo-Pacific around Australia and Antarctica is certainly also responsible for the break-up of eastern and western Gondwana.

The position of the Indian plate with respect to Africa is defined by the oceanic isochrons in the Somalia–Mozambique basins from Late Jurassic to Late Cretaceous. The rotation of east Gondwana (comprising the future Indian plate) with respect to Africa was responsible for intra-oceanic subduction within the NeoTethys along a paleo-transform and the onset of spreading of the Semail Marianna-type back-arc (Fig. 9). The direction of the Semail intra-oceanic subduction is controlled by the age of the oceanic crust on each side of the transform fault, the older one subducting under the younger one.

The complex obduction/collision of the Vardar plate with the surrounding passive margins, followed the Late Triassic–Early Jurassic intra-oceanic subduction of the Meliata–Maliac oceans, related to the southward subduction of the Küre Ocean. The north-east-directed subduction of the combined remnant Vardar and Izmir–Ankara oceans, generated the collision of an intra-oceanic arc with the Austro–Carpathian and Balkanide areas in late Early Cretaceous times. All these events are well recorded through formation of accretionary mélanges, fore-deep basins, deformation, magmatism and metamorphism. At about the same time, the Iberic plate became part of the African plate and drifted eastward, its eastern promontory, the Briançonnais, becoming implicated in the Alpine orogenic system.

The Alpides orogenic system sensu stricto (Alps, Carpathian and Balkans) is directly related to the evolution of the Maliac–Maliata/Vardar evolution and the fact that the subduction of the Maliac–Meliata slab was directed southward. The orogenic prism moved from the Austro-Carpathi-



Oxfordian (M25)

centered 20N/20E

Sinemurian (~200Ma)

centered 20N/20E

Aalenian (~180Ma)

centered 20N/20E

Fig. 8. See legend of Fig. 3.

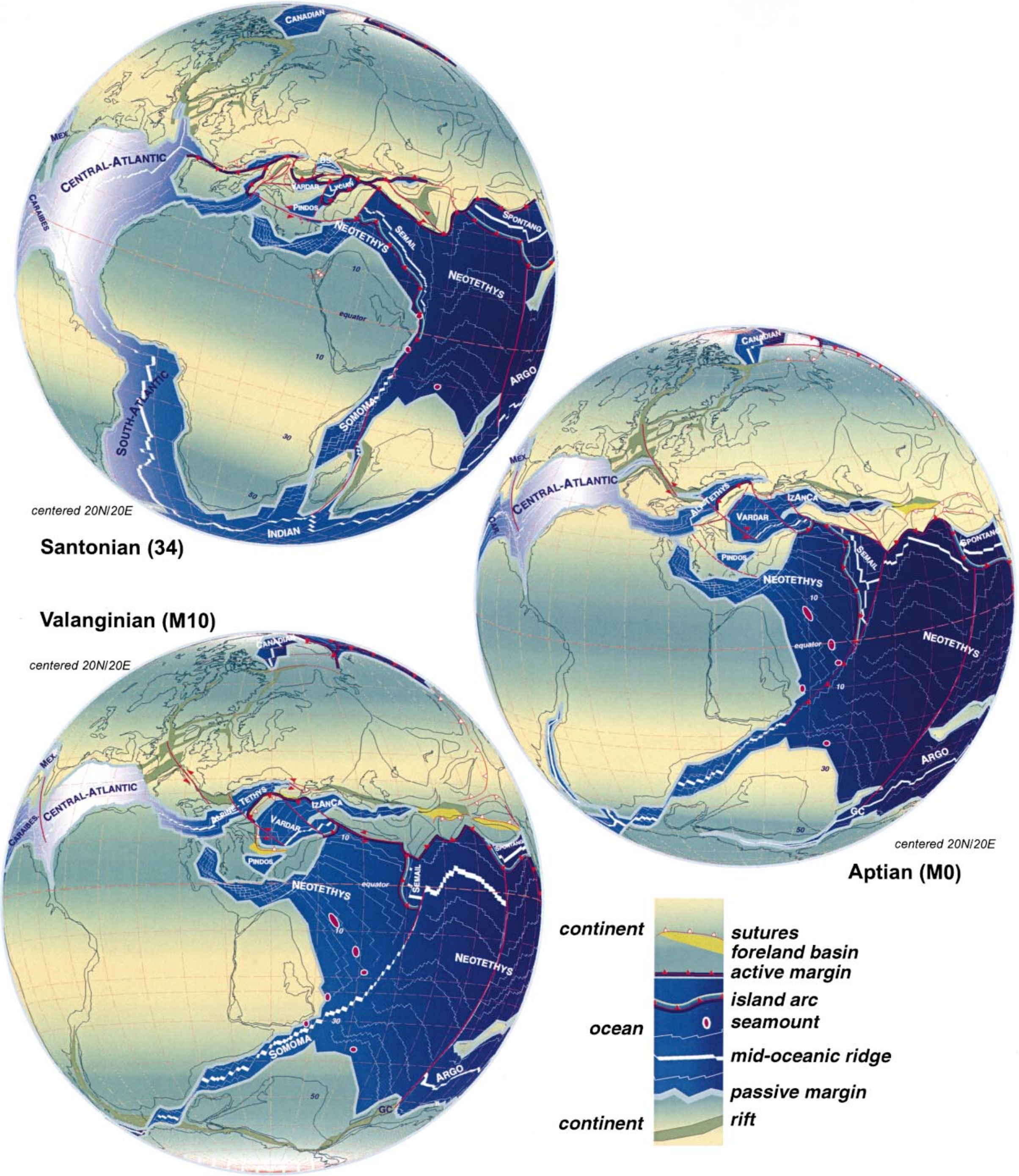


Fig. 9. See legend of Fig. 3.

an area to the Alpine Tethys and extended westward to the western Alps in Late Cretaceous time.

In contrast, the Tethysides system is related to a north-directed subduction of the NeoTethys and associated back-arc basins (e.g. Semail and Spongtang), the large NeoTethys slab was entirely subducted, leaving hardly any ophiolitic traces; all NeoTethyan ophiolites being derived from Cretaceous back-arc basins

5. Conclusions

The plate tectonic model presented here with its dynamic plate boundaries and synthetic paleo-isochrons offers new information on oceans widths, on the timing of major tectonic events and on the processes responsible for their existence and disappearance. Geodynamic principles provide stable constraints when geological information is sparse.

The PaleoTethys opened as a back-arc basin due to the slab rollback of the Rheic and Asiatic oceans, resulting in the rifting of a ribbon of superterranes from the Gondwana margin. The Variscan orogeny in Europe is not a continent/continent collision but the accretion of these terranes. The Late Carboniferous–Early Permian calc-alkaline intrusions and volcanism found in the Variscan Alpine–Mediterranean domain is related to the northward subduction of the PaleoTethys. Slab rollback of the latter produced the collapse of the pre-existing Variscan cordillera and led to the opening of NeoTethys.

NeoTethys replaced PaleoTethys even when Pangea was stable during Permian and Triassic times, pointing out the key role played by slab-pull forces on ocean evolution and consequently on plate distribution.

The major changes in the Late Jurassic to Early Cretaceous plate tectonics can be associated with the diachronous subduction of the NeoTethys active ridge along the Eurasian northern margin. The slab pull forced opened the Argo Abyssal Plain and detached the Argo-Burma terrane from Australia, possibly together with the Indian plate.

The subsequent Valanginian rotation of east Gondwana relative to Africa induced an intra-oceanic subduction within the NeoTethys south of Iran and the onset of spreading of the Semail Marianna-type back-arc ocean.

The history of the western Tethys is complex; cannibalism of three generations of back-arcs (Maliac, Maliata, Vardar) took place and resulted in the Alpides orogenic system. Such a great complexity in a small region tests the limits of the reconstruction process.

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