Jurassic–Cretaceous low paleolatitudes from the circum-Black Sea region (Crimea and Pontides) due to True Polar Wander

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Abstract

In a recent study, paleomagnetic and paleoenvironmental data from Adria (as part of the African plate) suggest a trend toward much lower (~15°) latitudes from Early Jurassic to Earliest Cretaceous at the position of Adria than suggested by the apparent polar wander (APW) paths. The smoothing of existing (APW) paths has most likely caused this low-latitude episode to be overlooked. In this study, we test if the low paleolatitudes in the Jurassic to Early Cretaceous can also be found in Eurasia, i.e., Crimea (Ukraine) and the Pontides (Turkey) that are situated in the present-day Black Sea region. Our Eurasian data suggest the same low Late Jurassic to Early Cretaceous paleolatitudes as shown for Africa. The Jurassic to Lower Cretaceous time span is characterized by Tethys subduction between the African and Eurasian continents and these subduction zones likely functioned as an anchor in the mantle. Therefore, we regard it unlikely that both the African and Eurasian plates moved by ~1500 km south and subsequently north with respect to the mantle, as suggested by the paleomagnetic results. True polar wander (TPW) provides a mechanism that rotates the Earth’s crust and mantle with respect to its core, and it was recently quantified. The period from 195–135 Ma (Early Jurassic to Earliest Cretaceous) is subject to clockwise TPW, which could well explain our results. We conclude that TPW rather than plate tectonics is the cause of low Late Jurassic to Early Cretaceous African and Eurasian paleolatitudes in the eastern Mediterranean area.

1. Introduction

A recent paleomagnetic study on the Adria terrane, as part of the African continent in the Mesozoic, identified a rapid southward-then-northward movement of Adria within ~50 Myr, from the Early Jurassic to Earliest Cretaceous (Muttoni et al., 2005). These authors suggested that this Middle–Late Jurassic African southward movement, followed by a northward movement is underestimated in the apparent polar wander (APW) path of Besse and Courtillot (2002), as a result of smoothing due to the application of a moving average. In terms of displacement, the Adriatic promontory of Africa would move approximately 1600 km further southward than is expected from the APW path of Besse and Courtillot (2002). The conclusion of Muttoni et al. (2005) was based on new data from Adria and published data from African and North American magmatic rocks that were rotated to northwest African coordinates using the Atlantic plate circuit. The movement towards and away from equatorial latitudes was supported by a corresponding change in latitude suggested by the nature of deep marine sediments in Adria, changing from Lower Jurassic carbonate facies at tropical latitudes to Middle to Upper Jurassic radiolarites at equatorial latitudes, and back again to carbonate facies at tropical latitudes in the Cretaceous. Muttoni et al. (2005) concluded that the underestimated motion of Africa is the result of statistical procedures in the construction of APW paths, and that their revised pole path represents the true motion of the African plate to southerly latitudes in Middle–Late Jurassic times. However, they did not explore the possible reasons for this strong paleolatitudinal shift.

Plate kinematic reconstructions for the period following the breakup of Pangea are based on the constructions of plate circuits from the marine magnetic anomaly record. The placing of the continents with respect to the Earth’s magnetic field, which is aligned with the spin axis, is reconstructed using paleomagnetic data. The position of continents with respect to the mantle in the period after 130 Ma is further constrained using hotspot reference frames (Müller et al., 1993; Steinberger and O’Connell, 1998; O’Neill et al., 2005; Torsvik et al., 2008).
To filter out or reduce paleomagnetic and geochronologic errors, APW paths are constructed using sliding windows. Consequently, fast motions of the continents are underestimated in APW paths.

However, the movement of a plate recorded in an APW path, is not necessarily entirely unique for that plate, but may share a motion component with all other plates. There are several episodes wherein the entire mantle and crust rotated with respect to the Earth’s spin axis. Studies concerning the nature of true polar wander (TPW) have been carried out since the 1950s (Gold, 1955; Goldreich and Toomre, 1969).

TPW results from a redistribution of density inhomogeneities in the mantle, for example caused by the rise of mantle plumes or the subduction of plates (Steinberger and Torsvik, in revision). Since TPW represents a true rotation of the mantle and crust with respect to the Earth’s spin axis, it is also recorded in the sedimentary record, through climate controlled facies changes, and flora and fauna variations. Several post-Permian episodes of TPW were recently quantified by Steinberger and Torsvik (2008). One of the proposed intervals of TPW (between 195 and 135 Ma) coincides with the proposed southward movement of Africa of Muttoni et al. (2005). Therefore, there are two possibilities to explain the rapid motion of Africa to southerly latitudes in the Late Jurassic: 1) the African plate moved with respect to the surrounding plates (with major tectonic implications), or 2) all continents moved with respect to the spin axis, and therefore there is no relative motion between the continents other than that expected from plate kinematics.

If this rapid motion of Africa is (mainly) caused by TPW, we should find a similar southward motion in the Eurasian plate at longitudes comparable to the African paleolatitude, i.e. with respect to the Euler pole (positioned at the equator) that describes the Jurassic TPW event (Steinberger and Torsvik, 2008). The distance away from this Euler pole determines the paleolatitudinal effect of TPW. Although TPW affects all plates, which means that all plates move together, any differential (tectonically or geodynamically induced) motion is still reflected in the paleomagnetic data. Details on TPW calculation can be found in Steinberger and Torsvik (2008).

In this study, we test if the strong Middle to Late Jurassic southward movement is limited to the African plate, or if the same event can be recognized for the Eurasian plate. To this end, we aimed to determine the paleolatitudinal position of the southern Eurasian margin at the location of the Pontides (Turkey) and Crimea (Ukraine). We have sampled rocks ranging from the Lower Jurassic to Cretaceous. In total, we analyze the results of 27 new sites from the Pontides and Crimea and combine them with our 13 Cretaceous sites from the Pontides (Fig. 1a) (Meijers et al., in press) and with 43 previously published datasets. We corrected, where possible, for the inclination shallowing in sediments with the E/I method (Tauxe and Kent, 2004).

2. Geological setting

The southern Eurasian margin was affected by the subduction of the Paleo-Tethys and Neo-Tethys oceans since the Paleozoic. The Neo-Tethys opened in the Permian, and sediment attributes to this event are widely distributed in the present-day Mediterranean area (Dercourt et al., 2000; Stampfli and Borel, 2002; Gutierrez-Alonso et al., 2008). The Paleo- and Neo-Tethyan domains were separated by a series of presently east–west distributed “Cimmerian continents” that rifted away from the African margin upon opening of the Neo-Tethys. Following Paleo-Tethys closure, northward subduction of the Neo-Tethys ocean (Fig. 1b) controlled the development of the Eurasian continental margin and led to the formation of several back-arc basins on the overriding plate, of which the Cretaceous–Eocene Black Sea basin is a prominent example. The opening of the Black Sea since Middle to Late Cretaceous times (Okay et al., 1994) accommodated only ~100–150 km (~1–1.5° inclination) of extension (Cloetingh et al., 2003; Starostenko et al., 2004; Shillington et al., 2008), which is well within paleomagnetic errors and an order of magnitude smaller than the African southward movement. Therefore, the opening of the Black Sea is not expected to be significantly reflected in paleomagnetic results from the Pontides. Some authors suggested the presence of a small oceanic basin between the Pontides and Crimea in Triassic to Jurassic times (Küre Ocean) (Şengör and Yilmaz, 1981; Robertson and Dixon, 1984; Stampfli and Borel, 2002; Moï et al., 2008), although the oceanic nature of this basin was challenged by others (Dercourt et al., 2000; Barrier and Vrielynck, 2008).

The Paleozoic and/or older Crimean basement is formed by the thinned margin of the East European Craton (EEC): the Scythian Platform (Fig. 1a) (Stephenson et al., 2004; Saintot et al., 2006b). It is almost entirely covered by Mesozoic–Cenozoic volcano-sedimentary units (Nikishin et al., 2001), that can be subdivided in three units. 1) a lower unit of Triassic to Middle Jurassic (Bathonian) intensely deformed series of turbidites and shales, olistostromes, calc-alkaline volcanics and continental clastics. 2) a middle unit of Upper Jurassic to Lower Cretaceous (Berriasian) platform carbonates that changes eastward into conglomerates and turbidites. The Upper Jurassic platform carbonates are allochthonous thrust slices according to Mileyev et al. (1996), which we regard unlikely, because it would imply that exactly the time interval that is characterized by carbonate deposition is missing in the entire Crimean stratigraphy, except for Kimmeridgian conglomerates and turbidite sequences that can be found in the east of the peninsula. In case the Jurassic carbonates are allochthonous, their displacement would be on the order of tens of kilometers, which is well beyond the resolution of paleomagnetic studies (~2–3°, or ~200–300 km). An episode of folding and thrusting occurred in intra-Berriasian times (~145–140 Ma). 3) an upper unit of Lower Cretaceous (Upper Berriasian) to Eocene rift-related deposits (Zonenshain and Le Pichon, 1986), probably resulting from Black Sea opening (Okay et al., 1994; Banks et al., 1997). The upper unit experienced little deformation, compared to the lower two units (Mileyev et al., 1996; Mileyev et al., 1997; Saintot et al., 1999).

The Pontides constitute the region between the Black Sea in the north and the Izmir–Ankara–Erzincan suture zone in the south, which demarcates the (northern) Neo-Tethyan Ocean in Turkey (Şengör and Yilmaz, 1981). In the studied area, the Pontides consist of two different tectonic blocks: the Istanbul and Sakarya Zones (Fig. 1a) (Okay, 1989).

The age of amalgamation of the Istanbul and Sakarya Zones has been a matter of debate, and proposed ages range from Early Jurassic (Şengör et al., 1980) to early Late Cretaceous (Tüysüz, 1999). In the latter case, it was thought to result from closure of the so-called “Intra-Pontide ocean”, a narrow (~300 km) oceanic basin (Okay et al., 1994; Robertson and Üstãomer, 2004). Recent studies by Bozkurt et al. (2008) and Okay et al. (2008) revealed, however, that the Istanbul and Sakarya Zones amalgamated with Eurasia during the Paleozoic, with possibly some post-Triassic reactivation (Okay et al., 2008).

The Sakarya Zone constitutes an intensely deformed Variscan (i.e. Eurasian) basement and the locally metamorphosed pre-Jurassic Karakaya Complex (Tekeli, 1981; Okay et al., 1991). The Istanbul Zone comprises a non-metamorphic Ordovician to Carboniferous sedimentary sequence that experienced mild deformation during the Permo-Carboniferous, overlain by Triassic sediments. Its stratigraphy is generally correlated to the Moesian Platform, from which it separated during western Black Sea opening in the Early Cretaceous (Görür, 1988; Okay et al., 1994).

The Lower Jurassic of the Sakarya Zone consists of shallow marine clastics, and includes some ammonitico-rosso levels (Altun et al., 1991). In the eastern part of the Sakarya Zone, the Lower to Middle Jurassic sequences include volcanics and volcanoclastics (Yılmaz et al., 2003; Yılmaz and Kandemir, 2006). The Upper Jurassic to Lower Cretaceous deposits in the entire Pontides consist of platform carbonates. Carbonate deposition in the Sakarya Zone commenced slightly earlier than in the Istanbul Zone, namely in the Middle Jurassic (Callovian). Similar to Crimea, the Lower Cretaceous (Hauterivian) to
Eocene rift-related deposits are related to opening of the Black Sea (Görür, 1997).

It is of importance here that Africa and Eurasia were separated in the Jurassic by a Tethyan subduction zone (Ricou et al., 1998; Dercourt et al., 2000; Stampfl and Borel, 2004; van Hinsbergen et al., 2005; Barrier and Vrielynck, 2008; Schmid et al., 2008). Evidence for subduction in the studied area is however a matter of debate. In the Pontides, Crimea and the Greater Caucasus (Fig. 1a), Early and Middle Jurassic rift basin development probably took place in a back-arc setting, driven by the northward subduction of the Neo-Tethys south of the Pontides. This is evidenced by the large amount of volcanogenic sediments in Crimea and the eastern Pontides, and the dominantly volcanic Bathonian–Bajocian interval in the Greater Caucasus (Robinson et al., 1995; Banks and Robinson, 1997; Nikishin et al., 2001; Saintot et al., 2006a; Saintot et al., 2006b). The subduction zones in the Jurassic Tethyan realm acted as an anchor in the mantle, and therefore relatively fast motion of both the African and Eurasian continents with respect to the mantle is unlikely.

3. True Polar Wander

True Polar Wander (TPW) events were quantified in several studies for the last 200 Myr (Besse and Courtillot, 1991; Prevot et al., 2000; Besse and Courtillot, 2002). Recently, Steinberger and Torsvik (2008) calculated TPW over the last 320 Myr, by assessing the APW paths of all continents. For periods younger than 130 Ma, the paths were compared to a moving hotspot reference frame. By definition, a TPW event has an equatorial Euler pole. The paleomagnetic expression of TPW is dependent on the position of the sampling site with respect to the Euler pole during TPW, because it determines the sense of motion a location would experience during TPW.

Four intervals of TPW were identified by Steinberger and Torsvik (2008). In the period from 250–220 Ma a counterclockwise TPW (18°) around an equatorial Euler pole at 15°W would cause large northward movements in the present-day circum-Black Sea region, located at the southern margin of Eurasia. The effect of TPW was compensated in the period of 195–145 Ma with a clockwise movement around the same Euler pole. This was followed by dominantly east–west movements from 145–135 Ma, caused by 10° clockwise rotation around an equatorial Euler pole located at 37.5°E, compensated by a next period of counterclockwise TPW from 110–100 Ma that would have resulted in northwestward movement of the circum-Black Sea area. Therefore, in the case that TPW, instead of tectonics, has been the (main) mechanism to transport Adria to low latitudes, the present-day circum-Black Sea region should have experienced a similar, and even more pronounced movement.

4. Paleomagnetic sampling, analysis and reliability criteria

4.1. Paleomagnetic sampling and analysis

Sampled lithologies vary from limestones to sandstones, siltstones, shales, marls, clays, calcarenites and volcanoclastics (see Table 1 and Supplementary data). Cores were collected using a motor drill. Sample orientations were measured with a magnetic compass and corrected for the present-day declination. In most cases, cores were long enough to provide multiple specimens from a single core. Therefore, the number of demagnetized specimens is sometimes higher than the number of sampled cores (Table 1). For absolute ages, we correlate biostratigraphic ages to the GTS2004 timescale (Ogg, 2004; Ogg et al., 2004). For several sampled sites, new biostratigraphic ages from limestones were determined by D. Altuner. Ages for all sites can be found in the Supplementary data in Appendix A and in Table 1.

Magnetic carriers were determined by performing thermomagnetic runs and isothermal remanent magnetization (IRM) curves. IRM acquisition curves were performed on samples that had been heated already until 150 °C and used for AF demagnetization (Fig. 2a–f). Before IRM acquisition curves determination, all specimens were first demagnetized until 300 mT in three orthogonal directions, to minimize the influence of magnetic interaction and thermal activation (Heslop et al., 2004). The IRM was acquired in 57 steps until 700 mT, with an in-home developed robot assisted and fully automated 2G DC SQUID cryogenic magnetometer (noise level 10−12 Am²). The IRM measurements were analyzed using the cumulative log-Gaussian approach to identify the different coercivity components with the method developed by Kruiver et al. (2001). The diagrams were interpreted with either two or three magnetic components, overlapping in coercivity spectrum, to provide a best-fit to the IRM curves. The low intensity and low coercivity component that is usually observed using this method results from a skewed data distribution and has no physical meaning (Heslop et al., 2004). The magnetic components can be characterized by the saturation isothermal remnant magnetization (SIRM), the peak field, at which half of the SIRM is reached (B½) and the dispersion of its corresponding cumulative log-normal distribution (DP) (Kruiver et al., 2001). The thermomagnetic runs were carried out in air, using a modified horizontal translation type Curie balance, with a sensitivity of 5 × 10−15 Am² (Mullender et al., 1993) (Fig. 2g–i). Approximately 40 mg of powdered rock samples were put into a quartz glass sample holder and were held in place by quartz wool. Heating and cooling rates were 10 °C/min. Temperatures were increased to a maximum of 700 °C.

Samples were demagnetized using thermal and alternating field (AF) demagnetization methods, or a combination of both methods. Thermal demagnetization was carried out in a magnetically shielded oven, with steps of 30 °C–50 °C up to a maximum of 540 °C. AF demagnetization up to a maximum of 90 mT was carried out with steps of 3–20 mT. A 2G Enterprises horizontal 2G DC SQUID cryogenic magnetometer with a noise level of 3 × 10−12 Am² was used to measure the natural remanent magnetization (NRM) of all samples. The AF demagnetization procedure and measurement of the samples was performed with an in-home developed robot assisted and fully automated 2G DC SQUID cryogenic magnetometer.

Test sets of samples were demagnetized both thermally and by alternating field, to allow comparison of both applied techniques (e.g. Gong et al. (2008)). To remove possible stress in magnetite grains caused by surface oxidation at low temperatures (Van Velzen and Zijderveld, 1995), most AF demagnetized samples were heated to 150 °C before demagnetization (see procedures in Gong et al. (2008)). Several samples of site UJ that were AF demagnetized were heated until 210 °C before AF demagnetization, while part of the samples of site TD14 were heated until 300 °C before demagnetization, the temperatures at which a secondary component was generally removed.

Demagnetization diagrams of the natural remanent magnetization (NRM) were plotted as orthogonal vector diagrams (Zijderveld, 1967) (Fig. 3). Results from generally five to eight successive temperature or AF steps were analyzed by principal component analysis (Kirschvink, 1980) to determine the characteristic remanent magnetization (ChRM) in the samples (Table 1). Fisher statistics (Fisher, 1953) were used to calculate directional and virtual geomagnetic pole (VGP) means (Fig. 4). Because secular
Table 1: The inclination after correction for inclination (I) error results from 5000 bootstraps of TK03.GAD, with 95% lower and upper bounds (I₃, I₅), where I₃ is the inclination resulting from intersection of the distribution with TK03.GAD (Tauxe and Kent, 2004). I is the corresponding corrected latitude, with 95% lower and upper bounds (I₉₅, I₃₁). The inclination is determined from the mean virtual geomagnetic pole (VGP) direction, Kᵥ, and errors are given before and after correction for bedding tilt.

Variation of the Earth's magnetic field induces scatter in paleomagnetic directions, which is near-Fisherian at the poles, but gradually becomes more ellipsoidal towards the equator (Creer et al., 1959; Tauxe and Kent, 2004). We calculated the VGPs from all directions. Subsequently, a variable cut-off (Vandamme, 1994) was applied to remove outliers from the datasets (e.g. from excursions,
reversal transitions or other outliers) and the errors in declination ($\Delta D_x$) and inclination ($\Delta I_x$) were calculated following Butler (1992) (Table 1).

Table 1

<table>
<thead>
<tr>
<th>Ni/NvD</th>
<th>D</th>
<th>$\Delta D_x$</th>
<th>I</th>
<th>$\Delta I_x$</th>
<th>Paleolatitude</th>
<th>$k$</th>
<th>$\alpha_{95}$</th>
<th>$\lambda$</th>
<th>$\varphi$</th>
<th>$K$</th>
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<td>30.3</td>
<td>1.0</td>
<td>16.3</td>
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<td>64.1</td>
<td>-76.2</td>
<td>31.1</td>
<td>2.8</td>
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Since we sampled sedimentary rocks, we corrected sufficiently large datasets for a possible shallowing of inclination in sediments caused by compaction during burial with the elongation/inclination ($E/I$) method

Table 2

<table>
<thead>
<tr>
<th>TK03 after Vandamme cut-off</th>
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<tr>
<td>$D$</td>
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<td>-----</td>
</tr>
<tr>
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<td>169.6</td>
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of (Tauxe and Kent, 2004), which is based on the field model TK03.GAD (Fig. 5, Table 1). The model is based on the assumption that the field averaged over sufficient time resembles that of a geocentric axial dipole (GAD). A large number (preferably \( N > 100 \)) of individual directions is required to apply the model successfully. We ran the model for each dataset twice: once without applying a cut-off before running the model, and once applying a variable cut-off (Vandamme, 1994) before applying the model to remove outliers. The difference between both runs was not significant (Table 1).

Our data were compared to the paleolatitudes calculated from the APW paths of Torsvik et al. (2008) and Besse and Courtillot (2002) (Fig. 6), that are very comparable for periods younger than 160 Ma. We discuss results in more detail (per site) in the Supplementary data.

4.2. Reliability criteria

To guarantee the quality of both published and new datasets and to reliably reconstruct the paleolatitude of Crimea and the Pontides throughout the Jurassic and Cretaceous we applied a number of reliability criteria. The datasets and, if applicable, the reason of exclusion from further analysis is indicated in Tables 1 and 2. More detailed information of each site is given in the Supplementary data.

The following reliability criteria were applied:

1) Samples that were demagnetized using bulk demagnetization were excluded, for example sites G1–G5 and O1–O2 in the study of Orbay and Bayburdi (1979), Fig. 3.

Fig. 3. Orthogonal vector diagrams (Zijderveld, 1967), showing characteristic demagnetization diagrams for sampled sites. Closed (open) circles indicate the projection on the horizontal (vertical) plane. Alternating field and thermal demagnetization steps are indicated. All diagrams (except for TB4.4A notc) are displayed after correction for bedding orientation. For site TD15 we only took the thermally demagnetized samples into account (see Supplementary data).

Fig. 2. a)–f) Examples of IRM component analysis for three sites that were accepted for this study (Kruiver et al., 2001). A legend for the linear acquisition plots (LAP) and gradient acquisition plots (GAP) is given in the figure. The three distinguished components and their contributions, saturation IRM (SIRM), \( \log(B_{1/2}) \), \( B_{1/2} \) and DP are indicated in the tables. g)–i) Thermomagnetic curves measured on a Curie balance (Mullender et al., 1993) for the same three sites as the IRM component analysis examples. Red (black) curves indicate the heating (cooling) curves. The IRM curves and thermomagnetic curves indicate that in all three sites the main magnetic carrier is magnetite. j)–l) Non-parametric fold test (Tauxe and Watson, 1994) on sites UJ and KO. j) Equal area plots of the ChRM before correction for bedding tilt (geographic coordinates), and k) after correction for bedding tilt. Results of the fold test l) as 500 bootstrapped examples of the first eigenvalues (\( \tau_1 \)) upon progressive untilting. Above the diagram the 95% bootstrap error is given.
2) sites that have a mean ChRM direction in geographic coordinates that is indistinguishable from the present-day geocentric axial dipole (GAD) field at the sampling location were excluded,
3) datasets with suspect directions (e.g. N/up or S/down directions) that may result from an insufficiently removed (partial) overprint, datasets with an unresolved component and datasets from sites with samples that were too weak for proper demagnetization resulting in erratic behavior (e.g. TB1), were excluded from further analysis. An example is site TB5, where a temporary problem with the oven that was used for demagnetization of the samples resulted in the acquisition of a spurious component in the samples at higher temperatures (~300 °C). Another example is site TD15 which gave completely different and unexplainable (but consistent) results using AF and thermal demagnetization.
4) datasets with age uncertainties larger than 15 Myrs were excluded,
5) datasets that have an error in latitude (using Δγz, calculated from A95) that is larger than 7° (averaged over Δγz and Δαz), because this would not give us the resolution to compare with the APW path,
6) datasets that do not reach the minimum amount of samples (N>24) to allow reliable calculation of the paleolatitude (Van der Voo, 1990) were not taken into account. In the case that volcanic rocks were sampled, the minimum required number of flows/sites (with a minimum of demagnetized specimens per lava flow ≥5) that constitute one locality is 5,
7) datasets that do not pass the fold test were excluded. An example of this is site KD, because the six subsets with different bedding orientation do not pass the fold test (of Tauxe and Watson, 1994 (see Supplementary data)). The tightest grouping of data occurs at 40% unfolding. We also determined the paleofield direction from a synfolding remanence of site KD using the small circle intersection (SCI) method of Shipunov (1997), modified by Waldhörr and Appel (2006) (see Supplementary data). The directions from the foldtest and the SCI method are very comparable. The results suggest that remagnetization occurred at an inclination of 54.6°~62.4° (corresponding to a paleolatitude of 35.1°N~38.1°N). If we compare this value to the APW path of Eurasia (Torsvik et al., 2008), this coincides very well with values predicted for post-Paleocene times (Fig. 7), which supports remagnetization, likely during folding.

Fig. 4. Equal area projections of the ChRM directions of all sites except those where N = 0 (Table 1). Open (closed) symbols denote projection on upper (lower) hemisphere. Large black (blue) symbols with black circle indicate respectively the mean directions and their cone of confidence (α95) after (before) tilt correction. Red (small) circles indicate the individual directions rejected by the Vandamme cut-off angle (Vandamme, 1994). Black lines indicate the great circles that were used to calculate the best fitting ChRM directions (McFadden and McElhinny, 1988). Red star indicates the present-day geocentric axial dipole direction at the sampled location.

Fig. 5. a)–h) Equal-area projections of the individual VGP directions before E/I correction (a and f) and equal-area projections of the individual ChRM directions before (c and h) and after (d and i) E/I correction (symbols as in Fig. 4) (Tauxe and Kent, 2004) with corresponding elongation vs. inclination (b and g) and fraction (of 5000 bootstraps) vs. inclination plots (e and j) for TD14 (a–d) and UJ (e–h). In the elongation vs. inclination plots the E/I for the TK03.GAD model (green line) and for the datasets (red barbed line) for different degrees of flattening are plotted. The red bars indicate the direction of elongation (horizontal is E–W and vertical is N–S). Also shown are examples (yellow lines) from 20 (out of 5000) bootstrapped data sets. The crossing points (if the dataset intersects the model) represent the inclination/elongation pair most consistent with the TK03.GAD model, given as I and ΔI (in green) above the panel; Iorg = original inclination, Eorg = original elongation of the dataset, IE and IEW are the elongation and inclination according to the E/I model, respectively. In the fraction/inclination plot, a histogram of intersecting points from 5000 bootstrapped data sets is shown. The most frequent inclination (solid red vertical line; dashed red line EI (in green) above the panel; vertical lines denote the 95% bootstrap error) is given as value (and error range) on top of the panel; the inclinations of the original distribution (blue vertical line) or the intersection with the model (green vertical line) are indicated; E = the elongation (and error range) resulting from the bootstrapped data sets.
we rejected site TD13 and the site in Crimene from Rusakov (1971), because the inclination of the reported data is even, when taking the error into account, higher than the present-day GAD field inclination at the sampling locality. Two sites with the same age that were sampled in close proximity within the same sampling sequence were rejected, because their mean ChRM directions are very different (see site KL and KJ, see Supplementary data).

Fig. 6. a) Blue/yellow/red circles (with ΔA error bars calculated from the Δλi) respectively from the studies by Muttoni et al. (2005), Aiello et al. (2008) and Satolli et al. (2007, 2008). Green circles (with their ΔA error bars calculated from the Δλi) or dp/dm error bars: literature data used in the reconstruction by Muttoni et al. (2005). All data from Adria were recalculated to 42.5°N,1°E. More information about the data: see Section 6. MEB05; Muttoni et al. (2005); SBC07; Satolli et al. (2007); SB08; Satolli et al. (2008); AHP06; Aiello et al. (2008). b) Small yellow (large circles) (with ΔA error bars calculated from the Δλi) or dp/dm error bars: literature data used in the reconstruction by Muttoni et al. (2005). All data from Adria were recalculated to 42.5°N,1°E. More information about the data: see Section 6. MEB05; Muttoni et al. (2005); SBC07; Satolli et al. (2007); SB08; Satolli et al. (2008); AHP06; Aiello et al. (2008).
5. Results

5.1. Results — this study

After applying the above reliability criteria, there are nine remaining datasets from the 41 datasets for the paleolatitude reconstruction of Crimea and the Pontides in Jurassic—Cretaceous times. The nine remaining datasets are from three age ranges: Callovian–Berriasian (~164.7–140.2 Ma, six sites), Aptian–Albian (~125.0–99.6 Ma, one site) and Coniacian–Santonian (~89.3–83.5 Ma, two sites) (Fig. 6b; Table 1, indicated in bold face). The oldest interval consists of datasets from both Crimea and the Pontides; the middle age interval contains only Crimean data, and the youngest interval consists only of datasets from the Pontides.

Two of our datasets that were taken from Upper Jurassic rocks have similar ages: sites UJ and KO. Because of their proximity and the difference in bedding tilt, we performed a fold test. The equal-area plots of directions from both limbs before and after tilt correction (Fig. 2j–l) show that in geographic coordinates the two sites have significantly different directions, while after tectonic tilt correction the directions of both sites form a single cluster. The nonparametric fold test of Tauxe and Watson (1994) (Fig. 2j–l) is considered to be positive because closest grouping is reached close to full unfolding (95% bootstrap errors: 88%–96%). The small deviation from 100% significance may be caused by orientation or bedding plane errors. This fold test checks for maximum clustering, but this need not always be the ideal case (McFadden, 1998), while also a well-recorded secular variation distribution would have a slight elongation at this latitude, which is not necessarily compatible with maximum clustering. Furthermore, the two groups of pre-unfolding directions that can be seen within the data of site KO (Fig. 2j), and that form one cluster after tectonic tilt correction (Fig. 4), give an extra indication that the ChRM direction is a pre-folding direction. Hence, we conclude that the magnetization of site UJ and KO was acquired before folding, even though the tilt corrected means just fail to have a common true mean direction (cTMD). To determine whether two distributions have a cTMD, we used the reversal test developed by McFadden and McElhinny (1990) and their classification (A, B, C, indeterminate). The classifications are based on the critical angle γc and the angle γ between the means. Because we use their test with simulation, the test is equivalent to using the Vc statistical parameter of Watson (1983).

In the oldest interval (~164.7–140.2 Ma), we have six datasets (two from the Pontides and four from Crimea); four of these were corrected for inclination error with the E/I method (Tauxe and Kent, 2004). The E/I method was carried out on the datasets before and after applying a variable cut-off to the datasets (Vandamme, 1994) (see Section 4.1). The difference between both approaches is negligible (Fig. 6), on average the calculated paleolatitude correction after applying the E/I method is not significant and only ~2–3° higher than before applying the method (Fig. 5). In the oldest age interval, when not taking into account site KA that yields a higher paleolatitude (~31°N) than the other sites, a trend through all other datasets can be observed that is consistent with the APW path (decreasing from ~21°N at ~165 Ma to ~16°N at ~140 Ma) (Fig. 6).

From the five sites that were sampled in rocks from intervals (overlapping) the Aptian–Albian (~125.0–99.6 Ma), one site from Crimea (KP) passed the reliability criteria. Site KP yields a paleolatitude that is within error (Δe) and age error) with the paleolatitude predicted by the APW paths (Besse and Courtillot, 2002; Torsvik et al., 2008), before and after correction with the E/I method. Unfortunately, the site has a relatively large age error (~12.7 Ma).

The two datasets from the Pontides from the youngest age group (~89.3–83.5 Ma) yield paleolatitudes that are very comparable (TA2) to slightly lower (TA5) than the paleolatitudes that are predicted by the APW paths (Besse and Courtillot, 2002; Torsvik et al., 2008), both before and after correction with the E/I method.

5.2. Results — literature data

All data reported for the area of interest from the global paleomagnetic database (GPMDB) (Smethurst, 2009) are listed in Table 2 and shown in Fig. 7. The studies in the GPMDB are from Van der Voo (1968), Anferova (1971), Rusakov (1971), Obay and Baysal (1979), Evans et al. (1982), Pechersky and Safonov (1993) and Pechersky et al. (1993). A full author list could not be traced for Pechersky et al. (1993). We added the data of...
Channell et al. (1996) to this review, because they are not part of the GPMD8. Many of the published data were rejected after applying the reliability criteria. For the Pontides, only three out of 13 results were accepted, all three from the combined results of Channell et al. (1996). None of the 22 Crimean datasets passed the reliability criteria. All sites that passed the reliability criteria are indicated in bold face in Table 2.

A major problem with the Crimean data in the database is that they can often not be traced back to the original publication. In some cases, the $k$ (precision parameter), $\alpha_{95}$ values and number of samples of datasets that were combined in the GPMD8 do not coincide with our calculations. The number of samples used for the calculations also differed sometimes between the paper and the database. In one case, a
single dataset was entered three times into the database, under different authors, and combined with several other sub-datasets.

6. Discussion

Data from five out of six sites from Callovian–Berriasian (164.7–140.2 Ma) rocks show very consistent behavior and suggest that the Pontides (sites TD14, TD2) and Crimea (sites KO, UJ, and KV) were not situated at significantly different latitudes in Late Jurassic times (Figs. 6 and 8), which would imply close vicinity of the Pontides and Crimea in this period. Therefore, even if there was an oceanic basin separating the Pontides and Crimea in this time span, it was of limited dimension (no more than several hundred of km). Our data (except site KA) yield paleolatitudes that are significantly lower (1600 km) than the paleolatitude expected from the APW paths of Besse and Courtillot (2002) and Torsvik et al. (2008). The consistent low paleolatitudes from Callovian to Berriasian (164.7–140.2 Ma) rocks from Pontides and Crimea, show a southward moving trend (Figs. 6 and 8), which is near-parallel to the trends in the Eurasian APW paths (Besse and Courtillot, 2002; Torsvik et al., 2008) in the same interval.

Data from Aptian–Albian (125.0–99.6 Ma) rocks from Crimea (site KP) yield a paleolatitude that are slightly higher than the paleolatitudes predicted by the APW paths, but identical within error (Fig. 6b, blue shaded area), both before and after correction with the E/I method (Figs. 6 and 8, Table 1). Coniacian–Sanctonian (89.3–83.5 Ma) data from the Pontides from site TA5 reveal a paleolatitude that, after correction with the E/I method, plot on the APW path, whereas the paleolatitude from site TA2 are slightly lower, but within error, to the Late Cretaceous APW paths (Besse and Courtillot, 2002; Torsvik et al., 2008). The datasets from Upper Cretaceous formations published by Channell et al. (1996) however, yield slightly lower latitudes than predicted by the APW paths. This could be the result of inclination shallowing, because the data were not corrected for this. The accepted site of Liassic age from Channell et al. (1996) plots within error of the APW path.

Our low latitudes in Middle Jurassic to Early Cretaceous times, compared to the Eurasian APW paths, are in line with the low latitudes of Adria as part of the African plate, presented in the study of Muttoni et al. (2005). On the basis of a magnetostatigraphic study on sections in the Northern Apennines (Italy), Satolli et al. (2007; 2008) calculated a paleopole for Adria for the 100–150 Ma interval. We used their poles to calculate the paleolatitude at our reference location (Fig. 6a). The paleolatitudes derived from their study in the 125–145 Ma interval are in line with the data presented by Muttoni et al. (2005). However, in the critical interval prior to 145 Ma that shows the southward movement of Africa, their calculated paleolatitude is higher than predicted by the scenario of Muttoni et al. (2005), and comparable to the APW paths. Therefore, they disagree with Muttoni et al.'s (2005) scenario of a more southerly position of Africa in the Middle to Late Jurassic times, compared to the APW paths. One datapoint from a study by Aiello et al. (2008) on Greek radiolarian cherts that has a small age error (<5 Myr, Fig. 6) yields also a paleolatitude that is much lower than expected from the African APW path, the other data point yields a slightly lower paleolatitude. In the critical interval the sampled localities are also a part of the African plate (Fig. 1b). In general the data from Aiello et al. (2008) from Greek radiolarian cherts support the scenario of Muttoni et al. (2005). The data from Aiello et al. (2008) do however not pass our reliability criteria due to too large age errors and too small datasets (Fig. 6a).

Muttoni et al. (2005) conclude that the southward movement and clockwise motion of Africa is underestimated by the APW path of Besse and Courtillot (2002) because of smoothing of the data. This discrepancy remains if their results are compared to the pole path of Torsvik et al. (2008), because both paths are nearly identical from the start of the critical time interval (~160 Ma) onwards (Figs. 6–8). Smoothing seems a likely mechanism, because of the relatively low amount of data entries in the global APW path of Torsvik et al. (2008): the average number of data entries per 10 Myr sliding window in the pole path is 27 (320–0 Ma), whereas this is only 13 in the critical time span (160–140 Ma). The pole path calculated by Satolli et al. (2008) does not support Muttoni’s scenario, but in their study they do recognize an abrupt change in plate movement direction around ~141 Ma. Therefore, Satolli et al. (2007) propose the possibility of TPW in this time span.

From our six datasets from Upper Jurassic to Early Cretaceous rocks that were deposited at the southern Eurasian margin, five do show a ~1600 km lower paleolatitude than expected from the Eurasian APW paths, out of which four yield a paleolatitude that is statistically significantly lower than the APW path (TD14, KO, UJ and KV) (Figs. 6c and 8a). This suggests that Muttoni et al.’s (2005) scenario wherein the southward movement of the African APW paths is underestimated, seems not only valid for Africa, but also for Eurasia. The fact that datasets from other pre- and post-TPW Jurassic and Cretaceous periods from the Pontides and Crimea (Fig. 8) plot within error on the APW path except for two sites that were not corrected for inclination error, confirms that we have a good control on paleolatitude. Because Africa and Eurasia were separated and partly surrounded by subduction zones, which serve as an anchor into the mantle, it is unlikely that both plates moved ~1600 km back and forth with respect to the mantle (Fig. 1b). Therefore, we conclude that the latitudinal shift is most likely the result of TPW. We concur with Muttoni et al. (2005) that the strong southward movement, followed by a northward movement in the APW paths is smoothed, and because these smoothed paths were used to calculate the TPW events by Steinberger and Torsvik (2008), the Jurassic TPW event was probably larger than determined so far.

7. Conclusions

Here, we tested whether recently published Jurassic to Early Cretaceous large southward movements, followed by northward movements of the African plate at the position of Adria can also be found on the Eurasian plate in the present-day circum–Black Sea area. We have presented large paleomagnetic datasets (41) from Jurassic and Cretaceous sediments from Crimea (Ukraine) and the Pontides (Turkey) that were part of the Eurasian plate. To correct for inclination error in sediments, we used the statistical E/I method of Tauxe and Kent on datasets with a sufficient number of samples. Our data were combined with 43 published datasets. After applying strict reliability criteria on all 84 datasets, only 12 datasets were accepted. Five out of six Late Jurassic to Early Cretaceous datasets plot on average ~1600 km lower than the paleolatitudes calculated by the Eurasian APW paths confirming that the southward movement of Africa is also observed in Eurasia. Moreover, the datasets from Crimea and the Pontides display very similar paleolatitudes in this time span, and therefore imply their proximity in the Late Jurassic to Early Cretaceous.

The weaker signature of this southward movement, followed by a northward movement in the APW paths, can result from data smoothing. This is very likely for a period with a low amount of high quality datasets and a sharp change in motion.

There are two mechanisms to explain this southward translation of the Eurasian and African plates in the eastern Mediterranean realm: 1) movement of the African and Eurasian plates with respect to the surrounding plates, 2) movement of the entire crust and mantle with respect to the Earth’s core: true polar wander (TPW), recently quantified by Steinberger and Torsvik (2008) for the critical time span. Because it is unlikely that Africa and Eurasia moved with such high speed with respect to the surrounding plates in a time span where both continents were surrounded by subduction zones, wherein the subducting slabs function as their anchors in the mantle, we regard the possibility of TPW the most likely mechanism to explain the low latitudes.

Acknowledgements

The authors would like to thank Nuretdin Kaymakçı for discussion. We would like to acknowledge the following people for their help in the
field: Wout Krijgsman, Martijn Deenen, Aline Saintot, Stephen Vincent, Vladimir Bakhmutov, Sergei Bolotov, Oleg Rusakov, Evgeny Polyachenko, Galina Slivinskaya, Sergey Yudin, Elena Yudina, Viktor Yudin, Aral Okay, Nurettin Kaymak, Bora Rojaj, Pinar Ertepinar Kaymak and Ane Wiersma. V.V. Arkadiev is thanked for age determination of Crimean ammonite samples. We would like to thank Bernhard Steinberger for providing the Eurasian and African TFW-corrected paths. We would like to thank Aral Okay, Rob van der Voo and two anonymous reviewers for their constructive comments. M.J.M.M. acknowledges The Netherlands Research Centre for Integrated Solid Earth Sciences (ISES) and The Netherlands Organization for Scientific Research (NWO) for financial support. D.J.v.H acknowledges financial support from Statoil (SPlates project). The global paleomagnetic database can be found at: http://www.ngu.no/geodynamics/gpmdb/.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.04.052.

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