The drift history of Adria and Africa from 280 Ma to Present, Jurassic true polar wander, and zonal climate control on Tethyan sedimentary facies

G. Muttoni \textsuperscript{a,b,*}, E. Dallanave \textsuperscript{c}, J.E.T. Channell \textsuperscript{d}

\textsuperscript{a} Dipartimento di Scienze della Terra “A. Desio”, Università degli Studi di Milano, via Mangiagalli 34, 20133 Milano, Italy
\textsuperscript{b} APU – Alpine Laboratory of Paleomagnetism, via Madonna dei Boschi 76, I-12016 Peveragno (CN), Italy
\textsuperscript{c} Department of Earth and Environmental Science, Ludwig-Maximilians University, Munich D-80333, Germany
\textsuperscript{d} Department of Geological Sciences, University of Florida, Gainesville, FL 32611, USA

\textbf{A R T I C L E  I N F O}

Article history:
Received 25 February 2013
Received in revised form 7 June 2013
Accepted 10 June 2013
Available online 18 June 2013

Keywords:
Paleomagnetism
Adria
Africa
Apparent polar wander path
True polar wander
Jurassic
Zonal climate
Tethys
Sedimentary facies

\textbf{A B S T R A C T}

The orogenic belts surrounding the undeformed Adriatic Sea represent the margins of an area known as Adria, the African promontory. We have undertaken a critical appraisal of paleomagnetic data from regions of Adria considered parautochthonous relative to Africa, obtained either from biostratigraphically dated sedimentary rocks, corrected for inclination shallowing, or from igneous rocks that are regarded as free from any inclination shallowing bias. Paleomagnetic directions were used to calculate paleomagnetic poles for comparison with coeval, and inclination flattening-free, paleomagnetic poles from stable Africa. Visual coherence of paleopoles for several time slices from the Early Permian to the Eocene supports the construction of a composite apparent polar wander path (APWP) valid for parautochthonous Adria and stable Africa. This composite APWP is compared to previous APWPs, finding good agreement with the global APWP of Kent and Irving (2010). Both APWPs show a remarkable and rapid polar shift of ~40° in the Jurassic that other APWPs tend to underestimate. We interpret this shift to represent a major episode of true polar wander (TPW), from ~183 Ma in the Early Jurassic to ~151 Ma in the Late Jurassic. Using a simple zonal climate model, the drift motion of Adria attached to Africa appears to be consistent with the distribution of Permian–Cretaceous sedimentary facies on Adria.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

The evolution of the Alpine orogeny and Atlantic spreading history (e.g., Dewey et al., 1989) and the debated paleogeographic evolution of Pangea in the Permian (Muttoni et al., 2003; Domeier et al., 2011a; Aubele et al., 2012) are intimately connected with the interpretation of Adria — the paleogeographic unit composed of the Adriatic foreland and surrounding fold-and-thrust belts (Fig. 1A) — as a promontory of the African plate (Channell et al., 1979; Channell, 1996; Rosenbaum et al., 2004). After several decades of extensive paleomagnetic research, we assert that even opponents (e.g., Márton et al., 2010) of the Adria–Africa coherence hypothesis would not deny that the general distribution of Permian–Cenozoic paleomagnetic poles from parautochthonous regions of Adria (see below) show a strong African affinity (Channell, 1996; Satolli et al., 2007, 2008). Given the far-reaching consequences of the Adria–Africa connection, however, it is important to re-evaluate the paleomagnetic database of Adria as a proxy for the drift history of Africa. We performed a thorough literature review of paleomagnetic data from Adria to compare with coeval data from Africa. Data from Adria have been obtained from well-dated sedimentary rocks and have been corrected for inclination shallowing, or from igneous rocks assumed free from inclination shallowing. Paleomagnetic data from Africa are mainly from igneous rocks. We find significant coherence of Adria and Africa paleomagnetic poles through the Permian–Cenozoic, and use this coherence to support a major, rapid, and previously underestimated event of polar wandering in the Jurassic, recently described by Kent and Irving (2010), as well as to explain the deposition of several paleolatitude-dependent sedimentary facies in the Tethys Ocean during the Permian–Cretaceous.

2. Adria, the African promontory

Adria is the term applied to the largely undeformed Po–Adriatic foreland basin rimmed by three post-Late Jurassic orogens, the Alps, the Apennines, and the Dinarides (Channell et al., 1979), and bounded by the Tyrrenhian Sea in the west and the Ionian Sea (Speranza et al., 2012) in the southeast (Fig. 1A). Due to this complexity, it took decades to realize and accept the ‘enigmatic’ (Channell, 1996) close concordance of Permian and Mesozoic paleomagnetic poles from Adria and Africa, suggestive of substantial tectonic coherence between the two lithospheric units (Channell, 1996). Through extensive research conducted...
in the 1960s and 1970s came the realization that the Alps — the heart of Europe — are not European insofar as they were found to possess Early Permian paleomagnetic directions deviating from coeval directions from non-Alpine Europe by up to 50° (e.g., Van Hilten, 1962; Van Hilten and Zijderveld, 1966; Zijderveld et al., 1970). Another important outcome of these two decades of pioneering work was the realization that the Early Permian paleomagnetic directions from the Southern Alps agree reasonably well with coeval directions from Africa (Zijderveld et al., 1970), a coherence that was later proven valid also for the Mesozoic (e.g., Channell and Tarling, 1975; Channell, 1996).

Another region of Italy that received attention in the early seventies of the last century was southeastern Sicily — the undeformed Hyblean platform facing the Ionian Sea (Fig. 1A) — where different authors sampled Pliocene–Pleistocene and Upper Cretaceous basaits and concluded that no relative movement occurred between autochthonous Sicily and Africa since the Late Cretaceous (e.g., Barberi et al., 1974; Gregor et al., 1975). At broadly the same time, attention was devoted to the Umbrian Apennines of central Italy, where ample evidence for tectonic rotations was found (e.g., Lowrie and Alvarez, 1975), in apparent contrast with the findings from southeastern Sicily. However, subsequent studies on classic Mesozoic–Cenozoic sedimentary successions revealed that the Umbrian Apennines are characterized by an apparent polar wander path (APWP) that is African in shape but rotated counterclockwise by ~20°–25° with respect to Africa essentially due to thrust-sheet rotations rather than lithospheric decoupling of peninsular Italy relative to Africa (Channell, 1996; Satolli et al., 2007, 2008). Somewhat similarly, Cretaceous paleomagnetic directions from the largely undeformed Adriatic foreland regions of Gargano and Istria (Fig. 1A), which were initially taken to suggest rotation of peninsular Italy relative to Africa (e.g., Heller et al., 1989), were subsequently superseded by higher-quality data that indicated no such rotations (Channell, 1996).

This brief historical overview indicates that the concept of the African affinity of largely undeformed foreland regions of the Alpine–Apennine–Dinaric orogen (Istria, Gargano, Hyblean platform), as well as parts of the deformed Southern Alps margin (see below), took shape in the 1970s (e.g., Zijderveld et al., 1970), became well established and documented since the 1990s (Van der Voo, 1993; Channell, 1996), and since then was reiterated and enhanced by inclusion of additional Permian–Triassic (Muttoni et al., 1996, 1997; Brack and Muttoni, 2000; Muttoni et al., 2001, 2003, 2010), Jurassic (Muttoni et al., 2005; Channell et al., 2010), and Paleocene–Eocene data (Dallanave et al., 2009; Agnini et al., 2011; Dallanave et al., 2012). After four decades of intensive paleomagnetic research, we conclude that Adria can be broadly divided into three regions (Fig. 1A):

1) The Apennines — the backbone of the Italian peninsula — running from Piedmont in the northwest to Sicily in the south, characterized by the ubiquitous presence of thrust sheets affected by complex vertical–axis rotations. These rotations are essentially counterclockwise in the Mesozoic–Cenozoic ‘hard core’ of the northern-central Apennines, from the juncture with the western Alps in Piedmont (Carra et al., 2003; Maffione et al., 2008) to the Emilia–Marche–Umbria Apennines (e.g., Channell et al., 1978; Hirt and Lowrie, 1988; Muttoni et al., 2001; Satolli et al., 2007, 2008), as well as in the Late Miocene Adriatic foredeep deposits at the main thrust front (Speranza et al., 1997), and essentially clockwise in the Sicilian Apennines (e.g., Channell et al., 1990). The Tyrrenhenian extensional margin in the west appears largely unrotated at least since the Late Miocene (Matté et al., 1996).

2) The substantially undeformed foreland of the Alpine–Apennine–Dinaric orogeny centered on the Adriatic Sea and exposed in Istria (Slovenia) and Gargano–Apulia (Puglia, southern Italy), as well as in southeastern Sicily (Hyblean platform) facing the Ionian Sea (Fig. 1A), which yielded Cretaceous paleomagnetic results coherent with coeval results from Africa and are therefore considered parautochthonous relative to the African craton (Channell, 1996; this study).

3) The Southern Alps represented by the Mesozoic–Cenozoic paleogeographic domains of the Trento plateau (including the Dolomites) bounded in the east by the Belluno basin and in the west by the Lombardian basin (Fig. 1B). In this segment of the Southern Alps, shortening deformation was broadly oriented N–S (e.g., Castellarin et al., 2012) and involved thick piles of Triassic platform carbonate rocks overlying Permian volcanics rocks resting above the Variscan crystalline basement, which conferred rigidity to the thrust sheets and prevented large and systematic vertical axis rotations, which are more typical of Apennine tectonics. This region of the Southern Alps, broadly spanning from Lake Como in the west to Belluno in the east (Fig. 1B), yielded Permian, Triassic, Jurassic, and Cretaceous paleomagnetic results that are substantially coherent with coeval data from Africa (Channell, 1996; Muttoni et al., 2003; this study), and, for this reason, they are interpreted as parautochthonous with respect to the African craton.

As several key papers have been published since the Channell (1996) review, an update of the Adria APWP for comparison with African paleomagnetic poles (hereafter paleopoles or simply poles) is warranted. In addition, it is now realized that several types of sedimentary deposits (e.g., hematite-bearing red beds) can be affected by (sometimes large) paleomagnetic inclination flattening errors (Tauxe and Kent, 1984) that can however be detected and corrected using the elongation/inclination (E/I) statistical method of Tauxe and Kent (2004) (see also Kent and Tauxe, 2005). In this paper, we review the available paleomagnetic data of Adria from volcanic rocks or sedimentary rocks that have been corrected for inclination shallowing.

We focus our analysis on sites pertaining to regions of Adria that are regarded as parautochthonous with respect to the African craton (i.e., regions #2 and #3 described above), whereas data from the Apennines (region #1), characterized by vertical axis rotations of up to ~25° (Satolli et al., 2007, 2008), are discussed but not included in our Adria compilation. Finally, we compare paleomagnetic data from parautochthonous Adria with coeval data mainly from igneous rocks from stable Africa for the construction of a composite Adria–Africa APWP.

3. Paleomagnetic poles from Adria and Africa

The paleomagnetic database of Adria and Africa adopted in this study is composed of 79 individual entries from the literature dated from the Early Permian to the Miocene (Table 1), with ages expressed relative to the Geological Time Scale 2012 of Gradstein et al. (2012). Early Permian data from the Southern Alps, and Late Cretaceous data from the Hyblean platform of southeastern Sicily, are from volcanic rocks for which no inclination shallowing is expected (Tauxe and Kent, 2004). Middle Triassic, Jurassic, Early Cretaceous, and Paleocene–Eocene data are from sedimentary rocks from the Southern Alps that we tested (and corrected) for inclination shallowing, as illustrated below.

3.1. Correction for sedimentary inclination bias

The applied method (Tauxe and Kent, 2004) consists of progressively unflattening paleomagnetic directions by decreasing the flattening parameter $f$ (King, 1955) in the equation $\tan I_i = f \cdot \tan I_0$ (where $I_i$ and $I_0$ are the measured inclination and the true inclination of the magnetic field during sedimentation, respectively) so that the directional dataset assumes an E/I pair of values that is consistent with the TK03.GAD field model (Tauxe and Kent, 2004; see also Kent and Tauxe, 2005; Tauxe et al., 2011).
Table 1
Paleomagnetic data from Adria and Africa.

<table>
<thead>
<tr>
<th>Entry rock unit and ref.</th>
<th>N</th>
<th>Dec_{10}</th>
<th>Inc_{10}</th>
<th>a95_{10}</th>
<th>N_{45}</th>
<th>Dec_{45}</th>
<th>Inc_{45}</th>
<th>k_{45}</th>
<th>a95_{45}</th>
<th>f</th>
<th>Clnc</th>
<th>Clnc_{(45)}</th>
<th>Long</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early Permian (~284–276 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Southern Alps volcanics 46.0°N/11.0°E (general locality) (Muttoni et al., 2003)</td>
<td>7*</td>
<td>151.5</td>
<td>-25.6</td>
<td>8.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 Lugano (Ganna) Porphyries, Ticino 45.8°N/8.8°E (mean locality) (Heiniger, 1979)</td>
<td>4*</td>
<td>142.9</td>
<td>-20.4</td>
<td>10.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 Auccia volcanics, Lombardy 45.8°N/10.4°E (mean locality) (Heiniger, 1979)</td>
<td>5*</td>
<td>139.7</td>
<td>-14.1</td>
<td>8.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4 Arona volcanics, Lombardy 45.7°N/8.5°E (mean locality) (Heiniger, 1979)</td>
<td>4*</td>
<td>134.9</td>
<td>-14.2</td>
<td>13.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5 Bolzano Porphyries, Alto Adige 46.2°N/11.5°E (mean locality) (Zijderveld et al., 1970)</td>
<td>39*</td>
<td>150</td>
<td>-19.5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Africa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Bolzano Porphyries, Alto Adige 46.5°N/11.3°E (mean locality) (Becke and Mauritsch, 1984)</td>
<td>50</td>
<td>155.2</td>
<td>-16.8</td>
<td>4.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7 L.Collo &amp; Auccia volcanics, Lombardy 45.8°N/10.2°E (mean locality) (Zijderveld and De Jong, 1969)</td>
<td>5*</td>
<td>135</td>
<td>-21</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Late Permian–Early Triassic (~260–245 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Tazzott Trachyandesites, Morocco 32.2°N/354°E (general locality) (Daly and Pozzi, 1976)</td>
<td>12*</td>
<td>136</td>
<td>-5</td>
<td>4.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9 Chougrane &amp; Mechra Volcs., Morocco 32.5°N/352.5°E (general locality) (Westphal et al., 1979)</td>
<td>4*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10 Jebel Nehoud 282 Ma, Sudan (Bachtadse et al., 2002)</td>
<td>8*</td>
<td>147</td>
<td>39.6</td>
<td>6.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Mt. Leyshon Intrusives Australia 20.2°S/146.3°E (Clark and Lackie, 2003)</td>
<td>34*</td>
<td>196.3</td>
<td>77.4</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12 Tuckers Igneous Complex Australia 20.1°S/146.5°E (Clark and Lackie, 2003)</td>
<td>42*</td>
<td>188.7</td>
<td>75.2</td>
<td>3.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>South America</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Karoo Upper Permian redbeds, Ouberg Pass, S. Africa (32.4°S, 20.3°E) (Lanci et al., in press)</td>
<td>136*</td>
<td>308</td>
<td>-53</td>
<td>4.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19 Karoo P/T boundary redbeds, Komandordridl, S. Africa (32.2°S, 26.1°E) (DeKock and Kirschvink, 2004)</td>
<td>35*</td>
<td>311.9</td>
<td>-61.6</td>
<td>7.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Middle–Early Late Triassic (Ladinian–earliest Carnian; ~241–236 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 Buchenstein Beds Belvedere, Dolomites 46.4°N/12.0°E (Brack and Muttoni, 2000)</td>
<td>93*</td>
<td>344.5</td>
<td>21.1</td>
<td>7.4</td>
<td>78</td>
<td>342.3</td>
<td>18.8</td>
<td>9</td>
<td>5.7</td>
<td>0.81</td>
<td>22.7</td>
<td>19.1/35.8</td>
<td>221.1</td>
<td>52.3</td>
</tr>
<tr>
<td>22 Buchenstein Beds Froetschbach, Dolomites 46.0°N/11.8°E (Muttoni et al., 1997)</td>
<td>92*</td>
<td>350.8</td>
<td>38.0</td>
<td>5.7</td>
<td>77</td>
<td>352.3</td>
<td>34.8</td>
<td>16</td>
<td>4.1</td>
<td>0.89</td>
<td>37.9</td>
<td>33.5/46.7</td>
<td>208.3</td>
<td>63.9</td>
</tr>
<tr>
<td>23 Val Cola Limestones Margin, Trenton 46.0°N, 11.1°E (Gialanella et al., 2001)</td>
<td>55*</td>
<td>342.5</td>
<td>34.0</td>
<td>4.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.85</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24 San Cassiano Fm. Stuores, Dolomites 46.6°N/11.9°E (Broglia Lorita et al., 1999)</td>
<td>89*</td>
<td>359.4</td>
<td>16.5</td>
<td>6.0</td>
<td>78</td>
<td>358.3</td>
<td>17.0</td>
<td>16</td>
<td>4.2</td>
<td>0.57</td>
<td>26.2</td>
<td>19.3/34.0</td>
<td>194.9</td>
<td>57.2</td>
</tr>
</tbody>
</table>
Africa

25 Al-Azizia & Kaf Bates combined, Libya 32.45°N/13.15°E (Muttoni et al., 2001) 2°/60° - - - 56 347.2 5.8 33 3.3 0.58 10.0 5.2/15.2 219.4 60.1

Earliest Jurassic (~201 ± 1 Ma)

Africa (Central Atlantic Magmatic Province)

26 Draa Valley sills, Morocco (Hailwood and Mitchell, 1971) 16° - 339.0 27.5 4.5 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 230.5 65.5 (A95 = 3.5)

27 Foum Zguid dyke, Morocco (Hailwood and Mitchell, 1971) 5° - 325.0 40.0 4.0 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 259.0 58.0 (A95 = 4.0)

28 Foum Zguid dyke, Morocco (Silva et al., 2006) 6° - 336.4 40.9 2.3 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 250.3 67.8 (A95 = 2.4)

29 Foum Zguid dyke, Morocco (Palencia-Ortas et al., 2011) 12° - 336.8 39.3 3.9 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 247.9 67.9 (A95 = 3.9)

30 Igrem dyke, Morocco (Palencia-Ortas et al., 2011) 11° - 348.4 42.1 6.8 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 238.2 78.4 (A95 = 6.7)

31 CAMP lavas, Morocco (Font et al., 2011) 9° - 333.5 27.0 3.0 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 241.6 60.0 (A95 = 2.6)

32 Liberian dikes and sills, NW Africa (Dalrymple et al., 1975) 26° - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 242.4 68.5 (A95 = 5.3)

33 Hank volc., North Mauritania (Sichler et al., 1980) 25° - 342.8 24 4.1 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 232.0 69.4 (A95 = 4.1)

34 Hodh volc., South Mauritania (Sichler et al., 1980) 24° - 342.5 18.5 6.1 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 240.2 71.4 (A95 = 6.1)

35 Freetown Complex, Sierra Leone (Hargraves et al., 1999) 13° - 174.8 - 6.9 6.2 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 212.7 82.9 (A95 = 5.6)

Early Jurassic (Sinemurian; ~199–191 Ma)

Adria

36 Colle di Sogno, Lombardy (Channell et al., 2010) 85° - 335.3 54.6 2.3 85 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 258.3 68.5 (A95 = 2.7)

Early Jurassic (Toarcian) (~183 ± 1 Ma)

Karoo Igneous Province, South Africa

37 Stromberg lavas, Lesotho (Van Zijl et al., 1962) 74° - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 262.9^b 78.6^b (A95 = 15)

38 Lesotho lavas (Kosterov and Perrin, 1996) 28° - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 270.3^b 79.3^b (A95 = 3.7)

39 Karoo mean pole South Africa, various localities (Hargraves et al., 1997) 84° - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 278.1^b 76.9^b (A95 = 3.3)

40 Naude's Nek lavas, South Africa (Moulin et al., 2011) 19° - 342.8 - 54.0 4.7 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 275.2^b 82.9^b (A95 = 5.8)

Late Jurassic (Callovian–Oxfordian; ~164–157 Ma)

Adria

41 Colle Sogno (CS), Lombardy (45.7°N, 9.5°E) sites CS8 + CS9 combined (Red Cherts-base Rosso Apicc) Callovian–Oxfordian (Muttoni et al., 2005) 19° - 350.9 18.0 4.9 19 - - - - - - - - - - - - - - - - - - - - - - 204.4 52.6

42 Torre de' Busi (TB), Lombardy (45.7°N, 9.5°E) Meter levels 48–54 (Red Cherts-base Rosso Apicc) Callovian–Oxfordian (Channell et al., 2010) 25° - 331.2 21.7 3.8 25 - - - - - - - - - - - - - - - - - - - - - - 234.0 47.7

43 Passo del Branchetto (PB), Veneto 45.6°N/11°E Fonzaso Cherty Limestone Late Oxfordian (Channell et al., 2010) 54° - 299.3 28.1 3.5 54 - - - - - - - - - - - - - - - - - - - - - - 0.72 36.6 39.0/48.0 275.1 34.7

Late Jurassic (Early Tithonian, Chron 22; ~151 ± 1 Ma)

Adria

44 Colle di Vignola, Trentino 45.8°N, 10.9°E (Channell et al., 2010) 87° - 304.5 28.5 2.5 87 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 266.2 34.7

45 Foza, Veneto 45.9°N, 11.6°E (Channell et al., 2010) 41° - 308.2 30.7 1.9 41 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 264.7 38.1

46 Frisoni, Veneto 45.9°N, 11.7°E (Channell et al., 2010) 47° - 308.2 33.2 2.1 47 - - - - - - - - - - - - - - - - - - - - - - 1.0 - - 265.4 39.9

(continued on next page)
Table 1 (continued)

<table>
<thead>
<tr>
<th>Entry rock unit and ref.</th>
<th>N</th>
<th>Dec~95</th>
<th>Inc~95</th>
<th>a95</th>
<th>N~45</th>
<th>Dec~45</th>
<th>Inc~45</th>
<th>k~45</th>
<th>a95~45</th>
<th>f</th>
<th>CInc</th>
<th>CInc_s</th>
<th>Long</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Late Jurassic (Mid-Late Tithonian, Chrons 20–21; ~147 ± 1.5 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Adria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47 Torre de' Busi, Lombardy 45.7°N, 9.5°E Chrons 20 &amp; 21 combined (Channell et al., 2010)</td>
<td>312*</td>
<td>312.4</td>
<td>30.9</td>
<td>1.6</td>
<td>309</td>
<td>312.3</td>
<td>30.9</td>
<td>30</td>
<td>1.5</td>
<td>0.76</td>
<td>38.3</td>
<td>32.5/43.9</td>
<td>263.9</td>
<td>44.4</td>
</tr>
<tr>
<td>48 Foza, Veneto 45.9°N, 11.6°E Chrons 20 &amp; 21 (Channell et al., 2010)</td>
<td>73*</td>
<td>312.9</td>
<td>31.2</td>
<td>2.1</td>
<td>73</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.98</td>
<td>33.6</td>
<td>32.6/45.8</td>
<td>262.2</td>
<td>42.5</td>
</tr>
<tr>
<td>49 Frisoni, Veneto 45.9°N, 11.7°E Chrons 20 &amp; 21 (Channell et al., 2010)</td>
<td>122*</td>
<td>316.9</td>
<td>30.0</td>
<td>1.7</td>
<td>122</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.81</td>
<td>35.3</td>
<td>30.2/44.8</td>
<td>259.6</td>
<td>45.9</td>
</tr>
<tr>
<td><strong>Early Cretaceous (Berriasian, Chrons 17–19; ~143 ± 2 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Adria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Colme di Vignola, Trentino 45.8°N, 10.9°E Chrons 17–19 (Channell et al., 2010)</td>
<td>5 8</td>
<td>309.0</td>
<td>34.8</td>
<td>2.8</td>
<td>58</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.90</td>
<td>37.8</td>
<td>34.3/47.8</td>
<td>267.8</td>
<td>41.9</td>
</tr>
<tr>
<td>51 Foza, Veneto 45.9°N, 11.6°E Chrons 17–19 (Channell et al., 2010)</td>
<td>135*</td>
<td>314.1</td>
<td>36.3</td>
<td>1.1</td>
<td>135</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.86</td>
<td>40.6</td>
<td>36.5/47.5</td>
<td>265.9</td>
<td>46.7</td>
</tr>
<tr>
<td>52 Frisoni, Veneto 45.9°N, 11.7°E Chrons 18–19 (Channell et al., 2010)</td>
<td>113*</td>
<td>319.4</td>
<td>35.0</td>
<td>1.4</td>
<td>113</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.81</td>
<td>40.8</td>
<td>35.3/47.8</td>
<td>261.1</td>
<td>50.3</td>
</tr>
<tr>
<td><strong>Africa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53 Swartruggens kimberlite and Bumbeni syenite complex (~145 Ma) southern Africa (Hargraves et al., 1997)</td>
<td>6*</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>283.8*</td>
<td>39.3*</td>
</tr>
<tr>
<td>54 Ithaca kimberlite (~143 Ma) North America (Van Fossen and Kent, 1993)</td>
<td>7*</td>
<td>317.3</td>
<td>58.9</td>
<td>2.6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>266.4*</td>
<td>35.6*</td>
</tr>
<tr>
<td><strong>Late Cretaceous (Hauterivian–Barremian; ~134–126 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Adria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 Northern Italy Maiolica Capriolo, Lombardy 45.6°N, 10.0°E (Channell et al., 1987)</td>
<td>252*</td>
<td>331.7</td>
<td>41.0</td>
<td>3.8</td>
<td>215</td>
<td>334.7</td>
<td>36.1</td>
<td>16.2</td>
<td>2.5</td>
<td>0.78</td>
<td>43.6</td>
<td>37.4/50.0</td>
<td>244.6</td>
<td>61.8</td>
</tr>
<tr>
<td>56 Cismon, Veneto 46.6°N, 11.8°E (Channell et al., 2000)</td>
<td>239*</td>
<td>317.4</td>
<td>30.4</td>
<td>2.4</td>
<td>230</td>
<td>315.8</td>
<td>29.2</td>
<td>32.2</td>
<td>1.7</td>
<td>0.56</td>
<td>45.1</td>
<td>38.7/51.3</td>
<td>268.3</td>
<td>50.2</td>
</tr>
<tr>
<td>57 Polaveno, Lombardy 45.7°N, 10.1°E (Channell and Erba, 1992)</td>
<td>504*</td>
<td>319.3</td>
<td>37.3</td>
<td>1.4</td>
<td>494</td>
<td>319.0</td>
<td>36.6</td>
<td>27.7</td>
<td>1.2</td>
<td>0.82</td>
<td>42.1</td>
<td>38.3/45.8</td>
<td>262.2</td>
<td>51.2</td>
</tr>
<tr>
<td>58 San Giovanni, Lombardy 45.7°N, 10.1°E (Channell and Erba, 1992)</td>
<td>86*</td>
<td>323.4</td>
<td>36.0</td>
<td>2.7</td>
<td>85</td>
<td>323.3</td>
<td>35.5</td>
<td>39.4</td>
<td>2.5</td>
<td>0.94</td>
<td>37.1</td>
<td>34.6/45.5</td>
<td>253.2</td>
<td>51.4</td>
</tr>
<tr>
<td>59 Val del Mis, Veneto 46.2°N, 12.1°E (Channell et al., 1993)</td>
<td>158*</td>
<td>308.8</td>
<td>28.9</td>
<td>3.1</td>
<td>153</td>
<td>308.8</td>
<td>28.9</td>
<td>18.2</td>
<td>2.7</td>
<td>0.86</td>
<td>32.7</td>
<td>28.4/39.5</td>
<td>266.2</td>
<td>40.0</td>
</tr>
<tr>
<td><strong>Africa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 Etendeka, Kaoko lavas, Namibia (Gidskehaug et al., 1975)</td>
<td>40*</td>
<td>315.0</td>
<td>– 44.5</td>
<td>3.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>263.5*</td>
<td>55.9*</td>
</tr>
<tr>
<td>(A95 = 6.3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61 Etendeka, Messum gabbros, Namibia (Renne et al., 2002)</td>
<td>6*</td>
<td>323.7</td>
<td>– 48.7</td>
<td>3.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>260.8*</td>
<td>57.7*</td>
</tr>
<tr>
<td>(A95 = 4.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Late Cretaceous (Cenomanian–Coniacian; ~100–71 Ma)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Adria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>62 Iblei volcanics (~84–71 Ma) Capo Passero, Sicily 36.7°N, 15.1°E (Grauso et al., 1983)</td>
<td>12*</td>
<td>173.6</td>
<td>– 31.2</td>
<td>7.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>212.3</td>
<td>69.3</td>
</tr>
<tr>
<td>63 Iblei volcanics (~84–71 Ma) Capo Passero, Sicily 36.7°N, 15.1°E (Gregor et al., 1974)</td>
<td>15*</td>
<td>162.9</td>
<td>– 30.1</td>
<td>9.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>236</td>
<td>64</td>
</tr>
<tr>
<td>64 Iblei volcanics (~84–71 Ma) Capo Passero, Sicily 36.7°N, 15.1°E (Barberi et al., 1974)</td>
<td>8*</td>
<td>165</td>
<td>– 26</td>
<td>7.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>229</td>
<td>63</td>
</tr>
<tr>
<td>65 Iblei volcanics (~84–71 Ma) Capo Passero, Sicily 36.7°N, 15.1°E (Schult, 1973)</td>
<td>19*</td>
<td>167</td>
<td>– 22</td>
<td>7.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>223.3</td>
<td>62.1</td>
</tr>
<tr>
<td><strong>Africa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>66 Group 1 Kimberlites (~100–81 Ma) South Africa, 29°S, 24°E (Hargraves, 1989)</td>
<td>14*</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>226.1</td>
<td>64.1</td>
</tr>
<tr>
<td>(A95 = 5.2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>67 Madagascar volcanics (87 ± 3 Ma) (Torsvik et al., 1998)</td>
<td>8**</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
<td>230.3</td>
<td>68.5</td>
</tr>
<tr>
<td>(A95 = 5.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Paleocene–Eocene (65–36 Ma)

**Adria**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Rock Unit and Ref.</th>
<th>Dec.tc</th>
<th>Inc.tc</th>
<th>a95tc</th>
<th>N45</th>
<th>Dec.45</th>
<th>Inc.45</th>
<th>k45</th>
<th>a9545</th>
<th>Long</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>South Ardo, Veneto 46.0°N, 12.1°E (Dallanave et al., 2012)</td>
<td>239°</td>
<td>356.5</td>
<td>34.8</td>
<td>2.1</td>
<td>233</td>
<td>356.4</td>
<td>34.4</td>
<td>25.1</td>
<td>1.9</td>
<td>60</td>
</tr>
<tr>
<td>69</td>
<td>Cigionga, Veneto 46.1°N, 12.2°E (Dallanave et al., 2009)</td>
<td>229°</td>
<td>356.2</td>
<td>27.6</td>
<td>2.9</td>
<td>220</td>
<td>355.7</td>
<td>27.3</td>
<td>15.2</td>
<td>2.5</td>
<td>041</td>
</tr>
<tr>
<td>70</td>
<td>Alano di Piave, Veneto 45.9°N, 11.9°E (Agnini et al., 2011)</td>
<td>104°</td>
<td>350.8</td>
<td>40.5</td>
<td>4.5</td>
<td>95</td>
<td>351.5</td>
<td>37.2</td>
<td>18.7</td>
<td>3.4</td>
<td>062</td>
</tr>
</tbody>
</table>

**Africa**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Rock Unit and Ref.</th>
<th>Dec.tc</th>
<th>Inc.tc</th>
<th>a95tc</th>
<th>N45</th>
<th>Dec.45</th>
<th>Inc.45</th>
<th>k45</th>
<th>a9545</th>
<th>Long</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>Wadi Abu Tereifya volcanics, Egypt (Hussain et al., 1979)</td>
<td>12°</td>
<td>007.9</td>
<td>20.8</td>
<td>5.8</td>
<td>– – – –</td>
<td>– – – –</td>
<td>– –</td>
<td>1.0</td>
<td>– –</td>
<td>189.4</td>
</tr>
<tr>
<td>72</td>
<td>Africa plate (DSDP524, ODP707, Gubbio), inclination-only data, Paleocene (Schneider and Kent, 1990)</td>
<td>3°</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>– – –</td>
<td>– – –</td>
<td>– –</td>
<td>013G3</td>
<td>– –</td>
<td>213</td>
</tr>
</tbody>
</table>

**Oligocene (34–23 Ma)**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Rock Unit and Ref.</th>
<th>Dec.tc</th>
<th>Inc.tc</th>
<th>a95tc</th>
<th>N45</th>
<th>Dec.45</th>
<th>Inc.45</th>
<th>k45</th>
<th>a9545</th>
<th>Long</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>Yemen Traps (~30 Ma) (Risager et al., 2005)</td>
<td>48°</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>– – –</td>
<td>– – –</td>
<td>– –</td>
<td>1.0</td>
<td>– –</td>
<td>224.4</td>
</tr>
<tr>
<td>74</td>
<td>Ethiopian Traps (~30 Ma) (Kidane et al., 2002)</td>
<td>76°</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>– – –</td>
<td>– – –</td>
<td>– –</td>
<td>0.41</td>
<td>– –</td>
<td>209.4</td>
</tr>
<tr>
<td>75</td>
<td>Africa plate (DSDP523, ODP706, Gubbio), inclination-only data, Oligocene (Schneider and Kent, 1990)</td>
<td>3°</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>– – –</td>
<td>– – –</td>
<td>– –</td>
<td>013G3</td>
<td>– –</td>
<td>193</td>
</tr>
</tbody>
</table>

**Miocene (23–5 Ma)**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Rock Unit and Ref.</th>
<th>Dec.tc</th>
<th>Inc.tc</th>
<th>a95tc</th>
<th>N45</th>
<th>Dec.45</th>
<th>Inc.45</th>
<th>k45</th>
<th>a9545</th>
<th>Long</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>Jebel Soda alkali basalts, Libya (16–8 Ma according to Bardintzeff et al., 2012) (Schult and Soffel, 1973)</td>
<td>12°</td>
<td>359.9</td>
<td>31.6</td>
<td>8.3</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>1.0</td>
<td>– –</td>
<td>196.1</td>
</tr>
<tr>
<td>77</td>
<td>Turkana volcanics (~17 Ma) (Reilly et al., 1976)</td>
<td>62°</td>
<td>004.1</td>
<td>01.7</td>
<td>3.1</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>1.0</td>
<td>– –</td>
<td>163.3</td>
</tr>
<tr>
<td>78</td>
<td>Canaries–Madeira volcanics (Miocene) (Watkins, 1973)</td>
<td>90°</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>– – –</td>
<td>– – –</td>
<td>– –</td>
<td>1.0</td>
<td>– –</td>
<td>114.4</td>
</tr>
<tr>
<td>79</td>
<td>Fuerteventura volcanics (Storevetd et al., 1979)</td>
<td>10°</td>
<td>004.3</td>
<td>31.0</td>
<td>5.2</td>
<td>– – – –</td>
<td>– – –</td>
<td>– –</td>
<td>1.0</td>
<td>– –</td>
<td>146.2</td>
</tr>
</tbody>
</table>

Notes: Entry = reference entry number of paleomagnetic data from magmatic (bold) and sedimentary (regular font) units; N = number of samples/sites/areas (* = number of sampling sites; ** = number of sampling areas [each with multiple sites]); Dec.tc = mean declination in tilt corrected coordinates (expressed in °E); Inc.tc = mean declination in tilt corrected coordinates (expressed in °); a95tc = half cone of confidence at 95% level around the mean in tilt corrected coordinates (expressed in °); N45 = number of paleomagnetic directions with VGP > 45° and VGP < 45°; Dec.45 = mean declination of samples with VGP > 45° and VGP < 45° (expressed in °E); Inc.45 = mean inclination of samples with VGP > 45° and VGP < 45° (expressed in °); k45 = Fisher precision parameter of mean direction of samples with VGP > 45° and VGP < 45°; a9545 = half cone of confidence at 95% level around the mean direction of samples with VGP > 45° and VGP < 45° (expressed in °); f = flattening factor; CInc = E/I corrected mean inclination (expressed in °); CInc(±) = error of CInc (expressed in °); Long = Longitude of paleomagnetic pole (expressed in °E); Lat = Latitude of paleomagnetic pole (expressed in °N); A95 = half cone of confidence at 95% level around the paleomagnetic pole (expressed in °).

- **239° E** erroneously reported as 239°E in Van der Voo (1993) and Muttoni et al. (2003).
- **209.4° E** rotated to NW Africa using rotation parameters of Lottes and Rowley (1990).
- **163.3° E** rotated to NW Africa (Adria) coordinates using rotation parameters of Riisager et al. (2005).
- **114.4° E** rotated to NW Africa (Adria) coordinates using rotation parameters of Storetvedt et al. (1979).
- **146.2° E** rotated to NW Africa (Adria) coordinates using rotation parameters of Reilly et al. (1976).
- **196.1° E** rotated to NW Africa (Adria) coordinates using rotation parameters of Bardintzeff et al. (2012).
- **163.3° E** rotated to NW Africa using rotation parameters of Schult and Soffel (1973).
- **114.4° E** rotated to NW Africa using rotation parameters of Watkins (1973).
- **146.2° E** rotated to NW Africa using rotation parameters of Reilly et al. (1976).
- **196.1° E** rotated to NW Africa using rotation parameters of Bardintzeff et al. (2012).
- **163.3° E** rotated to NW Africa using rotation parameters of Schult and Soffel (1973).
- **114.4° E** rotated to NW Africa using rotation parameters of Watkins (1973).
The seven paleomagnetic poles from the Southern Alps and the three paleopoles from Africa (Morocco and Sudan) are used to compute a mean paleopole for Adria–Africa located at Long = 241.6°E, Lat = 42.0°N (Amp = 4.4°; Table 2) that is entirely based on data from volcanic rocks and is therefore considered free from inclination shallowing. This mean paleopole, when compared to the coeval data from Europe, again from volcanic rocks, supports the Irving (1977) Pangea B model (Muttoni et al., 2003; but see Domeier et al., 2011a, versus Aubele et al., 2012, for an update on the Pangea B controversy). Notably, two additional paleopoles from the Mount Leysdon and Tucker’s intrusions of Australia dated at 286 ± 2 Ma (Clark and Lackie, 2003; Table 1, entries #11 and #12), when rotated into northwest African (= Adria) coordinates using the rotation parameters of Lottes and Rowley (1990), also fall very close to the Adria–African poles (Fig. 2A, gray triangles), and support Pangea B in the Early Permian (Clark and Lackie, 2003).

3.3. Late Permian–Early Triassic

Five Late Permian–Early Triassic paleopoles used in our compilation (Table 1, entries #13–17) come from the Southern Alps. Two of them come from the Bulla and Siusi sections from the Dolomites, which have been studied for magnetotratigraphy, from the Upper Permian Bellerophon Formation to the Lower Triassic Werfen Formation (Scholger et al., 2000). We obtained a digital listing of the characteristic component directions of the Bulla section (Scholger, pers. comm.), and ran a standard E/I test (Supplementary Fig. 2A), obtaining a flattening factor $f = 0.80$. This was applied to the mean paleomagnetic inclination to yield a flattening-free paleomagnetic pole (Table 1, entry #13). For the coeval Siusi section (Table 1, entry #14), as well as for the remainder of the entries used in our compilation, namely the Lower Triassic Siusi and Campil members of the Werfen Formation from the Dolomites (#15; Channell and Doglioni, 1994), the Upper Permian Verrucano Lombardo metasedimentary rocks and redbeds combined from Lombardy (#16; Kipfer and Heller, 1988), and the Upper Permian Val Gardena Sandstones from the Dolomites (#17; Manzoni, 1970), we could not run an E/I test due to insufficient numbers of independent samples at each sampled site, and we therefore applied the same flattening factor obtained at Bulla ($f = 0.8$), assuming a similar response of these broadly similar rock types to sedimentary inclination flattening processes.

The Late Permian–Early Triassic paleopoles from the Southern Alps (Fig. 2B) are compared to the paleopole of Lanci et al. (in press) from South Africa obtained by averaging $N = 136$ normal and reverse polarity characteristic magnetizations from Upper Permian redbeds of the lower Beaufort Group at Ouberg Pass, Karoo basin, that are regarded as primary in age and only partially overprinted by the emplacement of the Jurassic Karoo Large Igneous Province (LIP) (Lanci et al., in press). These characteristic magnetizations have been corrected for sedimentary inclination shallowing obtaining a flattening factor $f = 0.7$ (Lanci et al., in press; Table 1, entry #18). We note that before unflattening, the Ouberg Pass paleopole, rotated to northwest Africa coordinates using rotation parameters of Lottes and Rowley (1990), falls far to the east of the Adria paleopoles, yet with progressive unflattening, the paleopole moves towards the Adria paleopoles such that for $f = 0.7$, the original paleopole discrepancy is substantially reduced (and by assuming that $f = 0.6$, it would be virtually eliminated) (Fig. 2B). Similarly, the South African paleopole from Permian–Triassic boundary redbeds at Komandodrifdam, Karoo basin, considered to carry primary magnetizations and to be substantially free from later magnetization events (DeKock and Kirschvink, 2004; Table 1, entry #19), moves towards Adria paleopoles for flattening factors progressively decreasing from 1.0 (no flattening) to 0.6 (Fig. 2B). As no E/I test is available for the sparse ($N = 35$) data from Komandodrifdam, we adopted a value of $f = 0.7$ as derived from Ouberg Pass.

The Late Permian–Early Triassic overall mean paleomagnetic pole of Adria–Africa is based on five entries from Adria, corrected for inclination shallowing assuming a flattening factor of 0.8 as deduced from Bulla, and two entries from the Karoo basin, assuming a flattening factor of 0.7 as deduced from Ouberg Pass. This overall mean paleopole (Table 2) differs by 4°–7° from previous Late Permian–Early Triassic
mean paleopoles based on data from the Southern Alps without E/I correction (Muttoni et al., 1996, 2009; Angiolini et al., 2013).

There are no data from Upper Permian volcanic rocks from Africa that can be used to check the validity of our assumptions regarding flattening corrections in the Verrucano–Valgardena (or Karoo) sedimentary rocks. Notably, the only well-dated entry from volcanic rocks of comparable age from outside Adria–Africa (not included in our Adria–Africa APWP) comes from the Choiyoi Volcanic Complex of Argentina, South America, dated at about 263 (+1.6/−2.0) Ma (Table 1, entry #20; Domeier et al., 2011b), which, when rotated to northwest Africa (=Adria) coordinates using rotation parameters of Lottes and Rowley (1990), falls at Long = 244.3°E, Lat = 52.4°N, very close to the overall mean paleomagnetic pole of Adria–Africa (Fig. 2B).

3.4. Middle Triassic

Several magnetostratigraphic investigations on biostratigraphically dated Tethyan limestones with radioisotopically dated tuff intervals of Middle Triassic age from the Dolomites have been conducted since the late 1990s (see Hounslow and Muttoni, 2010, for a review). We accepted in our compilation (Table 1) the paleomagnetic data from the Belvedere section (Brack and Muttoni, 2000; entry #21), the Frötschbach section (Muttoni et al., 1997; entry #22), the Margon–Val Gola section (Brack...
Margon and were subjected to only alternating sparse data from the Ladinian (Brack and Muttoni, 2000) which are too sparse, as well as the (also tuff). In addition, we did not consider data from the Pedraces section and carbonate turbidites (Broglio Loriga et al., 1999). In our compilation, we exclude data from the ~110 m-long Seceda drill-core from the base of the Carnian (Broglio Loriga et al., 1999; Mietto et al., 2004). The Lower Pietra Verde ash layer at 241.2 Ma is closely tied to the Buchenstein Beds of ~10 m/m.y. (Brack and Muttoni, 2000; Muttoni et al., 2001), indicating an average sediment accumulation rate for the ~235 Ma) are compared with the only dataset from Africa (Channell et al., 2010), which we found to be free from inclination flattening (f = 1) (Table 1; entry #36). Data from the Karoo LIP (Muttoni et al., 2010) were not considered because the resolved magnetizations do not pass a reversal test, probably due to the presence of an unresolved magnetization overprint (Muttoni et al., 2010). Most data for the Early Jurassic come from the ~201 Ma Central Atlantic Magmatic Province (CAMP) and the ~183 Ma Karoo Large Igneous Province (LIP) from Africa, both of which are regarded as free from inclination flattening (Table 1).

For the African CAMP extrusions, we used data from the Draa Valley sills of Morocco (Hailwood and Mitchell, 1971; entry #26), the Foum Zguid and Ighrem dykes of Morocco (Hailwood and Mitchell, 1971; Silva et al., 2006; Palencia-Ortas et al., 2011; entries #27–30), the CAMP lavas of Morocco (Font et al., 2011; #31), the Liberian dikes and sills of northwest Africa (Dalrymple et al., 1975; #32), the Hank and Hodh volcanic rocks from Mauritania (Sichler et al., 1980; #33–34), and the Freetown Complex of Sierra Leone (Hargraves et al., 1999; #35). We follow Kent and Irving (2010) in considering these entries as all likely to belong to the CAMP event, which was presumably emplaced over a short (~1–2 Myr) interval at around 201 Ma (Kent and Irving, 2010, and references therein). For the Torciano Karoo LIP, presumably emplaced over a short (~1–2 Myr) interval at around 183 Ma (Courtillot and Renne, 2003; but see Jourdan et al., 2005 who proposed a longer duration of emplacement), we used data from the Stromberg and Lesotho lavas of Lesotho (Van Zijl et al., 1962; Kosterov and Perrin, 1996; #37–38), the Karoo mean pole from several extrusions in South Africa (Hargraves et al., 1997; #39), and the Naudé’s Nek lavas of South Africa (Moulin et al., 2011; #40). These entries from South Africa have been rotated to northwest Africa (= Adria) coordinates using rotation parameters of Lottes and Rowley (1990) (Fig. 2D).

The CAMP and Karoo paleomagnetic poles are compared with the Sinemurian (~199–191 Ma) Colle di Sogno (Adria) paleopole (Fig. 2C) of the CAMP and Karoo LIP, presumably emplaced over a short (~1–2 Myr) interval at around 201 Ma (Kent and Irving, 2010, and references therein). For the Torciano Karoo LIP, presumably emplaced over a short (~1–2 Myr) interval at around 183 Ma (Courtillot and Renne, 2003; but see Jourdan et al., 2005 who proposed a longer duration of emplacement), we used data from the Stromberg and Lesotho lavas of Lesotho (Van Zijl et al., 1962; Kosterov and Perrin, 1996; #37–38), the Karoo mean pole from several extrusions in South Africa (Hargraves et al., 1997; #39), and the Naudé’s Nek lavas of South Africa (Moulin et al., 2011; #40). These entries from South Africa have been rotated to northwest Africa (= Adria) coordinates using rotation parameters of Lottes and Rowley (1990) (Fig. 2D).

The CAMP and Karoo paleomagnetic poles are compared with the Sinemurian (~199–191 Ma) Colle di Sogno (Adria) paleopole (Fig. 2C). The Colle di Sogno paleopole falls relatively close to the immediately older CAMP paleopoles, whereas the younger Karoo paleopoles lie at higher northern latitudes. We therefore averaged entries from the CAMP and Colle di Sogno to calculate an overall mean paleopole for Africa–Adria, to which we attach a mean age of ~201 Ma because the pole is essentially based on ~201 Ma CAMP data (Table 2). Paleopole entries from the Karoo LIP define an overall mean paleomagnetic pole interval of their mean paleopole (Fig. 2C). This allows us to calculate an overall mean paleomagnetic pole for Adria–Africa based on four entries from the Dolomites and one from Libya (Table 2).

3.5. Early Jurassic

Our Early Jurassic database (Table 1, #26–40) includes one entry from Adria: the Sinemurian (~199–191 Ma) marine limestones from the Colle di Sogno section from Lombardy (Channell et al., 2010), which we found to be free from inclination flattening (f = 1) (Table 1; entry #36). Data from the Karoo–Lettier Hettangian sedimentary rocks from Lombardy (Muttoni et al., 2010) were not considered because the resolved magnetizations do not pass a reversal test, probably due to the presence of an unresolved magnetization overprint (Muttoni et al., 2010). Most data for the Early Jurassic come from the ~201 Ma Central Atlantic Magmatic Province (CAMP) and the ~183 Ma Karoo Large Igneous Province (LIP) from Africa, both of which are regarded as free from inclination flattening (Table 1).
valid for Africa at ~183 Ma, which lies north of the CAMP mean paleopole (Fig. 2D; Table 2).

3.6. Middle–Late Jurassic

Middle Jurassic data from Adria are sparser than those of Late Jurassic age. Hence, we opted to start from the Late Jurassic before attempting to fill in the Middle Jurassic gap. Late Jurassic data from Adria come from magneto-biostratigraphically dated sections from the Trento plateau and the Lombardian basin in the Southern Alps (Channell et al., 2010). These sections have been successfully correlated to marine magnetic anomalies (M sequence) and used to improve the definition of the Jurassic magnetic polarity time scale (Channell et al., 2010). A total of nine entries have been checked and corrected for inclination shallowing (Table 1; entries #44–52). Three entries (#44–46) from Colme di Vignola, Foza, and Frisoni sections, dated to polarity chron CM22 at ~151 ± 1 Ma in the Early Tithonian, show no evidence of inclination shallowing (f = 1). Three entries (#47–49) from Torre de’ Busi, Foza, and Frisoni sections, dated to polarity chron CM20–21 at ~147 ± 1.5 Ma in the Mid–Late Tithonian, yield flattening factors ranging between 0.98 and 0.76 (Supplementary Fig. 3A–C), whereas three other entries (#50–52) from Colme di Vignola, Foza, and Frisoni, dated to Berriasian polarity chron CM17–19 at ~143 ± 2 Ma, yield flattening factors between 0.90 and 0.81 (Supplementary Fig. 3E–F). The three Early Tithonian (~151 Ma) corrected paleopoles fall close to each other and to the south of the three Mid–Late Tithonian (~147 Ma) and the three Berriasian (~143 Ma) corrected paleopoles, which are also located close to each other (Fig. 3). We therefore calculated an overall mean paleomagnetic poles for Adria at 151 ± 1 Ma in the Early Tithonian, and an overall mean paleopole again for Adria at 147–143 Ma (mean of 145 ± 2 Ma) in the Mid Tithonian–Berriasian (Table 2).

There are few Middle–Late Jurassic data from igneous rocks from Africa that can be used for comparison with data from Adria. A paleomagnetic pole combining data from the Swartruggens kimberlite and the Bumbeni syenite complex of southern Africa, dated to about 145 Ma (Hargraves et al., 1997) and rotated to northwest Africa (=Adria) coordinates using rotation parameters of Lottes and Rowley (1990) (Table 1, entry #53), falls somewhat to the east of (albeit encouragingly not too far from) the presumably coeval paleopoles from Adria (Fig. 3). The Ithaca kimberlite paleopole (~143 Ma) from North America of Van Fossen and Kent (1993), rotated to northwest Africa coordinates using rotation parameters of Klitgord and Schouten (1986), is similar in location (Fig. 3). The poorly dated Swartruggens–Bumbeni paleopole and the North American Ithaca paleopole have, however, not been used to calculate the Late Jurassic part of the Adria–Africa APWP. This segment is entirely based on data from Adria (Table 2).

The ~151 Ma mean paleopole from Adria is displaced to the south by ~40° on a great circle relative to the ~183 Ma Karoo LIP mean paleopole from Africa (Fig. 3) and the Sinemurian (~199–191 Ma) paleopole from Colle di Sogno, Adria (Fig. 2D). A polar shift of similar magnitude and age has also been observed in data from North America and other cratons, and was referred to as the Jurassic ‘monster shift’ (Kent and Irving, 2010; see also Section 4). No reliable paleopoles are available from both the global APWP of Kent and Irving (2010) and our Adria–Africa APWP to describe the details of this Jurassic ‘monster shift’. Only three paleomagnetic sites with a relatively limited total number of samples are available for Adria from the time interval of main pole shift comprised between the ~183 Ma Karoo LIP paleopole and the ~151 Ma Adria paleopole: these define (i) a paleopole based on N = 19 characteristic magnetizations from Callovian–Oxfordian red cherts and Rosso ad Aptici cherty marls at Colle di Sogno, Lombardy (Muttoni et al., 2005; Tables 1 and 2, entry #41), (ii) a coeval paleopole based on N = 25 characteristic magnetizations from the same stratigraphic interval from the nearby Torre de’ Busi section (Channell et al., 2010; entry #42), and (iii) a more robust paleopole based on N = 54 characteristic magnetizations from Upper Oxfordian (~158 Ma) cherty limestones of the Fonzaso Formation at

Fig. 3. Paleomagnetic poles corrected for inclination shallowing from parautochthonous Adria for the Late Jurassic compared with coeval poles from Africa (Swartruggens and Bumbeni) and North America (Ithaca); see Table 1 for paleopole entries (#) and text for discussion.
Passo del Branchetto, Veneto (Channell et al., 2010; entry #43). Paleopoles #41 from Colle di Sogno and #42 from Torre de' Busi were not corrected for inclination shallowing due to the limited number of paleomagnetic directions that define them, whereas the Passo del Branchetto paleopole (#43) yielded a flattening factor $f = 0.72$ (Supplementary Fig. 3G; Table 1). Inspection of Fig. 3 reveals that these single-site

Fig. 4. Paleomagnetic poles corrected for inclination shallowing from parautochthonous Adria for the Early Cretaceous (A), Late Cretaceous (B), Paleocene–Eocene (C), Oligocene (D), and Miocene (E) compared with coeval poles from Africa; see Table 1 for paleopole entries (#) and text for discussion.
paleopoles (CS, TB, PB for entries #41, #42, and #43, respectively) are dispersed in apparent age progression along a swath of longitudes/latitudes from the northern Pacific to the southern U.S., with the ∼158 Ma PB paleopole falling close to the ∼151 Ma mean paleopole of Adria. We therefore infer that the polar ‘monster shift’ from ∼183 Ma to ∼151 Ma includes a (poorly resolved) cusp centered on the northern Pacific (Fig. 3) that actually explains the sub-equatorial paleolatitudes associated with deposition of radiolarian cherts typical of the Late Jurassic of Adria (Aiello and Hagstrum, 2001; Mutti et al., 2005; see also Section 5).

3.7. Early Cretaceous

Early Cretaceous (Hauterivian–Barremian; ∼134–126 Ma) data have been obtained from classic sections of the Maiolica Formation that have been used for the definition of all modern generations of geomagnetic polarity time scales; these sections are Capriolo from Lombardy (Channell et al., 1987; Table 1, entry #55), Cismon (outcrop section) from Veneto (Channell et al., 2000; #56), Polaveno and San Giovanni from Lombardy (Channell and Erba, 1992; #57 and #58), and Valle del Mis, Veneto (Channell et al., 1993; #59). We obtained flattening factors of $f = 0.78$ at Capriolo, $f = 0.56$ at Cismon outcrop section (data from the Cismon core section were not considered as the core was not oriented precisely during drilling; Channell et al., 2000), $f = 0.82$ at Polaveno, $f = 0.94$ at San Giovanni, and $f = 0.86$ at Valle del Mis (Supplementary Fig. 4). The corrected paleopoles are reasonably well clustered, and the overall mean paleopole that they yield is close to two key entries from igneous rocks from Africa: the paleomagnetic pole from the Etendeka Kaoko lavas from Namibia (Gidskehaug et al., 1975), and the paleopole from the Etendeka Messum gabbros from Namibia (Renne et al., 2002), both rotated to northwest Africa (= Adria) coordinates using the rotation parameters of Lottes and Rowley (1990) (Table 1, entries #60 and #61; Fig. 4A). The Kaoko lavas (dated to 128–110 Ma according to Gidskehaug et al., 1975) and the Messum gabbros (dated to ∼133 Ma according to Renne et al., 2002) were emplaced during peak Etendeka magmatism at 133–132 Ma (Renne et al., 2002), making the agreement of these paleopoles with the ∼134–126 Ma paleopole from Adria a strong argument in favor of Adria–Africa tectonic coherence at these times. We thus calculate a combined Adria–Africa overall mean paleopole with mean age of ∼130 Ma in the Early Cretaceous (Table 2).

3.8. Late Cretaceous

Several paleomagnetic studies are available from classic sections of Late Cretaceous (Turonian–Maastrichtian; ∼94–66 Ma) age encompassing the Scaglia Rossa Formation from the Southern Alps (Channell et al., 1992; Mårton et al., 2010) and the Istra and Gargano foreland of eastern and southeastern Adria (see references in Channell, 1996). We could not check for inclination shallowing at these sites/sections either because they comprise insufficient paleomagnetic directions to perform a statistically significant E/I test, or because the paleomagnetic directions are not available for testing. Hence, we focused on data from Late Cretaceous volcanic rocks from Sicily.

Four entries are listed in Table 1 (#62–65) from basalt flows at Capo Passero in the Hylbelean foreland of southeastern Sicily (Schult, 1973; Barberi et al., 1974; Gregor et al., 1975; Grasso et al., 1983) and radiometrically dated to ∼84–71 Ma and thus Campanian in age (Barberi et al., 1974). These paleomagnetic poles, assumed to be free from inclination shallowing, yield an overall mean paleopole that is consistent with two key entries from broadly coeval igneous rocks from Africa, namely the 100–81 Ma Group 1 Kimberlites from South Africa of Hargraves (1989; entry #66), and the ∼87 Ma Madagascar volcanic rocks of Torsvik et al. (1998; entry #67) (Fig. 4B), allowing the calculation of a Cenomanian–Campanian (100–71 Ma) Adria–Africa overall mean paleomagnetic pole (Table 2).

3.9. Paleocene–Eocene

Several magnetostratigraphic and biostratigraphic studies have been conducted in recent years on expanded, continuous sections of Paleocene–Eocene age from the Belluno Basin of the Southern Alps. In our review, we include data from the Paleocene–Eocene South Ardo section (Dallanave et al., 2012; Table 1, entry #68), for which we obtained a flattening factor $f = 0.6$, the Paleocene–Eocene Cicogna section (Dallanave et al., 2009; entry #69), which yielded $f = 0.41$, and the Eocene Alano section (Agnini et al., 2011; entry #70) with $f = 0.62$ (Supplementary Fig. 5A, B, C). The corrected mean paleomagnetic pole calculated from these three entries agrees reasonably well with two paleopoles from Africa, the Wadi Abu Tereifiyah volcanic rocks paleopole from Egypt, tentatively attributed to the Eocene (Hussain et al., 1979) (Table 1, entry #71; Fig. 4C), and the Paleocene paleopole of Schneider and Kent (1990) that is based on paleomagnetic inclination data from sediments at DSDP Site 524, ODP Site 707, and Gubbio (Italy), which define three colatitude small circles that intercept at one point (the paleopole) assuming no (0%) octupole (G3) contribution, and presumably also no significant inclination shallowing (Table 1, entry #72; Fig. 4C). These five entries have been used to calculate an overall mean Adria–Africa paleomagnetic pole valid for the Paleocene–Eocene, from 65 to 36 Ma (mean age of 50 Ma; Table 2).

3.10. Oligocene–Miocene

No reliable paleomagnetic data are available from Oligocene–Miocene rocks from parautochthonous Adria. Paleomagnetic poles from the Yemen Traps of the Arabian peninsula (Riisager et al., 2005; entry #73), rotated into northwest Africa using rotation parameters of Besse and Courtillot (2002), and the Ethiopian Traps from Ethiopia (Kidane et al., 2002; entry #74), pertain to the same large igneous province (LIP) dated at ∼30 Ma (Riisager et al., 2005). These paleopoles plot close to the Oligocene paleopole of Schneider and Kent (1990) based on paleomagnetic inclination data from sediments at DSDP Site 523, ODP Site 706, and Gubbio (Italy), which define colatitude small-circles that intercept at the paleopole after assuming a 5% octupole (G3) contribution (Table 1, #75; Fig. 4D); this procedure of optimizing small-circle intersections by adopting an octupole field contribution of proper sign (Schneider and Kent, 1990) most likely removed any unrecognized sedimentary inclination flattening bias. The Oligocene data from the Yemen and Ethiopian Traps, and the G3-corrected entry from the African plate, are used to calculate an overall mean paleopole for Africa at ∼28 Ma (Table 2).

Finally, for the Miocene we used paleomagnetic poles from the Jebel Soda alkali basalts of Libya (Schult and Soffel, 1973) dated to 16–8 Ma according to Bardintzeff et al. (2012) (Table 1, entry #76), the east African volcanic rocks dated to around 17 Ma (Reilly et al., 1976; entry #77), the Canary Islands and Madeira volcanic rocks with ages between 5.2 and 25 Ma (Watkins, 1973; entry #78), and the Fuerteventura volcanic rocks (lava series II) of Miocene–Pliocene age (Storevetd et al., 1979; entry #79). These entries, used also in the apparent polar wander path of Tauxe et al. (1983), fall relatively close to each other (Fig. 4E) and define an overall mean high latitude paleopole for Africa with mean age of ∼14 Ma (Table 2).

4. The Adria–Africa APWP

Our parautochthonous Adria–stable Africa composite APWP spans the Early Permian to Miocene (Table 2) and consists of two distinct tracks. From ∼280 Ma to ∼183 Ma, during Pangea time, paleopoles show a clockwise progression over North America from low to high latitudes, whereas from ∼151 Ma to ∼14 Ma, paleopoles show a second regular progression from low to high latitudes over North America. The ∼151–130 Ma segment of our Adria–Africa APWP is broadly similar.
in shape to the APWP recently derived from sedimentary successions from the central Apennines (Satolli et al., 2008). We plotted selected paleopoles of the Apennine APWP of Satolli et al. (2008) at 145 Ma, 141 Ma, 130 Ma, 116 Ma and 102 Ma for comparison with our Adria–Africa APWP (analysis not shown). We found that the Apennine paleopoles are variably displaced relative to our Adria–Africa paleopoles at 151 Ma, 145 Ma, and 130 Ma by about 24°–27° counter-clockwise due to Apennines deformation, and therefore, they have not been incorporated in our Adria–Africa data compilation. An earlier compilation of paleopoles from the central Apennines (Umbria) includes 8 sites from the Corniola Formation of Plensbachian (~185 Ma) age and the Ammonitico Rosso of Toarcian–Aalenian (~177 Ma) age (Chanell, 1999). After compensation of the originally-assumed 20° counter-clockwise rotation, the resulting mean pole position (67.7°N, 260.6°E) lies close to the Adria (Colle di Signo) pole for the Early Jurassic (Table 1, entry #36; Fig. 2D) and would be coincident with it if a slightly larger rotation (~25°) rotation were assumed.

The large magnitude pole shift of ~40° in the Adria–Africa APWP between ~183 Ma and ~151 Ma (Fig. 5A) is, therefore, supported by paleomagnetic data from the central Apennines (Chanell, 1999; Satolli et al., 2008) although these data are not used in this paper to resolve it. On the other hand, the details of the path of this ~40° Jurassic pole-shift are defined, with only three single-site paleopoles available from stable Adria (CS, TB, PB in Fig. 3 and Section 3.6) that are dispersed along a swath of longitudes/latitudes but are associated with a narrow range of ages (~150–158 Ma, Fig. 3), and are provisionally not included in the composite Adria–Africa APWP (Fig. 5A, Table 2). It is during this major Jurassic pole shift that Adria attained sub-equatorial paleolatitudes consistent with the concurrent deposition of upwelling-related radiolarian cherts (Aiello and Hagstrum, 2001; Muttoni et al., 2005) and the carbonate platform productivity crisis due to eutrophication of parts of the Tethyan Ocean (Bartolini and Cecca, 1999).

A pole shift of similar magnitude—termed ‘monster shift’—is present in the global APWP of Kent and Irving (2010), based on a compilation of inclination flattening-free paleomagnetic poles from North America and other continents, between the Early–Middle Jurassic (~190–160 Ma) paleopole standstill (~lack of significant polar movement), and the ~145 Ma mean paleopole obtained by averaging the Swartruggens and Bumbeni kimberlites paleopole of southern Africa (Hargraves et al., 1997), the Ithaca kimberlite paleopole of North America (Van Fossen and Kent, 1993), and the Hinlopenstreet dikes of Svalbard (Halvorsen, 1989) (see Kent and Irving, 2010 for further details).

We migrated the Kent and Irving (2010) (hereafter KI10) global APWP from North American to northwest Africa (=Adria) coordinates (Supplementary Table 1) and found a remarkable overall agreement between the 230, 200, 145, 130, 90, and 50 Ma paleopoles of the rotated KI10 APWP, and the 238, 201, 145, 130, 85, and 50 Ma paleopoles of our proposed Adria–Africa APWP (Fig. 5B). This agreement is regarded as significant, considering that the two curves represent substantially independent readings of the past positions of the Earth’s spin axis, with only a moderate degree of redundancy in the Early Jurassic where both curves include paleopoles from the African CAMP and the Karoo LIP. The greatest discrepancy is observed between the ~183 Ma Adria–Africa paleopole, based entirely on Karoo LIP data, and the 190 and 180 Ma standstill paleopoles of the KI10 APWP (Fig. 5B), which are based on virtually the same data (~90% of shared paleopoles) with comparable mean ages (184.6 Ma and 182.3 Ma, respectively; Kent and Irving, 2010). Much of the observed discrepancy is accounted for by the incorporation in the 190–180 Ma KI10 paleopoles of five (out of a total of 8) paleopoles from igneous rocks (the White Mt. plutons of North America, the Garrawillla and Nombi volcanics and Tasmanian Dolerite of Australia, and the Marifil and Lepa-Osta Arena formations of South America; Kent and Irving, 2010) that, after rotation to northwest Africa coordinates (using rotation parameters listed in Kent and Irving, 2010), fall ~10–15° to the south of the Karoo LIP paleopole. We note that a high latitude for the ~183 Ma Adria–Africa paleopole is supported by the Ferrar Dolerite paleopole from Antarctica of Lanza and Zanella (1993) (also used in the KI10 APWP), which, after rotation to northwest Africa coordinates, falls at 71°N, 270°E, only ~8° away from the Karoo LIP paleopole.

Notwithstanding uncertainties in the position of the ~183 Ma Adria–Africa and ~180 Ma KI10 paleopoles, the remarkable agreement between the Adria–Africa and KI10 APWPs across the ‘monster shift’, especially its younger (~151–145 Ma) age limit (Fig. 5B), is not reproduced in other APWPs (e.g., Besse and Courtillot, 2003 [BC03]; Torsvik et al., 2008 [T08]; Torsvik et al., 2012 [T12]), after rotation to northwest Africa (=Adria) coordinates (Supplementary Table 1). The rapid polar shift observed in the Adria–Africa and KI10 APWPs (Fig. 5B) is not defined in the BC03 (Fig. 5C), T08 (Fig. 5D), and T12 (Fig. 5E) APWPs, which show broadly similar, smooth, and regular progressions of paleopoles over the Jurassic from northern latitudes at ~190 Ma to southern latitudes at 140 Ma. This discrepancy is probably caused by the fact that the ~160–140 Ma time window of the BC03, T08, and T12 APWPs is based on the time-averaging of paleopoles from Europe that are sparse, are not sufficiently well dated to define the rapid change in paleopoles of the APWP, and have complicated magnetizations (Muttoni et al., 2005; Kent and Irving, 2010). For example, the Jura Blue Limestone and Jura Mountains Oolites carry pre- and post-tectonic magnetizations, and the Sub-Tatric nappe sediments and Krakow Upland sediments are dominated by normal polarity magnetizations throughout a Middle–Late Jurassic time interval of high magnetic polarity reversal rates (see references to individual entries in Besse and Courtillot, 2002; Torsvik et al., 2008). A notable aspect of the T12 global APWP relative to the older T08 version is that in T12 an attempt is made to correct for sedimentary inclination shallowing by applying a blanket flattening factor of 0.6 to paleopole entries from sedimentary rocks (unless otherwise calculated by the original authors); however, we have seen in our compilation that the sedimentary flattening factor varies between 0.41 and 0.98 with a mean of 0.76 (Table 1).

The Jurassic ‘monster shift’ is identified in largely independent paleomagnetic datasets from different plates (North America, Adria–Africa), and it therefore represents a rapid event of contemporaneous plate motion with respect to the spin axis, which, according to Adria–Africa data, took place from ~183 Ma in the Early Jurassic to ~151 Ma in the Late Jurassic (or from the 190–160 Ma paleopole standstill to the 145 Ma paleopole according to Kent and Irving, 2010), and seems coincident with an episode of true polar wandering (TPW) recognized in the 195–145 Ma interval by Steinberger and Torsvik (2008). Invoking similarities between Eurasian (Pontides and Crimea) mid-Jurassic paleomagnetic data and coeval data from Adria of Muttoni et al. (2005), Meijers et al. (2010) also invoked TPW, considering it unlikely that Africa and Eurasia would have moved in close association relative to the surrounding plates at a time when Eurasia was bordered to the south by subducting slabs anchored in the mantle. Acknowledging that more data are required from non-Atlantic-bordering continents, we tentatively conclude that the rapid polar shift observed in Jurassic paleomagnetic data from North America, Adria–Africa, and Eurasia represent a major TPW event.

5. The role of paleolatitude on sedimentation

The Adria–Africa APWP can be used to estimate paleolatitudes for any given point of the African plate in order to gauge their influence on the overall distribution of climate-sensitive facies assuming a simple zonal climate distribution. To infer the latitudinal position of zonal climate belts in the past, we use the difference between precipitation and evaporation (P – E) based on the general circulation model of Manabe and Bryan (1985) with idealized geography (see also Kent and Muttoni, 2013). Although the model shows that the amplitude or climate severity of P – E increases with increasing pCO2 from
Fig. 5. The Adria–Africa apparent polar wander path (panel A; see Table 2 for mean paleomagnetic poles) compared with the apparent polar wander paths of Kent and Irving (2010) (B), Besse and Courtillot (2002, 2003) (C), Torsvik et al. (2008) (D), and Torsvik et al. (2012) (E), all rotated into northwest Africa (= Adria) coordinates (Supplementary Table 1). See text for discussion.
one-half to 8-times the pre-industrial value (Fig. 6A), the latitudinal positions of the zonal boundaries where \( P - E = 0 \) tends to stay relatively fixed, within \(-2°-3°\) (Fig. 6B). We therefore set the equatorial humid belt where \( P > E \) as occurring between 5°S and 5°N, the tropical arid belts (\( P < E \)) as extending from 5° to 30° latitude, and the temperate humid belts from 30° to the latitudinal limits of our paleolatitudinal reconstruction (Fig. 7).

The paleolatitude curve of northern Adria, calculated for a nominal point in the Southern Alps (Adamello Massif) (Fig. 7), shows a marked northward drift during the Permian–Triassic, reaching high northern latitudes by the time of emplacement of the Karoo LIP at ~183 Ma in the Early Jurassic. Then, the curve plummets to subequatorial latitudes during the ~183–151 Ma ‘monster pole shift’ and subsequently moves into tropical northern latitudes where it remains until ~50 Ma when a final northward progression restores the African plate to its modern location. To first order, as Adria (part of Pangea) drifted northward during the Permian–Triassic, the vertical sequence of climate sensitive facies in individual Tethyan basins changed as they passed from one climate belt to another. Fig. 7 shows that the interval between ~260 Ma in the Late Permian and ~205 Ma, close to the Norian–Rhaetian boundary, is characterized by Adria transiting across latitudes in the arid tropical belt from ~10°N to ~30°N when, on Adria and surrounding Tethyan realms, sediments of arid affinity were deposited in abundance. These arid sedimentary facies include the upper Permian fluvial deposits of the Verrucano Lombardo–Valgardena Sandstones (Cassinis and Perotti, 2007), the several Anisian–Norian shallow water carbonate platforms with coral build-ups from the southern Alps (e.g., Cernera Dolomite, Fois and Gaetani, 1984; Esino Limestone, Jadoul et al., 1992; Contrin Formation, Schler/Scliar Dolomite, Maurer, 2000; Dolomia Principale/Hauptdolomit, Jadoul et al., 2012), the Norian carbonate–evaporite platforms of the central-northern Apennines (Grezzoni Formation and Burano Anhydrite; Ciarapica, 2007), and the upper Olenekian–Lower Anisian and Carnian evaporitic deposits of the Carniola di Bovegno and San Giovanni Bianco Formation of the southern Alps (Jadoul et al., 2012).

At ~205 Ma, when, according to our projection, northern Adria entered the mid-latitude humid belt (Fig. 7), a major change in depositional style occurred on Adria and surrounding Tethyan domains with the demise of carbonate productivity (end of Dolomia Principale/Hauptdolomit deposition in the southern Alps and of carbonate–evaporite deposition of the central-northern Apennines) and the onset of deposition of shale-rich successions (e.g. Riva di Solto Shale in the southern Alps, Kössen beds in Austria, Mt. Cetona Formation in the central-northern Apennines; Berra et al., 2010; Jadoul et al., 2012; Berra, 2012; Ciarapica, 2007). Further to the south on Adria, in the central-southern Apennines, the carbonate platforms continued to grow apparently without significant detrital influx (Ciarapica, 2007). However, a change in dolomitization is observed in the carbonate platforms of the southern Apennines whereby during the Norian, early dolomitization was intense and controlled by the occurrence of shallow, warm, and saline seawater, whereas the end Triassic (Rhaetian) and the Jurassic experienced a more humid climate during which early diagenetic dolomite formation was negligible (Iannace et al., 2011).

This shift from arid to humid climate has been recently interpreted as due to an equator-ward (southward) migration of the northern hemisphere humid temperate belt during a postulated Late Triassic glaciation that (1) exposed carbonate platforms to subaerial erosion forming terra-rossa paleosols and breccias, and (2) triggered the subsequent deposition of mudstones typical of more humid climates with higher rainfall rates (Berra et al., 2010; Berra, 2012). Indeed, the Manabe and Bryan (1985) circulation model predicts a contraction of the tropical arid belts by ~2–3°, accompanied by a parallel equator-ward migration of the temperate humid belts, with pCO₂ diminishing from 8-times to one-half the pre-industrial value (Fig. 6B). Moreover, climate simulations incorporating the northward drift of Pangea during the Late Triassic suggest significantly diminished greenhouse conditions with pCO₂ declining from more than 3000 ppm in the Carnian to less than 1000 ppm in the Rhaetian (Godderis et al., 2008). However, the tropical contraction model advocated by Berra (2012) to explain platform erosion followed by mudstone deposition requires the existence of a
discrete glacioeustatic event in the latest Norian, for which there is no sound evidence. As an alternative and simpler scenario, the demise of carbonate productivity and onset of mudstone deposition was triggered by the crossing of the arid–humid belt boundary centered on ~30°N as Adria, attached to Pangea, moved northward at speeds of ~0.45° latitude per Myr, passing a (focused) zonal belt boundary in less than 1 Myr (Fig. 7). In our model, the formation of terra-rossa paleosols and breccias at the top of Norian carbonate platforms resulted from the demise of carbonate productivity coupled with an accelerated hydrologic cycle conducive to erosion and weathering typical of mid-latitude humid climates.

As a consequence of the fragmentation of Pangea and opening of the Atlantic Ocean, Upper Triassic shallow-water sediments were replaced by mainly pelagic limestones in the Early Jurassic, radiolarian cherts in the Middle–Late Jurassic, and again pelagic limestones in the Late Jurassic–Cretaceous (Fig. 7). Previous analysis of paleolatitudinal data from a continuous succession of sediments from the Lombardian basin (Muttoni et al., 2005) showed that carbonate facies dominated when Adria was located at tropical latitudes in the Early Jurassic, radiolarian oozes were deposited when it moved to near-equatorial latitudes in the Middle–Late Jurassic, and nannofossil oozes became progressively dominant when it returned to higher tropical latitudes in the Late Jurassic–Cretaceous (Muttoni et al., 2005). Our analysis, which incorporates data of Muttoni et al. (2005) from the radiolarian cherts and overlying basal Rosso ad Aptici cherty marlstones (that define the CS paleopole of entry #41), shows that the sub-equatorial latitudes consistent with radiolarian ooze deposition occurred during the ‘monster pole shift’ from ~183 Ma to ~151 Ma. At broadly this time, several carbonate platforms experienced biodiversity loss, absence of deposition in hiatuses, and productivity crisis due to increased eutrophication of this part of the Tethyan Ocean (Bartolini and Cecca, 1999) that we believe was associated with subequatorial latitudes (Muttoni et al., 2005). In addition, Wiedenmayer (1980) refers to a “revolution” in central Mediterranean (Adria) ammonite fauna...
immediately after the Pliensbachian–Toarcian boundary (~183 Ma) that may be a response to abrupt latitudinal change at this time. The subsequent deposition of the nanofossil ooze of the Maiolica Formation occurred when Adria returned to tropical latitudes of ~20°–25°N in the latest Jurassic–Cretaceous (Fig. 7).

Although short-term climate change like the so-called Carnian Pluvial Event, which was recently associated with rapid emplacement of the Wrangellia LIP (Dal Corso et al., 2012), or the high frequency monsoon variability observed in the Triassic of Pangea (Muttoni and Weissert, 1995), are not taken into account in our simple zonal climate model, we have shown that much of the overall architecture of the Mesozoic sedimentary succession of Adria can be explained using the “plate-stratigraphy” concept of Berger and Winterer (1974) based on continents drifting across standard zonal climate belts.

6. Conclusions

1. We examined a series of independent paleomagnetic mean directions from regions of Adria considered parautochthonous relative to the African craton, spanning from the Early Permian to the Eocene. Paleomagnetic data were obtained either from biostratigraphically dated sedimentary rocks that have been systematically corrected for inclination shallowing or from radiometrically dated igneous rocks that are considered free from inclination flattening.

2. Flattening-corrected and flattening-free paleomagnetic directions from parautochthonous Adria were used to calculate paleomagnetic poles for comparison with coeval paleopoles from Africa, again calculated from flattening-corrected or flattening-free data from sedimentary or igneous rocks, respectively.

3. Paleomagnetic poles from parautochthonous Adria and stable Africa are essentially coherent for several time slices from the Early Permian to the Eocene. The African affinity of paleopoles from Adria has been previously observed in data from the central Apennines (Channell, 1992; Satolli et al., 2007, 2008), however, paleopoles from the Apennines have not been included in the present compilation because they are variably rotated relative to the parautochthonous Adria paleopoles by as much as ~24°–27° counter-clockwise. On the other hand, compensation for central Apennine (Umbrian) tectonic rotation provides support for the composite Adria–Africa APWP, including the Early Jurassic ‘monster shift’ (point #5 below).

4. A composite APWP valid for parautochthonous Adria and stable Africa and extending from the Early Permian to the Miocene has been constructed for comparison with APWP from the literature rotated into northwest Africa (= Adria) coordinates using standard rotation parameters. Particularly good visual agreement exists with the global APWP of Kent and Irving (2010) constructed from flattening-free paleomagnetic poles that are largely independent of (different from) poles used in our Adria–Africa APWP construction.

5. Both the Kent and Irving (2010) and our Adria–Africa APWPs show a major pole shift in the Jurassic (from ~183 Ma to ~151 Ma according to Adria–Africa data) that other APWPs (Besse and Courtillot, 2002, 2003; Torsvik et al., 2008; Torsvik et al., 2012) tend to underestimate — we surmise — because of time-averaging of data affected by remagnetizations. Considering that this Jurassic ‘monster shift’ was observed in independent paleomagnetic datasets from different plates (North America, Adria–Africa, Eurasia; Kent and Irving, 2010; Meijers et al., 2010; this study), it is considered evidence for a major, and previously largely unrecognized, TPW event that awaits confirmation from non-Atlantic bordering continents.

6. The composite Adria–Africa APWP provides estimates of paleolatitudes of northern Adria in order to gauge their potential control on Tethyan facies deposition under the assumption of simple zonal climate. We found that during the Triassic–Early Jurassic, Adria (attached to Pangea) moved northward at speeds of ~0.45° latitude per Myr, crossing the entire span of the northern hemisphere arid belt (~5–30°N) before entering the mid latitude humid belt. This drift motion across contrasting zonal climate belts determined the main architecture of the Mesozoic sedimentary succession of Adria. For example, widespread shallow-water carbonate platforms frequently associated with sabkha or evaporitic sediments characterize the Middle–Late Triassic when Adria moved across the tropical arid belt, while the demise of carbonate productivity at around the Norian–Rhaetian boundary occurred when northern-central Adria crossed the arid–humid zonal boundary at ~30°N.

7. Despite geologic complexities of the Adria–Africa connection (e.g., Speranza et al., 2012), our well-dated composite Adria–Africa APWP can be regarded as a useful ancillary curve to describe the last 280 million years of motion of the African continent.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.palaeo.2013.06.011.

Acknowledgments

John Geissman and Fabio Speranza are warmly thanked for useful reviews. Robert Scholer is thanked for providing a digital listing of the Bulla data. Luca Lanci, Fabrizio Berra and Dennis V. Kent are thanked for insightful comments on earlier versions of this manuscript. Research partly supported through NSF grant EAR-0337102 (to JC).

References


Manabe, S., Bryan, K., 1985. CO2-induced change in a coupled ocean


Reilly, T., Raja, P., Mussett, A., Brock, A., 1976. The palaeomagnetism of Late Cenozoic

Lanza, R., Zanella, E., 1993. Palaeomagnetism of the Ferrar Dolerite in the northern

Jourdan, F., Feraud, G., Bertrand, H., Kampunzu, A.B., Tshoso, G., Watkeys, M.K., Le Gall, B.,

Kosterov, A.A., Perrin, M., 1992. Late Cretaceous low paleolatitudes from the circum-Black

Mattei, M., Zanchi, A., 2009. Opening of the Neo-Tethys Ocean and the Pangea B

Maurer, F., 2000. Growth mode of middle Triassic carbonate platforms in the western


Maurer, F., 2000. Growth mode of middle Triassic carbonate platforms in the western

Dolomites (eastern Alps, Italy). Tectonophysics 480, 57–72.


