Adria in Mediterranean paleogeography, the origin of the Ionian Sea, and Permo-Triassic configurations of Pangea

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ARTICLE INFO

Keywords:
Mediterranean Mesozoic paleogeography
Permian Pangea configurations
Paleomagnetic poles
Ionian Sea
Tyrrhenian and Apennine subduction
Mantle lithospheric delamination

ABSTRACT

The African affinity of the deformed Mesozoic continental margins surrounding the Adriatic Sea (a region known as Adria) was recognized in the 1920s. However, over the last several decades, the majority view of Mediterranean Mesozoic paleogeography has featured an ocean (Mesogea) that separated Adria and Africa in Mesozoic and early Cenozoic time. The presence of a Mesogea ocean has become an argument against the use of paleomagnetic data from Adria as a proxy for Africa, which has been central to the controversy surrounding alternative Permian configurations of Pangea (Pangea A or B). The rationale for Mesogea has been derived from the perceived need for oceanic lithosphere to feed Miocene to Recent subduction beneath the Tyrrhenian and Aegean seas, the apparent presence of Early Jurassic oceanic basement beneath the present-day Ionian Sea, and the presence of deep-water Permian and younger sedimentary rocks in Sicily. On the other hand, the presence of Mesogea is incompatible with the apparent continuity of Mesozoic sedimentary facies from North Africa and Sicily into Adria, and with increasingly well-documented consistency of paleomagnetic data from Adria and NW Africa. We argue that the subducting slabs beneath the Tyrrhenian and Aegean seas are delaminated continental-margin mantle lithosphere of Adria/Africa stripped of its sedimentary cover and most of its crustal basement by thrusting. We propose, rather than an early Mesozoic (Mesogea) ocean between Adria and Africa, a sinistral strike-slip fault system linked Atlantic spreading in the West to the Neo-Tethys in the East, during the Middle and Late Jurassic, and featured pull-apart basins that included the Ionian and Levant basins of the eastern Mediterranean. In our modelling, Adria moved with Iberia during initial opening of the Central Atlantic in the Early and Middle Jurassic (after 203 Ma until 170 Ma). From mid-Jurassic time (170 Ma), Adria began to break away from Iberia with onset of rifting in the Piemonte-Ligurian Ocean, and, as the rate of southeasterly motion of Adria relative to North America lagged that of Africa, the Ionian-Levant basins formed as pull-apart basins along a sinistral strike-slip fault system parallel to a small circle about the 170–154 Ma Euler stage pole for motion of Africa relative to Adria. From marine magnetic anomaly M25 time (154 Ma), Adria moved in synch with Africa and therefore pull-apart extension in the eastern Mediterranean came to a halt. The modeled opening of eastern Mediterranean pull-apart basins is consistent with the observed resemblance of Permian and younger paleomagnetic poles from Adria and NW Africa. The Atlantic Euler poles used to map these paleogeographic changes, when applied to Permian paleomagnetic poles from Adria, Africa, and elsewhere, support the existence of Pangea B in Early Permian time (280 Ma) with transformation to Pangea A by the Late Permian (260 Ma).

1. Introduction

The centenary of Emile Argand's seminal address at the International Geological Congress (IGC) in Brussels in 1922 is an opportunity to review the status of Adria, the continental area centered on the Adriatic Sea, as a paleogeographic and tectonic entity, and as a "*promontoire Africain*" (Argand, 1924a, 1924b). The role of Adria is relevant to the controversial use of paleomagnetic data from Adria as a proxy for Africa, and hence to the vexed question of Pangea configurations in Permo-Triassic time.

Argand (1879–1940), the Swiss alpine geologist, was an early advocate of Alfred Wegener's widely distributed, though not widely accepted, *Die Entstehung der Kontinente und Ozeane* (The Origin of Continents and Oceans) published in 1915 and in English in 1924. The dominant mountain-building hypothesis at the time was "geosynclinal theory" pioneered by Americans James Hall and James Dana in the mid-19th century, then applied in Europe in the early 20th century notably by Hans Stille and Leopold Kober. Geosynclinal (or "fixist") hypotheses dominated Alpine tectonics for almost a century well into the 1960s (e, g., Aubouin, 1965), and finally lost traction with general acceptance of plate tectonics. Argand's "mobilist" framework for Eurasian tectonics, exemplified by *La Tectonique de l'Asie* (Argand, 1924b), was at odds with the prevailing "fixist" paradigm. This now-classic work was initially largely ignored outside the small Swiss francophone geological community (Schaer, 2010), only translated into one other language in Argand's lifetime (Russian in 1935) and did not appear in English until 1977 (Carozzi, 1977). Argand (1924b) not only recognized the African affinity of Adria, he also considered this region to be a promontory of the African continent that collided with Europe. He recognized the importance of post-collisional extension in the eastern Mediterranean (including the Ionian Sea) as well as in the western Mediterranean together with the counterclockwise tectonic rotation of Corsica and Sardinia away from southern France.

At a time when the composition and configuration of ancient supercontinents such as Rodinia (~1 Ga) and Nuna (~2 Ga) are active areas of research, it is noteworthy that the configuration of the most recently assembled supercontinent (Pangea), in late Paleozoic and earliest Mesozoic time, is still not firmly settled. Two options (Pangea A and Pangea B) for late Carboniferous to late Permian time have been debated for over 40 years and involve contrasting juxtaposition of Gondwana and Laurasia at this time. Pangea A is essentially the same as the so-called "Bullard fit" (Bullard et al., 1965) at the onset of Triassic rifting in the Central Atlantic and is not seriously challenged as the Late Triassic reconstruction. Some advocate, however, the long-lived existence of Pangea A, or a variant of Pangea A that accommodates Late Triassic to Middle Jurassic extension in the Gulf of Mexico, from Late Carboniferous culmination of Hercynian (Variscan) orogeny until the onset of Triassic central Atlantic continental rifting (e.g., Torsvik et al., 2012; Domeier et al., 2011, 2012, 2021). The alternative (Pangea B) in which the north Andean margin of South America is adjacent to Laurentia, rather than NW Africa adjacent to Laurentia for Pangea A, has been advocated for Late Carboniferous and Early Permian time mainly based on paleomagnetic data (e.g., Irving, 1977; Morel and Irving, 1981; Muttoni et al., 1996, 2001, 2003, 2009; Bachtadse et al., 2018; Muttoni and Kent, 2019a, 2019b; Kent and Muttoni, 2020). The transition from Pangea B to Pangea A requires an episode of large-scale (~3500 km) dextral shear in (late) Permian time to bring the Pangea B configuration to Pangea A (Bullard fit) prior to the onset of Triassic central Atlantic continental rifting. Although largely obscured by Alpine deformation events, there is some evidence from Sardinia and elsewhere for this episode of mid-Permian dextral shear (Arthaud and Matte, 1977; Goldstein, 1989; Muttoni et al., 2009; Aubele et al., 2012; Bachtadse et al., 2018). The two views on the evolution of Pangea (static Pangea A versus mobile Pangea B to A) hinge on the use of Permian and Mesozoic paleomagnetic data from northern Italy as a proxy for paleomagnetic data from Africa, and more generally, on the application of presumed corrections for inclination error in the Torsvik et al. (2012) compilation of sedimentary paleomagnetic data (see Kent and Muttoni, 2020). In addition, although Global Positioning System (GPS) data for modern decoupling of autochthonous Adria and Africa are equivocal (see below), Domeier et al. (2021) stated that "*a tectonic decoupling between (Adria and Africa) in deeper time is nevertheless required by the existence of the Ionian basin that separates them ……. if the Ionian basin is Mesozoic, all pre-Mesozoic paleomagnetic data from Adria must necessarily have been rotated with respect to Africa by the opening of that basin.*" Our objective here is to provide a viable kinematic model for Ionian extension consistent with Atlantic spreading history and existing geological data, and assess the effect of Ionian extension on paleomagnetic data from Adria and hence reevaluate data pertaining to Pangea configurations.

2. Adria and the Mesogea ocean

The term "Adria" has been used for the region of continental crust centered on the present-day Adriatic Sea surrounded by deformed Mesozoic and Cenozoic continental margins (Fig. 1; Channell et al., 1979), equivalent to the "*promontoire Africain*" of Argand (1924a, 1924b). Thrust sheet loading, both from the Apennines and Dinarides-Hellenides, combined with mantle upwelling in the surrounding thrust belts, produces a large negative residual topography for the Adriatic Sea (D'Agostino and McKenzie, 1999; Shaw and Pysklywec, 2007; Faccenna et al., 2014a). Arguments for the African affinity of Adria were made in the 1970s based on Mesozoic sedimentary facies and the apparent continuity of the now-deformed continental margin of Adria from the Atlas Mountains into Sicily, through the Apennines, Southern Alps, Dinarides and Hellenides (e.g., D'Argenio, 1971, 1974; Bernoulli, 1972; Bernoulli and Laubscher, 1972; Bernoulli and Jenkyns, 1974; D'Argenio et al., 1975, 1980) and on Mesozoic paleomagnetic data from Adria that showed African affinity (e.g., Zijderveld et al., 1970; Channell and Tarling, 1975; Channell and Horvath, 1976). At the time, the crustal basement in the Ionian Sea and eastern Mediterranean were thought to be continental, albeit thinned, based on seismic data, with a well-defined mantle lithosphere implying continuity with the African plate (e.g., Hinz, 1974; Weigel, 1974; Makris, 1978).

A Mesozoic "Mesogea" ocean dissecting Adria leaving Sicily and Apulia/Apennines on its southern and northern margins, respectively, and merging eastward into the Neo-Tethys, appeared in the paleogeographic maps of Dewey et al. (1973), Biju-Duval et al. (1977) and Sengör et al. (1984) from Triassic time (Fig. 2a). Following an early review of Mediterranean paleomagnetic data by Westphal et al. (1986), Dercourt et al. (1986) proposed that Apulia moved with Africa other than during an interval in the mid-Cretaceous when ~30° anticlockwise rotation of Apulia relative to Africa resulted in formation of Mesogea in the eastern Mediterranean. The case for Permo-Triassic development of Mesogea was strengthened by identification of Early to Late Permian deep-water radiolarians, ostracodes and conodonts in sediments of the Sicani Basin in western Sicily (Catalano et al., 1991) where overlying pelagic sediments indicate long-lived deep-water conditions interrupted by Miocene deformation. The Permian of the Sicani Basin was linked to similar facies in the Lagonegro Basin of the Southern Apennines and to sediments in Crete, Kurdistan and Oman (Catalano et al., 1991). This led to a paleogeography in which a Permian Mesogea ocean widened to the east separating Adria from Sicily/Africa (Fig. 2b), and with an *in situ* remnant of this Permian ocean being preserved in the basement of the modern Ionian Sea (e.g., Catalano et al., 2001). This Permian to Cenozoic Mesogea merged into Neo-Tethys in the East and was not thought to have been connected to the Mesozoic Vardar Ocean to the North (e.g., Stampfli et al., 1991; Stampfli and Borel, 2002, 2004), the remnants of which are found in the ophiolite belts of the Dinarides and Hellenides (Fig. 1).

Almost without exception, a Mesogea Ocean is prominent in Mesozoic to early Cenozoic paleogeographies published in the last 30 years (e.g., Stampfli et al., 1991; Rosenbaum et al., 2002, 2004; Stampfli and Borel, 2002, 2004; Garfunkel, 2004; Argnani, 2005, 2018; Faccenna et al., 2004, 2014b; Handy et al., 2010; Frizon de Lamotte et al., 2011; Schettino and Turco, 2011; Carminati and Doglioni, 2012), although some authors (e.g., Carminati et al., 2012; van Hinsbergen et al., 2020) provide reconstructions featuring a narrow continental Africa-Adria land-bridge crossing Mesogea, thereby acknowledging apparent continuity between the Sicilian and Apennine Mesozoic continental margins. Other "hybrid" paleogeographies feature continuity of the internal (oceanward) platforms and basins (Panormide and Apenninic platforms and Imerese and Lagonegro basins) of the Sicilian-Southern Apennine

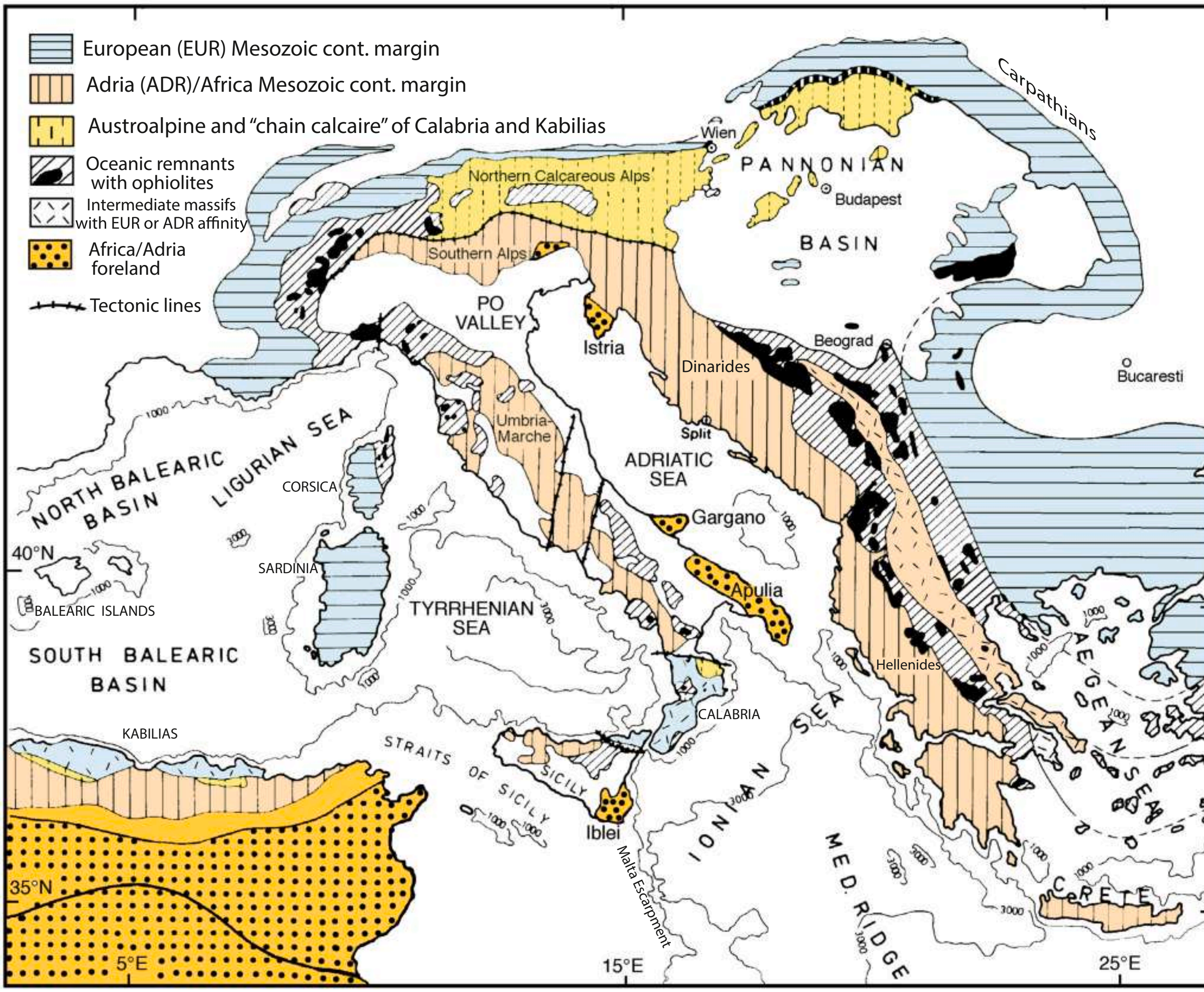

Fig. 1. Map of Adria, an area centered on the Adriatic Sea and surrounded by deformed Mesozoic continental margins extending from North Africa into Sicily and the Apennines, and connecting to the Dinarides and Hellenides (after Channell et al., 1979).

continental margins, with the external paleogeographic elements (Trapanese-Sicani-Sciacca in Sicily) being truncated northward by the Mesogea Ocean (Fig. 3; Patacca and Scandone, 2007; Speranza et al., 2012) or continuity of the platforms and basins of the continental margins but foreland elements in Sicily (Iblei) and the Southern Apennines (Apulia) being bordered by Mesogea to the east (Muttoni et al., 2001).

Atlantic spreading history based on marine magnetic anomalies provides kinematic constraints on the relative motion of Africa and Europe that in turn provide the boundary conditions for Alpine tectonics (e.g. Dewey et al., 1973). During Central Atlantic spreading in Early Jurassic to mid-Cretaceous time, prior to opening of the North Atlantic, the motion of Africa relative to Europe was southeasterly, allowing for the opening of Alpine Tethys (Fig. 2a), an ocean comprising the Ligurian-Piemonte-Penninic-Magura oceans that separated Adria from Europe (Figs. 2a and 4). To the east of Adria, the prominent Mesozoic ocean was the Vardar Ocean (Fig. 4), ophiolitic remnants of which are found in the Dinarides and Hellenides in two sub-parallel ophiolitic zones: the Pindos Zone (and its extension northwards) lying west of the Vardar Zone (Fig. 1). The Pindos ophiolites, rather than representing an ocean separate from Vardar, were probably derived from the Vardar Ocean and obducted over the intervening Pelagonian Massif (Schmid et al., 2008; Gawlich et al., 2016; Maffione and van Hinsbergen, 2018). Remnants of Alpine Tethys are found in the ophiolite belts of the western Alps, of Tuscany, and of the Southern Apennines and Calabria. The Early Jurassic to mid-Cretaceous partially corresponds to the development of Mesogea in the paleogeographic scenarios cited above. For some authors (e.g., Rosenbaum et al., 2002; Handy et al., 2010; Carminati et al., 2012), the Alpine Tethys and Mesogea oceans were contiguous, although the kinematics of the two oceans must have been very different in view of the large angle between their elongation directions. Mesogea must have had a large sinistral strike-slip component during Early Jurassic to mid-Cretaceous time whereas seafloor spreading in the Alpine Tethys (and Central Atlantic) was approximately orthogonal to its elongation direction (Fig. 2a).

In contrast to sediments of the same age from the European margin, the basinal sediments of Mesozoic age deposited on the margins of Adria are often referred to as "pelagic" because of relatively low rates of detrital influx. The analogy was drawn between western central Atlantic Mesozoic facies recovered by drilling, and indeed the modern carbonate-rich continental margin of the Bahamas, to facies observed in the deformed margins of Adria (D'Argenio, 1974; D'Argenio et al., 1975, 1980; Bernoulli, 1972; Bernoulli and Laubscher, 1972; Bernoulli and Jenkyns, 1974). The relatively "starved" setting of the Adria continental margin results in normal faults on the continental margin controlling the elongation direction and juxtaposition of ancient platforms and basins

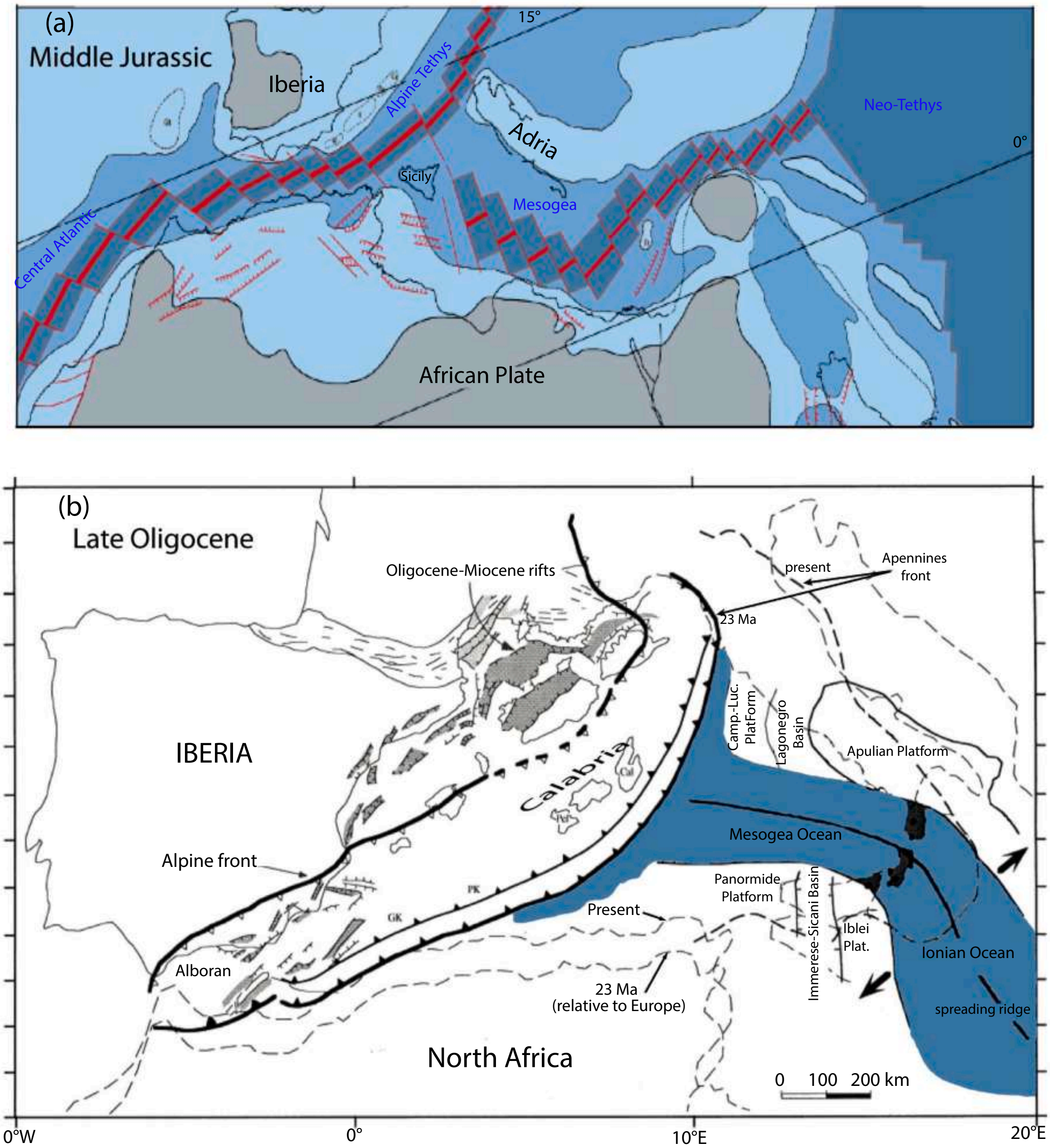

Fig. 2. (a) Middle Jurassic reconstruction showing Alpine Tethys between Adria and Europe as an extension of the Central Atlantic and a Mesogea ocean separating Africa/Sicily from Adria. Gray: exposed continent, Light blue: shallow marine, Medium blue: deep marine, Dark blue with red: oceanic spreading ridges and transform faults. Barbed red lines depict normal faults. Diagram after Biju-Duval et al. (1977), Ricou (1994), Frizon de Lamotte et al. (2011). (b) Late Oligocene Mesogea after subduction of Alpine Tethys beneath the Sardinia-Calabria volcanic arc. The present-day position of the Calabria volcanic arc is shown in black. The positions of the Apennines deformation front, and the positions of the northern coast of North Africa, are shown for present and for latest Oligocene (23 Ma). Diagram after Catalano et al. (2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recognized from Mesozoic sedimentary facies. The platforms and basins can be traced from Sicily into the Southern Apennines, then into the Southern Alps and through the Dinarides and Hellenides (e.g., Channell et al., 1979). In contrast, high detrital influx on the European ("Helvetic") Mesozoic continental margin, or on the modern eastern seaboard of north/central North America for that matter, results in sedimentary facies being not obviously linked to basement faulting.

Subsidence on continental margins is driven by short-term crustal stretching, largely inherited from the continental rifting stage, superimposed on longer-term thermal relaxation of mantle lithosphere as the site of rifting moved offshore (e.g., McKenzie, 1978). Non-volcanic continental margin crust is inherently extensional, as illustrated by finite element modeling, with extensional stresses in the brittle upper crust being amplified by hot-creep oceanward of the more ductile lower crust (Bott, 1971, 1992; Kusznir and Bott, 1977). In this setting, normal faults bounding platforms and basins are oriented sub-parallel to the junction between continental and oceanic crust in either the classical "pure shear" model of continental rifting (Bott, 1971; Buck, 1991; Huismans and Beaumont, 2007) or for the upper plate in the "simple shear" model (Wernicke, 1985). For this reason, the platforms and basins recognized from Mesozoic facies on the Adria continental margin would be expected to be elongated parallel to the junction of oceanic and continental crust, and the development of normal faults bounding the platforms and basins would be expected to develop progressively

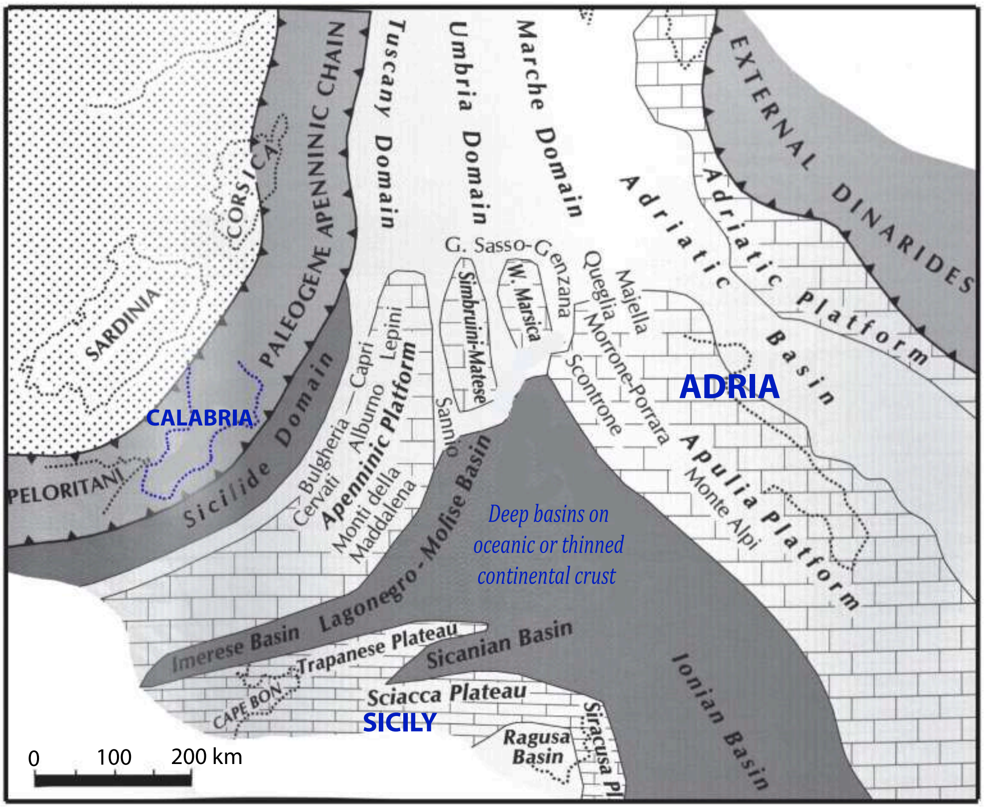

Fig. 3. Palinspastic restoration for the Late Oligocene, prior to the collision of the Adria continental margin with the active Corsica-Sardinia-Calabria volcanic arc. European foreland (stippled at top left), Paleogene "Alpine" deformation and Dinaric deformation (light gray), thrust fronts (closed triangles), shallow-water carbonate platforms (thick brickwork pattern), pelagic plateaus (thin brickwork pattern), basinal areas of the continental margins with isolated structural highs (no pattern or shading), deep basins floored by oceanic or thinned continental crust (dark gray). Diagram after Patacca and Scandone (2007).

from internal (oceanward) to external (continental interior) elements of the continental margin (Bott, 1971, 1992; Kusznir and Bott, 1977).

Throughout the deformed continental margins of Adria (Sicily, Apennines, Dinarides and Hellenides), the Mesozoic sediment cover is imbricated into thin-skinned thrust sheets verging towards the Adriatic-African continental foreland: namely southward in Sicily, northeastward in the Apennines, and southwestwards in the Dinarides and Hellenides. Paleotectonic normal faults that bounded platforms and basins were often reactivated as thrust faults. Deformation of this continental margin began in the latest Jurassic on the eastern side of Adria (Dinarides and Hellenides), in the Oligocene in the Northern Apennines, and in the Miocene in the Southern Apennines and Sicily. In the region of the Tyrrhenian Sea, palinspastic reconstructions of the deformed margins must compensate for large-scale clockwise rotations in Sicily (e.g. Channell et al., 1980, 1990; Speranza et al., 1999, 2003) and smaller-scale counterclockwise rotations in the Southern Apennines (e.g., Catalano et al., 1976; Scheepers et al., 1993; Scheepers and Langereis, 1994) determined from paleomagnetic data from individual thrust sheets in the nappe piles (Fig. 5). Palinspastic reconstruction of the Sicilian and Southern Apennine deformed margins results in approximately consistent NE-SW elongation direction of platforms and basins (e.g., Oldow et al., 1990; Pinter et al., 2016; Maffione et al., 2013) thereby making the case for continuity of the two passive margins prior to Miocene deformation (Fig. 5). In addition, the temporal evolution of the margin indicates that the oceanward (interior) part of the margin was to the west and the relevant ocean was, therefore, the Alpine Tethys (Piemonte-Ligurian Ocean) that developed from mid-Jurassic time and was contiguous and partially coeval with the Central Atlantic (Fig. 2a). The truncation of platforms and basins against Mesogea (e.g., Rosenbaum and Lister, 2004; Patacca and Scandone, 2007; Speranza et al., 2012) or the existence of a Mesogea immediately to the east of Iblei and to the south of Apulia (Muttoni et al., 2001) do not fit with a standard "pure shear" model for development of platforms and basins on the Sicilian-Southern Apennine continental margin.

The Numidian Flysch (Oligocene to mid-Miocene), widespread in North Africa from Morocco to Tunisia, is also found in Sicily and the Southern Apennines (Thomas et al., 2010). It originated from North Africa and was apparently deposited progressively northward along basins in Sicily and the Southern Apennines (Patacca et al., 1992; Fornelli et al., 2015). In northern Sicily, Burdigalian (early Miocene) deposition of the Numidian flysch occurred in the very early stages of deformation of the Adria margin and was largely controlled by active thrust faults (Pinter et al., 2016). The existence of the African-derived Numidian flysch in the Southern Apennines supports continuity of the continental margin of Adria from North Africa into Sicily, and into the Southern Apennines, at least at this time.

Fossils and footprints of dinosaurs (theropods and sauropods) of African provenance, are preserved in Tithonian (Late Jurassic) to Santonian (Late Cretaceous) carbonate platform sediments in Sicily, the Apennines and Apulia and provide evidence for a land bridge between Africa, Sicily and Apennines/Apulia from the Late Jurassic to Late Cretaceous (Nicosia et al., 2000; Bosellini, 2002; Conti et al., 2005; Zarcone et al., 2010). Fossil finds include a spectacularly well-preserved specimen of a small theropod (*Scipionyx samniticus*) found ~40 km south of Bari (Dal Sasso and Signore, 1998). The theropods and sauropods are believed to have had limited swimming ability, and would not have been able to traverse a wide Mesogea Ocean (Fig. 2a,b) as often envisaged (e.g., Catalano et al., 2001; Rosenbaum et al., 2002; Handy et al., 2010; Carminati et al., 2012).

3. Anomalous oceanic structure of the basement beneath the Ionian Sea

The nature of the basement beneath the Ionian Sea has been debated for at least 50 years. Early seismic refraction and surface wave data (e.g. Hinz, 1974; Weigel, 1974) indicated a mature mantle lithosphere. The Ionian Sea has low heat flow of 30–40 mW/m^2 (Della Vedova and Pellis, 1989) indicating either ancient oceanic lithosphere or (African)

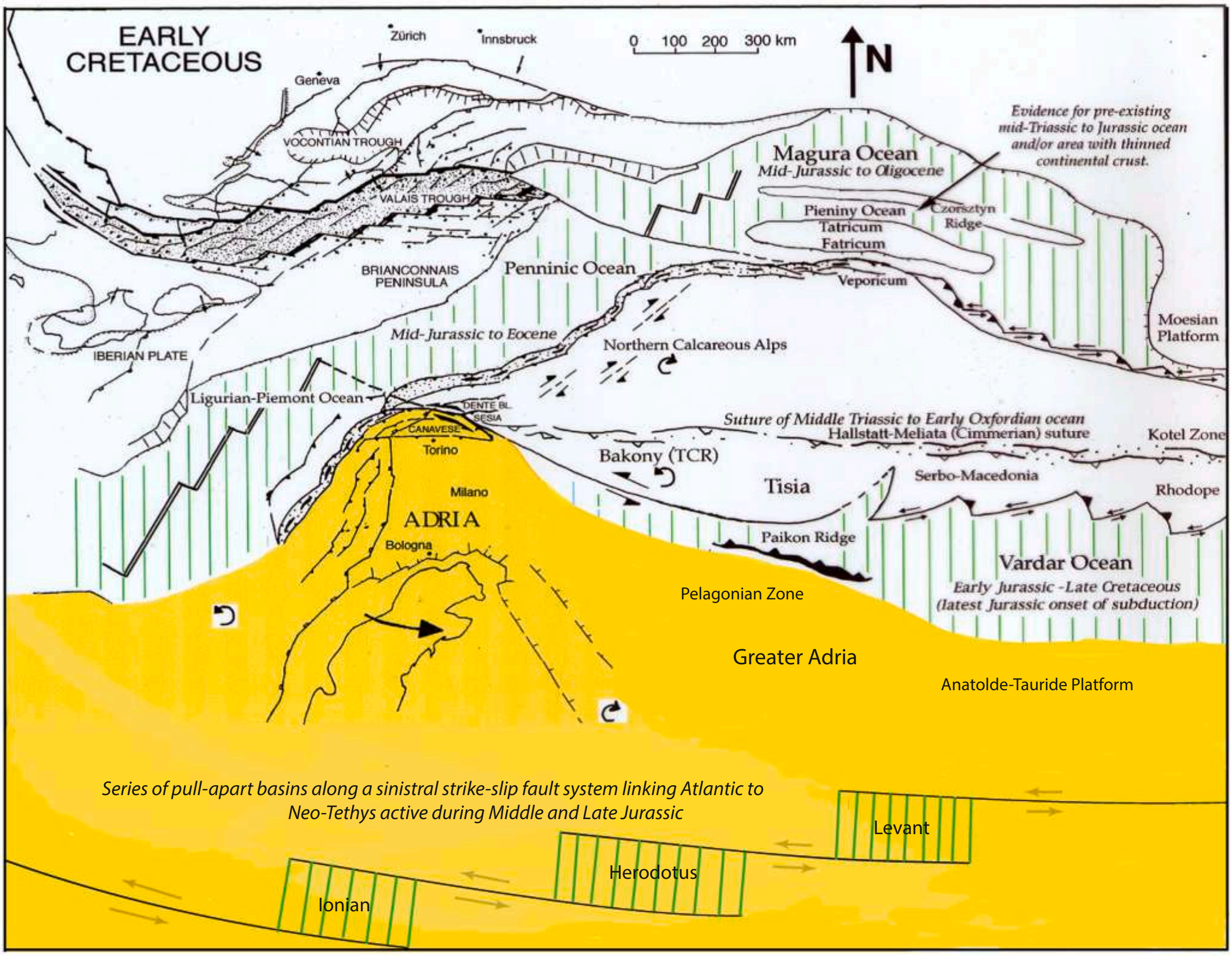

Fig. 4. Paleogeographic map for the Early Cretaceous modified after Channell and Kozur (1997), particularly with regard to a Vardar Ocean from which both Pindos and Vardar ophiolites were derived (see Schmid et al., 2008) and the introduction of pull-apart basins in a sinistral strike-slip fault zone, active in mid-Jurassic, to account for the Ionian-Herodotus-Levant basins (see text). Orange colors represent Adria, and Greater Adria extending to the east. Vertical green lines represent ocean basins, including oceanic rifting in the Ionian-Herodotus-Levant pull-apart basins. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

continental lithosphere. Thick sedimentary cover in the Ionian Sea and eastern Mediterranean hampers seismic penetration to basement, exacerbated by the masking effect of velocity inversion due to several km of Messinian evaporites. In the Ionian Sea, thrusts from active tectonics in the Calabrian Arc and in the Hellenic Arc (Mediterranean Ridge) further thickened sedimentary cover thereby obscuring much of the basement structure. An area of a few thousand square km, less affected by the two thrust fronts (the Ionian abyssal plain), is characterized by ~6 km of sediments overlying a ~ 8 km crustal basement of probable oceanic origin (Dannowski et al., 2019; Tugend et al., 2019), broadly consistent with earlier interpretations of 6–8 km of sediments overlying a 8–10 km oceanic basement (e.g., De Voogd et al., 1992). Gravity data imply oceanic crust or highly thinned continental crust in the Ionian abyssal plain and Sirte Basin (Cowie and Kusznir, 2012). Although oceanic crust beneath the Ionian Sea is the consensus view, the upper part of the Ionian basement has higher than expected seismic velocities possibly indicating gabbroic intrusions characteristic of slow and ultra-slow spreading rates (Tugend et al., 2019). Abundant mantle-derived serpentinite diapirism has been recognized from seismic and other geophysical data beneath the Calabrian arc segment of the Ionian Sea, NW of the abyssal plain (Polonia et al., 2017). Pre-Messinian tilted blocks and syn-rift sediments in the Ionian abyssal plain have been interpreted to indicate a stretched (African) continental crust (Hieke et al., 2003). In addition, the efficient transmission of *Sn*, the shear phase refracted at the Moho, across the Ionian Sea implies that its uppermost mantle is a prolongation of the African continent, consistent with interpretations of surface wave data in the eastern Mediterranean (Mele, 2001; Marone et al., 2004; Meier et al., 2004; Legendre et al., 2012). The prolongation of the Malta Escarpment on land in NE Sicily now acts as a dextral strike-slip fault zone related to Calabrian thrusting (Barreca et al., 2016; Gutscher et al., 2017). Seismic profiles have been interpreted to indicate numerous small-scale extensional basins along the NE side of the Malta Escarpment, some showing later inversion related to the Calabrian thrust tectonics (Argnani and Bonazzi, 2005; Gallais et al., 2011). Both the Malta Escarpment, and the Apulian Escarpment on the northern side of the Ionian Sea, appear as abrupt steps in seafloor bathymetry and may have behaved as normal faults and/or sinistral strike-slip faults during Jurassic extension (Dellong et al., 2018; Gallais et al., 2011; Frizon de Lamotte et al., 2011; Dannowski et al., 2019), rather than representing conjugate passive margins of Mesogea (Fig. 2b; Catalano et al., 2001).

Lineated marine magnetic anomalies, typical of the major oceans, have not been recognized in the Ionian Sea although they have been identified in small Western Mediterranean oceanic basins such as the

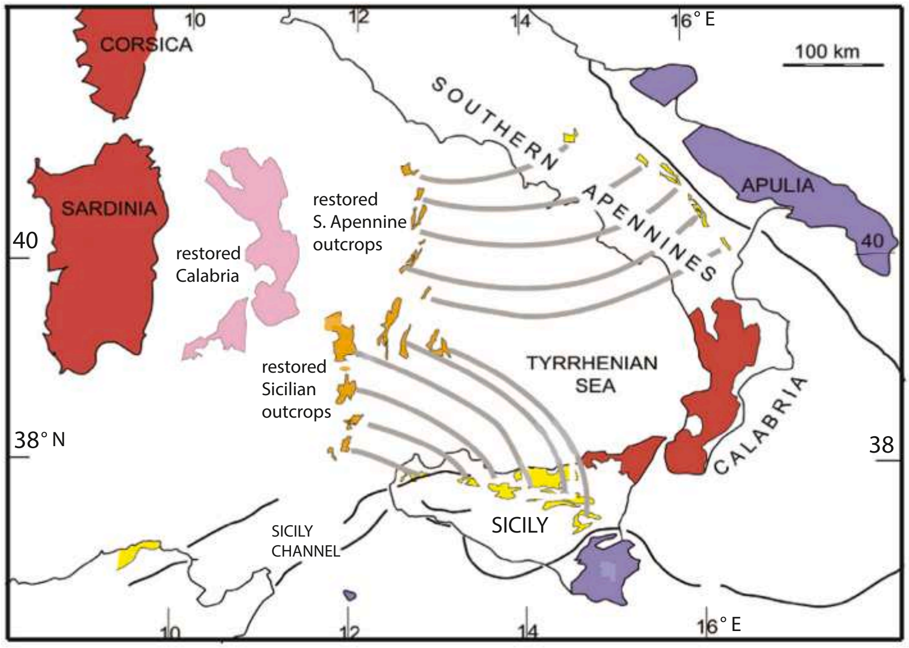

Fig. 5. Palinspastic reconstructions of the Calabrian volcanic arc relative to Sardinia in Early Miocene, and of platform/basin elements of the Sicilian and Southern Apennine continental margin incorporating paleomagnetically-determined rotations of thrust sheets: clockwise in Sicily and counterclockwise in the Southern Apennines (diagram after Pinter et al., 2016).

Ligurian-Provençal Basin (Bayer et al., 1973) and the Marsili Basin of the Tyrrhenian Sea (Nicolosi et al., 2006) where high heat flow values (up to 140 mW/m^2 in the Marsili Basin) are consistent with Oligocene seafloor spreading in the Ligurian-Provençal Basin and modern seafloor spreading in the Marsili Basin. Igneous bodies (e.g., Mt. Etna) and crustal thickness changes are manifested in satellite-derived magnetic anomaly maps (e.g., Maus et al., 2007) from along the Malta Escarpment and close to Calabria. Speranza et al. (2012) considered that the lack of clear lineated magnetic anomalies in satellite data over the Ionian abyssal plain indicate that seafloor spreading occurred during a unique (single) magnetic polarity chron. The averaged anomaly value (−7 nT) measured above the abyssal Ionian Sea, albeit very low intensity, can be modeled as a oceanic slab formed during a predominantly reverse polarity interval such as the 7.6 Myr-long Carnian interval (E8r-E12r, see Kent and Olsen, 1999), although any prolonged interval of predominantly reverse polarity of Late Triassic or Early Jurassic age would suffice (Speranza et al., 2012). Granot (2016) correlated a particular magnetic anomaly across a series of parallel ship's tracks in the Herodotus Basin and across another set of ship's tracks farther east between the Herodotus Basin and the Levant Basin. Skewness (shape) analysis led Granot (2016) to infer that both anomalies were formed by oceanic seafloor spreading in the Early Carboniferous, implying ocean floor of remarkable antiquity. On the other hand, similar magnetic anomalies in the Levant Sea have been modeled as irregular (Jurassic) igneous bodies where the dominant structures in seismic reflection profiles are NE-SW oriented normal faults associated with a mid-Jurassic NW-SE direction of extension during an intercontinental rifting phase that did not evolve beyond the early magmatic phase, without development of typical oceanic crust (Gardosh and Druckman, 2006; Gardosh et al., 2010). This view is not universally accepted, however, with others emphasizing the importance of Cretaceous plume-related magmatism in Levant rifting (Segev et al., 2018).

The basement beneath the Ionian Sea is not typical oceanic basement, not only because of the lack of marine magnetic anomalies but also because of higher than normal seismic velocities in the upper part of the basement attributable to gabbroic intrusions (Tugend et al., 2019), or to a hybrid crust formed by extension and igneous intrusion of a continental margin. Le Pichon et al. (2019) made the case for extension in the Ionian Sea and eastern Mediterranean being controlled by Late Jurassic–Early Cretaceous sinistral strike slip faulting along the so-called eastern Mediterranean shear zone (EMSZ). One of the proposed sinistral strike-slip faults zones within the EMSZ, the eastern Mediterranean south transform (EMST), was traced along the northern coast of Libya and Egypt and continued into NE Sicily, and is a prominent feature in the free-air gravity maps (Sandwell and Smith, 2009; Cowie and Kusznir, 2012; Sandwell et al., 2014). Le Pichon et al. (2019) postulated the existence of two other sinistral transform fault zones to the north of the EMST with all three postulated Mesozoic sinistral transform faults considered to lie along small circles about a common Euler pole of rotation, estimated to be at 52°N 39°E in the Central Russian Uplands, south of Moscow.

4. Subduction of continental mantle lithosphere beneath the Tyrrhenian Sea and the Aeolian Arc

Part of the rationale for the existence of a Mesogea Ocean is the perceived requirement for oceanic lithosphere in the Ionian Sea to feed modern subduction along the Aeolian Arc and create the inclined zone of seismicity beneath the Tyrrhenian Sea. Popular models for the development of the Tyrrhenian Sea (e.g., Alvarez et al., 1974; Scandone, 1979; Malinverno and Ryan, 1986; Doglioni, 1991; Gueguen et al., 1998; Catalano et al., 2001; Faccenna et al., 2001, 2004; Rosenbaum et al., 2002, 2004; Handy et al., 2010; Carminati et al., 2012; Malinverno, 2012) postulate that oceanic crust of Mesogea separating Adria (Apennines) and Africa (Sicily) was subducted westwards from late Oligocene-early Miocene time (Fig. 2b). In these models, the Calabrian volcanic arc (attached to Sardinia until earliest Miocene) collided with the Adria (Apenninic and Sicilian) continental margin in the Burdigalian (Early Miocene) (Fig. 6). Soon after the initial collision, in mid-Tortonian (Late Miocene), the collision suture evolved into extension driving further thrusting in the surrounding Calabrian arc and leading to present-day oceanic rifting in the Tyrrhenian Sea (Fig. 6). According to the consensus model, the Calabrian Massif now occupies the "gap" between two distinct facing Mesozoic continental margins (Sicilian and

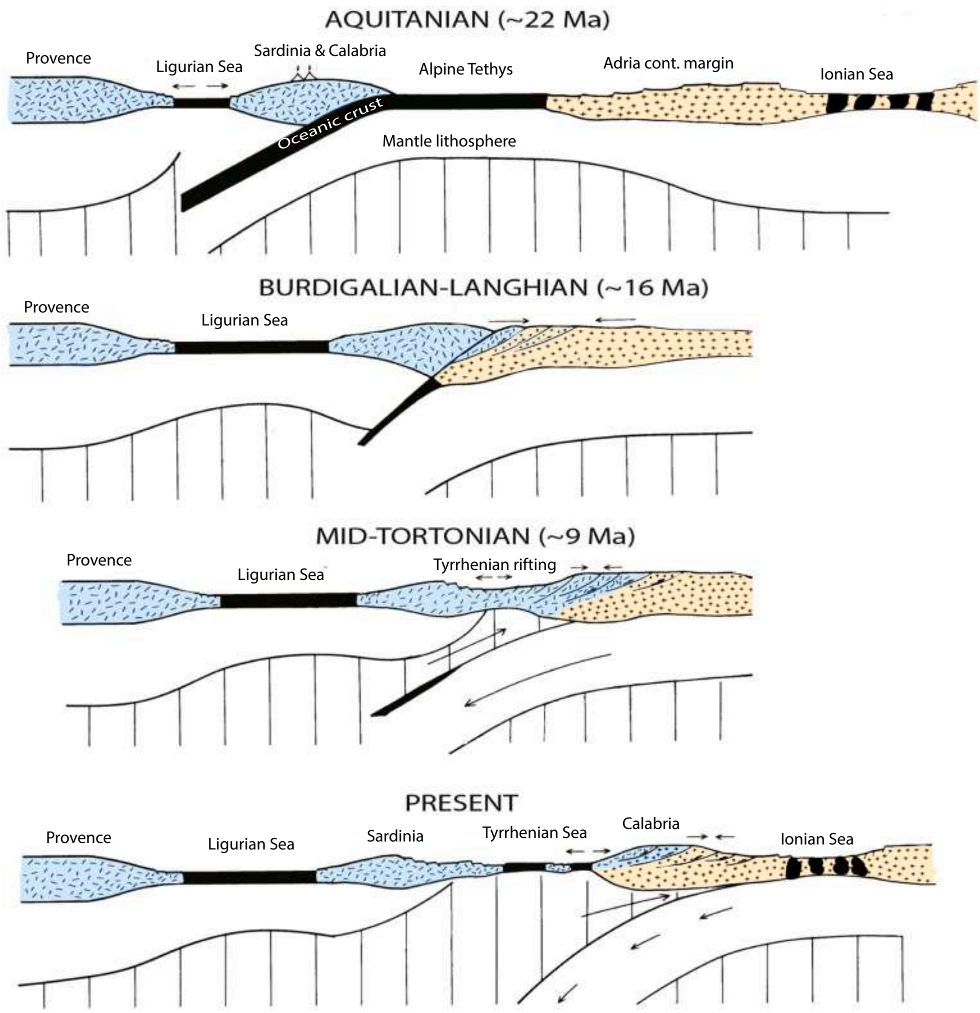

Fig. 6. Interpretive cross sections for intervals of the Miocene, and for the present, for a cross-section from the coast of Provence (France) to the Ionian Sea crossing the Ligurian Sea, Sardinia, Tyrrhenian Sea and Calabria (see Fig. 1) (after Channell and Mareschal, 1989). Blue (orange) represent continental crust of European (African/Adria) origin. Black represents oceanic crust with the Ionian Sea represented as transitional crust between thinned continental and oceanic. Vertical lines represent asthenosphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Southern Apennine) once occupied by Mesogea (Fig. 2b), and the basement of the modern Ionian Sea is a remnant of it. Thrusting in the Apenninic-Sicilian fold and thrust belt is coeval with, and therefore driven by, extension in the Tyrrhenian Sea. As noted by Malinverno and Ryan (1986), the estimated southeastward extension in the Tyrrhenian Sea (~500 km) is similar in scale to the estimated shortening along two cross-sections in the Southern Apennines thrust belt (D'Argenio et al., 1975). Similarly, collision of the Corsican volcanic arc with the continental margin of Adria in late Oligocene led to the onset of thrusting in the Northern Apennines that was shortly thereafter affected by early Miocene to Quaternary extension (e.g., Carmignani and Kligfield, 1990). The locus of extension moved progressively eastward, driving thrusting into the Adriatic foreland (e.g., Carmignani et al., 1994; Keller et al., 1994; Frepoli and Amato, 1997). Late Oligocene to Quaternary thin-skinned thrusting, driven both by the initial (late Oligocene) collision, and by subsequent extensional phases, produced predominantly counterclockwise thin-skinned rotations detected by paleomagnetism in the eastward vergent nappes of the Northern Apennines and Umbria (e.g., Channell et al., 1978a; Muttoni et al., 2000) and Southern Apennines (e.g., Scheepers and Langereis, 1994). Large magnitude earthquakes in the Northern Apennines are most often associated with shallow normal faults denoting E-W extension of the thrust belt. Apennine extension extends southward and merges into on-going oceanic extension in the Tyrrhenian Sea.

Seismicity in the Aeolian Arc, which extends to depth below the Tyrrhenian Sea, is traditionally interpreted as denoting a subducted slab of Mesogea (Ionian and eastern Mediterranean oceanic lithosphere) dipping to the Northwest. Some NW-SE oriented cross-sections across Calabria indicate a steeply inclined (50°-60° dip) Benioff Zone, more or less continuous earthquake foci and high P-wave velocities (*Vp*) to depths of ~300 km (Chiarabba et al., 2008; Neri et al., 2009). More recent interpretations imply more discontinuous *Vp* anomalies and earthquake foci, with necking and partial or total detachment of the subducted slab (Neri et al., 2012; Scarfì et al., 2018; Presti et al., 2019). Below 300 km depth, earthquake events are infrequent and locations of foci imply radical reduction in dip of the subducting slab (Chiarabba and Palano, 2017). The lack of shallow seismicity, particularly from thrust faults at the surface projection of the slab, may indicate that subduction has now ceased (Anderson and Jackson, 1987) or is at least locked (Sgroi et al., 2021). Modern uplift rates in Calabria exceed 2 mm/yr, approximately double mean uplift estimates based on identification of marine terraces associated with the last interglacial stage (Westaway, 1993; Antonioli et al., 2006), implying accelerated Holocene uplift and possibly recent slab detachment and rebound (see Hippolyte et al., 1994).

Extension along the collision suture (from early Miocene) and the rapid evolution from continental rifting to on-going oceanic rifting in the Tyrrhenian Sea (Fig. 6) is often viewed (e.g., Alvarez et al., 1974; Malinverno and Ryan, 1986; Doglioni, 1991) as western-Pacific-type back-arc (marginal) basin extension (e.g., Hsui and Toksoz, 1981; Sdrolias and Muller, 2006) with the Calabrian-Aeolian Arc being the active volcanic arc, Sardinia being the remnant arc, with Tyrrhenian extension driven by roll-back of the hinge of the subducting Ionian oceanic lithosphere. The same mechanism is often invoked for middle

Miocene to Recent extension in the Aegean Sea with extension driven by roll-back of Hellenic subduction, supposing the existence of oceanic basement in the eastern Mediterranean. On the other hand, van Hinsbergen et al. (2005) considered that the subducted slab in the Hellenic Arc is comprised entirely of continental mantle lithosphere that was the substrate of the sedimentary thrust-sheet pile in the accretionary prism.

Here, we refer to basins formed along Alpine continental collision sutures shortly after the culmination of the shortening (such as the Alboran, Aegean, Pannonian and Tyrrhenian basins in the Mediterranean region) as “episutural” basins (terminology after Bally et al., 1982). An important question is whether western-Pacific-type roll-back of subducting oceanic lithosphere remains a relevant mechanism to explain Mediterranean episutural basins. Roll-back of the hinge of the subducting slab, in a Western Pacific context, requires active subduction of oceanic lithosphere (see Hsui and Toksoz, 1981). In the case of the Pannonian Basin, there was no *in situ* oceanic lithosphere available for subduction at the time of basin extension, and, therefore, some models for basin extension have involved steepening of the dip of the subducted slab after cessation of oceanic subduction (Royden et al., 1982, 1983).

Continental mantle lithospheric delamination, whereby the mantle lithosphere separates from the overlying continental crust and descends into the underlying asthenosphere, has been advocated as an important process controlling uplift and the overall stress field in mountain belts since the 1970s (e.g., Bird, 1978, 1979; Houseman et al., 1981; Fleitout and Froidevaux, 1982; Meissner and Mooney, 1998; Gogus and Pysklywec, 2008; Gogus et al., 2011). Mantle lithospheric roots in mountain belts provide a mechanism for maintaining convergence in mountain belts in cases where the mantle lithospheric root is intact (e.g. Swiss Aps, see Fig. 7). Delamination of a mantle lithospheric root leads to rapid (within a few Myrs) evolution of mountain-belt convergence into regions of extension as seen in Mediterranean episutural basins such as the Tyrrhenian, Aegean, Pannonian and Alboran. The regions of extension drive further thrusting in the surrounding arcs (e.g., the Calabrian Arc). Lithospheric delamination is restricted to continental lithosphere because of the contrast in strength-depth profile for oceanic and continental lithosphere (see Molnar, 1988; Meissner and Mooney, 1998). Delamination has been postulated to account for uplift and extension of the Colorado and Tibetan plateaus (Bird, 1978, 1979; England and Houseman, 1989; England, 1993; Kosarev et al., 1999; Levander et al., 2011). Dewey (1988) invoked “extensional collapse of orogens” to explain localized regions of extension within mountain belts not only in the Mediterranean region (Alboran, Tyrrhenian, Pannonian and Aegean basins) but also in the Tibetan Plateau, the Basin and Range province of the western US, and in the Altiplano of the central Andes.

Mantle lithospheric delamination has worked its way into discussions of Apennine tectonics (e.g., Fig. 8, modified after Serri et al., 1993) to explain geochemical and isotopic characteristics of Miocene to Recent magmatism, seismicity, mantle tomography, and eastward migration of coeval extension and compression from the Corsica-Sardinia-Adria suture into the Adriatic (Adria) foreland (Reutter et al., 1980; Channell, 1986; Wang et al., 1989; Serri et al., 1993; Keller et al., 1994; Frepoli and Amato, 1997; Aoudia et al., 2007; Roure et al., 2012; Argnani, 2012; Chiarabba and Chiodini, 2013; Chiarabba et al., 2014; Koulakov et al., 2015; Li et al., 2016; Caracausi and Sulli, 2019; D’Acquisto et al., 2020). Continental lithospheric delamination has also become central to tectonic models for the Neogene evolution of the Alboran Sea (Platt and Vissers, 1989; Docherty and Banda, 1995; Seber et al., 1996; Molnar and Houseman, 2004; Duggen et al., 2005; Pérouse et al., 2010; De Lis Mancilla et al., 2013; Timoulali et al., 2014; Baratin et al., 2016; Heit et al., 2017; Spakman et al., 2018), although for counter arguments see Doglioni et al. (1997). Continental lithospheric delamination has also entered the debate over the formation of the Pannonian Basin (Knapp et al., 2005; Houseman and Gemmer, 2007; Bennett et al., 2008; Lorinczi and Houseman, 2009; Matenco and Radivojević, 2012; Balling et al., 2021) and the Aegean Sea (Mantovani et al., 1997; van Hinsbergen et al., 2005; Roure et al., 2012). In the context of the Tyrrhenian Sea, Channell and Mareschal (1989) applied finite element analysis to demonstrate that continental mantle lithospheric delamination, triggered by localized lithospheric thickening, can rapidly change a region of compression into a region of extension, and that the extension can drive further shortening in a surrounding thrust belt. In the Tyrrhenian region, initial collision of the Sardinia-Calabria volcanic arc with the margin of Adria occurred in the early Miocene, followed by the mid-Miocene onset of extension and on-going contemporaneous extension

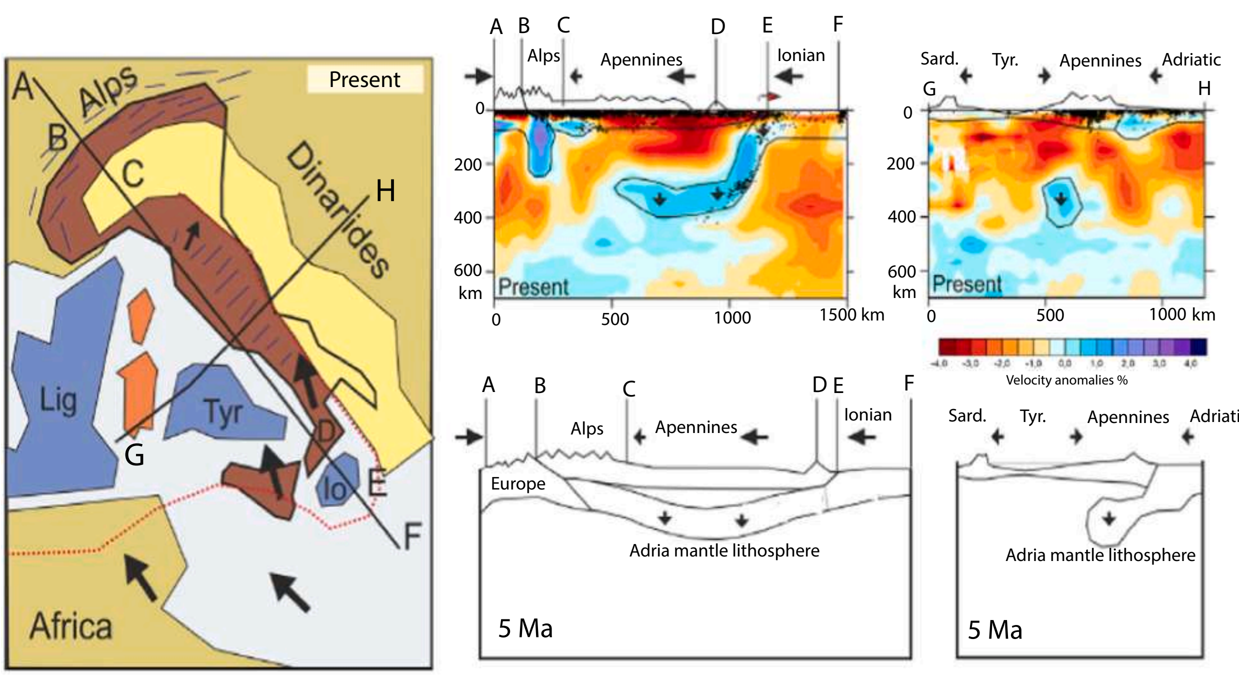

Fig. 7. Cross-sections along two lines from Europe and the central (Swiss) Alps to the Ionian Sea (A-F), and across the central Apennines from Sardinia to the Dinarides (G-H) based on *P*-wave velocities from seismic tomography (diagram after Koulakov et al., 2015). Interpretations for Present and for 5 Ma. Abbreviations: Lig: Ligurian Sea, Tyr: Tyrrhenian Sea, Io: Ionian Sea.

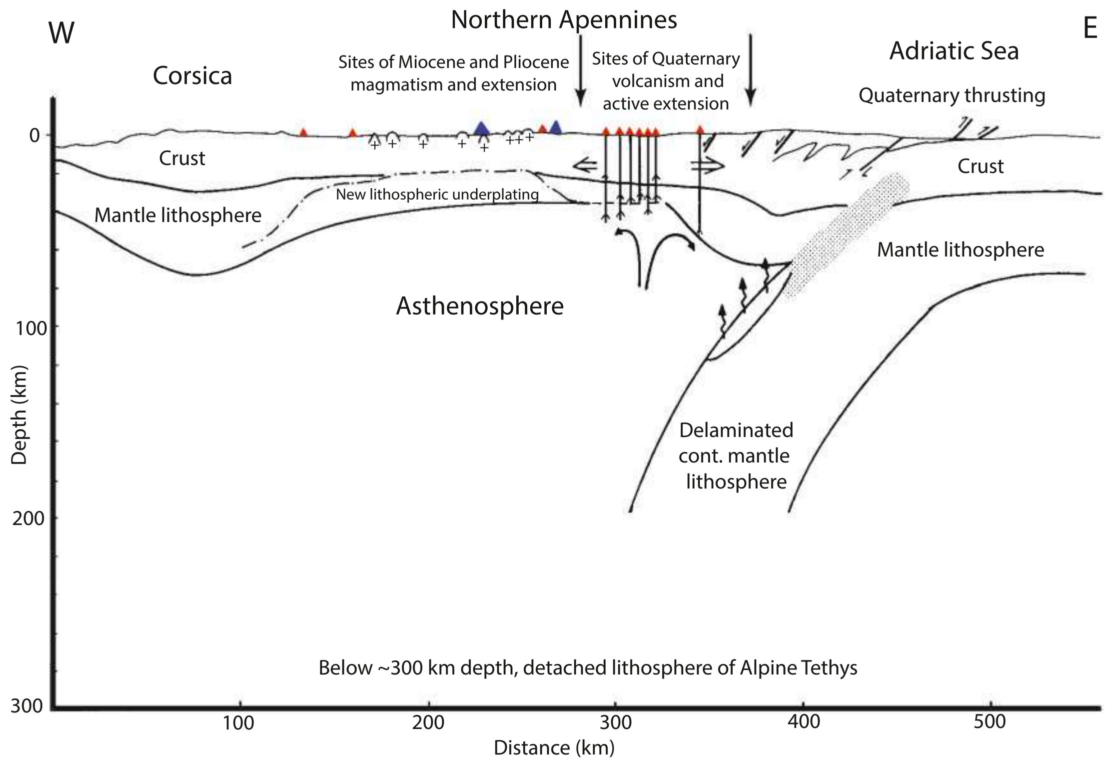

Fig. 8. Interpretative E-W cross-section across the Northern Apennines for the Quaternary (diagram after Serri et al., 1993) indicating sites of late Miocene and Pliocene acidic plutons (crosses), Pliocene acidic volcanics (large blue triangles), Quaternary volcanic centers containing mantle-derived magmas (closed small red triangles with root-type arrows indicating source depth estimates). "New lithospheric underplating" took place from late Miocene to Present, with delamination of continental mantle lithosphere of Adria and, at depth, postulated remnant of lithosphere of Alpine Tethys. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and thrusting (Fig. 6).

Kay and Kay (1993) made the case for "delamination-related" magmatism in the central Andes, beneath the Altiplano, that included shoshonitic lavas with high K and incompatible element contents, and steep rare earth element (REE) patterns. Plio-Quaternary calc-alkaline to ultrapotassic lavas of the Roman and Phlegraean (Neopolian) magmatic provinces of the central Apennines are genetically related to recent Aeolian volcanism off Calabria characterized by calcalkaline to shoshonitic lavas (e.g. Peccerillo, 1985, 2001, 2005). These volcanic centers have been associated with both shallow mantle sources and continental rifting (Fig. 8) (Serri et al., 1993; De Astis et al., 2003; Zamboni et al., 2016), and with mantle outgassing as a result of delamination of continental mantle lithosphere (Chiarabba and Chiodini, 2013; Caracausi and Sulli, 2019). Shoshonitic lavas have been associated with the terminal stages of oceanic lithospheric subduction (e.g., Morrison, 1980), and the onset of continental mantle lithospheric delamination beneath both the Tibetan Plateau (e.g., Turner et al., 1992, 1996) and the Alboran Sea (Duggen et al., 2005).

Seismic tomography in the Mediterranean region has often been interpreted to indicate subduction of partially detached *oceanic* lithosphere with "slab-tear" migration and location of "slab windows" controlling arc curvature (e.g. Spakman et al., 1988, 1993; Bassi et al., 1997; Carminati et al., 1998; Wortel and Spakman, 2000; Rosenbaum and Lister, 2004; Chiarabba et al., 2008; Faccenna et al., 2014b; Gutscher et al., 2016). According to Wortel and Spakman (2000), beneath Mediterranean "episutural" basins, "*the geometry of the high velocity anomalies in the upper mantle ….. appear to rule out (continental lithospheric) delamination*". Conversely, seismic tomography in the Tyrrhenian region has been interpreted to indicate a steeply-dipping 150-200-km thick partially detached "sausage" of continental mantle lithosphere, the former substrate of the Adria continental margin, to depths of ~400 km that expands at this depth horizontally over a distance of ~400 km beneath the Tyrrhenian Sea (Fig. 7; Koulakov et al., 2015). Following subduction of Alpine Tethys situated between the Adria continental margin and the Calabria-Sardinia-Corsica volcanic arc (Fig. 6), the continental mantle lithosphere beneath the Apennines is thought to have delaminated with recent slab detachment (Koulakov et al., 2015). Along strike of Apennine delamination and contiguous with it, mantle lithospheric subduction beneath Calabria is apparently "locked" (Sgroi et al., 2021) with necking and sinking of the slab underway (Neri et al., 2012; Koulakov et al., 2015; Scarfi et al., 2018; Presti et al., 2019) (Fig. 7).

5. Atlantic seafloor spreading and Jurassic Mediterranean sinistral transcurrent faulting

Since the pioneering work of Pitman III and Talwani (1972), Atlantic spreading history has been progressively refined mainly based on analyses of marine magnetic anomalies (e.g., Klitgord and Schouten, 1986; Srivastava and Tapscott, 1986; Srivastava and Verhoef, 1992; Srivastava et al., 2000; Bird et al., 2007; Schettino and Turco, 2009; Labails et al., 2010; Vissers et al., 2013). Atlantic seafloor spreading provides the boundary conditions for Mediterranean tectonics because it provides a history of the relative motions of the bounding continental landmasses of Africa and Europe (Dewey et al., 1973). Below, we use an age of 203 Ma for the age of maximum closure in the central Atlantic (Labails et al., 2010), 170 Ma for the Blake Spur Magnetic Anomaly (BSMA) (Klitgord and Schouten, 1986), and 154 Ma and 121 Ma for magnetic anomalies M25 and M0, respectively (Channell et al., 1995).

Our paleogeographic modelling (Figs. 9 and S1) covers the interval from the closure fit of North America and Africa in the latest Triassic (203 Ma) and the ensuing initial phase of seafloor spreading until the mid-Cretaceous at 121 Ma, shortly before the onset of North Atlantic spreading between North America and Eurasia. Using Euler

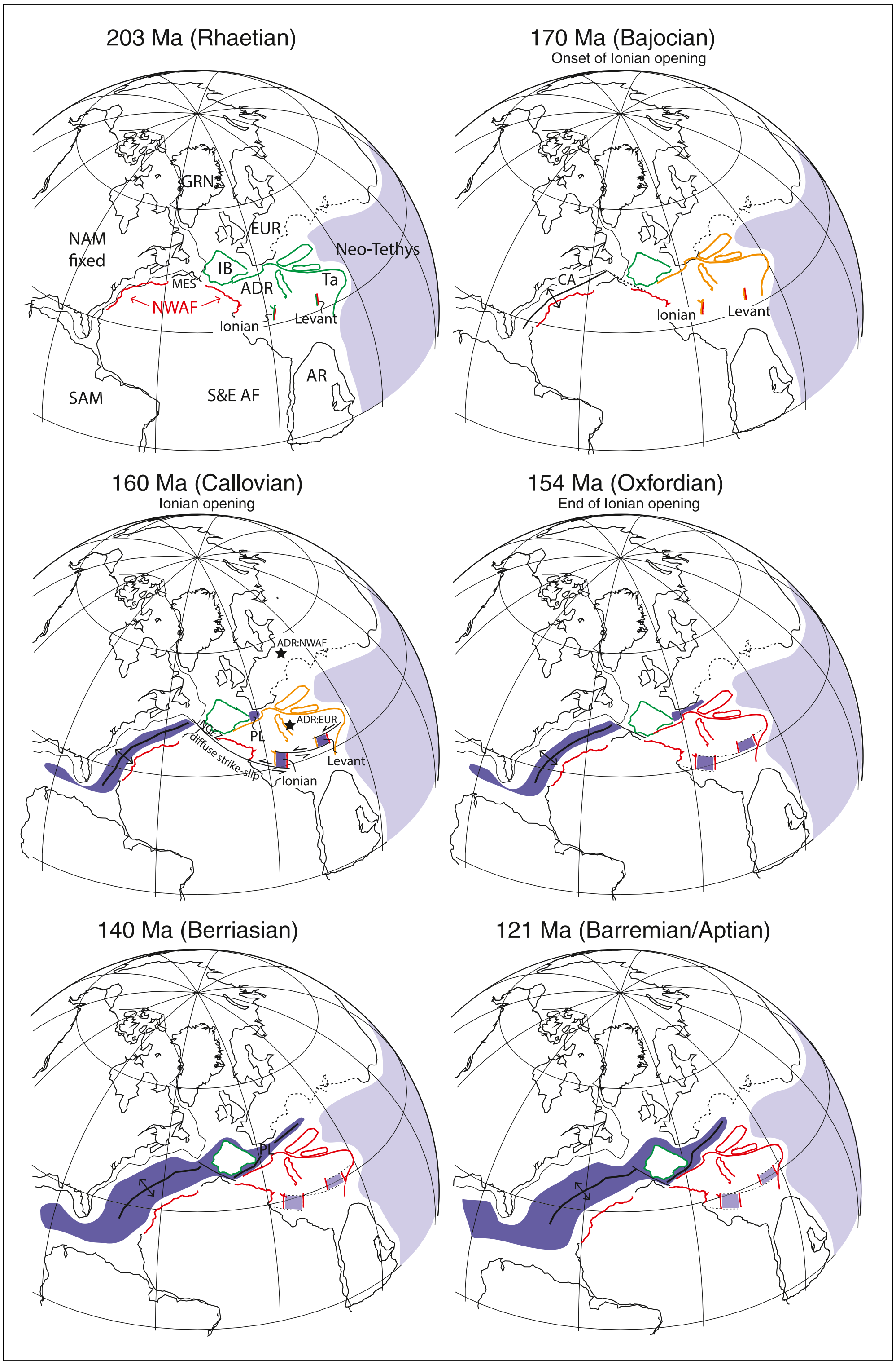

Fig. 9. Map sequence for 203 Ma (Rhaetian), 170 Ma (Bajocian), 160 Ma (Callovian), 154 Ma (Oxfordian), 140 Ma (Berriasian), 121 Ma (Barremian/Aptian). Reconstructions relative to a fixed North America based on Euler rotation poles listed in Table 1. In this scenario, Adria (ADR) moved with Iberia (IB) from the start of Central Atlantic rifting (203 Ma) until 170 Ma (Bajocian), then with Northwest Africa (NWAF) from Oxfordian (154 Ma) until present. The motion of Adria in the intervening interval (170–154 Ma), between the Blake Spur magnetic anomaly (BSMA) and anomaly M25 in the Central Atlantic, is interpolated. The interpolation results in the opening of the Piemonte-Ligurian (PL) Ocean and the eastern Mediterranean pull-apart basins including the Ionian and Levant basins along a sinistral strike-slip fault zone oriented according to the Adria-NWAF stage pole shown by black star in the 160 Ma (Callovian) frame. The 170–154 Ma ADR-EUR stage pole describing the opening of the infant Alpine Tethys is also shown. Colors of plate outlines are intended to show motion coupling (e.g., ADR and IB are coupled at 203 Ma (green outline); and since 154 Ma, ADR is coupled with Africa (red outline)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reconstruction poles for NAM/IB (North America/Iberia) and NAM/NWAF (NW Africa) (Table 1; Labails et al., 2010; Vissers et al., 2013), we hypothesize that Adria (ADR) moved with Iberia (IB) early in Atlantic spreading history (203–170 Ma), a motion that was different from that of NWAF at that time (Vissers et al., 2013), and then with NWAF from mid-Jurassic time (M25 time at 154 Ma). The intervening interval between the BSMA at 170 Ma and the oldest easily recognizable M-sequence magnetic anomaly (M25) at 154 Ma features no clearly lineated magnetic anomalies (formerly referred to as the Jurassic Quiet Zone) and therefore is poorly defined in Atlantic spreading history. ADR motion relative to NWAF in this interval (170–154 Ma) is estimated by linear interpolation between estimated positions at 170 Ma and 154 Ma (Labails et al., 2010; Vissers et al., 2013). Spreading velocities in the Central Atlantic (NAM/NWAF) increased abruptly at 170 Ma and remained about 4× greater than the velocities in the NAM/IB sector until ~154 Ma when velocities in the two sectors became similar at ~15 mm/yr (see Fig. 6 of Vissers et al., 2013). As a result, sinistral strike-slip relative motion between NWAF and ADR, and the hypothesized pull-apart extension in the Ionian-Herodotus-Levant basins, began at this time (170 Ma) as did rifting in the Piemonte-Ligurian (PL) Ocean (Alpine Tethys) between Adria and Europe (Fig. 9). From 154 Ma (M25 time), Adria is constrained to move in synch with Africa and, therefore, Ionian-Levant pull-apart extension ceased (Fig. 9). As the NAM/IB and NAM/NWAF spreading velocities are similar after 154 Ma, until the onset of NAM/EUR spreading in the mid-Cretaceous, similar kinematics would result from Adria moving with Iberia until mid-Cretaceous time. A small circle around the ADR/AFR Euler stage pole for the 170–154 Ma interval (55.65°N, 11.93°W, $\Omega = 11.89°$), determined from Table 1, yields the orientation of the sinistral strike-slip fault system that formed the Ionian-Herodotus-Levant pull-apart basins (Figs. 4 and 9).

The width of a transition zone from thicker to thinner crust can help to determine whether a continental margin was associated with a transform or rifted margin. The short-lived pull-apart activity in the Ionian Sea, here constrained to 170–154 Ma, would likely have been associated with abrupt transition zones along the strike-slip boundaries of the pull-apart basins, and have had minor effect on the sedimentary facies on the Mesozoic continental margin of Adria in Sicily and the Southern Apennines. This would not have been the case for a long-lived Mesogea Ocean connecting Neo-Tethys in the east to Alpine Tethys in the west (Fig. 2b). As discussed above, the sequential Mesozoic and early Cenozoic facies development of the Adria continental margin in Sicily and the Southern Apennines clearly responded predominantly to an ocean to the west (Alpine Tethys).

Oldest sediments overlying oceanic basement in the abyssal Ionian Sea have been interpreted as Early and Middle Jurassic in age (Dannowski et al., 2019; Tugend et al., 2019), coeval with an intense phase of NW-SE extension in the Levant basin (Gardosh et al., 2010). The string of pull-apart basins in the eastern Mediterranean, not necessarily all floored by oceanic basement, would have connected Atlantic spreading to the Neo-Tethys in the East (e.g., Frizon de Lamotte et al., 2011). Radiometric ages from ophiolite exposures in the western Alps span the 170–150 Ma interval (Costa and Caby, 2001), consistent with the proposed early phase of rifting in Alpine Tethys. Based on an alternative scenario in which Adria moved with NW Africa throughout the Mesozoic and Cenozoic, spreading rates in Alpine Tethys (Piemonte-Ligurian Ocean) would have increased abruptly at ~170 Ma and decreased sharply toward the end of the Jurassic at ~148 Ma (Fig. 6 of Vissers et al., 2013). Reconstructions in which Adria behaved as a fixed, rigid promontory of the NW Africa (e.g., Vissers et al., 2013) are not preferred here partly because of the resulting overlap of palinspastically-restored continental margins of Adria and Europe-Iberia in Triassic (Pangea A) configurations (see Wortmann et al., 2001). This overlap is relieved by the kinematics advocated here, which also account for the formation of Early Jurassic "oceanic" basement in the Ionian Sea.

Diffuse sinistral strike-slip with NW-SE extension characterizes the Atlas Mountains of Morocco, Algeria, and Tunisia from mid-Jurassic

Table 1
Euler reconstruction poles used for the paleogeographic sequence in Fig. 9. Adria (ADR) moved with Iberia (IB) from 203 Ma to 170 Ma. ADR moved with NW Africa (NWAF) from 154 Ma to Present. Between 170 Ma and 154 Ma (Blake Spur Magnetic Anomaly to Anomaly M25), the motion of Adria is linearly interpolated.

Age Ma	NW AFRICA & E side of Ionian			MESETA			NE & S AFRICA			ADRIA & W side of Ionian			ARABIA			S AMERICA			IBERIA		
	Lat N	Long E	Rot	Lat N	Long E	Rot	Lat N	Long E	Rot	Lat N	Long E	Rot	Lat N	Long E	Rot	Lat N	Long E	Rot	Lat N	Long E	Rot
125	65.95	−20.46	−54.56	67.17	−19.51	−53.01	64.88	−19.46	−55.76	65.95	−20.46	−54.56	−62.59	164.41	58.93	−22.15	−85.61	15.17	64.71	−18.94	−58.11
150	66.08	−18.44	−62.80	66.61	−17.66	−61.83	65.11	−17.83	−64.00	66.08	−18.44	−62.80	−62.95	165.14	67.19	−41.68	−104.23	19.02	−65.56	163.34	64.83
154	67.10	−15.86	−64.23	68.52	−13.69	−61.75	66.13	−15.43	−65.43	67.10	−15.86	−64.23	−63.94	167.18	68.64	−41.81	−105.48	21.08	−66.18	164.26	63.74
170	67.09	−13.86	−70.55	69.47	−9.56	−66.59	66.19	−13.68	−71.76	−69.14	169.49	58.94	−64.11	168.30	74.99	−48.23	−117.41	25.82	−69.14	169.49	58.94
190	64.31	−15.19	−77.09	66.31	−11.78	−72.95	63.51	−15.03	−78.33	−65.81	166.64	65.36	−61.62	166.71	81.59	−52.79	−137.54	29.42	−65.81	166.64	65.36
203	64.28	−14.74	−78.05	66.23	−11.28	−73.91	63.49	−14.61	−79.29	65.72	−12.82	−66.32	−61.61	167.04	82.56	−52.80	−138.86	30.32	65.72	−12.82	−66.32

Notes
EUROPE to North America (NAM) fit: Lat = 72.8 N, Long = 154.7E, Rot −24.3 (Rowley and Lottes, 1988);
GREENLAND to NAM fit: Lat = 63.8 N, Long = 228.6E, Rot −10.9 (Rowley and Lottes, 1988);
NW AFRICA & East (E) side of Ionian, and MESETA to NAM: Labails et al. (2010);
NE & S AFRICA, and ARABIA to NAM: Besse and Courtillot (2002) into NW AFRICA plus Labails et al. (2010) into NAM;
S AMERICA to NAM: Nuernberg and Müller (1991) into NW AFRICA plus Labails et al. (2010) into NAM;
ADRIA & West (W) side of Ionian to NAM: from 203 Ma to 170 Ma attached to IBERIA, from 154 Ma to 125 Ma attached to NW AFRICA;
IBERIA to NAM: Vissers et al. (2013).

time until the mid-Cretaceous when Africa-Europe relative motion became compressive and the Tell and Atlas underwent N-S shortening (see Piqué et al., 2002). The southeastward motion of Africa relative to Europe that dominated the Jurassic period underwent progressive change by the time of the Cretaceous magnetic quiet-zone that extends between marine magnetic anomaly M0 (~121 Ma) and anomaly C34 (~84 Ma), within which the NAM/EUR segment of the North Atlantic began rifting. From sometime between M0 and C34 (121–84 Ma), as separation of NAM and EUR progressed, the motion of Africa relative to Europe became progressively more northerly heralding a change from sinistral E-W strike-slip to N-S compression along the complex Africa/Europe boundary (e.g., Dewey et al., 1989; Rosenbaum et al., 2002). An important phase of Late Cretaceous (Coniacian-Campanian) deformation affected the northern coast of Libya, Egypt and the coast of the Levant, eventually connecting to the Taurus and Zagros collision belts (the Ayyubid orogeny of Sengör and Stock, 2014). The Late Cretaceous encompasses both the spreading age and the emplacement age of the Troodos (Cyprus) ophiolite along a south-vergent fold and thrust belt (Cyprus Arc) and the emplacement of ophiolitic fragments of Neo-Tethys at Baer-Bassit in Syria and Hatay in Turkey (Robertson, 2000; Garfunkel, 2004; Maffione et al., 2017).

6. Paleomagnetic and GPS data, and the rotation of Adria with respect to Africa

GPS data pertaining to modern displacements of Adria have led to a wide range of interpretations. Part of the discrepancy in interpretation may be due to fact that GPS stations were sometimes placed in actively deforming zones, and the data were therefore relevant to local thrust-sheet displacements but not to autochthonous Adria. Whereas Babbucci et al. (2004) found no evidence for relative motion of Adria and Africa from earthquake slip-vectors and geodetic (GPS) data, Oldow et al. (2002) subdivided Adria into NW and SE parts, approximately along the Anzio-Ancona line, based on "African" motions in the SE part (~10 mm/yr NE relative to Europe) and little or no motion relative to Europe in the NW part. Battaglia et al. (2004) interpreted GPS data to indicate Africa (Nubia) moving NW at 6 mm/yr with respect to Eurasia and Adria moving to the NE at 4–5 mm/yr, with the proposed detachment between the two being along the Apulia Escarpment, the northern boundary of the Ionian Sea. Several authors have made the case for geodetic and seismotectonic data being consistent with counterclockwise rotation of the "Adriatic microplate" around a pole located in the western Po Plain with the southern boundary of the microplate being either in the central Adriatic Sea (Calais et al., 2002; D'Agostino et al., 2008), or south of Apulia along the Apulian Escarpment (Serpelloni et al., 2005). Elevated seismicity in the central Adriatic Sea along a line between Pescara and Split (north of Gargano) has been interpreted as thin-skinned without involvement of basement (Scrocca et al., 2005) and as deformation affecting the entire crust (Scisciani and Calamita, 2009).

Estimation of amounts of extension and shortening along specific cross-sections across the Apennines, Dinarides and Hellenides (Fig. 1) have led to an estimate of $5 \pm 3°$ counterclockwise rotation of Adria relative to Europe since 20 Ma (Le Breton et al., 2017). Estimates of shortening (as well as extension) can obviously be grossly inaccurate without precise knowledge of subsurface structure.

It has long been appreciated that Late Paleozoic and Mesozoic paleomagnetic poles of good quality from stable Adria have close affinity with those from Africa, and the rest of the reconstructed Gondwana continents, but systematically differ from those from Europe (Zijderveld et al., 1970; Channell and Horvath, 1976; Channell, 1996; Muttoni et al., 1996). Adria poles are, however, typically excluded from global composite apparent polar paths (e.g., Torsvik et al., 2012) because of uncertainty about their applicability to NW Africa. Domeier et al. (2021) noted that Ionian Sea extension would have affected pre-extension paleomagnetic data from Adria, although the magnitude of the effect would, of course, depend on the magnitude of the Adria-Africa rotation and location of the Euler pole.

Some workers have interpreted paleomagnetic data from Adria to indicate large-scale Cenozoic rotation of Adria relative to (NW) Africa. Although these studies have largely been superseded, they should be discussed here because such paleomagnetic interpretations, and interpretations of GPS data implying present-day rotations (e.g., Calais et al., 2002; Battaglia et al., 2004), have been incorporated into some tectonic models for the Alps and Carpathians (e.g., Ustaszewski et al., 2008).

Cenozoic counterclockwise rotations of Adria relative to both Africa and Europe were first advocated in the 1970s (Soffel, 1972, 1975; Lowrie and Alvarez, 1975; VandenBerg and Wonders, 1976; VandenBerg et al., 1978), however, these interpretations were based on a lack of appreciation of thrust-sheet kinematics in Umbria (Italy), incorrect interpretation of the age of volcanism at Colli Euganei and Monti Lessini (Veneto, Southern Alps) (Channell et al., 1978b; Channell et al., 1979), and perhaps most importantly, poor control on reference directions for NW Africa. Since the 1970s, paleomagnetic data from NW Croatia and NE Slovenia (Istria) (Márton and Veljovic, 1983) and from Apulia/Gargano (Channell, 1977; Vandenberg, 1983) were interpreted as indicating Cenozoic counterclockwise rotation of the most of Adria, that between the Southern Alps and Sicily, relative to Africa by ~17° (Lowrie, 1986). Márton and Nardi (1994), based on further paleomagnetic studies in Apulia, concluded that "*the case for net CCW rotation of the 'hard core' of the Adriatic region, with respect to Africa, since the late Cretaceous is established*", however, the African reference directions used for the study (from Lowrie, 1986) are entirely responsible for the postulated rotation. More recently, Maastrictian and Paleogene carbonates of Istria have been restudied to infer that Adria rotated counterclockwise by ~27° relative to Africa (and stable Europe) in Late Miocene and Early Pliocene time (Márton et al., 2003). Subsequent studies in the same region were interpreted in terms of a post-Coniacian (Late Cretaceous) ~10° counterclockwise rotation of Adria with respect to Africa (Márton et al., 2008). Farther west, in the region of Veneto, paleomagnetic data were interpreted in terms of ~20° *clockwise* rotation of Adria relative to Africa in Late Cretaceous to mid-Eocene time with subsequent post-Eocene ~30° *counterclockwise* rotation (Márton et al., 2010, 2011). Again, the outdated Africa reference directions used in these studies are largely responsible for the inferred rotations. Paleomagnetic studies in the same region (Veneto/Trentino) had, many years before, inferred that there was no evidence for coherent rotation relative to Africa (e.g., Channell et al., 1978b; Channell et al., 1992; Channell and Doglioni, 1994), and similar conclusions were drawn more recently from Paleocene-Eocene paleomagnetic data (e.g., Dallanave et al., 2009). Paleomagnetic data from Apulia (autochthonous southern Adria) have been re-evaluated with the addition of new data (van Hinsbergen et al., 2014, 2020). These authors inferred a barely resolvable post-Eocene counterclockwise rotation of Apulia of $9.8 \pm 9.5°$ relative to Africa. van Hinsbergen et al. (2014, 2020) used the African (Gondwana) apparent polar wander path (APWP) of Torsvik et al. (2012) to provide their NW African reference directions, however, recent refinements of African reference directions (Channell et al., 2010; Muttoni et al., 2013; Muttoni and Kent, 2019b; Kent and Muttoni, 2020) lead to further minimization of relative rotation of Adria and NW Africa.

Wide-ranging reviews of Permian and younger paleomagnetic studies from the Southern Alps, stretching from Lombardy to Veneto, and from elsewhere in "autochthonous" Adria, have failed to document coherent rotations of Adria relative to NW Africa (Channell, 1996; Muttoni et al., 1996, 2001, 2013; Channell et al., 2010; Muttoni and Kent, 2019b; Kent and Muttoni, 2020). We do not reiterate these conclusions here other than to say that the tight coordination of Adria and NW Africa since the Permian has stood the test of time, of an expanded paleomagnetic database, and on-going refinement of rotation parameters allowing paleomagnetic data from outside NW Africa to be rotated into NW African coordinates. The discrepancy in interpretation of paleomagnetic data in terms of relative rotation of Adria with respect to Africa can be attributed to three factors: (1) thin-skinned tectonic rotation (allochthony) in the deformed continental margins of Adria where sedimentary cover is commonly detached from its basement, (2) insufficient distribution and numbers of sampling sites that failed to average out small-scale tectonic rotations, and (3) use of obsolete reference APWPs for NW Africa.

7. Paleomagnetic poles from Adria, Mediterranean kinematics, and Permian Pangea

As a test of the effect of the proposed Mediterranean kinematics on paleomagnetic data from Adria, we revisit a recent analysis (Kent and Muttoni, 2020) of Permian paleomagnetic poles from Adria and Africa (and the rest of Gondwana) for a time window of 20 Myr centered on 280 Ma in the Early Permian. We chose this interval because there are sufficient high quality Adria poles for comparison to those from NW Africa and the rest of Gondwana, and ultimately with contemporaneous high quality poles from Laurasia. If we can demonstrate that the proposed Mediterranean kinematics (Fig. 9) are consistent with the observed resemblance of *Permian* Adria and NW Africa paleomagnetic poles, then the proposed kinematics would also not have affected Adria paleomagnetic poles younger than Permian. In addition, demonstration that the proposed kinematics do not affect Permian Adria paleomagnetic poles, within assigned errors, can be viewed as support for the kinematic model itself.

There are seven high quality paleomagnetic poles from Adria for 270–290 Ma (Early Permian), and six from Gondwana (Table 2). Displacement between Adria and Gondwana poles might be expected due to the postulated opening of the Ionian basin in the Middle and Late Jurassic (170–154 Ma) described above. These 13 poles from Adria and Gondwana are plotted (Fig. 10a,b) after rotation to NW Africa coordinates using Option 1 and Option 2 parameters (Table 2). For Option 1 (from Kent and Muttoni, 2020), Adria moved throughout with NW Africa, whereas for Option 2 (this study) the postulated extension in the eastern Mediterranean (Ionian Sea) is taken into account. For Option 1 (Fig. 10a), there is insignificant difference of only 2.5 ± 8.5° between the mean 280 Ma poles from Adria (pLat = 42.7° pLon = 242.1°, A95 = 5.9°) and the selected (six igneous) poles from Gondwana rotated to NW Africa coordinates (pLat = 40.2° pLon = 242.5°, A95 = 6.1°). For Option 2 (Fig. 10b), using the modified plate tectonic reconstruction that incorporates the opening of the Ionian basin, the 280 Ma mean Adria pole is now shifted to pLat = 36.1° pLon = 252.9° (A95 = 5.9°) compared to a mean 280 Ma Gondwana pole in NW Africa coordinates that also shifts a few degrees due to relative motion of Meseta (see Table 2) and is located at pLat = 37.9° pLon = 244.3° (A95 = 5.9°). The arc distance between the Adria and NW Africa (Gondwana) poles is now larger than Option 1 because it includes relative motion associated with subsequent opening of the Ionian basin, but the difference of 7.1 ± 8.3° is not significant at the 95% confidence level. The statistical agreement of Adria and Gondwana mean poles for 280 Ma, after taking into account the proposed opening of the Ionian basin, argues against the claim that the Pangea B configuration in the Early Permian (280 Ma) is an artifact of Adria poles being used as a proxy for Gondwana (e.g., Domeier et al., 2021).

Torsvik et al. (2012) did not consider Adria poles in their paleogeographic reconstructions, and explicitly rejected a Pangea B configuration for the Late Carboniferous-Early Permian. Paleomagnetic poles for various continental elements are listed in Table 1 of Torsvik et al. (2012), from which a 280 Ma mean pole was determined for reconstructed Gondwana in their Table 7 based on 17 pole entries, the most numerous for any 20 Myr window between 200 and 550 Ma for Gondwana in their compilation. Most of the entries (12 of 17) are results from sedimentary rocks for which a blanket (uniform) correction for presumed inclination error (flattening factor, f = 0.6) was applied. As shown by Kent and Muttoni (2020), the mean 280 Ma pole of Torsvik et al. (2012) with 'corrected' sedimentary results in NW Africa coordinates gives a mean (north) pole position at pLat = 37.1° pLon = 230.5° (N = 17, K = 21, A95 = 7.4°) (Fig. 10c), which disagrees with large uncertainty by 11.4 ± 11.9° when compared to the mean Gondwana pole based on igneous results (and without Adria data) at pLat = 39.7° pLon-244.7° (*N* = 5, K = 134, A95 = 6.6°). The Euler poles for this 280 Ma reconstruction (Fig. 10c) are from Table 6 of Torsvik et al. (2012) and were used by these authors to support a Pangea A-type reconstruction at 280 Ma. An indication that blanket (uniform) adjustment for presumed inclination error may not be appropriate is that the overall uncertainty for the 280 Ma pole of Torsvik et al. (2012) becomes greater (A95 increases from 6.5° to 7.4°) after applying a blanket correction factor to the sedimentary results. Moreover, the mean pole for the twelve 'corrected' sedimentary results (pLat = 34.1° pLon = 230.9 °K = 26 A95 = 8.8°) differs by 14°, again with large uncertainty, from the mean pole for the five igneous results in their compilation (pLat = 38.3° pLon = 247.5 °K = 30 A95 = 14.1°), pointing to incompatible populations of generally poor-quality data. Yet the 280 Ma igneous pole of Torsvik et al. (2012) differs by only 2.6° from the 280 Ma Gondwana igneous pole of Kent and Muttoni (2020) (bearing in mind that 3 of the 5 poles are common). As shown below, both igneous mean poles for 280 Ma are compatible with Pangea B, as is the contemporaneous independent mean pole from Adria when treated as a proxy for Gondwana.

Similar arguments can be made for compatibility of paleomagnetic data with alternative Late Carboniferous Pangea configurations, the key issue again being the position of Gondwana based on different selection of poles. Torsvik et al. (2012) used 14 poles (listed in their Table 1) to calculate a mean 300 Ma Gondwana pole (their Table 7) and showed a Pangea A configuration at around the Carboniferous/Permian boundary in their Fig. 19. As for their 280 Ma mean Gondwana pole, most of the entries in their 300 Ma mean pole are from sedimentary results (10 of 14) for which a blanket correction factor (f = 0.6) was again applied. Kent and Muttoni (2020) assessed available Gondwana (and Laurasia) poles in a time window centered on 310 Ma, for which there is appreciable overlap in pole entries with the 300 Ma mean (and again no relevant paleomagnetic results from Adria). As was pointed out in Kent and Muttoni (2020), there is a strong deviating bias and more scatter introduced by 'correction' of the predominantly sedimentary results, as can also be seen in the wide scatter of the poles in the 300 Ma window of Torsvik et al. (2012), which according to their Fig. 19 would allow a Pangea A configuration at around the Carboniferous/Permian boundary. If instead, only the igneous subset of Gondwana poles is used, Pangea A is not feasible at 310 Ma or 300 Ma (or 280 Ma), whereas Pangea B is supported.

Torsvik et al. (2012, their Fig. 18) postulate a Pangea B-like juxtaposition of Gondwana and Laurasia at 350 Ma in the Early Carboniferous, prior to the Hercynian continental collision that formed Pangea. Similar Pangea B-like configurations have been proposed further back in the Paleozoic (e.g., McKerrow and Ziegler, 1972; Miller and Kent, 1988). Paleomagnetic data imply that the ~3500 km strike-slip transformation from Pangea B to Pangea A occurred not between 350 Ma and 300 Ma, within the Carboniferous, as supposed by Torsvik et al. (2012), but ~50 Myr later between 280 Ma and 260 Ma in the mid-Permian during the final stages of Alleghanian orogeny (e.g., Muttoni et al., 1996, 2003; Kent and Muttoni, 2020). The disputed time interval in the evolution of Pangea is the Early Permian, for which the available paleomagnetic data for Gondwana and Laurasia are relatively robust (see Haldan et al., 2014). For latest Permian and Triassic time, the basic configuration of Pangea (Pangea A) is not seriously disputed, even by the most recently available data (e.g., Kent et al., 2021). Our proposed reconstructions are shown (Fig. 11) for the Late Permian (Pangea A, 260 Ma) and for early Permian (Pangea B, 280 Ma).

In the 45 years since Pangea B was first proposed as a viable Permian paleogeography (Irving, 1977), the debate has not been universally settled. The debate has focused on several issues: (1) Permian

Table 2
Early and Late Permian paleomagnetic poles from Adria (ADR), South America (SAM), Australia (AUS), South Africa (SAF), NW Africa (NWAF), Moroccan Meseta (MES), NE Africa (NEAF), Europe (EUR), and North America (NAM). Reference numbers from Table S1 of Kent and Muttoni (2020). Option 1: Preferred option of Kent and Muttoni (2020) assuming ADR and MES moved with NWAF, paleomagnetic poles rotated to NWAF according to Euler poles of Lottes and Rowley (1990). Option 2: ADR rotated to NWAF using Euler poles of Labails et al. (2010) and Vissers et al. (2013) as follows: MES to NWAF (Labails et al., 2010) using 29.44 N, 12.12 W, Ω = 5.11° for age ≥203 Ma. ADR/IB to NAM (Vissers et al., 2013) plus NAM to NWAF: 55.63 N, 11.92 W, Ω = 11.89° for age ≥170 Ma. Other paleomagnetic poles rotated to NWAF according to Euler poles of Lottes and Rowley (1990).

Ref #	Unit		Original Coordinates			NW Africa Coordinates					
						Option 1			Option 2		
		Plate	Lat N	Long E	A95	Lat N	Long E	Rot	Lat N	Long E	Rot
LATE PERMIAN (260 ± 10 Ma)											
67	Bellerophon&Werfen Fms.	ADR	47.5	228.9	3.0	47.5	228.9	no rot	41.3	241.3	V&L
68	Sierra Chica	SAM	80.1	168.6	3.3	52.4	244.3	L&R	52.4	244.3	L&R
69	Upper Choiyoi	SAM	73.7	135.6	4.1	53.4	228.4	L&R	53.4	228.4	L&R
70	Gerringong volcanics	AUS	56.9	334.8	9.1	50.7*	239.4	L&R	50.7*	239.4	L&R
71	Karoo redbeds	SAF	48	260	8.5	55.3	255.7	L&R	55.3	255.7	L&R
72	Tambillos Fm.	SAM	78.9	139.6	6.5	55.5	236.8	L&R	55.5	236.8	L&R
Kent et al. (2021)	Ikakern Fm.	NWAF	48.8	246.3	7.2	48.8	246.3	no rot	48.8	246.3	no rot
						Overall Mean			*Overall Mean*		
						52.3	*239.8*		*51.3*	*241.7*	
						A95 = 5.0, K = 146, N = 7, AD1 = 0.1			*A95 = 5.3, K = 130, N = 7, AD1 = 1.5*		
EARLY PERMIAN (280 ± 10 Ma)											
73	Taztot trachyandesite	MES	38.7	236.8	4.6	39.0§	236.7§	L&R	34.5	240.4	LA
74	Jebel Nehoud Complex	NEAF	40.8	251.3	6	46.5	248.0	L&R	46.5	248.0	L&R
75	S. Alps volcanics	ADR	50	236	8.6	50	236	no rot	43.6	247.8	V&L
76	Lugano Porphyries	ADR	43	243	10	43	243	no rot	36.4	253.8	V&L
77	Auccia volcanics	ADR	38	245	8	38	245	no rot	31.4	255.5	V&L
78	Arona volcanics	ADR	35	248	14	35	248	no rot	28.3	258.2	V&L
79	Bolzano Porphyries comb.	ADR	45	239	4	45	239	no rot	38.5	250.2	V&L
80	L.Collio&Auccia volcanics	ADR	39	252	20	39	252	no rot	32.3	261.9	V&L
81	Bolzano Porphyries	ADR	47	228	4	47	228	no rot	40.9	240.4	V&L
82	Mechra&Chougrane	MES	36	238	20.9	36.3§	237.9§	L&R	31.8	241.4	LA
83	Mt. Leyshon intrusives	AUS	43.2	317.3	3.4	35.5	251.6	L&R	35.5	251.6	L&R
84	Tuckers Igneous Complex	AUS	47.5	323	3.8	41.0	249.2**	L&R	41.0	249.2**	L&R
Domeier et al. (2021)	Meseta volc.	MES	41.4	232.1	6.8	41.7	231.9	L&R	37.3	236.1	LA
						Overall Mean			*Overall Mean*		
						41.5	*242.3*		*37.0*	*249.0*	
						A95 = 3.8, K = 118, N = 13, AD2 = 0.7			*A95 = 4.2, K = 100 N = 13, AD2 = 6.3*		
						Mean Adria			*Mean Adria*		
						42.7	242.1		36.1	252.9	
						A95 = 5.9, K = 105, N = 7			*A95 = 5.9, K = 105, N = 7*		
						Mean Non-Adria			*Mean Non-Adria*		
						40.2	242.5		37.9	244.3	
						A95 = 6.1, K = 121, N = 6			*A95 = 5.9, K = 130, N = 6*		

Notes
Ref #: reference number (#) in Table S1 of Kent and Muttoni (2020). Paleopoles not listed in Kent and Muttoni (2020) (hence with no Ref #) are referenced according to the original publication.
Plate: NWAF = Northwest Africa; MES = Meseta; NEAF = Northeast Africa; SAF = South Africa; ADR = Adria; AUS = Australia; SAM = South America.
Lat N, Long E: Latitude (°N) and Longitude (°E) of paleomagnetic pole. *A95, K, N*: standard Fisher precision parameters.
AD1: angular distance with respect to Late Permian mean pole of Kent et al. (2021).
AD2: angular distance with respect to Early Permian mean pole #22 in Table 1 of Kent and Muttoni (2020).
Rot: Euler rotation parameters to bring paleomagnetic poles from the original coordinates into NW Africa (NWAF) coordinates. *L&R*: Euler poles derived from Lottes and Rowley (1990) as follows:
Morocco (MES) to NWAF: Lat = 17.55 N, Lon = −165.40E, Angle = 0.50. NEAF to NWAF: Lat = 19.38 N, Lon = −7.59E, Angle = −6.25. AU to NWAF: Lat = −28.13 N, Lon = −66.79E, Angle = 52.06. SAM to NWAF: Lat = 53.00 N, Lon = −35.00E, Angle = 51.01. SAF to NWAF: Lat = 9.34 N, Lon = 5.70E, Angle=7.82.
LA: MES to NWAF Euler pole derived from Labails et al. (2010): Lat = 29.44 N, Lon = −12.12, Angle = 5.11, Age ≥203 Ma.
V&L: ADR to NWAF Euler pole calculated by multiplying the Iberia (IB) to North America (NAM) pole of Vissers et al. (2013) by the NAM to NWAF pole of Labails et al. (2010) thus obtaining a pole describing the IB to NWAF rotation at Lat = 55.63 N, Lon = −11.92, Angle = 11.89. This pole is applied to rotate also ADR to NWAF for ages ≥ 170 Ma.
Option 1: ADR and MES paleomagnetic poles considered in NWAF coordinates. Other paleomagnetic poles rotated from Original Coordinates to NWAF coordinates according to Euler poles in Lottes and Rowley (1990).
Option 2: ADR and MES paleomagnetic poles rotated from Original Coordinates to NWAF coordinates according to Euler poles in Labails et al. (2010) and Vissers et al. (2013). Other paleomagnetic poles rotated from Original Coordinates to NWAF coordinates according to Euler poles in Lottes and Rowley (1990).
* Reported as 50.1°N in Kent and Muttoni (2020), (Table S1).
** Reported as 249.0°E in Kent and Muttoni (2020), (Table S1).
§ Rotated according to the Morocco (MES) to NWAF Euler pole ofLottes and Rowley (1990). This rotation, being virtually null (0.5°), was not considered inKent and Muttoni (2020), (Table S1).

Table 3
Early and Late Permian paleomagnetic poles from Laurasia in original coordinates and European (EUR) coordinates. Reference numbers from Table S1 of Kent and Muttoni (2020) with additional poles referenced to original publication. North American poles rotated to EUR coordinates using the Euler pole of Bullard et al. (1965).

LATE PERMIAN (260 ± 10 Ma)

			Original coordinates (EUR)		
Ref #	Unit	Plate	Lat N	Long E	A95
1	Taimyr Siberian Traps	EUR	59	150	10.0
2	Kotuy River Siberian Traps	EUR	52.7	148.4	13.9
3	Siberian Traps NSP1 pole	EUR	56.4	141.7	2.1
4	Stolbovaya R. Siberian Traps	EUR	53.3	150.2	5.3
5	Moyero River Siberian Traps	EUR	58.5	134.5	2.7
6	Big Nirundaiver intrusion&sed.	EUR	54.3	143	5.0
7	Siberian Traps	EUR	56.2	146	3.3
8	Siberian Traps Mean recalc.	EUR	52.8	154.4	9.7
9	Esterel extrusives	EUR	51.5	142	6.1
10	Krakow volcanics B	EUR	50	164	4.1
		Overall Mean			
			54.7	*147.7*	
		A95 = 3.3, K = 210, N = 10,AD2 = 0			

EARLY PERMIAN (280 ± 10 Ma)

			Original Coordinates			EUR Coordinates*	
Ref #	Unit	Plate	Lat N	Long E	A95	Lat N	Long E
11	Intrusions Southern Illinois	NAM	56.3	122.9	3.8	56.5	162.5
12	Lunner dikes	EUR	53	164	5.9	53	164
13	Lunner dikes	EUR	51	163	2.5	51	163
14	Hicks Dome breccia	NAM	54.8	112.1	8.6	55.2	151.6
15	Downey Bluff sill	NAM	53	128.7	3.8	53.1	168.2
16	Bohuslan dikes combined	EUR	51	165	8.6	51	165
17	Scania melaphyre dikes	EUR	54	172	11	54	172
18	Mauchline lavas	EUR	47	157	14	47	157
19	Bohemian Massif igneous	EUR	42	166	10	42	166
20	Bohemian quartz porphyry	EUR	37	161	7	37	161
21	Oslo volcanics	EUR	47	157	1	47	157
22	Sarna alkaline intrusion	EUR	38	166	6.9	38	166
23	Ringerike lavas	EUR	44.6	157.4	13.4	44.6	157.4
24	Churchland pluton	NAM	33.5	126.3	16.3	33.6	165.1
25	Trachytes, Ukraine	EUR	49.4	179.7	6.5	49.4	179.7
26	Krakow volcanics	EUR	43	165	7.9	43	165
27	Lower Silesia volcanics	EUR	40	172	13.2	40	172
28	North Sudetic Basin volcanics	EUR	42	174	8.1	42	174
29	Intrasudetic Basin volcanics	EUR	43	172	3.2	43	172
30	Moissey volcanics	EUR	41	172	6.7	41	172
31	Mount Hunneberg Sill	EUR	38	166	6.3	38	166
32	Exeter Lavas	EUR	48	163	10	48	163
33	Black Forest volcanics	EUR	49	176	5.9	49	176
34	Black Forest rhyolites	EUR	42	173	1	42	173
35	Exeter Lavas	EUR	50	150	4	50	150
36	Piedmont Mafic intrusions	NAM	38.9	120.8	10.2	39.1	159.7
Haldan et al. (2014)	Oslo Graben volc.	EUR	48.3	155.5	1.9	48.3	155.5
					Overall Mean:		
					46.0	165.1	
					A95 = 2.7, K = 103, *N* = 27, AD2 = 0.4		

Notes
Ref #: reference number (#) in Table S1 of Kent and Muttoni (2020). Paleopoles not listed in Kent and Muttoni (2020) are referenced according to the original publication.
Plate: EUR = Eurasia; NAM = North America.
Lat N, Long E: Latitude (°N) and Longitude (°E) of paleomagnetic pole. *A95, K, N*: standard Fisher precision parameters.
AD2: angular distance with respect to mean pole of Kent and Muttoni (2020).
* NAM paleomagnetic poles rotated from Original Coordinates to EUR coordinates according to Euler pole ofBullard et al. (1965).

paleomagnetic data and their relative paucity, (2) the admissibility of paleomagnetic data from Adria as a proxy for Africa, (3) the possibility, albeit remote, of enhanced importance of non-dipole (octupole) components in the (Early) Permian geomagnetic field and (4) the application of inclination correction (flattening factors) in sedimentary paleomagnetic data. We conclude that the case for Pangea B in the Early Permian is strengthened by using Permian data from Adria as a proxy for Africa but is not dependent on it. Paleomagnetic data from Adria and elsewhere require a Pangea B configuration in Early Permian and exclude Pangea A at this time. We reject the *ad hoc* hypothesis that enhanced non-dipole contributions to the Permian geomagnetic field are required to modify existing Early Permian paleomagnetic data and hence explain the accommodation of Pangea A at this time (Van der Voo and Torsvik, 2001; Torsvik and Van der Voo, 2002). The geocentric axial dipole hypothesis has served us well throughout Phanerozoic time, and an exception for the Early Permian is unwarranted. Inclination errors in paleomagnetic data are more critical in some sedimentary data than others, and unresolved overprinting and remagnetization may be more important

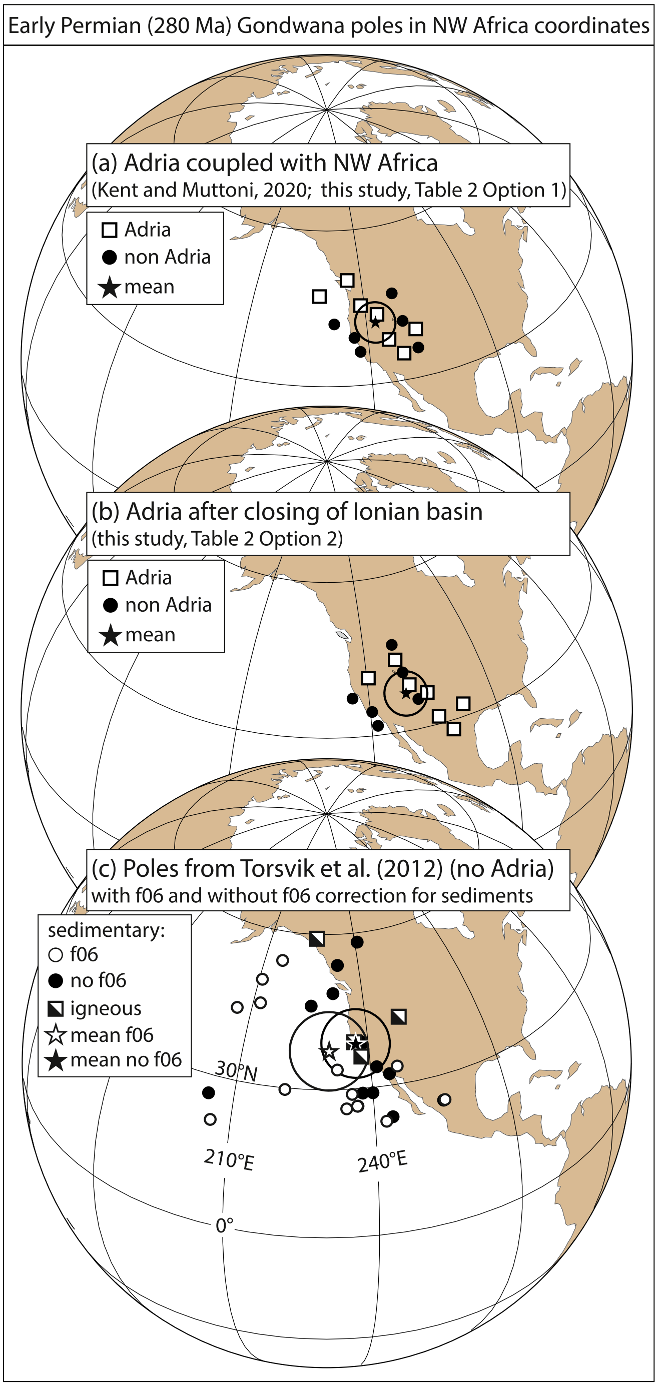

Fig. 10. Early Permian (280 Ma) poles from Adria, from Gondwana elements other than Adria (non-Adria), with mean poles (stars). (a) Option 1 rotated to NWAF coordinates (see Table 2) based on rotation parameters in which Adria moved as a rigid promontory of NW Africa (Kent and Muttoni, 2020). (b) Option 2 rotated to NWAF coordinates (see Table 2) based on rotation parameters in which Adria moved independent of Africa until Oxfordian time (154 Ma) (this paper). (c) Early Permian poles before and after flattening correction (f = 0.6) applied to sediment data (from Table 1 of Torsvik et al., 2012) rotated to NWAF coordinates as in Table 6 of Torsvik et al. (2012), used by these authors to support a Pangea A-type reconstruction at this time.

factors. Although an assessment of flattening factors requires analysis of large high-quality datasets (Tauxe and Kent, 2004) or measurements of remanence anisotropy (Bilardello, 2016) which are usually not available in published studies, the general application of "universal" flattening factors for sedimentary paleomagnetic data (e.g., Torsvik et al., 2012) is a unsatisfactory substitute for renewed studies to improve the database of paleomagnetic poles.

8. Conclusions

Almost without exception, published Mesozoic paleogeographies of the Mediterranean include a Mesogea Ocean separating Sicily from Adria, from early Mesozoic or Permian time, that existed into the Cenozoic and linked Alpine Tethys (the Piemonte-Ligurian Ocean between Adria and Europe) to Neo-Tethys in the east (Fig. 2a). Part of the rationale for the existence of this ocean is the perceived need for oceanic lithosphere to feed present-day subduction beneath the Aeolian Arc (and Aegean Arc) and drive modern seafloor spreading in the Tyrrhenian (Aegean) back-arc basin. Here, we emphasize the case for continuity of the Mesozoic continental margin from Sicily into the Apennines, and the Apenninic connection to continental margins of the same age on the eastern side of Adria in the Dinarides and Hellenides. Rather than explaining the Miocene to Present opening of the Tyrrhenian Sea, and the deep seismicity in the Aeolian Arc, in terms of subduction of Mesogea oceanic lithosphere, we contend that delamination of Adria continental-margin mantle lithosphere at the site of collision of the Calabria-Sardinia-Corsica volcanic arc with Adria can account for the seismicity, magmatism and the juxtaposition of extension and compression both in the Calabrian Arc and in the Apennines as a whole (Fig. 6). Models based on continental mantle lithospheric delamination have been successfully applied to other episutural basins in the Mediterranean (Alboran, Aegean and Pannonian basins; references provided in Section 4).

We explain the presence of oceanic and thinned continental lithosphere in the Ionian, Herodotus and Levant basins of the eastern Mediterranean in terms of pull-apart extension associated with a Middle and Late Jurassic sinistral strike-slip fault motion between Adria and Africa that linked the Atlantic Ocean and Alpine Tethys to Neo-Tethys in the East. We present a model for paleogeographic evolution in which Adria moved with Iberia during the early history of Central Atlantic extension (203–170 Ma). Subsequently, Adria moved with NW Africa from 154 Ma to present. The motion of Adria in the intervening interval (170–154 Ma), represented by a magnetic quiet zone in the Central Atlantic, was linearly interpolated and results in the onset of extension in Alpine Tethys (between Adria and Europe) as well as sinistral strike-slip between Adria and NW Africa and the development of eastern Mediterranean pull-apart basins (Figs. 9 and S1). The pull-apart extension ceased when Adria began to move with NW Africa at 154 Ma. The model implies Middle and Late Jurassic extension in the eastern Mediterranean that is broadly consistent with the projected age of rifting in the Ionian and Levant basins.

It is well established that Mesozoic and Cenozoic APWPs for autochthonous and parautochthonous Adria, derived mainly from the Southern Alps, mimic those from NW Africa and APWPs from other continents rotated into NW Africa coordinates (references provided in Section 6). Here we focus on the Permian, and test to what extent the hypothesized Jurassic extension in the Ionian Sea and eastern Mediterranean would affect Permian paleomagnetic data from Adria. We show that, within the errors, Permian and indeed other younger paleomagnetic data from Adria, are not significantly offset (from their fit with the NW African APWP) by Ionian extension as envisaged here. The modeled

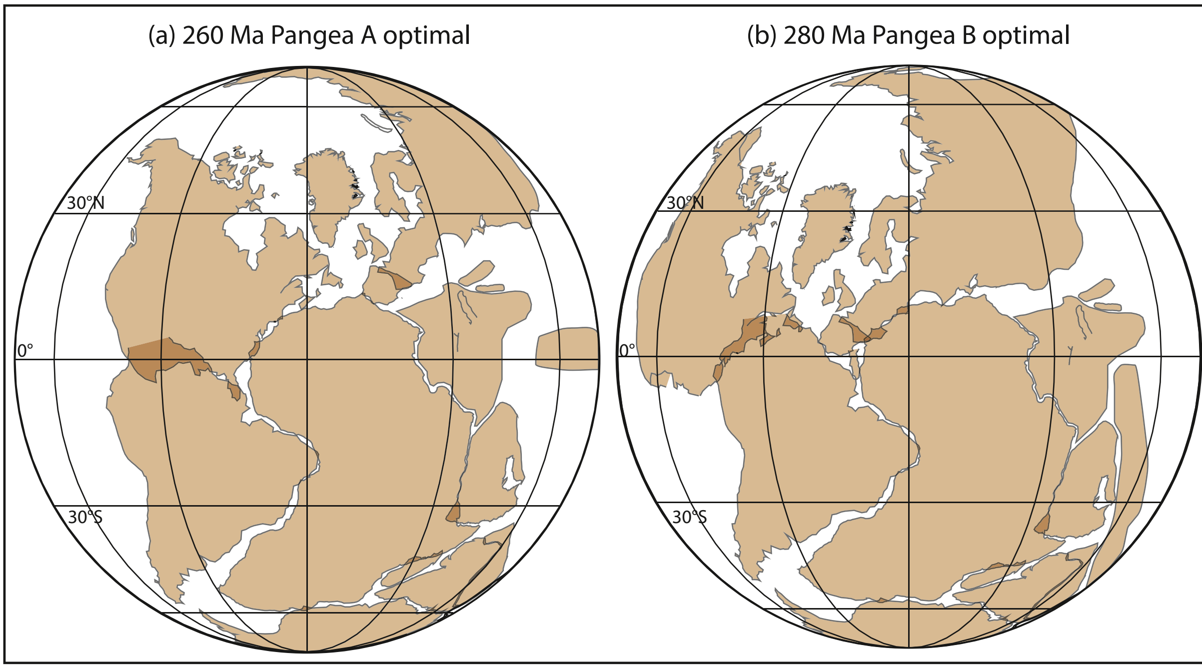

Fig. 11. (a) Optimal Pangea A reconstruction for Late Permian (260 Ma) based on mean paleomagnetic poles for Gondwana (Table 2, Option 2) and for Laurasia (Table 3). The 260 Ma paleomagnetic pole for Laurasia is slightly adjusted within its A95 and rotated about a 90°N Euler pole to attain a Pangea A fit with Gondwana, and multiplied by internal Laurasia Euler rotation poles (Bullard et al., 1965; Vissers et al., 2013) to generate total reconstruction poles of Table S1 (bold red poles in section B.2). The 260 Ma paleomagnetic pole for Gondwana is slightly adjusted within its A95 to optimize a Pangea A fit with Laurasia, and multiplied by internal Gondwana Euler rotation poles (Lottes and Rowley, 1990) to generate total reconstruction poles of Table S1 (bold red poles in section B.3). (b) Optimal Pangea B reconstruction for Early Permian (280 Ma) based on mean paleomagnetic poles for Gondwana (Table 2, Option 2) and for Laurasia (Table 3). The 280 Ma paleomagnetic pole for Laurasia is slightly adjusted within its A95 and rotated about a 90°N Euler pole to attain a Pangea B fit with Gondwana, and multiplied by internal Laurasia Euler rotation poles (Bullard et al., 1965; Vissers et al., 2013) to generate total reconstruction poles of Table S1 (bold red poles in section C.3). The 280 Ma paleomagnetic pole for Gondwana is slightly adjusted within its A95 to optimize Pangea B fit with Laurasia, and multiplied by internal Gondwana Euler rotation poles (Lottes and Rowley, 1990) to generate total reconstruction poles of Table S1 (bold red poles in section C.5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

opening of eastern Mediterranean pull-apart basins is consistent with the observed similarity of Permian and younger paleomagnetic data from Adria and NW Africa whereas the commonly conceived orthogonal opening of Mesogea (Fig. 2b) is not.

Permian paleomagnetic data from Adria and elsewhere, rotated to NW Africa coordinates, support a Pangea B configuration in the Early Permian. Pangea B yields optimal grouping of poles whether paleomagnetic data from Adria are utilized or not, either using the rotation parameters for Option 1 (Table 2) from Kent and Muttoni (2020) in which Adria moved with Africa, or optimal rotation parameters (Option 2, Table 2) based on the kinematics described above (Fig. 10a,b). The Pangea A configuration is found to be appropriate for the Late Permian (Fig. 11a), but Pangea A for the Early Permian (280 Ma) leads to unacceptable overlap of continental outlines (see Fig. 5a of Kent and Muttoni, 2020). Application of a uniform flattening correction (f = 0.6) led to retention of numerous entries from sedimentary rocks in the Torsvik et al. (2012) pole compilation despite the increased dispersion it produces (Fig. 10c). Although the inclusion of these scattered data does increase Pangea A feasibility, Pangea B provides a more credible option for the Early Permian (Fig. 11b). Due to overprinting by Alpine orogenic events and by the break-up of Pangea, there is a paucity of geologic evidence for the large-scale (~3500 km) dextral strike-slip motion in mid-Permian to bring the Pangea B configuration to Pangea A. The scale of the required displacement is often cited as an argument against a Permian Pangea B configuration. The dextral strike-slip displacement is, however, of similar scale (and location between Gondwana and Laurasia) as the dextral strike-slip motion required by Torsvik et al. (2012) to bring their 350 Ma reconstruction (Pangea-B-like) to their 300 Ma reconstruction (Pangea-A-like). In this scenario, the dextral displacement occurred prior to or during the early stages of Alleghanian (Hercynian) orogeny. We advocate an analogous shift in the juxtaposition of Gondwana and Laurentia, but about 50 Myrs later at ~270 Ma, during the final mid-Permian episodes of Alleghanian continent-continent collision. One of the consequences of the tectonic shift is reduction of land area in the tropical humid belt (Kent and Muttoni, 2020); the concomitant decrease in CO_2 consumption by silicate weathering may have allowed greater greenhouse warming and contributed to meltdown of the Late Paleozoic ice age.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2022.104045.

Author contributions

J.E.T. Channell: Framework and initial drafts of the paper. G. Muttoni: reconstruction parameters for Atlantic spreading history and Adria/Africa motions. D.V. Kent: paleomagnetic datasets pertaining to the Permian configurations of Pangea.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Mat Domeier, Marco Maffione and an anonamous reviewer, for insightful and thorough reviews of the manuscript, and Carlo Doglione for editorial guidance. The paper developed from our attendance at a symposium in Munich convened to commemorate the retirement of Valerian Bachtadse in October 2019. We thank Valerian and the other organizers of this meeting, particularly Stuart Gilder. DK acknowledges support from the Lamont-Doherty Paleomagnetic Research Fund.

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