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ADRIA AS PROMONTORY OF AFRICA AND ITS CONCEPTUAL ROLE IN THE TETHYS TWIST AND PANGEA B TO PANGEA A TRANSFORMATION IN THE PERMIAN

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Abstract. It has been almost 60 years since the first results from the Early Permian Bolzano Quartz Porphyries from the Trento Plateau of northern Italy (Southern Alps) showed paleomagnetic inclinations steeper than inclinations from broadly coeval units from central Europe. This experimental discrepancy, confirmed ever since at varying levels of magnitude and certitude, implied that northern Italy had paleolatitudes too northerly relative to Europe to be considered part of the European continent. On the other hand, it became progressively more apparent that paleomagnetic data from northern Italy were more compatible with data from Africa than with data from Europe, and this observation revived and complemented Argand's original concept of Adria as a promontory of Africa. But if Adria was part of Africa, then the paleolatitude anomaly of Adria relative to Europe translated into a huge crustal misfit of Gondwana relative to Laurasia when these landmasses were forced into a classic Wegenerian Pangea as typified by the Bullard fit of the circum-Atlantic continents. This crustal misfit between Gondwana and Laurasia was shown to persist in the ever-growing paleomagnetic database even when data from Adria were provisionally excluded as non-cratonic in nature. Various solutions were offered that ultimately involved placing Gondwana to the east (allowing it to be more northerly) relative to Laurasia and envisaging a dextral shear occurring in the Tethys (Mediterranean) realm between these supercontinental landmasses. This shear or transformation was initially thought to occur as a *continuum* over the course of the Mesozoic–Cenozoic (the so-called 'Tethys Twist') but soon afterwards when plate tectonics came into play and limited the younger extent, as a discrete event during the post-Triassic, Triassic or most probably – as in the latest and preferred reconstructions – the Permian between a configuration of Pangea termed B – with the northwestern margin of Africa against southern Europe – to a configuration termed Pangea A-2, with the northwestern margin of Africa against eastern North America, that is more proximal in shape to the classic Pangea A-1 that started fragmenting in the Jurassic with the opening of the Atlantic Ocean. The Permian timing and presumed locus of the ~2300 km dextral shear is supported by rotated tectonic domains in Sardinia and elsewhere along the interface between Lauarasia and Gondwana. The concept of Pangea B and its transformation into Pangea A developed therefore in close conjunction with the concept and paleomagnetic support of Adria as a promontory of Africa, and has ramifications to many aspects of tectonics, climate change and biogeography yet to be explored.

Introduction

We argue that the most reliable paleomagnetic data point to a major albeit contentious tectonic change in the Permian (Gallo et al. 2017; Muttoni et al. 2009a): the transformation of the pole-to-pole supercontinent of Pangea from a 'B' configuration (Irving 1977; Morel & Irving 1981), with the northwestern margin of South America adjacent to eastern North America in the Early Permian, to the classic pre-drift Pangea A-1 or A-2 configuration (Bullard et al. 1965; Van der Voo & French 1974), with the northwestern margin of Africa now against eastern North America in the Late Permian. The tightly age-constrained transformation of Pangea B to a Pangea A configuration between ~275 and 260

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Ma would have produced appropriately timed tectonic rotations about local vertical axes along a long dextral shear zone between Laurasia and Gondwana and affected land-sea distribution in the critical tropical humid belt, and hence continental silicate weathering, that may eventually be more precisely gauged as a contributing forcing to the demise of the Late Paleozoic Ice Age.

Here we offer a review of the critical role of Adria, the long presumed (and still debated) promontory of Africa (Argand 1922), as the source of key paleomagnetic data that first led to the concept of the 'Tethys Twist' by the Dutch school (Van Hilten 1964; DeBoer 1965) to its increasing modern role (Channell & Horvath 1976; Channell et al. 1979; Lowrie 1986; Channell 1996; Muttoni et al. 2001) in support of the concept of Pangea B (Irving 1977; Morel & Irving 1981) and its transformation during the Permian to a Pangea A-type configuration (Muttoni et al. 1996; 2003; 2009a). We begin with an historical overview of the debate that since the early 1960's has concerned the configuration of Pangea in the Permo-Triassic, with Adria as a central locus of relevant paleomagnetic data. We then proceed to discuss and discard interpretations of the data that infer a quasi-static Pangea A in the Permo-Triassic, and conclude by summarizing various predictions of the Pangea B to Pangea A Permian transformation hypothesis that are not nearly as well explain by a more or less static Pangea A configuration in the Late Paleozoic.

Pangea B to Pangea A Transformation

Origin of the idea: Adria and the 'Tethys Twist'

The concept of Pangea B and its transformation to the classic Pangea A (as typified by the Bullard et al. 1965 fit of the Atlantic-bordering continents) is deeply rooted in the rise of paleomagnetism as a discipline to demonstrate continental drift and the advent of modern plate tectonics (see Irving 2004, 2005, 2006 for reviews) and evolved in close relationship with the concept of Adria as a promontory of Africa, first put forward by Argand (1922). A specific region and a specific rock type played a fundamental role in the mutually influencing Adria and Pangea B concepts: the Southern Italian Alps, particularly their least deformed northeastern sector comprising the Trento Plateau with the majestic Dolomites (Fig. 1A), where the products of the Early Permian volcanic cycle crop out in three main provinces informally termed Arona-Lugano, Auccia, and Bolzano (Fig. 1A), and are provided with modern U/Pb ages of ~285–275 Ma (Schaltegger & Brack 2007) (Fig. 1B). It has been shown since the 1960's (e.g., Van Hilten 1964; De Boer 1965; Schwarz 1965; Zijderveld et al. 1970) that paleomagnetic data from the Early Permian Bolzano Quartz Porphyries from the Trento Plateau (Fig. 1A), studied for paleomagnetism since Dietzel (1960), Van Hilten (1962), De Boer (1963), and Guicherit (1964), better agree with the available record from nearly contemporaneous rock units in Africa than with that of Europe. This dichotomy of agreements is at the foundation of the modern concept of parauthocthonous Adria as a promontory of Africa. Parauthocthonous Adria is comprised of regions of the present-day Italian peninsula – for example the Trento Plateau in the Southern Alps (Fig. 1A) – that are characterized – generally speaking – by a Variscan crystalline basement overlain by non-metamorphic and relatively mildly deformed Permo–Cenozoic sedimentary and volcanic units that yielded paleomagnetic data statistically indistinguishable from data from cratonic Africa and Gondwana (Channell & Horvath 1976; Channell et al. 1979; Lowrie 1986; Channell 1996; Muttoni et al. 1996, 2001, 2003, 2013). In general, Adria is a term applied to the mildly deformed Po-Adriatic foreland basin rimmed by three orogens: the Alps, the Apennines, and the Dinarides (Channell et al. 1979), and bounded by the Plio-Pleistocene Tyrrhenian Sea (Chiarabba et al. 2008) in the west and the much older (Triassic?) Ionian Sea (Speranza et al. 2012) in the southeast (Fig. 2A). An indicative paleogeography of Adria in the Paleogene, before main Alpine and Apennine tectonics, is illustrated in Figure 2B where Adria is depicted as a set of platforms and basins on continental crust protruding from Africa (Muttoni et al., 2001). Bosellini (2002) reviewed geological, paleontological and paleoecological-straigraphic data from Adria and concluded that 'Adria was an African Promontory and the Apulia Platform was (…) a sort of Florida Peninsula, subdividing the "Mesozoic Mediterranean" into a western Ionian basin and an eastern Levantine basin' (see Figure

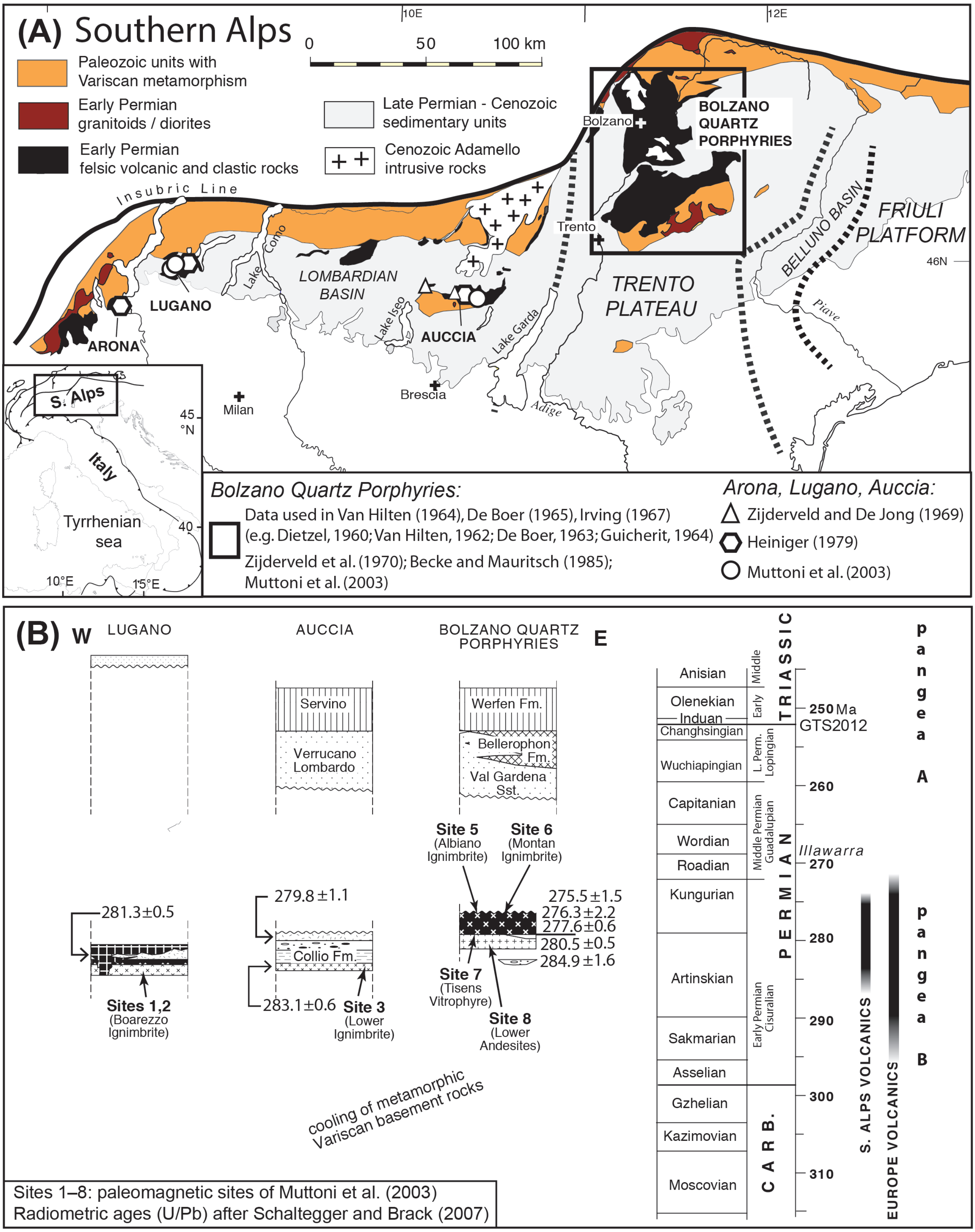

Fig. 1 - A) Geologic sketch map of the Southern Alps with location of various sampling areas in Early Permian volcanic units discussed in the text. The paleogeographic domains of the Trento Plateau and surrounding Lombardian and Belluno basins and Friuli Platform are also indicated (for these paleogeographic units, see also Figure 2). Modified from Muttoni et al. (2003). B) Chronology of Early Permian volcanics from the Southern Alps (see Fig. 1A for locations) that were sampled for paleomagnetism by Muttoni et al. (2003) finding support for Pangea B in the Early Permian. These volcanics are overlain by sediments that support Pangea A (Muttoni et al. 2003). The chronology is erected on U/Pb data from Schaltegger and Brack (2007). Figure modified from Schaltegger and Brack (2007) and adapted to the Geological Time Scale 2012 (GTS2012).

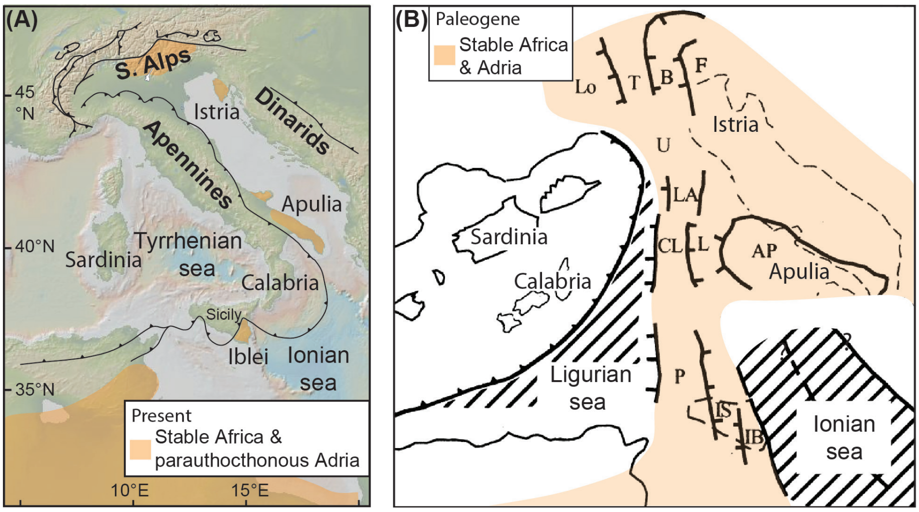

Fig. 2 - A) The present setting of the Italian peninsula with indication of areas considered parauthocthonous relative to Africa. B) Tentative model of Adria as a promontory of Africa in the Paleogene (~50 Ma), with broadly continuous north-south structural trends from Tunisia to the Southern Alps. AP = Apulia-Gargano platform, B = Belluno basin, CL = Campano-Lucana platform, F = Friuli-Istria platform, IB = Iblei platform, IS = Imerese-Sicani basins, L = Lagonegro basin, LA = Laziale-Abruzzese platform, Lo = Lombard basin, P = Panormide platform, T = Trento Plateau, U = Umbria-Marche basin. Modified from Muttoni et al. (2001).

17 in Bosellini 2002).

Some of the same paleomagnetists who first pointed out the Adria-Africa connection (Van Hilten 1964; De Boer 1965; Schwarz 1965; Irving 1967) showed also that the paleomagnetic inclinations of these Early Permian Bolzano volcanics from the Trento Plateau of Adria – and hence their paleolatitude of formation via the geocentric axial dipole (GAD) hypothesis – are invariably higher than those from broadly coeval units from Europe. This implies that if Africa – with Adria attached – and Europe were to be reconstructed in their present relative longitudes in a Pangea A configuration according to something like the Bullard et al. (1965) fit, a considerable – and geologically untenable – crustal overlap between the northern and southern continents would result. Solutions to this paleomagnetic inclination discrepancy involved shifting the southern continents of Gondwana to the east relative to the northern continents of Laurasia (Van Hilten 1964), and envisaging a dextral transformation to progressively bring them to their present relative longitudes. This translation was termed the 'Tethys Twist' by Van Hilten (1964) because the shearing between Gondwana and Laurasia occurred in the Tethys belt, as described in more detail below.

Van Hilten (1964) used paleomagnetic data from various continents including data from the non-cratonic 'Alpine Tethys' of southern Europe, e.g. the Early Permian Bolzano Quartz Porphyries from the Trento Plateau (Fig. 1A), and was among the first to recognize a Permian paleomagnetic-based paleogeographic assembly of Gondwana and Laurasia very different from the canonic Wegenerian (Pangea A-type) assembly. He stated: 'It is emphasized that it is not possible to collect all continents into single assemblage, usually called Pangaea; anyway not in the arrangement proposed originally by Wegener (…) The paleomagnetic data do not allow such a arrangement during the late Paleozoic and early Mesozoic (…)'. Van Hilten (1964) proposed an arrangement of Gondwana and Laurasia in the Permian closer to what Irving (1977) eventually referred to as Pangea B, and proposed a continuous translation of the two supercontinents, called the 'Tethys Twist', from the Permian to the Alpine orogeny in the Cenozoic. This protracted timing was eventually rejected when it was realized that the Alpine orogeny was rather the result of Africa-Europe convergence from the opening of the Southern Atlantic in the Cretaceous (e.g., Dewey et al. 1973). But as pointed out by Irving (2004) in his historical overview, '…one notable feature of Van Hilten's maps has endured: his placement of Italy jutting out from what is now Tunisia'. This placement represents the beginning of the modern concept of parauthocthonous Adria as a promontory of Africa, as summarized by Van Hilten's (1964): '(…) a very surprising fact can be observed now: the southern Alps can be attached to the African continent from the Permian on, keeping perfectly their position and orientation with respect to this continent during all the Mesozoic (…)'. It should be noted that in Van Hilten (1964) maps, the Southern Alps are depicted by a square symbol located off Tunisia and are not part of Italy (Fig. 3A).

De Boer (1965) (working in Utrecht) used paleomagnetic data from stable Europe and the 'Alpine Tethys' of southern Europe, including data from northern Italy (e. g., the Early Permian Bolzano Quartz Porphyries studied earlier by Dietzel 1960; De Boer 1963; Guicherit 1964), and reached conclusions similar to Van Hilten's (working in Delft): 'The deviation of the inclination of the paleomagnetic directions may be explained by assuming that the structural units of Italy, southern France, and Spain have moved westward with respect to meso-Europe. This late Paleozoic, Mesozoic, and Cenozoic westward drift of rigid blocks in the mobile Tethys zone is considered to be due to dextral shear movements, which developed in the Tethys zone during the northwestward drift of the Gondwana shields (Africa, Arabia, and India) and the contemporaneous eastward movement of meso-Europe' and that the 'main conclusion drawn from the paleomagnetic data is that the Tethys mobile belt was and still is a zone of primary dextral shear'. However, De Boer (1965) did not use Van Hilten's term 'Tethys Twist' to describe the prolonged (Permian to Cenozoic) shear in the Tethys. Independently, Schwarz (1965) made a statistical analysis of the inclinations from the 'Alpine Tethys' realm and northern Europe and showed the differences between them to be systematic.

Irving's paper in 1967 (titled 'Palaeomagnetic evidence for shear along the Tethys') followed in the footsteps of Van Hilten (1964) and De Boer (1965). Irving used paleomagnetic data from undeformed regions of Africa, North America, South America, and Australia and observed crustal overlaps of up to ~1000 km between the reassembled northern and southern continents of Gondwana and Laurasia if they were to remain in their present relative longitudes in the Permian and Triassic (Fig. 3B). He also reviewed the extensive Permian to Cretaceous database from the 'Alpine Tethys' realm including northern Italy as well as Spain, France, and Austria, in conjunction with data from former Czechoslovakia and the USSR and elsewhere, e.g., Turkey, Japan, and China, and stressed that 'latitudes calculated for deformed regions within the Tethys are inconsistent with those calculated for their present borderlands'. For example, the Permian paleolatitude of Irving's 'Venezia Tridentina' – or northeastern Italy – is far to the north relative to an Italian peninsula considered part of the European continent. Irving (1967) was evidently not an advocate of northern Italy (Adria) as part of Africa, as Van Hilten (1964) was, because he placed 'Venezia Tridentina' to the east of Europe (to resolve the paleolatitude mismatch) but not close to western Africa, where it should be according to the Adria promontory concept (see Figure 2 in Irving 1967). In any case, one way that Irving found to explain the paleolatitude inconsistencies between regions within the 'Alpine Tethys' and those calculated for their present borderlands 'is to suppose that the northern and southern continents have since undergone relative longitudinal movements, the Tethys being the shear zone between them.' He also added that the 'time of these postulated motions is not closely defined. They were post-Triassic and appear to have been completed by the late Tertiary'. Hence Irving (1967) reached conclusions similar to those of Van Hilten (1964) and De Boer (1965) at least in reaffirming the paleolatitude 'anomaly' of data from the 'Alpine Tethys', e.g. of northern Italy, and stressing the crustal misfit of Gondwana and Laurasia in a standard Pangea configuration that was however (and mistakenly in our view) extended well after the Late Paleozoic.

Zijderveld et al. (1970) reported new results from the Early Permian Bolzano Quartz Porphyries from the Trento Plateau for comparison to an updated review of Permian data from Europe. What came out of their analysis was a clear endorsement for parauthocthonous Adria as a promontory of Africa: '(s)ince the paleomagnetic direction of the Early Permian volcanics of the Southern Alps fits in reasonably well with the (poorly known) Early Permian paleomagnetic pattern of Africa, a coherence between both regions is presumed', implying 'for the Southern Alps an original position somewhere in the Western Mediterranean area, not far from its present position' and consequently 'hardly any relative movements with respect to Africa…'. However, the paleomagnetic inclination discrepancy between the Trento Plateau and Europe at the basis of the 'Tethys Twist' concept, which was on the order of ~20° or more at the times of Van Hilten (1964, Fig. 4), was reduced (but not completely eliminated) to less than 10° for Zijderveld et al. (1970, Fig. 8) as their new data from the Bolzano Quartz Porphyries and from Europe (Zijderveld 1967) became available. This reduction (but not elimination) of discrepancy allowed these authors to propose an alternative reconstruction in which they 'squeezed' Gondwana and Laurasia into Pangea A similar to the classic and cited Bullard et al. (1965)

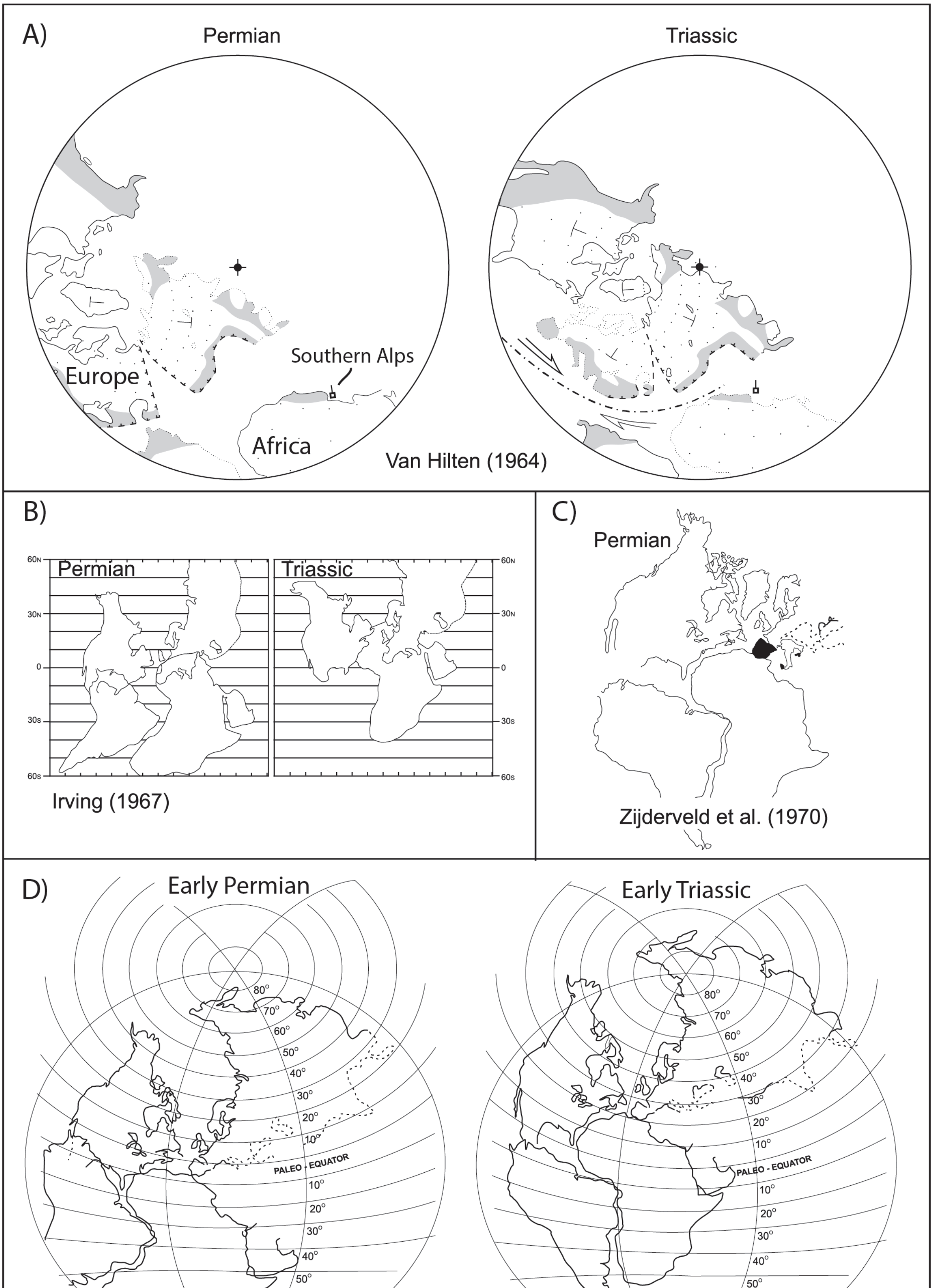

Fig. 3 - Permian–Triassic paleogeographies according to A) Van Hilten (1964), B) Irving (1967), C) Zijderveld et al. (1970), and D) Van der Voo and French (1974). See text for discussion.

fit (Fig. 3C). Interestingly, however, Zijderveld et al. (1970) did not rule out altogether the Permian 'Pangea B-like' reconstruction of the Atlantic-bordering continents of Van Hilten (1964) and Irving (1967) (see Zijderveld et al. 1970, Fig. 11) because the available paleomagnetic data alone did not allow them to make a definitive choice: the discrepancy, although reduced, was still there. A decision to lean in favor of Pangea A for the Permian did not come from paleomagnetism but from their considerations regarding the structure of the Atlantic Ocean floor.

Four years later, Van der Voo and French (1974) took the skeptical view of Zijderveld et al. (1970) against a mobile Pangea in the Permian to a further level by presenting a compilation of paleomagnetic poles from five continental plates (North America, Europe, the Iberian Peninsula, Africa, and South America) for ten time intervals ranging from Late Carboniferous to Eocene. These authors dismissed altogether – and with little explanation – data from Adria (e.g., Trento Plateau) used by Van Hilten (1964), De Boer (1965), and Irving (1967) to infer shear in the Tethys, yet they still found a clear discrepancy of Gondwana and Laurasia paleopoles when continents are repositioned in a Pangea A configuration in the Permian: '… the fit of the continents by Bullard et al. (1965) cannot be used for this period. Van Hilten (1964) did note this possibility and proposed an alternative continental reconstruction, implying subsequent dextral shear in the Tethys zone: the Tethys twist. Since then so many data have become available that the Tethys twist concept is no longer tenable'. Some of the discrepancy between Gondwana (without Adria) and Laurasia data in the Permian was resolved by proposing a modified version of the Bullard et al. (1965) fit in which Gondwana was restoratively rotated ~20° clockwise relative to Laurasia about a pivot point in the southern Sahara. This very tight Pangea A – that will become termed Pangea A-2 by Morel and Irving (1981) – was thought to be valid from Late Carboniferous through Late Permian times (Fig. 3D). The authors infer that the corresponding dynamic counterclockwise rotation of ~20° from Pangea A-2 to a configuration similar to that proposed by Bullard et al. (1965) (that Morel and Irving (1981) termed Pangea A-1), started in the latest Permian/Early Triassic and was completed in the Late Triassic (Fig. 3D) (see also Van der Voo, 1993 for a discussion on Pangea A-1 and A-2).

To summarize, the 1960's and early 1970's saw a central role of paleomagnetic data from northern Italy (e.g., Early Permian Bolzano Quartz Porphyries from the Trento Plateau) and elsewhere in the 'Alpine Tethys' of southern Europe in revealing systematic inclination (paleolatitude) incongruences with coeval data from central Europe (Van Hilten 1964; De Boer 1965; Irving 1967 and even Zijderveld et al. 1970, who considered the misfit minimal). Van Hilten (1964) pointed out that data from northern Italy were consistent with data from Africa, and in our opinion he can be considered the founder of the modern (after Argand 1922) concept of Adria as a promontory of Africa, which has been developed since with the progressive acquisition of new data (Channell & Horvath 1976; Channell et al. 1979; Lowrie 1986; Channell 1996; Muttoni et al. 2001, 1996, 2003, 2013; see also below). Van Hilten (1964) used data from the main continents including Adria (e.g., Trento Plateau of northern Italy) to infer the occurrence of a crustal misfit of Africa and Europe if reconstructed in present-day relative longitudes according to something like the Bullard et al. (1965) fit (now referred to as Pangea A-1). The conundrum was resolved by placing Gondwana to the east relative to Laurasia by variable amounts of up to ~5000 km and by envisaging a prolonged (~Permian–Cenozoic) dextral shear of Gondwana relative to Laurasia – Van Hilten's (1964) 'Tethys Twist' – that brought global paleogeography toward its modern configuration. Irving (1967) confirmed the existence of an 'anomaly' in the paleolatitudes of the 'Alpine Tethys' of southern Europe (e.g., northern Italy) relative to those of central Europe. He was no advocate of Adria as a promontory of Africa and he did not place northern Italy close to western Africa, as Van Hilten (1964) did, yet by reviewing data from the main continents he confirmed Van Hilten's view of Gondwana displaced to the east relative to Laurasia. Zijderveld et al. (1970) retained the African promontory concept and confirmed the African congruence of data from northern Italy (Adria) pointed out by Van Hilten (1964), but then took a skeptical view of the highly mobilistic inferences put forward by Van Hilten (1964), De Boer (1965) and Irving (1967), and considered the inclination (paleolatitude) 'anomaly' between data from northern Italy (Adria) and Europe as sufficiently reduced to allow Gondwana and Laurasia to be squeezed in a Pangea A configuration. Van der Voo and French (1974) did not confront the data from Adria and concluded in favor of a very tight Pangea A-2 in the Late Carboniferous–Permian (with a reduced crustal overlap between Gondwana and Laurasia in the Gulf of Mexico area) and a more canonic Bullard et al. (1965) Pangea A-1 in the Late Triassic.

Development of the idea: Early Permian Pangea B to Late Permian Pangea A

As paleomagnetic data continued to accumulate, Irving (1977) published apparent polar wander (APW) paths for all major continents to derive a set of global paleogeographic reconstructions from the Devonian to the Cenozoic. An innovation was to assign all studied poles (listed in the Ottawa Catalogs) a numerical geological age and average the poles in a moving time window (40 Myr for all but the youngest intervals and stepped 10 Myr in this analysis) for the APW paths. No data from Adria were used presumably because he excluded 'results from deformed beds in foldbelts'. Nonetheless, when reconstructing the Variscan docking of Laurasia and Gondwana in the Carboniferous, he encountered the same old problem (after Van Hilten 1964; De Boer 1965; Irving 1967): a crustal misfit between Africa and Europe when reconstructed according to modern relative longitudes. He proposed a reconstruction where 'Africa is opposite Europe, and South America opposite North America' (Fig. 4A), and officially termed this configuration 'Pangaea B'. He also suggested that: 'At the Permian-Triassic boundary the palaeomagnetically determined latitudes now allow Gondwana to rotate anticlockwise, and the transformation from Pangaea B to A to begin'. Hence, for Irving (1977), and subsequently for Morel and Irving (1981), the transformation occurred essentially in the Early Mesozoic (Triassic), well before the Cenozoic Alpine orogeny, and was thus not the long, drawn-out Tethys twist of Van Hilten (1964).

A few years later, Van der Voo et al. (1984) reexamined critically the database used in Irving (1977) and Morel and Irving (1981), and even after eliminating a substantial number of entries deemed to have poor or questionable age control, they conceded that 'both the Pangea A-2 and Pangea B fits are paleomagnetically permissible for the Late Carboniferous and Early Permian'. They further stated that '(f)or the Late Permian, Irving's Pangea B fits better suggesting that for that time either the Pangea A2 fit is less valid, or that the paleopoles and/or their ages are incorrect.' Van der Voo et al. (1984) also made interesting considerations on the impact that different methods of APW path construction – based on running window (30 to 40 Myr) averages of paleopoles as in Irving (1977) or discrete time-slice (~15 Myr) averages as in Van der Voo et al. (1984) – can have on paleogeography and the Pangea debate in particular. In any case, it is of interest to note that even after critical scrutiny of data available at that time, Pangea B kicked back and remained viable.

The concept of Pangea B then remained essentially fallow until the publication of the paleomagnetism and tectonics textbook of Van der Voo (1993), which was skeptical of Pangea B but allowed Muttoni et al. (1996) to develop a regional strategy centered on an updated review of paleomagnetic data from Laurasia, exploiting the excellent global pole database tabulated in Van der Voo's book, and from Adria-northwest Africa (Western Gondwana), reviving and extending the Permian–Triassic database of northern Italy (Adria). Their main conclusions were: (1) confirmation of Argand's Adria as the Africa promontory, as anchored in extensive paleomagnetic data from Adria as reviewed by Channell (1996), which boosted the APW path database for West Gondwana (Africa with Adria, plus South America) for comparison with the APW path of Laurasia, (2) that the Early Permian mean paleopole for West Gondwana, in conjunction with the coeval Laurasia mean paleopole, support Pangea B of Irving (1977) and Morel and Irving (1981), (3) that the Late Permian/Early Triassic and the Middle Triassic/early Late Triassic paleopoles from Adria and Laurasia support Pangea A-2 of Van der Voo and French (1974), but only just after the transformation from Pangea B (Fig. 4B), (4) that the Tethyan megashear probably occurred mainly during the Permian at the end of the Variscan orogeny (while our current view is that it occurred entirely after the Variscan orogeny; Muttoni et al., 2003), and (5) that the Late Triassic/Early Jurassic paleopoles from West Gondwana and Laurasia agree with Pangea A-1 of Bullard et al. (1965), the widely accepted Pangea configuration at the time of its Jurassic breakup (Fig. 4B).

Work in the western Mediterranean was

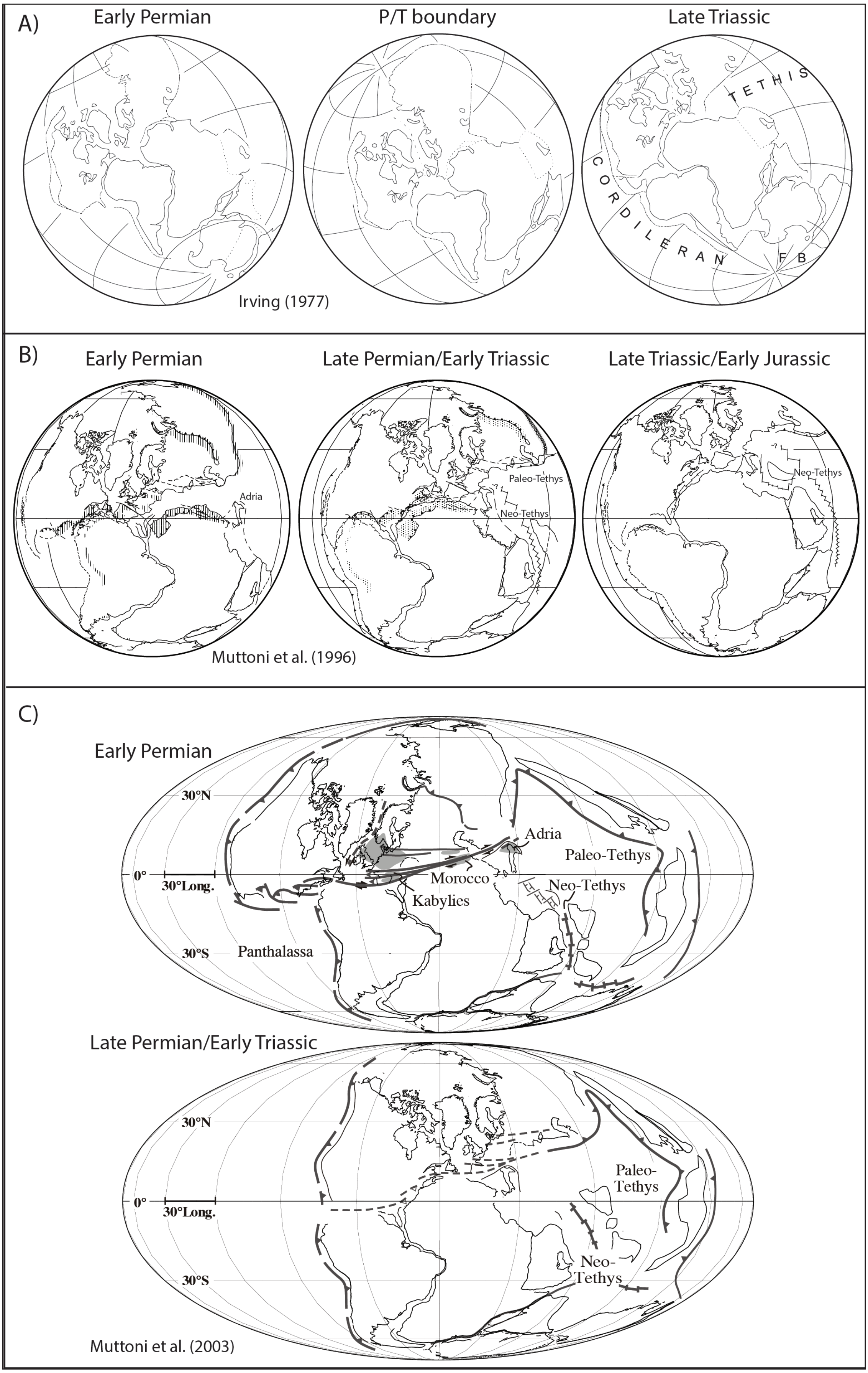

Fig. 4 - Permian–Triassic paleogeographies according to A) Irving (1977), B) Muttoni et al. (1996), and C) Muttoni et al. (2003). See text for discussion.

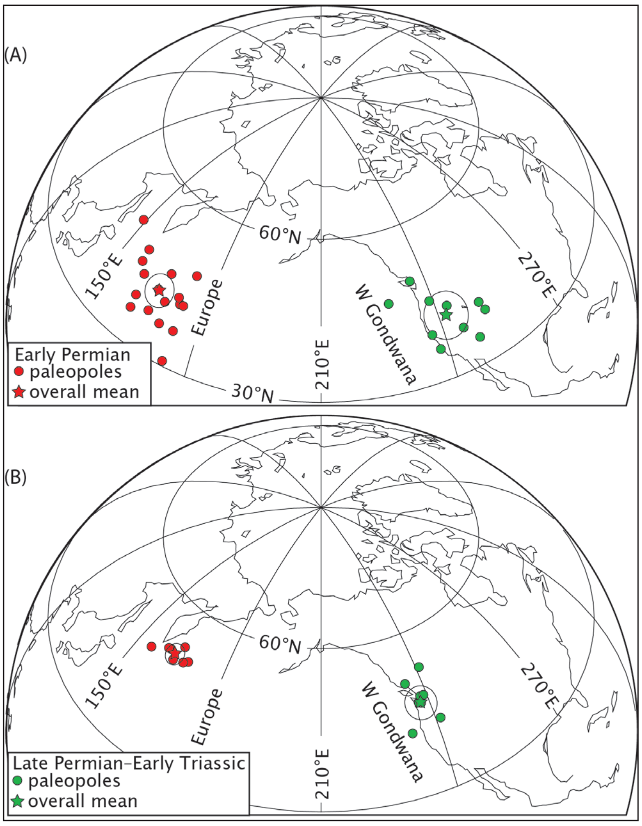

Fig. 5 - Early Permian (A) and Late Permian–Early Triassic (B) paleomagnetic poles from Gondwana and Laurasia used by Muttoni et al. (2009a) for the paleogeographic reconstructions of Pangea of Figure 6. See Table 1 for listing, Table 2 for mean poles, and text for discussion.

extended by Muttoni et al. (2003) with resampling of the Early Permian Bolzano Quartz Porphyries from the Trento Plateau as well as Early Permian volcanics in areas to the west of the Dolomites (Lugano, Auccia) (Fig. 1A), focusing on a few key localities from these areas spread across most of the Southern Alps that were provided with radiometric (U/Pb) age constraints (anticipated in Muttoni et al., 2003, and published in Schaltegger and Brack, 2007) in a known structural and stratigraphic context (Fig. 1B). Muttoni et al. (2003) compared their results with data of Becke and Mauritsch (1984), Zijderveld et al. (1970), Zijderveld and De Jong (1969), and Heiniger (1979) from the same general areas (Fig. 1A) (see Table 1, entries #1-7), confirming what Heiniger (1979) already found about the general along-strike (W–E) coherence of the Southern Alps, at least as far as these volcanic units are concerned. Muttoni et al. (2003) extended the comparison to include also Early Permian data from northwest Africa in Morocco (Daly & Pozzi 1976; Westphal et al. 1979) (see Table 1, entries #8-9), finding enough congruence with data from Adria to be able to construct an updated (after Muttoni et al. 1996) Early Permian Adria-northwest Africa overall mean pole (241.0°E, 41.4°N, A95 = 4.7°, N = 9). By comparing this Adria-Africa pole with a pole derived from averaging a total of 18 entries from Early Permian magmatic units from Europe (166.2°E, 42.2°N, A95 = 3.1°, N = 18) (see Table 1, entries #19-36), an offset similar to Pangea B was required to avoid crustal overlap with a standard GAD time-averaged field model.

Muttoni et al. (2003) also responded to a number of arguments that in the early 2000's were variably invoked 'to explain away the paleomagnetic evidence that has consistently resulted in a crustal misfit if a Pangea 'A' configuration is maintained in especially the Early Permian', such as a departure from the standard GAD model of the time-averaged field whereby the crustal misfit at the basis of the Pangea B model is an artifact of an arbitrary large and persistent octupolar nondipole field (Van der Voo & Torsvik 2001; Torsvik & Van der Voo 2002) (which is precluded because data from Adria and Europe have similar low inclinations), or potential inclination error in sediments that may have produced paleolatitude artifacts and a misplacement of Gondwana relative to Laurasia (Rochette & Vandamme 2001) (which is precluded because the discrepancy is also found in igneous data). Muttoni et al. (2003) concluded that neither a persistent zonal octupole field contribution nor inclination flattening in sediments can explain the paleomagnetic evidence for Pangea B in the Early Permian (Fig. 4C). They also added two important elements to the Pangea debate, that (1) according to their analysis the transformation from Pangea B to Pangea A occurred within the Permian and after the cooling of the Variscan basement (hence, it had little to do with the Variscan orogeny and should not be referred to as a late Variscan event), and (2) that the transformation was closely associated with the opening of the Neotethys Ocean in the east between India/Arabia and the Cimmerian microcontinents, hence linking the Permian transformation with the Neotethyan plate circuit.

Pangea B to A transformation during Neotethys opening

Connections between the Pangea B to A transformation, the opening of the Neotethys

Tab. 1 - Early Permian and Late Permian-Early Triassic poles for Adria/Gondwana and Europe/Laurasia used by Muttoni et al. (2009a) to calculate their mean poles as reported in Table 2.

Entry:	Lon (°E)	Lat (°N)	A95 (°)	Reference
Early Permian (275-285 Ma), Adria (Southern Alps) and NW Africa				
[1] Southern Alps Volcanics, Italy	236	50	7	Muttoni et al., 2003
[2] Lugano (Ganna) Porphyries, Ticino	243	43	10	Heiniger, 1979
[3] Auccia Volcanics, Lombardy	245	38	8	Heiniger, 1979
[4] Arona Volcanics, Lombardy	248	35	14	Heiniger, 1979
[5] Bolzano Porphyries comb., Suedtirol	239	45	4	Zijderveld et al., 1970
[6] L.Collio & Auccia Volcanics, Lombardy	252	39	20	Zijderveld and De Jong, 1969
[7] Bolzano Porphyries, Suedtirol	228	47	3.5	Becke and Mauritsch, 1984
NW Africa, volcanic units:				
[8] Taztot Trachyandesites, Morocco	237	39	5	Daly and Pozzi, 1976
[9] Chougrane & Mechra Volcs., Morocco	238	36	20	Westphal et al., 1979
[10] Jebel Nehoud ring complex, Sudan rotated to NW Africa	248	46.5	6	Bachtadse et al., 2002
Late Permian-Early Triassic (247-259 Ma) Adria (Southern Alps)				
[11] Staro&Camparmo volcs, Vicent. Alps[a]	241[a]	53[a]	6[a]	De Boer, 1963[a]
[12] Werfen Formation, Dolomites	233	42	5.1	Channell and Doglioni, 1994
[13] Verrucano Lombardo Ss., Lombardy	241	43	5.7	Muttoni, 1996
[14] Val Gardena Ss., Dolomites	235	51		Guicherit, 1964
[15] Verrucano Lombardo Ss., Lombardy	239	48	5	Kipfer and Heller, 1988
[16] Val Gardena Ss., Vicentinian Alps	238	48	7	De Boer, 1963
[17] Verrucano Lomb. metass., Lombardy	237	47	6	Kipfer and Heller, 1988
[18] Val Gardena Ss., Dolomites	237	42	18	Manzoni, 1970
Early Permian (273-294 Ma) Europe				
[19] Exeter Lavas, U.K.	163	48	10	Cornwell, 1967
[20] Exeter Lavas, U.K.	149	50	4	Zijderveld, 1967
[21] Thueringer Volc., L. Rotlieg., Germany	170	37	7	Mauritsch and Rother, 1983
[22] Oslo Graben Lavas, Norway	157	47	1	Van Everdingen, 1960
[23] Arendal Diabase, Norway	160	43	7	Halvorsen, 1972
[24] Saar-Nahe Volcanics, Germany	167	41	16	Berthold et al., 1975
[25] Nahe Volcanics, Germany	167	46	13	Nijenhuis, 1961
[26] Black Forest Volc., Germany	174	48	6	Konrad and Nairn, 1972
[27] Ny-Hellesund diabases, Norway	161	39	3	Halvorsen, 1970
[28] Mt. Billingen Sill, Sweden	174	31	2	Mulder, 1971
[29] Mt. Hunneberg Sill, Sweden	166	38	5	Mulder, 1971
[30] Skaane Dolerite Dikes, Sweden	174	37	7	Mulder, 1971
[31] Black Forest Volc., Germany	173	42	1	Edel and Schneider, 1995
[32] Bohemia Quartz Porphyries, Germany	161	36.5	5	Thomas et al., 1997
[33] Bohemia Quartz Porphyries, Germany	166	42	6	Soffel and Harzer, 1991
[34] North Sudetic Volc., Poland	174	42	6	Nawrocki, 1997
[35] Intrasudetic Volc., Poland	172	43	2	Nawrocki, 1997
[36] Ringerike Lavas, Norway	157	45	12	Douglass, 1988
Late Permian-Early Triassic (247-259 Ma) Europe				
[37] North Sudetic Sed. Zechstein, Poland	168	51	5.5	Nawrocki, 1997
[38] Intraudetic Sed. Zechstein, Poland	160	51	3	Nawrocki, 1997
[39] Lower Buntsandstein, Germany	166	51	3	Szurlies et al., 2003
[40] Buntsandstein Holy Cross, Poland	155	49	2	Nawrocki et al., 2003
[41] Saint-Pierre pelites, France	163	50	5	Diego-Orozco and Henry, 1993
[42] Massif du Maures pelites, France	161	51	4	Merabet and Daly, 1986
[43] St Affrique sediments, France	167	50	12	Cogne et al., 1993
[44] Lunner dykes 243±5 Ar/Ar, Norway	164	53	6	Torsvik et al., 1998

Entry = paleopole entries used for mean paleopole determinations of Table 2. Paleopoles are given as longitude (Lon), latitude (Lat), and 95% confidence radius (A95).

[a] The area sampled by De Boer (1963) is known for Middle Triassic volcanism, so pending radiometric dating, this entry should be excluded from mean pole calculation, yielding a revised Late Permian-Early Triassic mean pole that is only 1° from the mean pole used by Muttoni et al. (2009a).

Ocean, and motions of Cimmerian terranes in the Permian were explored in more detail by Muttoni et al. (2009a; see also Muttoni et al. 2009b). In his seminal work, Şengör (1979) proposed that a continental strip, termed the Cimmerian Continent, rifted from the northeastern margin of Gondwana – from Ara-

Tab. 2 - Mean Early Permian and Late Permian-Early Triassic poles for Adria/Gondwana and Europe/Laurasia of Muttoni et al. (2009a) with projected directions and paleolatitudes of mean poles at Bolzano.

Entry	Geologic interval	Age Range (Ma)	Lon (°E)	Lat (°N)	A95 (°)	K	N	D (°)	I (°)	Plat±A95 (°N)
	Adria/Gondwana mean poles									
[1-10]	Early Permian	285-275[a]	242.0	41.4	4.4	122	10	324.1	17.1	8.8±4.4°
[11-18]	L. Perm-E. Trias.	259-247[b]	237.6	46.8	3.1	317	8	329.7	22.5	11.7±3.1°
	Europe/Laurasia mean poles									
[19-36]	Early Permian	294-273[a]	166.2	42.2	3.1	126	18	18.4	2.9	1.5±3.1°
[37-44]	L. Perm-E. Trias.	259-247[b]	162.9	50.8	2.0	764	8	17.8	20.1	10.3±2.0°

Entry = paleopole entries from Table 1 used for mean paleopole determination. Age Range = numerical age ranges (Ma) of mean paleopoles according to ([a]) radiometric age constraints of volcanic units (see also Table 2 in Muttoni et al., 2003) and ([b]) chronostratigraphic age of sediments according to the geologic timescale GTS2012. Mean paleopoles are given as longitude (Lon), latitude (Lat), 95% confidence radius (A95), precision parameter (K) and number of poles used to calculate the Fisher mean (N). Projected directions at Bolzano (present coordinates: 46.5°N 11.35°E) calculated as declination (D), inclination (I) and paleolatitude (Plat) with associated A95 angle. Note that difference in projected paleolatitude in Early Permian is significant 7.3±5.4° (motivating Pangea B) but is insignificant 1.4±3.7° in the Late Permian-Early Triassic (allowing Pangea A).

Item	Reference	f	Lon (°E)	Lat (°N)	A95 (°)
Adria:					
Bellerophon&Werfen, Bulla, Dolomites	Scholger et al., 2000	0.8^a	228.9	47.5	3.8
Bellerophon&Werfen, Siusi, Dolomites	Scholger et al., 2000	0.8^b	230.6	49.5	3.3
Entry #12 of Table 1	Channell and Doglioni, 1994	0.8^b	234.2	44.3	6.6
Entries #15 and #17 combined, Table 1	Kipfer and Heller, 1988	0.8^b	249.1	53.0	7
Entry #18 of Table 1	Manzoni, 1970	0.8^b	240.4	46.2	18
South Africa, rotated to NW Africa:					
Karoo Upper Permian redbeds	Lanci et al., 2013	0.7^a	255.0	55.5	4.1
Karoo P/T boundary redbeds	DeKock and Kirschvink, 2004	0.7^b	244.2	56.8	7.6

Mean paleopole: Lon = 239.7°E, Lat = 50.7°N, A95 = 5.8°, K = 109, N = 7 (Muttoni et al., 2013).

Arc distance with respect to Late Permian–Early Triassic mean paleopole of Muttoni et al. (2009a) based on entries 11-18 of Table 1 = 4°

f = flattening factor: ^{a}f calculated; ^{b}f assumed. Mean E/I corrected paleopoles are given as longitude (Lon), latitude (Lat), and 95% confidence radius (A95). See Muttoni et al. (2013) for further information.

Tab. 3 - Late Permian–Early Triassic poles from E/I corrected sedimentary units from Adria and South Africa (Gondwana) (Muttoni et al. 2013).

bia to Australia – during the Triassic to collide with the Eurasian southern margin in the Late Triassic–Middle Jurassic. The Neotethys Ocean was thus interpreted as a back-arc basin related to the southward subduction of the Paleotethys Ocean lithosphere under the Cimmerian Continent in a static Pangea A geometry of Gondwana and Laurasia (see Fig. 2 in Şengör 1979). Muttoni et al. (2009a) provided new Permian paleomagnetic data from Iran and Karakoram, putative parts of the Cimmerian Continent but which they referred to as Cimmerian terranes in deference to the possibility that Cimmerian drifting could have taken more complex forms than those predicted by a single 'ribbon continent' sweeping across the Tethys in a 'windshield wiper' fashion. Samples from western Karakoram were collected years earlier by Maurizio Gaetani in a lateritic profile near the Lashkargaz village in Pakistan from within the Middle Permian Gharil Formation (Gaetani et al. 1995) pertaining to the Lashkargaz/Baroghil tectonic unit (Gaetani et al 1996), whereas samples from Iran came from a lateritic profile near the Aruh village in the Alborz Mountains (see Muttoni et al. 2009a for more details).

For reconstructing Gondwana in the Early Permian, Muttoni et al. (2009a) used the same paleopoles of Muttoni et al. (2003) from volcanic units of Adria-Africa plus the paleopole from the Early Permian Jebel Nehoud ring complex of Sudan (Bachtadse et al. 2002), as summarized for reference in Table 1 (entries #1-10) and plotted in Figure 5A, that altogether yielded a volcanic-only overall mean pole at 242°E, 41.4°N (Table 2). For reconstructing Laurasia in the Early Permian, they used the same paleopoles of Muttoni et al. (2003) as listed in Table 1 (entries #19-36) and plotted in

Fig. 6 - On the left, Pangea evolution during the Permian according to Muttoni et al. (2009a). The Early Permian configuration is very similar to Irving's (1977) Pangea B whereas the Late Permian–Early Triassic Pangea is similar to Pangea A-2 (Van der Voo and French, 1974; Morel and Irving, 1981). The Middle Permian Pangea was generated by linear interpolation of Early Permian and Late Permian–Early Triassic mean paleopoles of Gondwana and Laurasia (see Table 3 in Muttoni et al. 2009a). According to this scheme, the transformation of Pangea B to Pangea A occurred within the Permian during the opening of the Neotethys Ocean and migration of Cimmerian terranes (Iran, Afghanistan, Karakorum, Qiangtang). Paleolatitude control points of Cimmerian terranes are from the Ruteh lavas from the Alborz region of north Iran (IR1; Besse et al. 1998), the Gharil ferricrete from the western Karakoram (KK; Muttoni et al. (2009a), the Aruh ferricrete from the Alborz region of north Iran (IR2; Muttoni et al. 2009a), the Hambast Formation from Abadeh in central Iran (IR3; Besse et al. 1998), the Hambast and Elikah formations from Abadeh in central Iran (IR4; Gallet et al. 2000), and the Tuoba Formation from eastern Qiangtang (QT; Huang et al. 1992). Paleolatitude control points for Gondwana and Laurasia as part of Pangea are from the Kama region sediments combined ('Kama'; Khramov 1982), the Thini Chu Group of Nepal ('Thini Chu'; Klootwijk & Bingham 1980), and the Gerringong volcanics ('Gerringong'; Irving & Parry 1963); the open circles associated with these error bars represent the paleolatitudes expected at these sites from the paleogeographic reconstruction. The green band centered on the equator in these reconstructions represents the area between about 5°S and 5°N of high temperature and humidity straddling the Intertropical Convergence Zone according to a standard climate zonality. (Manabe & Bryan 1985) Permian glaciations on Gondwana are indicatively reported. The right side of figure reports a schematic timescale for the Permian (GTS2012) with main Pangea events discussed in the text.

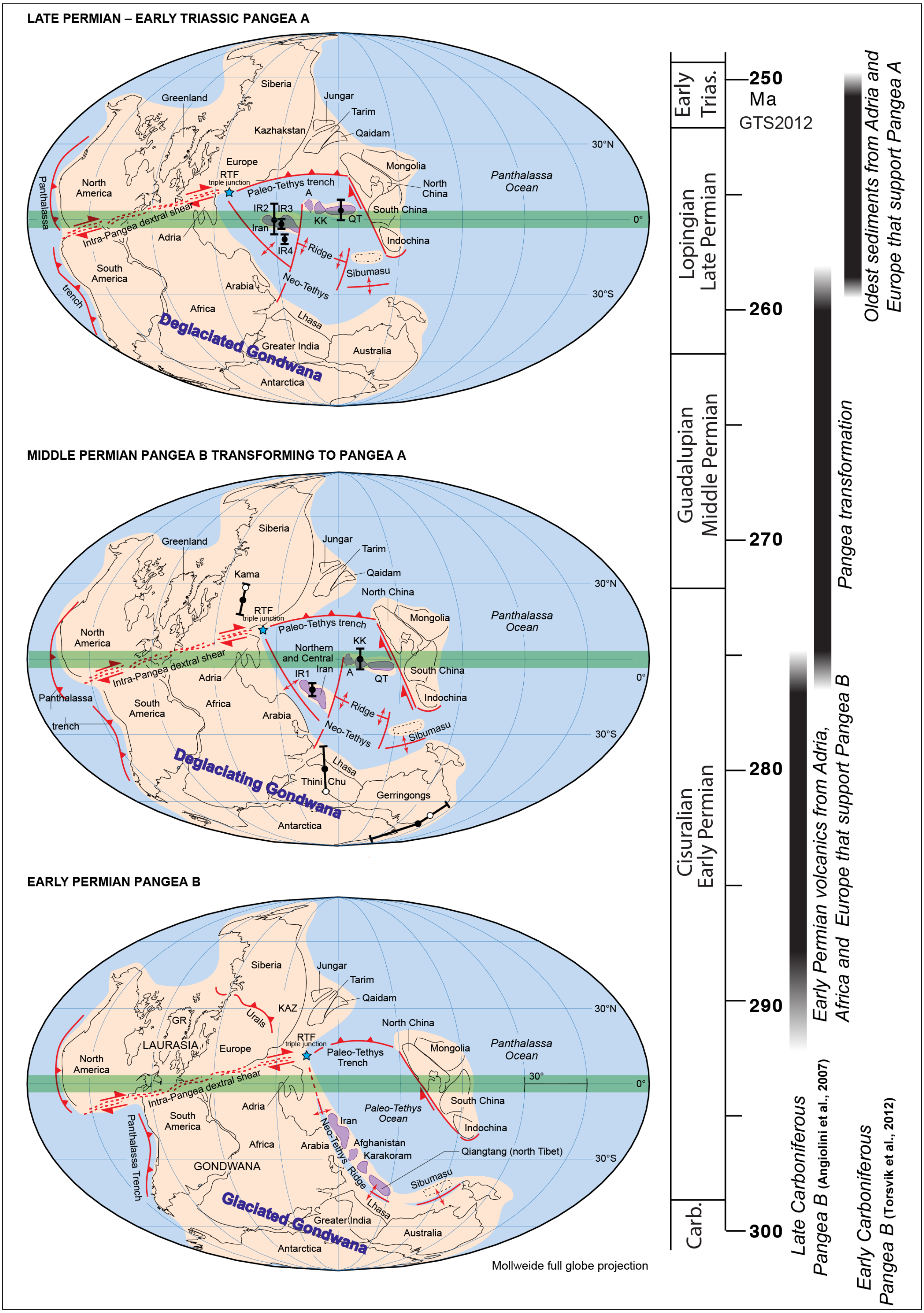
LATE PERMIAN – EARLY TRIASSIC PANGEA A
Greenland
Siberia
Jungar
Tarim
Kazhakstan
Qaidam
Europe
RTF
triple junction
Mongolia
North China
North America
Paleo-Tethys trench
Panthalassa Ocean
Panthalassa
IR2
IR3
KK
QT
South China
Iran
Intra-Pangea dextral shear
Adria
IR4
Ridge
Indochina
South America
Sibumasu
Arabia
Neo-Tethys
trench
Africa
Lhasa
Deglaciated Gondwana
Greater India
Australia
Antarctica
30°N
0°
30°S
MIDDLE PERMIAN PANGEA B TRANSFORMING TO PANGEA A
Kama
North China
Northern and Central Iran
IR1
A
Thini Chu
Gerringongs
Deglaciating Gondwana
EARLY PERMIAN PANGEA B
KAZ
Urals
GR
LAURASIA
Paleo-Tethys Trench
Paleo-Tethys Ocean
Panthalassa Trench
Afghanistan
Karakoram
Qiangtang (north Tibet)
GONDWANA
Glaciated Gondwana
30°
Mollweide full globe projection
Early Trias.
Lopingian Late Permian
Guadalupian Middle Permian
Cisuralian Early Permian
Carb.
250 Ma
GTS2012
260
270
280
290
300
Oldest sediments from Adria and Europe that support Pangea A
Pangea transformation
Early Permian volcanics from Adria, Africa and Europe that support Pangea B
Late Carboniferous Pangea B (Angiolini et al., 2007)
Early Carboniferous Pangea B (Torsvik et al., 2012)

Figure 5A, that yielded a volcanic-only overall mean pole at 166.2°E, 42.2°N (Table 2). For reconstructing Gondwana in the Late Permian–Early Triassic, Muttoni et al. (2009a) used paleopoles from Adria of Muttoni et al. (1996) (Table 1, entries #11-18; note caveat about #11), that are plotted in Figure 5B and that yielded a sedimentary-based overall mean pole at 237.6°E, 46.8°N (Table 2). Finally, for reconstructing Laurasia in the Late Permian–Early Triassic, Muttoni et al. (2009a) used paleopoles from sediments from Europe (Table 1, entries #37-44, plotted in Figure 5B), which gave a sediment-only overall mean pole at 162.9°E, 50.8°N (Table 2).

These paleopoles (Table 2) were used to generate the paleogeographic maps of Figure 6 (Muttoni et al. 2009a) where the Middle Permian reconstruction is based on an interpolation of the Early Permian and Late Permian–Early Triassic mean poles. Pangea B in the Early Permian is virtually the same Pangea B of Muttoni et al. (2003) as it is based essentially on the same data, that importantly are entirely from volcanic units for both Europe/Laurasia and Adria/Africa (and hence not affected by inclination flattening that typically affects sediments), pertaining to the same (northern) hemisphere (hence less apt to be differentially affected by any persistent nondipole fields), and frequently provided with robust radiometric age estimates (especially entries from the Southern Alps of Adria). The Late Permian–Early Triassic Pangea A (Fig. 6) is ironically entirely based on entries from sediments for both Europe/Laurasia and Adria/Africa. Their age is inferred from stratigraphy (relative to the geologic timescale GTS2012: Gradstein et al. 2012), which especially in the case of entries from the Southern Alps, is relatively well established, placing these sediments uncomformably above the Early Permian volcanics (e.g. Bolzano Quartz Porphyries, see Fig. 1B). Inclination flattening is expected for these sediments, but it is at present not possible to assess for all (Table 3; see discussion below) given the general lack of sufficient reportage of sample and site characteristic directions in these vintage studies. We notice in any case that all the entries are from the tropics of the northern hemisphere and hence less apt to be differentially affected by inclination flattening; for example, an average inclination flattening of, say, f = 0.8 or even 0.6, would result in a general northerly shift of both Gondwana and Laurasia by a few degrees. Besides, data producing the crustal overlap invoking Pangea B is what inclination flattening has sometimes been called upon to explain, not a loose fit of Laurasia and Gondwana, as with the Late Permian-Early Triassic data, that allow a Pangea A-type configuration.

When the Cimmerian terranes were placed on these Pangea reconstructions according to their paleomagnetically-derived paleolatitudes (IR1, IR2, IR3, IR4, Karakoram (KK), and Quingtang (QT), the terranes were found to have migrated from southern Gondwanan paleolatitudes in the Early Permian to subequatorial paleolatitudes by the Middle Permian–Early Triassic (Fig. 6). Muttoni et al. (2009a) concluded that the 'timing, rates, and geometry of Cimmerian tectonics are broadly compatible with the transformation of Pangea from a B to a A-type configuration with Neo-Tethyan opening taking place contemporaneously essentially in the Permian.' Moreover, it appeared that the Neotethys Ocean may have opened asymmetrically during the Permian with terranes such as western Karakoram, central Afghanistan, and Qiangtang that appear to have moved faster in the Middle Permian compared to others such as Iran (and possibly also Sibumasu) that have been relatively steady in the Middle Permian to then speed up in the Late Permian–Early Triassic. Muttoni et al. (2009a) also outlined geologic evidence in favor of a northward subduction of the Paleotethys lithosphere under the Eurasian margin (instead of southward subduction under Cimmeria; Şengör 1979) and envisaged a grand scale scenario characterized by Neotethys opening, Paleotethys subduction, and Pangea B to A transformation occurring together in the Permian as part of an internally consistent plate circuit.

Summary and present views on Permian paleogeography

Pangea B remains a strongly debated issue. For example, Domeier et al. (2012) argued in their review that paleomagnetic data from the literature can be reconciled with Pangea A in the Early Permian only barely without invoking non-dipole field contributions, but this conclusion was reached by excluding without circumstantial explanation — all data from Adria. In contrast, we maintain that contemporaneous and more recent analyses provide strong evidence for a more mobile Pangea with some interesting consequences, as itemized here:

• Data from parauthocthonous Adria (e.g., the Trento Plateau in northern Italy) retrieved from radiometrically dated igneous rocks and/or biostratigraphically-dated sedimentary rocks provided with a direct assessment and correction of sedimentary inclination flattening (Tauxe & Kent 2004) have been shown to robustly agree with available data from Africa from the Early Permian to the Cenozoic (Muttoni et al. 2013). For the critical Early Permian period, Muttoni et al. (2013) reaffirmed the congruence of data from Adria, Morocco, and Sudan (Muttoni et al. 2009a) and extended comparison to data from the 286±6 Ma Mount Leyshon Intrusive Complex and the Tuckers Igneous Complex of Australia that also supported Pangea B in the Early Permian (Clark & Lackie 2003). For the Triassic, a positive congruence test was obtained by targeting Middle Triassic rocks from northern Italy and northern Libya (Muttoni et al. 2001). An even more recent analysis reaffirmed the Adria-Africa congruence in the Jurassic–Early Cretaceous by stressing the remarkable coherence of data from Adria when reconstructed as part of northwest Africa to data from other plates reconstructed using independent plate circuits (North America, South America, Europe, southern Africa) in the Jurassic–Early Cretaceous (Muttoni & Kent 2019) during and after the so-called Jurassic monster polar shift, a novel feature of global plate motion (Kent & Irving 2010; Kent et al. 2015). At the same time, the tectonic coherence of parauthoctonous Adria and Africa found support (or non-opposition) from Alpine plate kinematics arguments (Wortmann et al. 2001), and has substantially resisted attempts expressly directed to disprove it. For example, the alleged (although technically not significant) rotation of 9°±9° of parauthoctonous Adria relative to Africa (van Hinsbergen et al. 2014) was calculated without considering the effects of the large and rapid Late Jurassic pole shift of Kent and Irving (2010) in making precise comparisons and needs therefore to be reconsidered. At present we can affirm that paleomagnetic data from parauthoctonous Adria, which according to Kent and Irving (2010) could not be used in APW path construction as in urgent need to be reassessed, have been reassessed, and we can also affirm that the road initially taken by Van Hilten (1964), the founder of the modern concept of Adria as a promontory of Africa, has been paved with a wealth of reliable data that cannot be ignored (e.g., Domeier et al. 2012).

• Paleomagnetic data from volcanic rocks provided with radiometric and/or stratigraphic age constraints from parauthocthonous Adria-Africa (Gondwana) and Laurasia support Pangea B in the Early Permian (Muttoni et al. 1996, 2003, 2009a) (Fig. 6). An important factor in making intercontinental comparisons of paleomagnetic data has been improvements in radiometric dating and the age registry between sedimentary and igneous rock units. For example, studies through the 1980s typically used the Van Eysinga (1975) geologic time scale, which placed the numerical age of the Permian to between 231 Ma and 281 Ma whereas it has more recently been placed between ~252 and 299 Ma (e.g., Shen et al. 2013), a shift of ~20 Myr to older ages. Potential correlation problems with mixed igneous-sedimentary data were already regarded by Van der Voo et al. (1984) as the most critical consideration in evaluating Pangea reconstructions.

• For the bracketing Carboniferous and the Late Permian–Early Triassic, the global paleomagnetic database of poles from Gondwana and Laurasia (e.g., Torsvik et al. 2012) is dominated by entries from sedimentary units frequently of early vintage and for which a direct assessment of inclination flattening is difficult to perform. Muttoni et al. (2013) attempted to estimate inclination flattening in Late Permian–Early Triassic data from Adria-Africa. They obtained a direct assessment of $f = 0.8$ for the Bellerophon and Werfen formations from the Bulla section in the Dolomites using data originally published by Scholger et al. (2000) (Table 3) as well as of $f = 0.7$ for the Karoo redbeds from South Africa originally published by Lanci et al. (2013) (Table 3). Flattening values for the other entries forming the Late Permian–Early Triassic Adria-Africa mean paleopole of Muttoni et al. (2013) (Table 3) were assumed using these estimates. With this caveat about data quality in mind, it seems ironic that some paleogeographic reconstructions show a Pangea B configuration in the Early Carboniferous yet a Pangea A configuration by the Permian (Fig. 18 and 19 in Torsvik et al. 2012), ostensibly requiring a large-scale dextral shear transformation from Pangea B to A in the Late Carboniferous. This seems no more nor less 'critically lacking' (Domeier et al. 2012) geological evidence than the major dextral shear between Laurasia and Gondwana, which in our assessment more likely occurred in the Permian (Muttoni et al. 1996, 2003, 2009a).

• Additional research is required to assess inclination flattening factors in Late Permian–Early Triassic sedimentary units from Gondwana and Laurasia (see above), but in any case, considering also inclination flattening-corrected paleopoles from Adria (Muttoni et al. 2013), there is no evidence that necessitates a Pangea B in the Late Permian or Triassic, as initially proposed by Irving (1977) (but see Irving 2004) and occasionally favored in some other studies (e.g., Torcq et al. 1997), nor has there been evidence for the long abandoned concept of a long continuum of transformation of Gondwana versus Laurasia as implied by Van Hilten's Tethys twist model. Nonetheless, the deep root of Pangea B is with Van Hilten (1964) and its transformation to Pangea A resembles the Tethys twist albeit in a much narrower time frame.

• The precise timing of the post-Variscan transformation from Pangea B to Pangea A in the Permian (Muttoni et al. 1996, 2006, 2009a) is presently difficult to set. Indicatively, it is younger than the age of the Early Permian volcanics of the Dolomites in northern Italy dated with modern U-Pb radiometric techniques to 285–275 Ma (Shaltegger & Brack 2007; see also Visonà et al. 2007; Berra et al. 2014) and that provide paleomagnetic data supportive of Pangea B, and it is older than the age of the overlying Late Permian sediments that support Pangea A (Muttoni et al. 2003) (Fig. 1B). These Late Permian sediments record polarity reversals, indicating an age no older than the Illawarra mixed polarity zone (end of Kiaman reverse polarity superchron) presently estimated at ~269 Ma (Lanci et al. 2013). Hence, the Pangea transformation apparently occurred between ~275 Ma and ~260 Ma or over a total of ~15 Myr. This represents a substantial revision of Irving's (1977) original suggestion of a latest Carboniferous to Jurassic Pangea transition, but which Şengör (2016) stressed that 'Irving himself modified his original suggestion by indicating that an early Permian (~280 Ma ago) Pangaea B had already become Pangaea A2 in the late Permian (~250 Ma ago)' undoubtedly because Irving (2004) cited – and accepted – the Muttoni et al. (2003) analysis.

• The total amount of dextral shear required to accommodate the transformation occurring over ~15 Myr (between ~275 Ma and ~260 Ma) was on the order of ~2300 km (Fig. 6), and hence considerably less than the ~3000 km originally proposed by Irving (1977). The shorter distance implies that the relative translation of Gondwana relative to Laurasia occurred at ~15 cm/yr. This is within the nominal speed limit of 18–20 cm/yr that the Indian plate set in the Cretaceous (Kumar et al. 2007).

• The transformation from Pangea B to Pangea A was linked with the opening of the Neotethys and associated motions of Cimmerian terranes (Muttoni et al. 2009a). The concept of Pangea B and its transformation into Pangea A has been developed independently from the concept of Cimmerian terranes and yet these concepts seem to be very much complementary when linked in a common scenario of Neotethys opening, Paleotethys closure, motion of Cimmerian terranes and Pangea transformation occurring contemporaneously in the Permian as part of an internally consistent plate circuit.

• Finally, there is no need to abandon the geocentric axial dipole field model, which provides an excellent fit to the best available data from lava flows for the past 5 to 10 Ma (Opdyke et al. 2015; Cromwell 2018) and has served as a robust working hypothesis for determining paleolatitudes in virtually all paleogeographic reconstructions using paleomagnetic data. In fact, evidence for a Carboniferous–Early Permian Pangea B was obtained also by Gallo et al. (2017) in their novel approach involving pure dipole analysis of Gondwanan data that, incidentally, did not include data from Adria.

Future Research Directions on Pangea B and its transformation to Pangea A

Aside from obtaining additional paleomagnetic data with good age and tectonic control either from volcanic rocks or sedimentary units provided with inclination flattening assessments, especially from the facing continents of Africa and Eurasia, future research directions concerning the still-debated Pangea paleogeography might delve into other aspects of tectonics, climate-sensitive biotic associations, and even long-term climate change that could be explained better by the largely neglected Pangea B and its transformation to Pangea A in the Permian.

The 'critically lacking' (Domeier et al. 2012) geological evidence for the major dextral shear between Laurasia and Gondwana required for the Pangea B to A transformation in fact may be represented by a belt of rotated blocks in the Mediterranean region. Such a tectonically-active lineament is what was postulated by Van Hilten (1964) and De Boer (1965) and suggested as a test of the putative Tethys Shear by R.M. Shackleton, as quoted in Irving (1967). This belt comprises tectonic blocks in southern France, Corsica, and Sardinia that variably rotated about vertical axes after the cooling of the Variscan basement and before the Late Permian-Triassic, entirely compatible with wrench faulting associated with intra-Pangea crustal instability and transformation during the Permian (Aubele et al. 2012, 2014; Bachtadse et al. 2018). Geological evidences of Permian dextral shear linked with Pangea transformation have also been proposed for the western Alps (Garde et al. 2015) and the Pyrenees (Şengör 2013). These shear zones may speculatively represent reactivations of Variscan shear zones sensu Arthaud and Matte (1977). The locus and timing of the local rotations and shear zones are essentially predictions of dextral shear in the transformation of Pangea B to A in the Permian, and are being borne out by the accumulating data.

Future research may also involve a better understanding of the timing of Neotethys opening and Cimmerian terrane motions as part of the grand-scale plate circuit involving Pangea transformation. After the seminal work of Şengör (1979) on the drifting Cimmerian Continent, and the sparse paleomagnetic studies on Permian rocks from these Cimmerian terranes as outlined above, very little has been done for progress on this line of research. It appears that there is increasing agreement that the tectonic evolution of the eastern Tethys can accommodate Pangea B and its transformation to Pangea A in the Permian (e.g., Sengor 2006), and this will require reappraisal of tectonic scenarios that were based on a static Pangea A context.

There is also an intriguing coincidence that requires more attention between the post-Variscan transformation from Pangea B to A and the waning stages of the Late Paleozoic Ice Age (LPIA) that culminated with the demise of Alpine ice sheets in eastern Australia in the Late Permian (~260 Ma) (Metcalfe et al. 2015; Montañez & Poulsen 2013). Goddéris et al. (2017) suggested from their climate and carbon cycling modeling that a topographically-reduced Variscan equatorial mountain belt (whose rise may have helped initiate the LPIA in the Carboniferous) and more arid continental area from the assembly and drift of a supercontinent resulted in reduced silicate weathering and thus a higher net atmospheric CO_2 concentration, which may have contributed to the termination of the LPIA in the Permian. However, their overall conclusions relied on paleogeographic reconstructions that had an essentially static Pangea A configuration and paleolatitudinal position from the Early to the Late Permian (i.e., compare Figures 19 and 20 in cited Golonka 2002). In contrast, a mobilist tectonic model with a transformation from Pangea B in the Early Permian to a Pangea A configuration in the Late Permian should offer more possibilities for significant changes in tectonic boundary conditions that could have affected long-term climate. For example, the transformation of Pangea B to Pangea A would have reduced land-sea distribution in the critical tropical humid belt, and hence continental silicate weathering, for a net increase in atmospheric greenhouse gases that might be linked as contributing to the demise of the LPIA (Kent & Muttoni 2019).

Finally, there have been hardly any analyses of biotic associations and paleogeographic distributions using an accurate Pangea B model for the Carboniferous-Early Permian. The few examples that show promise of further development include the work by Cisneros et al. (2012), who found support for Pangea B when trying to account for the close phylogenetic relationship of South American and eastern European dinocephalians in the Permian, and the work by Angiolini et al. (2007), who found that the distribution of climate-sensitive fossil biota, in particular, the warm-water Carboniferous-Permian biota of Iran and northern Arabia that are strikingly different from typical cold-water Gondwana associations, could be neatly explained when considered in the context of a Pangea B paleogeography.

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References

Argand E. (1922) - La tectonique de l'Asie. Conférence faite á Bruxelles, le 10 août 1922, paper presented at Congrès géologique international (XIIIe session)-Belgique 1922.

Arthaud F. & Matte P. (1977) - Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals. *Geol. Soc. Am. Bull.*, 88: 1305-1320.

Angiolini L., Gaetani M., Muttoni G., Stephenson M.H. & Zanchi A. (2007) - Tethyan oceanic currents and climate gradients 300 m.y. ago. *Geology*, 35: 1071-1074.

Aubele K., Bachtadse V., Muttoni G., Ronchi A. & Durand M. (2012) - A paleomagnetic study of Permian and Triassic rocks from the Toulon-Cuers Basin, SE France: Evidence for intra-Pangea block rotations in the Permian. *Tectonics*, 31(3): TC3015.

Aubele K., V. Bachtadse, V., Muttoni G. & Ronchi A. (2014) - Paleomagnetic data from Late Paleozoic dykes of Sardinia: Evidence for block rotations and implications for the intra-Pangea megashear system. *Geochem. Geophys., Geosyst.*, 15(5): 1684-1697.

Bachtadse V., Zanglein R., Tait J. & Soffel H. (2002) - Palaeomagnetism of the Permo/Carboniferous (280 Ma) Jebel Nehoud ring complex, Kordofan, Central Sudan. *J. African Earth Sci.*, 35(1): 89-97.

Bachtadse V., Aubele K., Muttoni G., Ronchi A., Kirscher U. & Kent D.V. (2018) - New early Permian paleopoles from Sardinia confirm intra-Pangea mobility. *Tectonophysics*, 749: 21-34.

Becke M. & Mauritsch H. (1984) - Rock and paleomagnetic investigations on the Quartzporphyry Complex near Bolzano (Bozen), Italy. *IGCP, Newsletter*, 6: 11-19.

Berra F., Tiepolo M., Caironi V. & Siletto G.B. (2015) - U–Pb zircon geochronology of volcanic deposits from the Permian basin of the Orobic Alps (Southern Alps, Lombardy): chronostratigraphic and geological implications. *Geol. Mag.*, 152(3): 429-443.

Berthold G., Nairn A.E.M. & Negendank J.F.W. (1975) - A palaeomagnetic investigation of some of the igneous rocks of the Saar-Nahe Basin. *N. Jb. Geol. Palaeont. Mh*: 134-150.

Besse J., Torcq F., Gallet Y., Ricou L.E., Krystyn L. & Saidi A. (1998) - Late Permian to Late Triassic palaeomagnetic data from Iran: contraints on the migration of the Iranian block through the Tethyan Ocean and initial destruction of Pangea. *Geophys. J. Int.*, 135(1): 77-92.

Bosellini A. (2002) - Dinosaurs 're-write' the geodynamics of the eastern Mediterranean and the paleogeography of the Apulia Platform. *Earth-Sci. Rev.*, 59: 211-234.

Bullard E.C., Everett J.E. & Smith A.G. (1965) - A symposium on continental drift. IV. The fit of the continents around the Atlantic. *Phil. Trans. Royal Soc. London*, A258: 41-51.

Channell J.E.T. (1996) - Palaeomagnetism and palaeogeography of Adria. In: Morris A. & Tarling D.H. (Eds) - Palaeomagnetism and Tectonics of the Mediterranean Region. *Geol. Soc. Spec. Publ., London*: 119-132.

Channell J.E.T. & Horvath F. (1976) - The African/Adriatic promontory as a palaeogeographical premise for Alpine orogeny and plate movements in the Carpatho-Balkan region. *Tectonophysics*, 35: 71-101.

Channell J.E.T., D'Argenio, B. & Horvath F. (1979) - Adria, the African promontory in Mesozoic Mediterranean palaeogeography. *Earth Sci. Rev.*, 15: 213-292.

Channell J.E.T. & Doglioni C. (1994) - Early Triassic paleomagnetic data from the Dolomites (Italy). *Tectonics*, 13(1): 157-166.

Chiarabba C., De Gori P. & Speranza F. (2008) - The southern Tyrrhenian subduction zone: deep geometry, magmatism and Plio-Pleistocene evolution. *Earth Planet. Sci. Letters*, 268(3-4): 408-423.

Cisneros J.C., Abdala F., Atayman-Güven S., Rubidge B.S., Şengör A.C. & Schultz C.L. (2012) - Carnivorous dinocephalian from the Middle Permian of Brazil and tetrapod dispersal in Pangaea. *Proc. Nat. Ac. Sci.*, 109(5): 1584-1588.

Clark D. & Lackie M. (2003) - Palaeomagnetism of the Early Permian Mount Leyshon intrusive complex and Tuckers igneous complex, North Queensland, Australia. *Geophys. J. Intern.*, 153: 523-547.

Cogné J.P., Van Den Driessche J. & Brun J.P. (1993) - Synextension rotations in the Permian basin of St Affrique (Massif Central, France): paleomagnetic constraints. *Earth Planet. Sci. Letters*, 115: 29-42.

Cornwell J. (1967) - Palaeomagnetism of the Exeter lavas, Devonshire. *Geophys. J. Royal Astronom. Soc.*, 12(2): 181-196.

Corsini M. & Rolland Y. (2009) - Late evolution of the southern European Variscan belt: Exhumation of the lower crust in a context of oblique convergence. *C R Geosci.*, 341(2-3): 214-223.

Cromwell G., Johnson C.L., Tauxe L., Constable C.G. & Jarboe N.A. (2018) - PSV10: A Global Data Set for 0–10 Ma Time-Averaged Field and Paleosecular Variation Studies. *Geochem., Geophys., Geosys.,* 19: 1533-1558.

Crowell J.C. (1999) - Pre-Mesozoic Ice Ages: Their Bearing on Understanding the Climate System. *Geol. Soc. America Memoir,* 192: 1-106.

Daly L. & Pozzi J.-P. (1976) - Resultats paleomagnetiques du Permien inferieur et du Trias Marocain; comparaison avec les Donnees Africaines et Sud Americaines. *Earth Planet. Sci. Letters*, 29: 71-80.

De Kock M. & Kirschvink J. (2004) - Paleomagnetic constraints on the Permian-Triassic boundary in terrestrial strata of the Karoo Supergroup, South Africa: implications for causes of the end-Permian extinction event. *Gondwana Res.*, 7(1): 175-183.

Dietzel G.F.L. (1960) - Geology and permian paleomagnetism of the Merano region, province of Bolzano, N. Italy. *Geologica Ultraiectina*, 4.

De Boer J. (1963) - The Geology of the Vicentinian Alps with special reference to their paleomagnetic history. *Geologica Ultraiectina*, 11.

De Boer J. (1965) - Paleomagnetic indications of megatectonic

movements in the Tethys. *J. Geophys. Res.*, 70(4): 931-944.
Dewey J.F., Pitman W.C.III, Ryan W.B.F. & Bonnin J. (1973) - Plate tectonics and the evolution of the Alpine System. *Geol. Soc. Am. Bull.*, 84: 3137-3180.
Diego-Orozco A. & Henry B. (1993) - Palaeomagnetic results from the Permian Saint-Affrique basin (France) and implications for late and post-Hercynian tectonics. *Tectonophysics*, 227: 31-47.
Domeier M., Van der Voo R. & Torsvik T.H. (2012) - Paleomagnetism and Pangea: the road to reconciliation. *Tectonophysics*, 514: 14-43.
Edel J.B. & Schneider J.L. (1995) - The Late Carboniferous to Early Triassic geodynamic evolution of Variscan Europe in the light of magnetic overprints in Early Permian rhyolites from the northern Vosges (France) and central Black Forest (Germany). *Geophys. J. Int.*, 122: 858-876.
Gallet Y., Krystyn L., Besse J., Saidi A. & Ricou L.-E. (2000) - New constraints on the Upper Permian and Lower Triassic geomagnetic polarity timescale from the Abadeh section (central Iran). *J. Geophys. Res.*, 105(B2): 2805-2815.
Gallo L.C., Tomezzoli R.N. & Cristallini E.O. (2017) - A pure dipole analysis of the G ondwana apparent polar wander path: Paleogeographic implications in the evolution of P angea. *Geochem., Geophys., Geosys.,*18(4): 1499-1519.
Gaetani M., Angiolini L., Garzanti E., Jadoul F., Leven E., Nicora A. & Sciunnach D. (1995) - Permian stratigraphy in the Northern Karakorum, Pakistan. *Riv. It. Paleontol. Strat.*, 101(2): 107-152.
Gaetani M., Le Fort P., Tanoli S., Angiolini L., Nicora A., Sciunnach D. & Khan A. (1996) - Reconnaissance geology in Upper Chitral, Baroghil and Karambar districts (northern Karakorum, Pakistan). *Geol. Rund.*, 85: 638–704.
Garde A.A., Boriani A. & Sørensen E.V. (2015) - Crustal modelling of the Ivrea–Verbano zone in northern Italy reexamined: Coseismic cataclasis versus extensional shear zones and sideways rotation. *Tectonophysics*, 662: 291-311.
Goddéris Y., Donnadieu Y., Carretier S., Aretz M., Dera G., Macouin M. & Regard V. (2017) - Onset and ending of the late Palaeozoic ice age triggered by tectonically paced rock weathering. *Nature Geosci*, 10: 382-386.
Golonka J. (2002) - Plate-tectonic maps of the Phanerozoic. *SEPM Spec. Publ.*, 72: 21-75.
Gradstein F.M., Ogg J.G., Schmitz M.D. & Ogg G.M., (Eds) (2012) - The Geologic Time Scale 2012. Amsterdam, Elsevier, 1144 pp.
Guicherit R. (1964) - Gravity tectonics, gravity field, and paleomagnetism in northeast Italy. *Geologica Ultraiectina*, 14.
Halvorsen E. (1970) - Palaeomagnetism and the age of the younger diabases in the Ny-Hellesund area, S. Norway. *Norsk Geologisk Tidsskrift*, 50: 157-166.
Halvorsen E. (1972) - On the palaeomagnetism of the Arendal diabases. *Norsk Geologisk Tidskrift*, 52(3): 217-228.
Heiniger C. (1979) - Paleomagnetic and rock magnetic properties of the Permian volcanics in the western Southern Alps. *J. Geophys.*, 46: 397-411.
Huang K., Opdyke N.D., Peng X. & Li J. (1992) - Paleomagnetic results from the Upper Permian of the eastern Qiangtang Terrane of Tibet and their tectonic implications. *Earth Planet. Sci. Letters*, 111(1): 1–10.
Irving E. (1967) - Palaeomagnetic evidence for shear along the Tethys, Aspects of Tethyan Biogeography. Systematics Association Publication, London, 7: 59-76.
Irving E. (1977) - Drift of the major continental blocks since the Devonian. *Nature*, 270: 304-309.
Irving E. (2004) - The case for Pangea B, and the Intra-Pangean megashear. In. Channell J.E.T., Kent D.V., Lowrie Q. & Meert J.G. (Eds.) - Timescales of the paleomagnetic field. *AGU Geophys. Monogr.*, 145: 13-27.
Irving E. (2005) - The role of latitude in mobilism debates. Proceedings of the National Academy of Sciences, 102(6): 1821-1828.
Irving E. (2006) - Geophysics: Same old magnetism. *Nature*, 444(7115): 43.
Irving E. & Parry L.G. (1963) - Magnetism of some Permian rocks from New South Wales. *Geophys. J.,* 7(4): 395-411.
Kent D.V. & Irving E. (2010) - Influence of inclination error in sedimentary rocks on the Triassic and Jurassic apparent polar wander path for North America and implications for Cordilleran tectonics. *J. Geophys. Res.*, 115(B10103): doi:10110.11029/12009aJB007205.
Kent D.V., Kjarsgaard B.A., Gee J.S., Muttoni G. & Heaman L.M. (2015) - Tracking the Late Jurassic apparent (or true) polar shift in U-Pb-dated kimberlites from cratonic North America (Superior Province of Canada). *Geochem., Geophys., Geosys.,* 16(4): 983-994.
Kent D.V. & Muttoni G. (2019) - Waning of the Late Paleozoic Ice Age and the Pangea B to Pangea A Transformation in the Permian. *Geophys. Res. Abstracts,* 21: p. EGU2019-8637-2.
Kipfer R. & Heller F. (1988) - Palaeomagnetism of Permian red beds in the contact aureole of the Tertiary Adamello intrusion (northern Italy). *Phys. Earth Planet. Interiors*, 52: 365-375.
Khramov A.N. (1982) - Paleomagnetic directions and pole positions: Data for the USSR: Soviet Geophysical Committee. World Data Center-B (Moscow), Issue 5, Catalogue.
Klootwijk C.T. & Bingham D.K. (1980) - The Extent of Greater India, III. Palaeomagnetic data from the Tibetan sedimentary series, Thakkhola Region, Nepal Himalaya. *Earth Planet. Sci. Letters*, 51(2): 381-405.
Konrad H.J. & Nairn A.E.M. (1972) - The palaeomagnetism of the Permian rocks of the Black Forest, Germany. *Geophys. J. Royal Astronom. Soc.*, 27: 369-382.
Kumar P., Yuan X., Kumar M.R., Kind R., Li X, & Chadha R. (2007) - The rapid drift of the Indian tectonic plate. *Nature*, 449(7164): 894.
Lanci L., Tohver E., Wilson A. & Flint S. (2013) - Upper Permian magnetic stratigraphy of the lower Beaufort Group, Karoo Basin. *Earth Planet. Sci. Letters*, 375: 123-134.
Lowrie W. (1986) - Paleomagnetism and the Adriatic promontory: a reappraisal. *Tectonics*, 5: 797-8807.
Manabe S. & Bryan K. (1985) - CO_2-induced change in a coupled ocean-atmosphere model and its paleoclimatic implications. *J. Geophys. Res.*, 90: 11689-11707.

Manzoni M. (1970) - Paleomagnetic data of Middle and Upper Triassic age from the Dolomites (eastern Alps, Italy). *Tectonophysics*, 10: 411-424.

Mauritsch H.J. & Rother K. (1983) - Paleomagnetic investigations in the Thuringer Forest (G.D.R.). *Tectonophysics*, 99: 63-72.

Merabet N. & Daly L. (1986) - Détermination d'un pole paléomagnétique et mise en évidence d'aimantations à polarité normale sur les formations du Permien supérior du Massif de Maures (France). *Earth Planet. Sci. Letters*, 80: 156-166.

Metcalfe I., Crowley J.L., Nicoll R.S. & Schmitz M. (2015) - High-precision U-Pb CA-TIMS calibration of Middle Permian to Lower Triassic sequences, mass extinction and extreme climate-change in eastern Australian Gondwana. *Gondwana Res.*, 28: 61-81.

Montañez I.P. & Poulsen C.J. (2013) - The Late Paleozoic Ice Age: An Evolving Paradigm. *Annual Rev. Earth Planet. Science*, 41: 24.1–24.28.

Morel P. & Irving E. (1981) - Paleomagnetism and the evolution of Pangea. *J. Geophys. Res.*, 86: 1858-1987.

Mulder F.G. (1971) - Paleomagnetic research in some parts of central and southern Sweden. Sveriges Geologiska Undersökning, Ser. C. 653, 56 pp.

Muttoni G. (1996) - Preliminary results on the paleomagnetism of Upper Permian Verrucano Lombardo sandstones from Val Camonica and of Upper Triassic Val Sabbia sandstones from Val Brembana, Southern Alps. *Natura Bresciana*, 30: 17-30.

Muttoni G., Kent D.V. & Channell J.E.T. (1996) - Evolution of Pangea: Paleomagnetic constraints from the Southern Alps, Italy. *Earth Planet. Sci. Letters*, 140: 97-112.

Muttoni G., Garzanti E., Alfonsi L. Cirilli S. Germani D. & Lowrie W. (2001) - Motion of Africa and Adria since the Permian: paleomagnetic and paleoclimatic constraints from northern Libya. *Earth Planet. Sci. Letters*, 192: 159-174.

Muttoni G., Kent D.V., Garzanti E., Brack P., Abrahamsen N. & Gaetani M. (2003) - Early Permian Pangea 'B' to Late Permian Pangea 'A'. *Earth Planet. Sci. Letters*, 215: 379-394.

Muttoni G., Gaetani M., Kent D.V., Sciunnach D., Angiolini L., Berra F., Garzanti E., Mattei M. & Zanchi A. (2009a) - Opening of the Neo-Tethys Ocean and the Pangea B to Pangea A transformation during the Permian. *GeoArabia*, 14: 17-48.

Muttoni G., Mattei M., Balini M., Zanchi A., Gaetani M. & Berra F. (2009b) - The drift history of Iran from the Ordovician to the Triassic. *Geol. Soc. London Spec. Publ.*, 312: 7-29.

Muttoni G., Dallanave E. & Channell J.E.T. (2013) - The drift history of Adria and Africa from 280 Ma to Present, Jurassic true polar wander, and zonal climate control on Tethyan sedimentary facies. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 386: 415-435.

Muttoni G. & Kent D.V. (2019) - Jurassic monster polar shift confirmed by sequential paleopoles from Adria, promontory of Africa. *J. Geophys. Res.*, accepted.

Nawrocki J. (1997) - Permian to Early Triassic magnetostratigraphy from the Central European Basin in Poland: Implications on regional and worldwide correlations. *Earth Planet. Sci. Letters*, 152: 37-58.

Nawrocki J., Kuleta M. & Zbroja S. (2003) - Buntsandstein magnetostratigraphy from the northern part of the Holy Cross Mountains. *Geol. Quarterly,* 47: 253-260.

Nijenhuis G. (1961) - A palaeomagnetic study of the Permian volcanics in the Nahe region (SW. Germany). *Geol. Mijnbouw,* 40(1): 26-38.

Rochette P. & Vandamme D. (2001) - Pangea B: an artifact of incorrect paleomagnetic assumptions?. *Annali di Geofisica*, 44: 649-658.

Schaltegger U. & Brack P. (2007) - Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. *Intern. J. Earth Sci.*, 96(6): 1131-1151.

Scholger R., Mauritsch H.J. & Brandner R. (2000) - Permian-Triassic boundary magnetostratigraphy from the southern Alps (Italy). *Earth Planet. Sci. Letters*, 176: 495-508.

Schwarz E. (1965) - On the paleomagnetic results derived from European rocks of Permian age. *J. Geophys. Res.*, 70(12): 2938-2939.

Şengör A.M.C. (1979) - Mid-Mesozoic closure of Permo-Triassic Tethys and its implications. *Nature*, 279: 590–593.

Şengör, A.M.C. (2013) - The Pyrenean Hercynian Keirogen and the Cantabrian Orocline as genetically coupled structures. *J. Geodyn.*, 65: 3-21.

Şengör A.M.C. (2016) - Tethys in marine sciences. In: Harff J. (Ed) - Encyclopedia of Marine Geosciences. Dordrecht, Springer Science+Business Media: 825-849.

Shen S.-z., Crowley J.L., Wang Y., Bowring S.A., Erwin D.H., Sadler P.M., Cao C.-q., Rothman D.H., Henderson C.M., Ramezani J., Zhang H., Shen Y., Wang X.-d., Wang W., Mu L., Li W.-z., Tang Y.-g., Liu X.-l., Liu L.-j., Zeng Y., Jiang Y.-f. & Jin Y.-g. (2011) - Calibrating the End-Permian Mass Extinction. *Science*, 334: 1367-1372.

Soffel H. & Harzer F. (1991) - An Upper Carboniferous-Lower Permian (280 Ma) palaeomagnetic pole from the western margin of the Bohemian Massif. *Geophys. J. Intern.*, 105(2): 547-551.

Speranza F., Minelli L., Pignatelli A. & Chiappini M. (2012) - The Ionian Sea: The oldest in situ ocean fragment of the world?. *J. Geophys. Res. Solid Earth*, 117(B12).

Szurlies M., Bachmann G.H., Menning M., Nowaczyk N.R. & Käding K.-C. (2003) - Magnetostratigraphy and high-resolution lithostratigraphy of the Permian–Triassic boundary interval in Central Germany. *Earth Planet. Sci. Letters*, 212: 263-278.

Tauxe L. & Kent D.V. (2004) - A simplified statistical model for the geomagnetic field and the detection of shallow bias in palaeomagnetic inclinations: was the ancient magnetic field dipolar?. In. Channell J.E.T., Kent D.V., Lowrie Q. & Meert J.G. (Eds.) - Timescales of the paleomagnetic field. *AGU Geophys. Monogr.*, 145: 101–115.

Thomas D.N., Rolph T.C. & Freil D.F. (1997) - Permo-Carboniferous (Kiaman) palaeointensity results from the western Bohemian Massif, Germany. *Geophys. J. Intern.*, 130: 257-265.

Torcq F., Besse J., Vaslet D., Marcoux J., Ricou L. E., Halawani M. & Basahel M. (1997) - Paleomagnetic results from Saudi Arabia and the Permo-Triassic Pangea configuration. *Earth Plant. Sci. Letters*, 148: 553-567.

Torsvik T.H., Eide E.A., Meert J.G., Smethurst M.A. & Walderhaug H.J. (1998) - The Oslo rift: new palaeomagnetic and $^{40}Ar/^{39}Ar$ age constraints. *Geophys. J. Intern.*, 135: 1045-1059.

Torsvik T.H. & Van der Voo R. (2002) - Refining Gondwana and Pangea palaeogeography: estimates of Phanerozoic non-dipole (octupole) fields. *Geophys. J. Intern.*, 151(3): 771-794.

Torsvik T.H., Van der Voo R., Preeden U., Mac Niocaill C., Steinberger B., Doubrovine P.V., van Hinsbergen D.J.J., Domeier M., Gaina C. & Tohver E. (2012) - Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Sci. Rev.*, 114(3): 325-368.

Van der Voo R. (1993) - Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans: Cambridge, Cambridge University Press, 411 p.

Van der Voo R. & French R.B. (1974) - Apparent polar wandering for the Atlantic-bordering continents: Late Carboniferous to Eocene. *Earth-Science Rev.* 10: 99-119.

Van der Voo R. & Torsvik T.H. (2001) - Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems. *Earth Planet. Sci. Letters*, 187: 71-81.

Van Everdingen R.O. (1960) - Palaeomagnetic analysis of Permian extrusives in the Oslo Region. *XVII Skr. Nor. Vidensk. Akad. Oslo*, 135: 1-80.

Van Eysinga F.W.B. (1975) - Geological Time Scale (3rd ed.), Elsevier, New York.

Van Hilten D. (1962) - A deviating Permian pole from rocks in northern Italy. *Geophys. J. Intern.*, 6(3): 377-390.

Van Hilten D. (1964) - Evaluation of some geotectonic hypotheses by paleomagnetism. *Tectonophysics*, 1: 3-71.

Van Hinsbergen D.J.J., Mensink M., Langereis C., Maffione M., Spalluto L., Tropeano M. & Sabato L. (2014) - Did Adria rotate relative to Africa?. *Solid Earth*, 5(2): 611-629.

Visonà D., Fioretti A.M., Poli M.E., Zanferrari A. & Fanning M. (2007) - U-Pb SHRIMP zircon dating of andesite from the Dolomite area (NE Italy): geochronological evidence for the early onset of Permian Volcanism in the eastern part of the southern Alps. *Swiss J. Geosci.*, 100(2): 313-324.

Westphal M., Montigny R., Thizat R., Bardon C., Bossert A. & Hamzeh R. (1979) - Paléomagnétisme et datation du volcanisme permien, triasique et crétacé du Maroc. *Can. J. Earth Sci.*, 16: 2150-2163.

Wortmann U.G., Weissert H., Funk H. & Hauck J. (2001) - Alpine plate kinematics revisited: the Adria problem. *Tectonics*, 20(1): 134-147.

Zijderveld J.D.A. (1967) - The natural remanent magnetizations of the Exeter volcanic traps (Permian, Europe). *Tectonophysics*, 4(2): 121-153.

Zijderveld J.D.A. & De Jong K.A. (1969) - Paleomagnetism of some Late Paleozoic and Triassic rocks from the eastern Lombardic Alps. *Geol. Mijnbouw*, 48(6): 559-564.

Zijderveld J.D.A., Hazeu G.J.A., Nardin M. & Van der Voo R. (1970) - Shear in the Tethys and the Permian paleomagnetism in the Southern Alps, including new results. *Tectonophysics*, 10: 639-661.