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Tethys and Apulia (Adria), 100 years of reconstructions

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Research article

Tribute to Jean Dercourt

Tethys and Apulia (Adria), 100 years of reconstructions

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Abstract. The lost Tethys Ocean was the favorite topic of Jean Dercourt's research. The Tethys project and his 1986 paper displaying detailed reconstructions in 9 plates from the Triassic to the Present was the beginning of a series of projects organized around large consortia associating scientists from the academic and industrial worlds. The most recent evolutions of these reconstructions show unprecedented images of the evolving geology, including tectonics and paleoenvironments, through time of this complex puzzle. Central to Tethyan tectonics, Apulia, or Adria, has been drawn with different geometries and dimensions from the first concepts by Emile Argand, Kenneth Hsü or John Dewey, to the recent reconstructions by Douwe van Hinsbergen or Paul Angrand. We review here the main reconstructions published since 1924 and the evolution of concepts and methods. We finally discuss the importance of this type of syntheses for understanding large-scale geodynamic processes.

Keywords. Tethys, Mediterranean, Apulia, Adria, Reconstructions.
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1. Introduction

The past Tethys Ocean was Jean Dercourt's favorite playground. One of his most memorable achievements is the detailed reconstructions he first published with a large group of colleagues in 1986 [Dercourt et al., 1986]. Except for ophiolitic nappes in different sutures zones, this almost entirely lost ocean is only locally preserved in the Eastern Mediterranean, south of Crete, subducting below the Aegean region in the Hellenic trench and in the Gulf of Oman, between Arabia and the Makran subduction zone. Most of it has now been swallowed in the subduction zones fringing the southern margin of Eurasia since the Late Cretaceous. This long period of convergence has seen the formation of major mountain belts, from the Caribbean to Indonesia, some of them still underway such as the Himalayas. Others have collapsed in back-arc regions, as shown by the Hellenides in the Aegean domain.

The younger Mediterranean Sea is the heir of the Tethys and its formation was entirely driven by the behavior of subducting lithospheric slabs in the asthenosphere. In the history of the Mediterranean, it is convenient to distinguish [Jolivet et al., 2021a,b] (1) a Tethyan period, before 30–35 Ma, (2) a Mediterranean period (from 30–35 to 8 Ma) and a Late Mediterranean period (from 8 Ma to the Present). The Tethyan period has seen the opening of the Tethys Ocean and then its subduction underneath Eurasia. The main engine is the large-scale convection driving plate tectonics with slabs and mantle plumes. The Mediterranean period starts because of a complete change of driving mechanism with the prominent role of slab retreat, leading to the opening of back-arc basins (Aegean Sea, Pannonian Basin, Tyrrhenian Sea, Liguro-Provençal Basin, Alboran Sea) at fast rates and the collapse of the mountain belts formed during the Tethyan period (Hellenides, Taurides, Pyrenees). The Late Mediterranean period sees the progressive cessation of back-arc opening and a return to compressional conditions from the westernmost Mediterranean to the Central Mediterranean. Understanding the dynamics (forces) of this complex puzzle first requires a precise description of the succession of tectonic events in the entire Tethyan realm, with their kinematics and thermal regimes, a goal achieved through reconstructions.

The name of the Tethys Ocean was given by Suess [1883, 1901, 1909] to the ancient deep basin sandwiched between Laurasia and Gondwana, after Neumayr [1885] first proposed its existence for the Jurassic period. Suess [1883, 1901, 1909] further proposed that the observed mountain belts were formed by the contraction of that former ocean, a remarkable intuition at that time. He further understood that the present Mediterranean is an offspring of the Tethys. We have since understood that the ophiolitic belts running from the Caribbean to Indonesia are the remnants of this lost ocean and it has been a challenge to reconstruct its evolution through time since Argand [1924]. This paper presents the various attempts to describe the tectonic evolution of the Tethys since the early work of Argand who had already understood some first order features, among which the major role played by what is now called Apulia, or Adria, in the deformation of the Mediterranean region. The presentation of these successive attempts, until the most recent ones, shows some major steps corresponding to conceptual breakthroughs, such as the discovery of plate tectonics. The core of the paper is focused on the notion of Apulia, a micro-continent drifted away from Africa and then shortened to form a large part of the Alps, the Dinarides and the Hellenides. Apulia, or Adria, is represented as an independent continental block carried by an independent plate during the Mesozoic in most reconstructions. The Apulian continent would have been drifted away from African during the early Mesozoic. However, several alternative reconstructions [Argand, 1924, Channell and Horvath, 1976, Angrand and Mouthereau, 2021, Mouthereau et al., 2021, Channell et al., 2022] show it still attached to Africa and the existence of an intervening oceanic tract, known as Mesogea, is thus still debated. The reasons for this disagreement mostly stem from the interpretation of the nature of the lithosphere flooring the deep basins of the Ionian Sea and the Eastern Mediterranean Sea, whether oceanic or continental, the continuity of platform deposits from Africa to Apulia and paleomagnetic data that tend to suggest that Apulia had always traveled exactly as Africa during the Mesozoic and the Cenozoic. We come back to this debate and finally discuss the consequences of these reconstructions for the understanding of geodynamic processes.

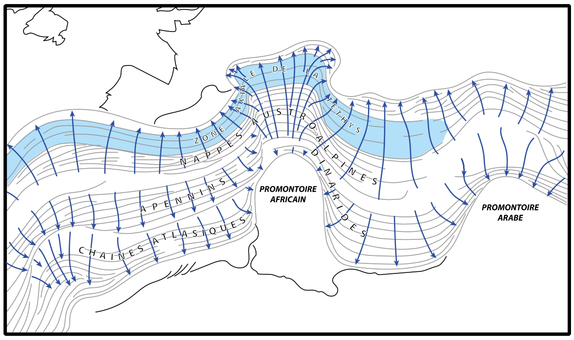

Figure 1. The "promotoire africain" and "promontoire arabe" and direction of crustal flow ("filets d'écoulement") during Tethys closure in Emile Argand's conceptions. Redrawn from Argand [1924].

2. Emile Argand and the "Promontoire Africain"

In *La Tectonique de l'Asie* [Argand, 1924], Emile Argand inferred the direction of a crustal flow ("*filets d'écoulement*") from the orientation of folds in mountain belts (Figure 1) introducing a dynamic aspect in continental tectonic studies. He saw the formation of the Mediterranean arcs as the result of such a flow, primarily controlled by the irregular shape of the Gondwanan margin ("*vieux bord gondwanien*") and proposed the existence of two promontories impinging the southern margin of Eurasia during the shortening of the Tethys Ocean, the so-called African and Arabian promontories.

This vision is of course outdated nowadays, but it already contained a major ingredient i.e., the complex geometry of the African margin playing a major role in controlling the dynamics of slab retreat in the Eastern and Western Mediterranean, forming the Calabrian and Hellenic arcs. It also contained the germs of the notion of continental blocks between Eurasia and Gondwana, named today Apulia (or Adria) and Arabia. The separation of these large blocks, we would say “plates” nowadays, away from Gondwana and their evolution during the lifetime of the Tethys until its final closure is still a major scientific question we will discuss at the end of this contribution. Argand [1924] went much further into the description of the Mediterranean region and his reconstructions already showed (Figure 2) the rotation of Iberia opening the Bay of Biscay and the rotation of a rigid block carrying Sardinia and Corsica and the associated formation of extensional basins since the Oligocene. He had thus seen the large picture, the Tethys as an ancestor of the Mediterranean, as first proposed by Suess [1883], and the details of the Mediterranean dynamics without any idea at that time of the importance of subduction dynamics.

3. The first reconstructions incorporating the plate tectonic concepts, the first notion of an Apulian microcontinent

As soon as 1971, a short time after the publication of the new global tectonics [Wilson, 1965, McKenzie and Parker, 1967, Le Pichon, 1968, Morgan, 1968], Hsü [1971] proposed to revised Argand’s scheme (Figure 3) and placed his reasoning in the new framework, although he did not incorporate any precise kinematics.

He suggested the existence of several oceanic basins, still named *geosynclines* in his paper, separating Gondwana from Eurasia, surrounding a so-called *Greco-Italian microcontinent*, the first graphical mention of what will then be named *Apulia* or more recently *Adria*. This is a major shift in Alpine studies with the first implication of the new paradigm. It must be noted, however, that Dewey and Bird [1970], in their seminal paper about mountain belts and the new global tectonics, explicitly already mention the possibility that the complexity of the Mediterranean region is due to the amalgamation of microcontinents with the southern margin of Eurasia during collision.

One important consequence of plate tectonics is also that all the pre-Atlantic kinematic reconstructions of the positions of the large plates leave a vast open space between Africa and Eurasia in the Mesozoic [Bullard et al., 1965, Le Pichon, 1968], a space where the Tethys Ocean had once developed during the Mesozoic (Neo-Tethys). The same year, Smith

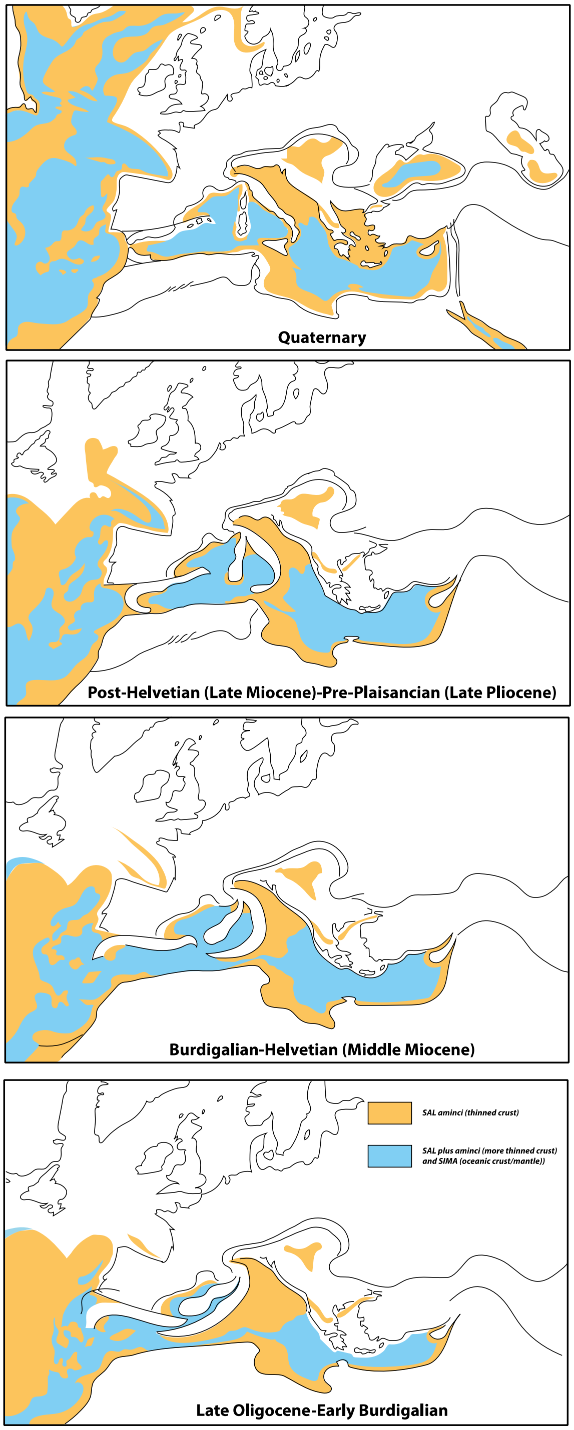

Figure 2. Evolution of the Mediterranean region as viewed by Argand with the rotation of Iberia and Corsica/Sardinia. Redrawn from Argand [1924].

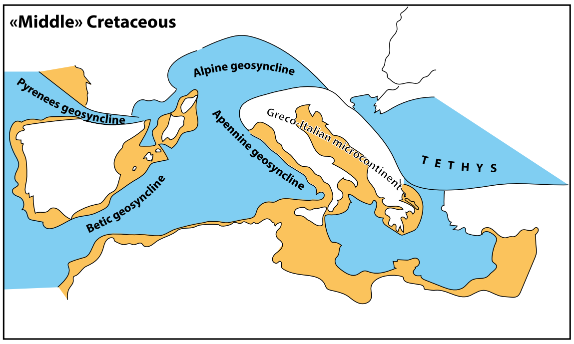

Figure 3. The first reconstruction of the Mediterranean region after the discovery of plate tectonics. The Greco-Italian microcontinent prefigurates Apulia/Adria. Redrawn from Hsü [1971].

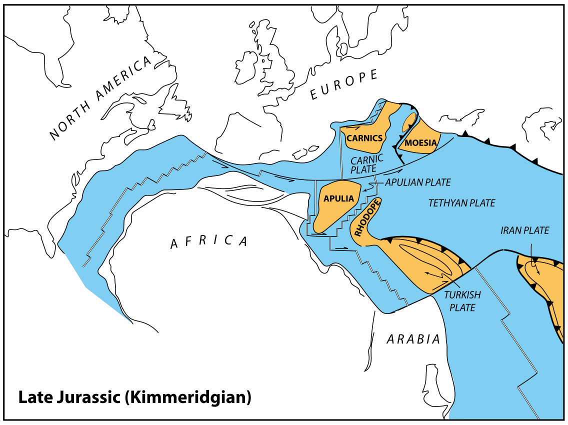

Figure 4. The first reconstruction of the Tethys involving plate tectonics concepts and a kinematics based on oceanic magnetic anomalies. The first explicit mention of an Apulian microcontinent in reconstructions. Redrawn from Dewey et al. [1973].

[1971] published a first attempt of rigorously reconstructing the geometry of the Mediterranean region using the kinematic parameters imposed by the Atlantic magnetic anomalies. This paper does not however show any detail of the temporal evolution of the Tethyan domain between the initial situation and the present-day. A major step is made with the publication of detailed reconstructions by Dewey et al. [1973] (Figure 4), also based on the Atlantic magnetic anomalies with eight stages, from the Late Triassic to the Present, and considering the tectonic evolution within the Tethyan domain.

Figure 4 shows the Late Jurassic (Kimmeridgian) stage of their reconstructions. The intervening domain between Europe and Africa is detailed with several continental blocks and several small oceanic domains. This is the first clear mention of an Apulian block in reconstructions. Apulia represents then the outer zones of the Dinarides, the Hellenides and the Apennines, a carbonate platform deposited on a continental crust. Other independent blocks such as the Carnic block or the Rhodope are shown. This paper is the first modern attempt of reconstructing the Tethys.

The shape and internal geometry of the Apulian or Adriatic block have been drawn very differently through time, as will be obvious in the following. One important constraint on its kinematics comes from paleomagnetic studies. In an important paper, Channell and Horvath [1976] attach the "Adriatic plate" to Africa (Figure 5), the main reason being the absence of any significant difference in its apparent polar wander path from that of Africa, as later studies will confirm and precise [Westphal et al., 1986]. The geometry they thus propose is quite similar to Argand's one with a promontory sticking out from the main body of the African plate. Through much of the Mesozoic Adria has followed a path that did not involve any latitudinal drift away from Africa.

In the same period, Biju-Duval et al. [1977a,b] (Figure 6) show a large Apulia, englobing all the microcontinents shown in older reconstructions, even Channell and Horvath [1976], in a single plate separated from Africa by a narrow oceanic domain, called Mesogea, which remnants are found today in the Eastern Mediterranean. The width of this domain is probably too small to be seen in paleomagnetic data. This reconstruction is constrained by the Africa/Eurasia/North America kinematics deduced from the Atlantic magnetic anomalies. It also involves a palinspastic restoration of the contractional deformation seen in mountain belts, for the first time [Biju-Duval et al., 1977a,b]. This study announces the next step in reconstructing the Tethys, best exemplified by Dercourt et al. [1986].

The new geometrical and kinematic concepts brought to light by the new global tectonics was indeed the starting point for many studies around the world. One important example is the new vision of

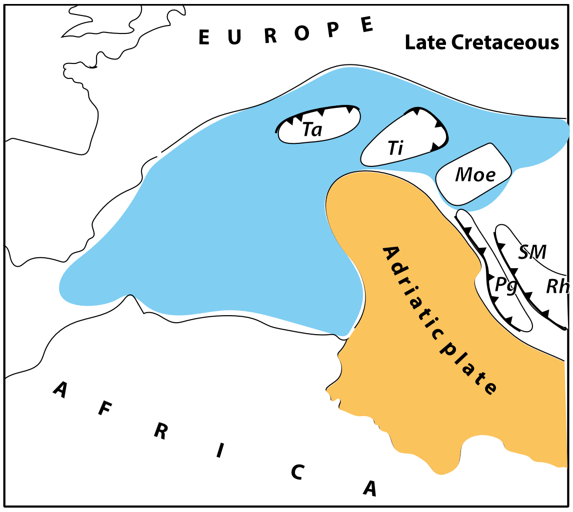

Figure 5. Paleomagnetic data suggest that Adria was always attached to Africa. Redrawn from Channell and Horvath [1976].

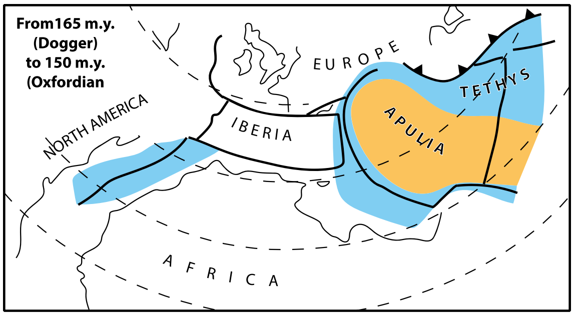

Figure 6. Apulia as a single plate separated from Africa by an oceanic corridor named Mesogea. The reconstruction takes into account oceanic magnetic anomalies and shortening of mountain belts. Redrawn from Biju-Duval et al. [1977a,b].

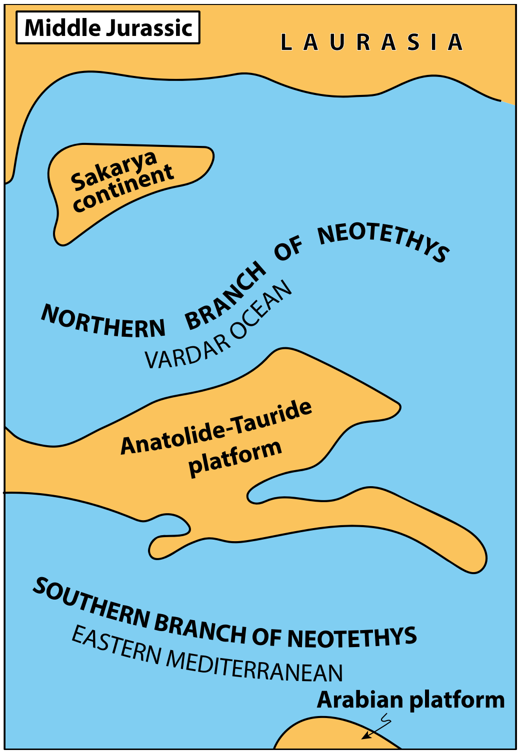

Figure 7. Plate tectonics concepts explain the geological history of Turkey with two continental blocks between Laurasia and the Arabian platform. Redrawn after Şengör and Yilmaz [1981].

the tectonic history of Turkey proposed by Şengör and Yilmaz [1981] still serving as the basis of all tectonic studies in this region nowadays (Figure 7). It shows three branches of the NeoTethys and two continental blocks, the Sakarya continent in the north and the Anatolide–Tauride platform in the south, each of the intervening oceanic tracts being represented by ophiolite nappes. The southern branch of the NeoTethys is now represented by the Eastern Mediterranean subducting underneath Crete, similar to the Mesogea of Biju-Duval et al. [1977a,b]. The Vardar Ocean is an extension of the large ophiolitic nappes of continental Greece.

4. Toward modern reconstructions, Tethys project

A major step forward was made through the Tethys Project, a collaborative research venture between French and Russian scientists [Dercourt et al., 1986, Ricou et al., 1986, Dercourt et al., 1993] (Figure 8). We shall not discuss here the details of these reconstructions but only point out a few lines that make it a milestone in tectonic reconstructions in general. The project was achieved through an association between geologists who had a wide experience in the

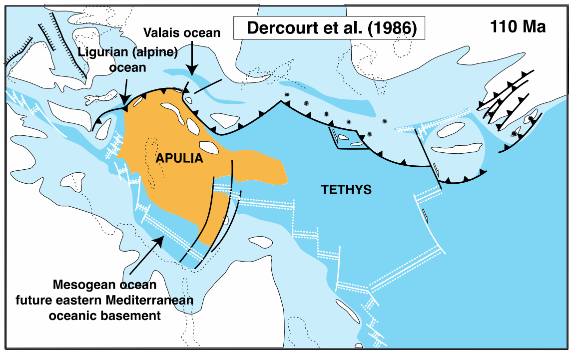

Figure 8. The Tethys Ocean reconstructed in the Tethys project. Apulia is separated from Africa by the Mesogea. Apulia rotates CCW by 30°. Kinematic framework after Savostin et al. [1986]. This reconstruction also shows paleoenvironments (not shown). Redrawn and simplified after Dercourt et al. [1986], paleoenvironments omitted.

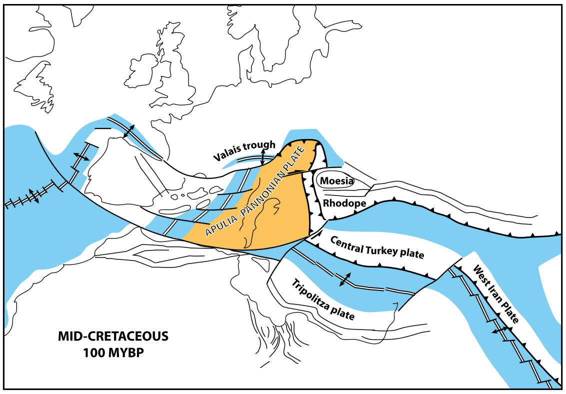

Figure 9. Tethys reconstructed based the kinematic model of Scotese et al. [1988]. Redrawn after Gealey [1988].

geology of the Tethyan realm both onshore and offshore. The reconstructions were based upon a coherent kinematic framework [Savostin et al., 1986] based on the magnetic anomalies in the oceans and on palinspastic restoration of mountain belts and basins, as in Biju-Duval et al. [1977a]. The details of the geological data are published in separate papers [Ricou et al., 1986, Zonenshain and Le Pichon, 1986]. One of the novelties is the interpretation of the Black Sea and the Southern Caspian Sea as back-arc basins formed above the subduction of the main Tethys Ocean underneath the southern margin of Eurasia [Zonenshain and Le Pichon, 1986]. The outcome is a series of 9 maps from 190 Ma (Pliensbachian) to the present, showing continental and oceanic domains, as well as paleo-coastlines and types of sedimentation, thus a first attempt to show paleoenvironmental changes through time.

In Dercourt et al. [1986] Apulia rotates CCW with respect to Africa by 30° from 130 to 80 Ma and the Mesogea does not communicate eastward with the large Tethys Ocean. Oceanic accretion dates back to the Cretaceous in these reconstructions, a point that will be actively debated in later years [Stampfli et al., 1998a,b, Stampfli, 2000]. The reconstructions encompass the entire Tethyan realm from the Caribbean to Indonesia. The position of plate boundaries within the oceanic domains are tentatively shown and kept consistent with the contemporaneous kinematics throughout. This set of maps thus contains many of the recent improvements in paleotectonic reconstructions although it was not made with the convenient softwares available today. The Tethys project was followed by several others involving large international consortia of academics and oil companies, Peri-Tethys, MEBE (Middle-East Basins Evolution), and DARIUS [Ricou, 1994, Dercourt et al., 2000, Gaetani et al., 2003, Barrier and Vrielynck, 2008, Barrier et al., 2018]. Since Peri-Tethys, the emphasis has been on paleoenvironments.

The 80's were a period of fast development of paleo-tectonic reconstructions. The Paleomap project [Scotese et al., 1988] has produced global maps on a long period spanning the last 200 Ma. These maps were used by Gealey [1988] to propose restorations of the Western Tethys (Figure 9) with different kinematic options.

In these reconstructions, Apulia is a unique large block as in Dercourt et al. [1986] with however a different geometry. The equivalent of the Mesogea opens even more recently than in Dercourt et al. [1986] between a Tripolitza plate and the main body of Africa, after the closure of an oceanic basin between this Tripolitza plate and a Central Turkey plate. Toward the east, the Central Turkey plate is relayed by a West Iran plate forming a ribbon of continental blocks detaching from Africa.

Paleomagnetic data, which provided the first independent positive test of continental drift [Irving,

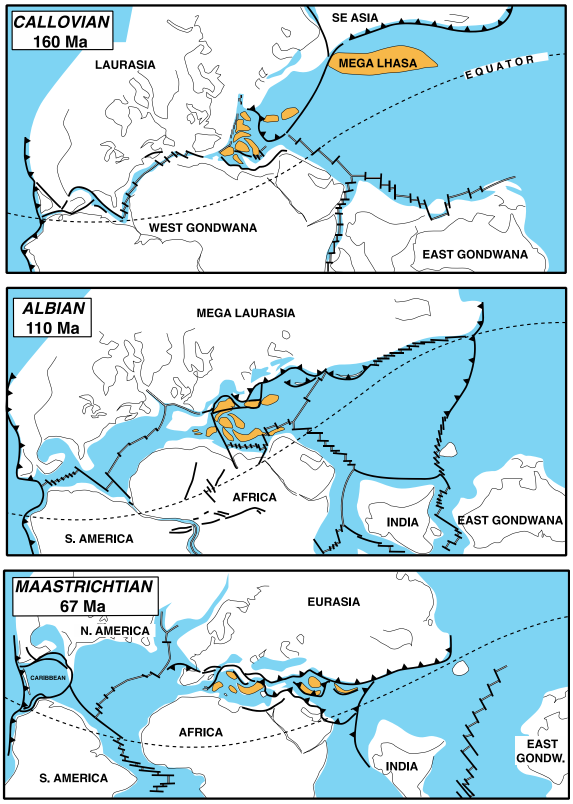

Figure 10. Reconstructions of the Tethys realm in the Peri-Tethys project. Redrawn from Dercourt et al. [1993].

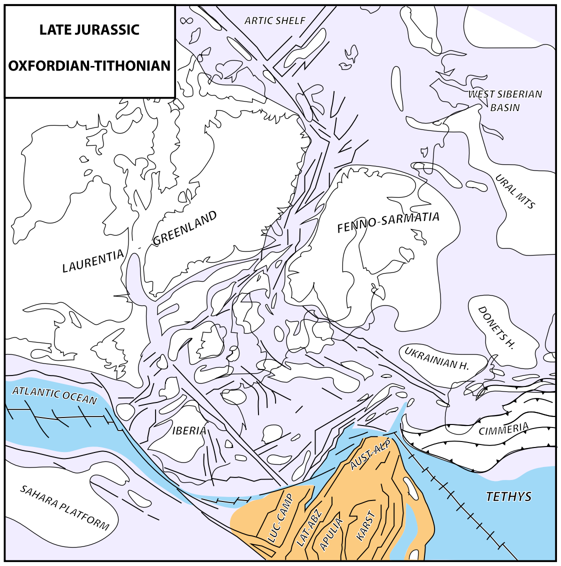

Figure 11. The northern connections of the Tethys. Redrawn after Ziegler [1999].

1958, Runcorn, 1962] played a major role in these series of reconstructions when large displacements were involved. The fast displacement of India is constrained by the magnetic anomalies in the Indian Ocean [Patriat and Achache, 1984, Patriat and Ségoufin, 1988] and by paleomagnetic data [Besse et al., 1984, Besse and Courtillot, 1988] that helped assessing intracontinental shortening in the Himalaya.

The question of the small blocks rifting away from Africa and drifting northward to ultimately collide with Eurasia comes into discussion at this period already. Clearly shown in Gealey [1988], they are also emphasized in Ricou [1994] (Figure 10). As will be shown below, this process was not only active in the NeoTethys but also in the PaleoTethys and is still active nowadays, the last of these blocks being Arabia.

The northern connections of the Tethys Ocean were described in details by Ziegler [1999] using the numerous data acquired offshore and onshore by oil companies. Figure 11 shows one of these maps at the time of opening of the Central Atlantic Ocean, before the formation of the Northern Atlantic in the Late Jurassic. In these reconstructions, Apulia is part of a large block attached to Africa and separated from Europe by an Alpine oceanic basin connected directly to the Atlantic by a system of transform faults.

5. Recent evolutions of paleotectonic reconstructions

Recently made paleotectonic reconstructions take advantage of the development of powerful kinematic softwares such as PaleoMap [Scotese et al., 1988, Schettino and Scotese, 2002] or more recently GPlates [Boyden et al., 2011]. These new methods allow fast and easy tests of various kinematic hypotheses and also to draw the detailed evolution of the intra-oceanic domain based on magnetic anomalies reconstructions. One of the salient examples is the detailed global scale reconstructions of Stampfli and Borel [2002] (Figure 12). Compared to Dercourt et al. [1986], besides some drastically different assumptions on the paleotectonic situation and age of some paleogeographic domains, they also show the details

Figure 12. The global reconstructions of Stampfli and Borel [2002], Anisian stage.

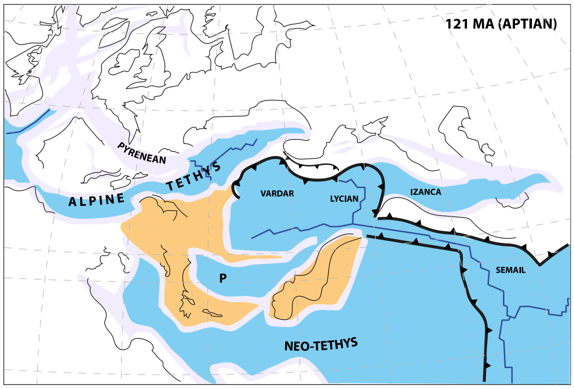

Figure 13. A detailed vision focused on the Tethys realm [Stampfli and Kozur, 2006].

of the intra-oceanic domains and they go way backward in time, back to the early Paleozoic. Figure 12 show the Anisian stage (240 Ma) on the Tethyan side of the globe. It shows the NeoTethys opening at the expense of the PaleoTethys that is closing to the north. A ribbon of continental blocks has detached from Africa and drifts northward toward the subduction zone. The NeoTethys includes part the Mesogea of Dercourt et al. [1986], which thus opens much earlier. The oceanic floor of the eastern Mediterranean in this set of reconstructions is as old as the Triassic, a drastic difference with Dercourt et al. [1986] who assumed a Cretaceous age. This question is not settled yet. Other options have been proposed such as the highly probable Late Jurassic age by Frizon de Lamotte et al. [2011]. The thick sedimentary cover of the oceanic crust between Crete and the North African coast makes all speculations possible but recent studies favor a Jurassic oceanic floor [Tugend et al., 2019].

Figure 13 shows a detail of the Western Tethys 121 Ma ago (Aptian) after Stampfli and Kozur [2006]. The Alpine Tethys is a continuous oceanic domain from the Ligurian Ocean preserved in the Alpine ophiolites and the Maghrebian Tethys between Spain and Morocco, connected with the Central Atlantic. The Vardar and Lycian oceanic domains have developed as back-arc basins above the subduction zones, totally consuming the older Maliac and Izanca oceans, a drastic assumption that renders possible the replacement of an ocean by a younger one. In Barrier and Vrielynck [2008] (Figure 14) a full connection of the Atlantic with the Tethys is shown and Apulia forms a large isolated block drifting away from Africa in the Late Jurassic, and the Alpine Ocean is a small tributary of the larger Tethys.

One recent trend of paleotectonic reconstructions is to explore their implications for the amount of slab imaged in the mantle by seismic tomography, orienting the reconstructions toward a 3-D approach. An early attempt was proposed by Faccenna et al. [2001] for the Western Mediterranean, allowing a new description of the history of subduction and slab retreat, which has consequences for the understanding of slab dynamics in the asthenosphere and at the upper/lower mantle discontinuity. A more detailed exercise, on a larger scale, was shown by Hafkenscheid et al. [2006] for the Tethys Ocean based on the reconstructions of Stampfli and Borel [2002] mentioned above and detailed comparison with the tomographic model of the Utrecht Group [Wortel and Spakman, 2000, Spakman and Wortel, 2004]. A reverse approach was later proposed at the scale of the globe to unravel the history of subduction and absolute kinematics for the last 300 Ma by van der Meer et al. [2010]. This study was based on a set of global reconstructions in a paleomagnetic framework [Steinberger and Torsvik, 2008, Torsvik et al., 2008] and the global travel-time tomography model

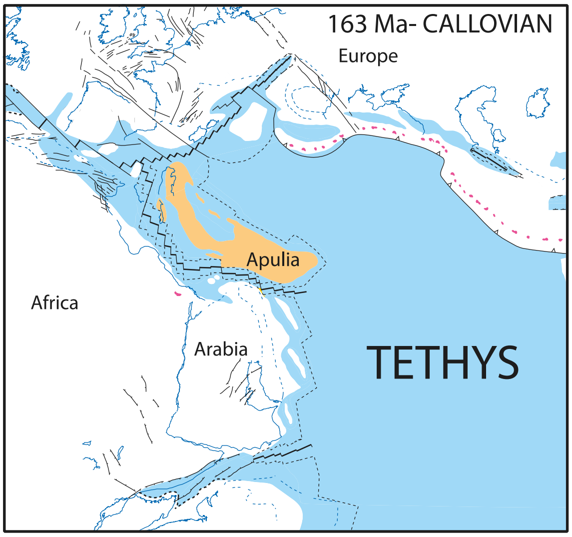

Figure 14. Callovian stage of Tethys reconstructions from the MEBE project. Apulia is totally separated from Africa by the Mesogea Ocean and the Alpine Ocean is a small tributary of the Tethys. Red spots represent active volcanism at the time of the reconstruction. Redrawn from Barrier and Vrielynck [2008].

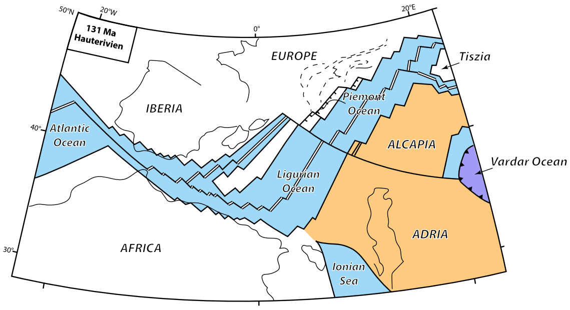

Figure 15. Cretaceous reconstruction of the western Tethys, a wide Ligurian Ocean fully connected to the Atlantic. With these reconstructions the authors estimate the amount of slab swallowed by Tethyan subduction zones. Redrawn from Handy et al. [2010].

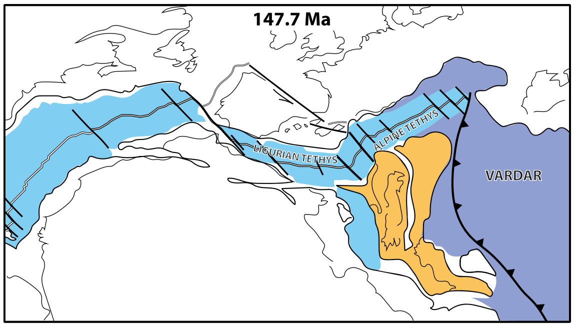

Figure 16. Latest Jurassic reconstruction of the Western Tethys. The Alpine Tethys is a tributary of the Atlantic Ocean. Redrawn from Schettino and Turco [2011].

of Amaru [2007]. This approach allows pinning the plates with respect to the underlying mantle with some simple assumptions on the behavior of slabs at depth (more or less vertical sinking) and it thus provides a complementary approach to absolute motions. Such a link between slabs at depth and kinematic reconstructions at the surface is proposed by Handy et al. [2010] for the western part of the Tethys (Figure 15).

The geometry of plate boundaries and continental margins in this set of reconstructions is a direct graphic translation of a simple kinematics linking the Ligurian and Piemont Ocean with the Atlantic Ocean. One consequence is the opening of a large Ligurian Ocean west of Adria, a solution that has been recently challenged by Angrand and Mouthereau [Angrand et al., 2020, Angrand and Mouthereau, 2021]. Such a simple kinematic pattern allows an easy calculation of the length of slab subducted in the mantle and facilitates the comparison with the tomographic images. Handy et al. [2010] conclude to a discrepancy between 10 and 30% in the amount of slab subducted deduced from the reconstructions and imaged by tomography. A similar direct kinematic link between the Alpine Ocean and the Atlantic is proposed by Schettino and Turco [2011] (Figure 16) and no direct connection with the large Tethys Ocean is postulated. Apulia remains attached to Africa.

The reference frame of the reconstructions is an important issue. One of the most difficult questions is to reconstruct the paleolatitudes as the whole system of plates may be positioned almost anywhere on the globe if considering only relative kinematics. This question was already addressed in the very first reconstructions by Köppen and Wegener [1924]. They used paleoclimatic proxies such as the presence of tillites, evaporites or coal to test the reliability of Wegener's reconstructions [Wegener, 1912, 1924,

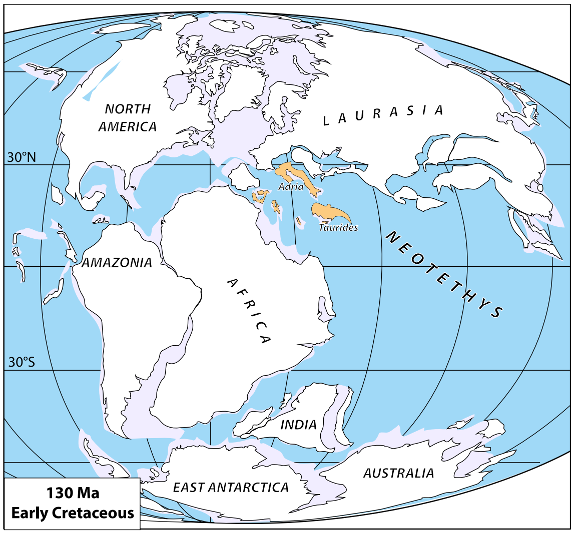

Figure 17. Global reconstruction in the Early Cretaceous and the Adria and Taurides continental blocks in a paleomagnetism-based model. Redrawn from Torsvik and Cocks [2016].

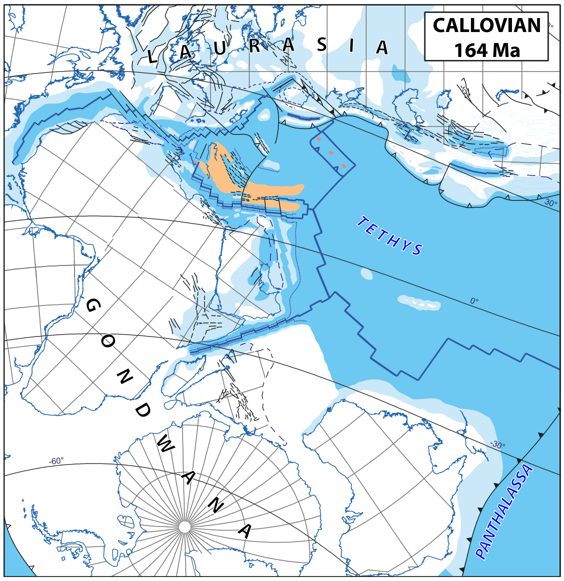

Figure 18. Callovian reconstruction of the Tethys from the DARIUS project. Redrawn from Barrier et al. [2018].

1929] on a globe where the present latitudinal zonation of climates would not change. One powerful tool to determine the paleolatitudinal position of a given plate is through paleomagnetic constraints. Torsvik et al. [2008] and Steinberger and Torsvik [2008] have proposed a set of global reconstructions based on a paleomagnetic framework, assuming little absolute motion of Africa (Figure 17). They thus obtained with an independent approach the paleolatitude and the paleolongitude. The reconstructions are not detailed in the Tethyan realm, but the position of Adria and the Taurides, shown here as two separate blocks in the Early Cretaceous, is mainly based upon paleomagnetic data.

The same kinematic parameters [Torsvik et al., 2008] were used for the large plates for the detailed DARIUS Project reconstructions of Barrier et al. [2018] (Figure 18), but the internal organization of the Tethyan realm is based upon geological data, onshore and offshore. The paleotectonic maps are then decorated with paleoenvironmental conditions based on the observed sedimentary deposits at each stage of the reconstructions (Figure 19) leading to an unprecedented image of the geological changes through time.

6. Discussion: future evolutions of plate models and geodynamic issues

The recent years have seen considerable improvements of tools for reconstructing past plate motions thanks to the development of user-friendly softwares, the most popular of which being certainly GPlates [Torsvik et al., 2008, Boyden et al., 2011, Seton et al., 2012, Müller et al., 2019]. The GPlates group has not only built a very convenient kinematic tool easy to use for geologists, but also a large database of kinematic and geophysical data. The modern reconstructions in addition include the possibility to deform plates along their boundaries, which is also a very useful improvement. These reconstructions can for instance be used for studying the interactions between mantle convection and plate motion at the surface with global numerical models [Rolf et al., 2012, Zahirovic et al., 2016, Coltice et al., 2017] linking in a single coherent tool all the approaches done “by hand” in the previous period. Modern plate reconstructions have reached another dimension and they can be used for discussing the internal dynamics of the Earth based on plate kinematics and geological observations.

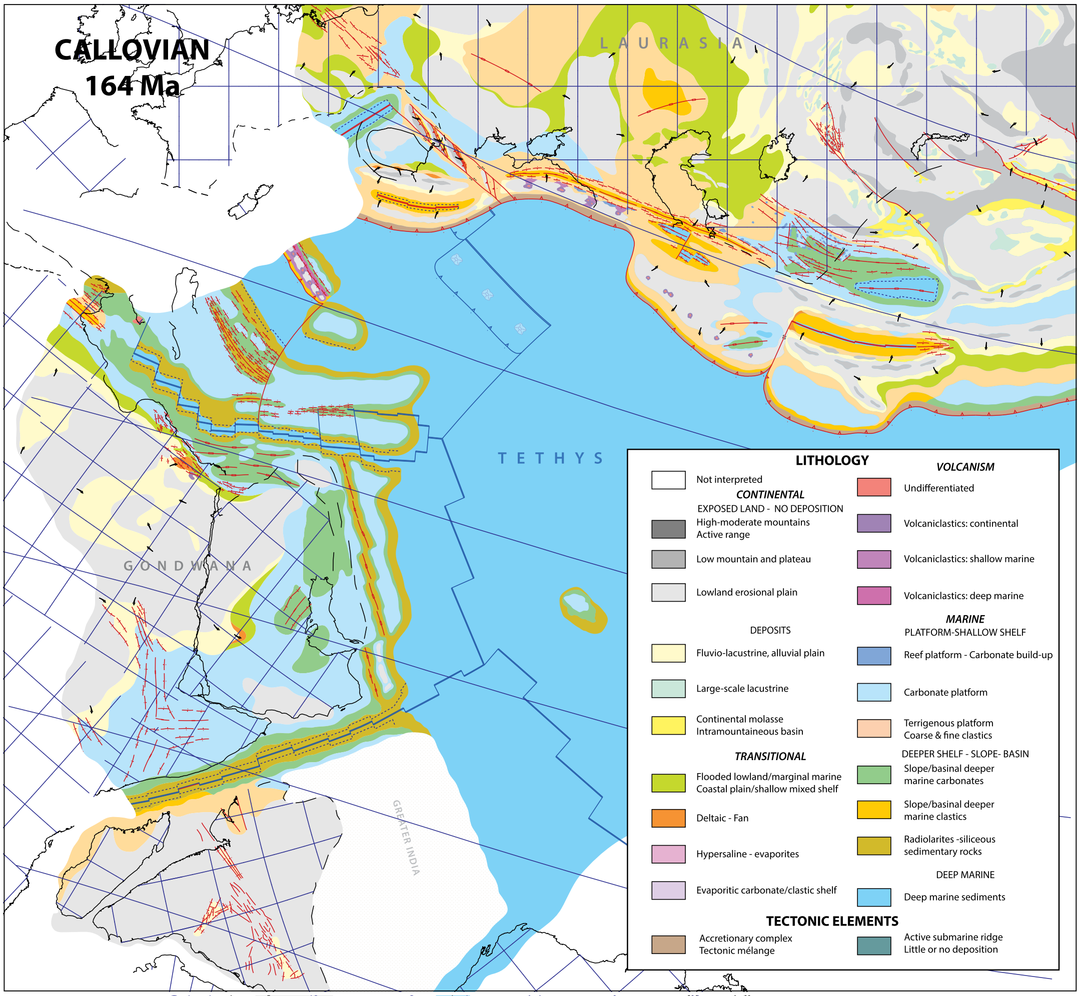

Figure 19. Callovian reconstruction of the Tethys from the DARIUS project with depositional paleoenvironments. Redrawn from Barrier et al. [2018].

This does not mean, however, that a full consensus has been reached in a complex setting such as the Mediterranean and the lost Tethys Ocean. Some debates are still active among geologists working in these regions. The geometry of the micro-continent either named Apulia or Adria is still actively discussed as well as the amount of oceanic crust swallowed by Alpine subduction zones in the Mediterranean, especially in the west where the nature of the crust between Africa and Eurasia is debated. The very existence of Adria as an independent micro-continent is also debated.

Figure 20 is an extract of the detailed reconstructions of the Tethys recently published by van Hinsbergen et al. [2019] and Figure 21 shows the same region in a set of reconstructions by Angrand and Mouthereau [Angrand et al., 2020, Angrand and Mouthereau, 2021].

The surface covered by oceanic crust is drastically different in the two sets of reconstructions. van Hinsbergen et al. [2019] connect the Alpine Ocean to the Atlantic Ocean [see also Handy et al., 2010] through the Gibraltar Strait and a rather wide oceanic domain is present in the location of the future Pyrenees, while Angrand and Mouthereau [Angrand et al., 2020, Angrand and Mouthereau, 2021] show much less oceanic domains and no continuity of oceanic crust from the Alpine Ocean to the

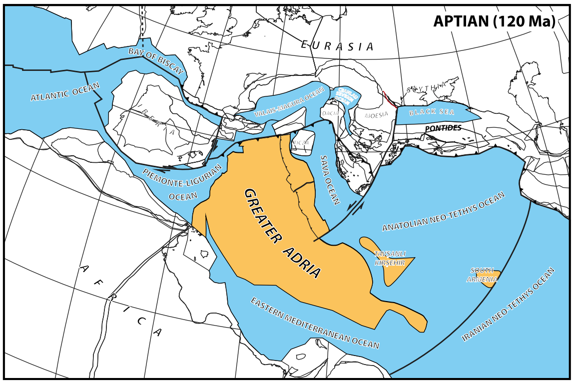

Figure 20. Aptian reconstruction of the Tethys and the Greater Adria, one of GPlates recent applications. Note the oceanic domain in the Pyrenees and the future Alboran Sea. Redrawn from van Hinsbergen et al. [2019]. To be compared with Figure 21.

Atlantic. At the maximum of divergence, only mantle exhumation is shown in the future Betics and the Pyrenees. This is due to drastically different interpretations of the geology of the Pyrenees and the Betics-Rif arc. I shall not show my preference here, but the interested reader can have a look at Romagny et al. [2020] or Bessière et al. [2021].

As a large majority of reconstructions show a separate micro-continent that has drifted away from Africa, we shall not enter too much into this debate in this paper focused on the different geometries of Apulia/Adria since the first publications. It is however important to mention this still active discussion because the alternative interpretations have drastically different geodynamic implications.

The discussion dates back to the first reconstructions in the 70's. Channell and Horvath [1976] represent Apulia as a promontory of Africa, the main reason being the absence of significant differences in the paleomagnetic drift of Apulia and Africa. This vision is the closest to the original interpretation of Argand [1924]. The recent interpretations of Angrand et al. [2020] and Channell et al. [2022] (Figure 22) come back to a partly similar interpretation without a wide Mesogean Ocean. The Mesogea is instead already present in Biju-Duval et al. [1977a,b] and Dercourt et al. [1986], although they keep a continental bridge between Apulia and Africa. An oceanic domain south of Apulia was also already present in Dewey et al. [1973].

The debate has been nicely summarized in the recent paper of Channell et al. [2022]. The authors of this paper argue in favor of the original model of Channell and Horvath [1976] and review the available data, in favor or against the existence of the Mesogea. I shall not enter into the details here again and the reader is referred to Channell et al.'s review. I shall only summarize the main points of the debate. The first observation often put forward against the existence of an oceanic domain between Apulia and Africa stems from paleomagnetic data. The paleomagnetic data show that, if an oceanic space ever existed, it could not have been wider than the error on the data that suggest no differential drift. In all reconstructions this oceanic space is not wider than a few hundreds of kilometers, which remain in agreement with the data. The paleomagnetic data alone thus cannot give a definitive answer, even less so because in these reconstructions Apulia is sandwiched between two oceanic spaces, the Mesogean and Alpine oceans, the widths of which being totally unknown. Both are thought to be a few hundreds of kilometers wide, but without any certainty as the only data are (1) the respective paleolatitudes of Africa, Apulia and Eurasia and (2) the reconstructed width of the passive margins, which both come with significant errors. The width of Apulia/Adria is thus largely speculative. Sedimentary facies in Apulian tectonic units show a certain continuity from Africa, which is one more argument against the existence of the Mesogea. The Mesogean Ocean was however narrow and similar depositional environments on either side would not be surprising. Detailed paleoenvironmental reconstructions such as Barrier et al. [2018] (Figure 19) show deep facies south of Apulia on the Mesogean margins. The presence of obducted ophiolites in Cyprus and southern Turkey is another argument in favor of an oceanic basin south of Apulia [Robertson, 1998, Maffione et al., 2017, van Hinsbergen et al., 2019]. The third type of data important in this debate is the nature of the crust in the deep basins of the Central and Eastern Mediterranean, respectively the Ionian Sea and the Herodotus/Levant Basin. Tugend et al. [2019] present a detailed reassessment of this question. Available seismic data, whether refraction or reflection, suggest an old Mesozoic oceanic basement in both basins, with a Permo-

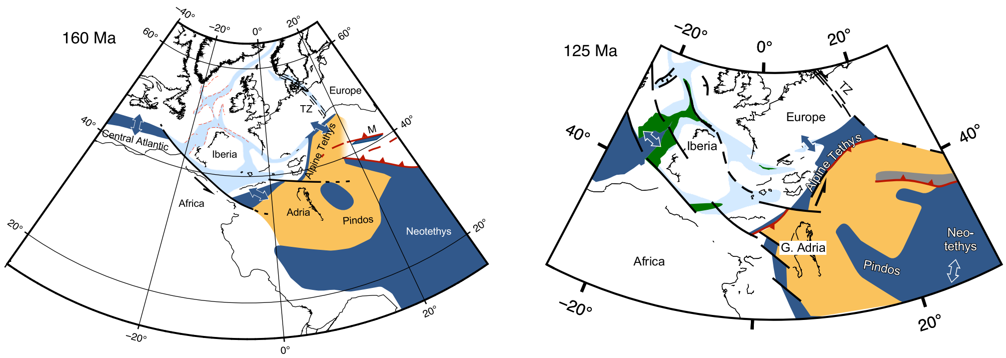

Figure 21. Two stages of the Tethys evolution showing much less oceanic lithosphere in the Western Tethys than in van Hinsbergen et al. [2019]. Compare to Figure 20. Redrawn from Angrand and Mouthereau [Angrand et al., 2020, Angrand and Mouthereau, 2021].

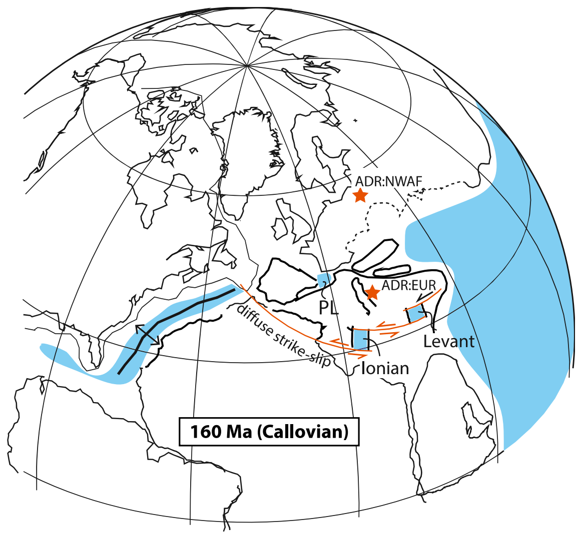

Figure 22. Jurassic reconstruction of Channell et al. [2022] showing no real separation between Africa and Adria. A left-lateral strike-slip fault is represented instead inducing the formation of small oceanic pull-apart basins in the Ionian Sea and Eastern Mediterranean.

Triassic rifting and a Jurassic oceanization. Channell et al. [2022] accept this conclusion and form this oceanic crust within small pull-apart basins, one for the Ionian Sea and one for the Levant Basin, along a left-lateral system of transform faults along which Africa moved with respect to Eurasia during the Mesozoic, a solution already used by Le Pichon et al. [2019]. This kinematic option offers a simple way to accommodate a significant displacement without much latitudinal motion to fit the paleomagnetic data. It however implies that the Ionian Sea and Levant Basin have been separate basins since their formation in the Mesozoic and that the Mediterranean Ridge accretionary wedge that separates them formed there just by chance. An alternative solution is that the two basins are parts of a single deep Mesozoic oceanic basin subducting underneath the Mediterranean Ridge.

The last point of discussion is the engine of the Cenozoic subductions in the Mediterranean realm. It is most of the time considered that convergence and slab retreat in the Calabrian and Hellenic trenches are powered by the weight of the Hellenic and Ionian oceanic lithospheric slabs [Faccenna et al., 1997, 2001, 2014, Carminati et al., 1998a,b, Jolivet and Faccenna, 2000, Spakman and Wortel, 2004, Wortel et al., 2009, Romagny et al., 2020, Jolivet et al., 2021a,b] and that the post-35 Ma dynamics of the Mediterranean is essentially driven by slab behavior in the upper mantle. This widely shared vision is supported by numerical and analogue modeling [Faccenna et al., 2003, Funiciello et al., 2003, Sternai et al., 2014, Capitanio, 2014]. In such models, the slabs are considered denser than the continental lithosphere of the overriding plate, and thus oceanic, which agrees with most published reconstructions and geophysical data in the Ionian Sea [Tugend et al., 2019, and references therein]. It also agrees with the presence of a calc-alkaline volcanic arc in Sardinia in the Late Eocene and Oligocene [Lustrino et al., 2009]. Channell et al. [2022] propose the alternative interpretation of a delamination of

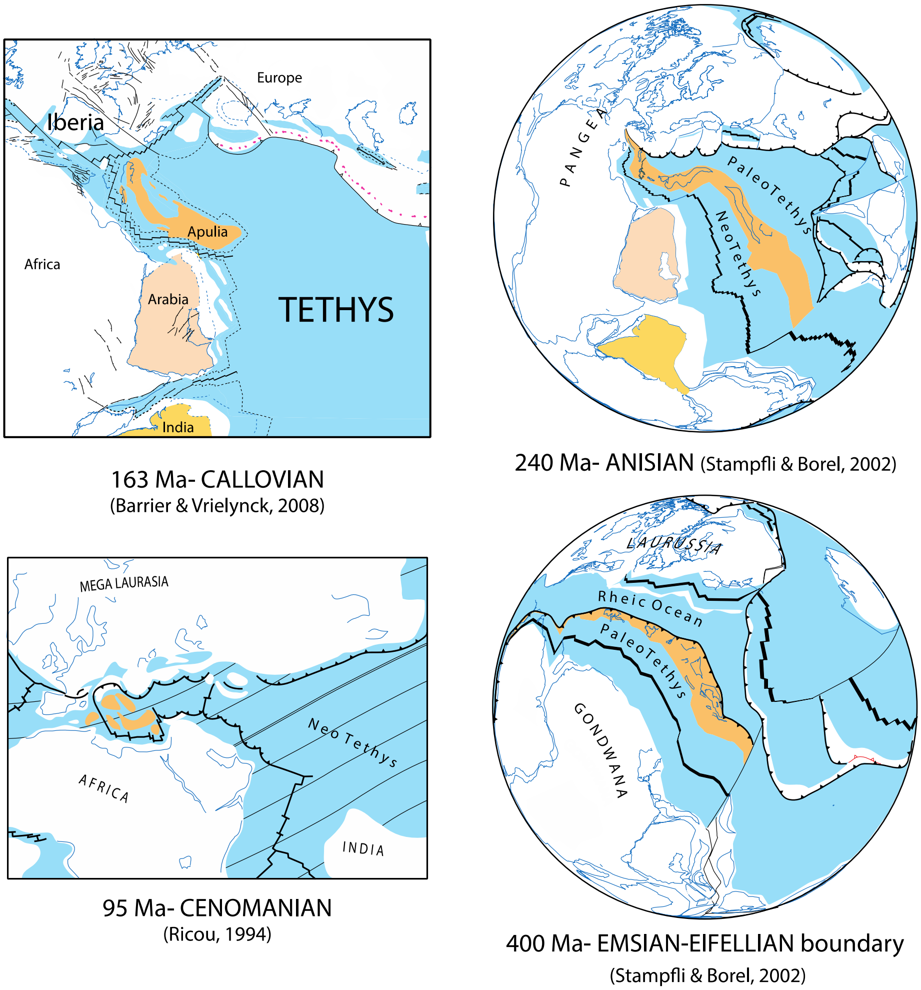

Figure 23. Four stages of the Tethys evolution showing continental blocks rifting away from Gondwana/Africa and drifting northward to ultimately collide with Laurasia/Eurasia. Redrawn from Barrier and Vrielynck [2008], Ricou [1994], Stampfli and Borel [2002].

the continental mantle below a previously thickened crust underneath the back-arc domain that would have similar consequences on the upper plate than the subduction of a retreating oceanic slab. Kinematic reconstructions taking into account paleomagnetic rotations, shortening rates in the Apennines and the amount of extension in the Liguro-Provençal Basin and Tyrrhenian Sea however impose about 600–800 km of maximum southeastward retreat of the Ionian slab since the Late Eocene [Dewey et al., 1989, Rosenbaum et al., 2002, Carminati et al., 2012, Romagny et al., 2020]. 600 or 800 km of shortening cannot be found in the Apennines, even when adding the Pyreneo-Provençal fold-and-thrust belt. This would then imply that delamination had been triggered by a convective instability below the moderately thickened Pyreneo-Provençal belt and had then been subsequently driven only by the weight of the continental mantle to reach the stage of complete continental break-up in the back-arc domain, first in the Liguro-Provençal Basin and then in the Southern Tyrrhenian Sea. Whether this is physically feasible is still unclear and future studies are required of this alternative geodynamic scenario.

Reading the terms of this debate, one can easily feel that such diverging interpretations will inevitably lead to very different geodynamic interpretations both in mechanical and thermal terms, depending upon whether an oceanic or a continental lithosphere has been consumed in the Mediterranean subduction zones.

Going back to the larger scale, we have seen in the present contribution the various representations of Apulia or Adria through time since Hsü [1971]. Whatever the exact shape and rifting time of these blocks away from Africa or Gondwana, they appear a constant feature of the Tethys geodynamics in most reconstructions considering that Apulia has been drifted away from Africa in the Mesozoic: ribbons of continental blocks rift away from Africa and drift northward faster than their mother continent, to ultimately collide with Eurasia. Before the separation of Apulia, the Cimmerian blocks detached in the Triassic–Liassic and their collision with Eurasia led to the Cimmerian Orogeny in the Jurassic [Şengör, 1979, Gyomlai et al., 2022].

Figure 23 shows four reconstructions by two independent groups of scientists at different periods, from the Devonian (400 Ma) to the Cenomanian (95 Ma). The Anisian stage shows the Cimmerian blocks [Stampfli and Borel, 2002], the Jurassic and Cretaceous stages show Apulia [Ricou, 1994] and the Devonian stage shows another ribbon of blocks drifting away from Gondwana during the opening of the Paleotethys at the expense of the Rheic Ocean [Stampfli and Borel, 2002]. The formation and drift of such blocks thus seems to be a constant scheme of the Tethys Ocean and it requires an explanation.

Figure 24 shows a reconstruction at 250 Ma [Torsvik and Cocks, 2016] highlighting the Cimmerian blocks drifting away from Gondwana. It also shows the projection at the surface of the Large Low Shear Velocity Zones observed by seismologists in the lowermost mantle where all major plumes originate. They represent the source of upwelling branches of whole-mantle convection [Burke, 2011]. The Cimmerian blocks lie to the NE of the Tuzo LLSVP and they migrate toward the main Tethyan subduction zone further northeast. It is thus tempting to conclude that they are carried by the convective flow that is responsible for the breakup of Gondwana. This mechanism has been proposed for the formation and migration of Apulia and Arabia [Faccenna et al., 2013, Jolivet et al., 2016] and tested by numerical modelling [Koptev et al., 2019]. This is only one example of how a first order geodynamic process, not proven yet, can be derived from the observation of

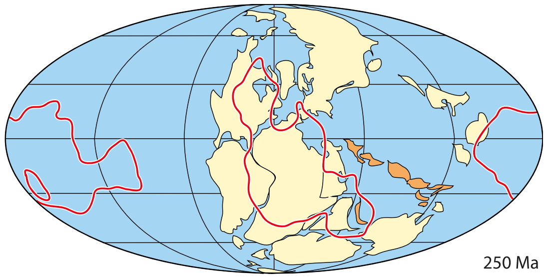

Figure 24. The globe 250 Ma ago. Cimmerian blocks drift northward away from Gondwana to the northeast of the "Tuzo" LLSVP (Large Low Shear Velocity Province). Redrawn from Torsvik and Cocks [2016].

paleotectonic reconstructions. The pioneer work of Jean Dercourt and his colleagues have far-reaching consequences, in terms of large-scale geodynamic processes as well as in terms of paleoenvironments, and thus in terms of prospection of natural resources.

Conflicts of interest

The author has no conflict of interest to declare.

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