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Mesozoic paleomagnetic data from North Dobrogea (Romania) and Crimea (Ukraine): Cimmerian deformation phases along the southern margin of the East European Platform

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Abstract

Paleomagnetic data for determination of paleolatitude were collected in the North Dobrogea Orogen (Romania) and on Crimea (Ukraine), to discriminate between scenarios on the Mesozoic geodynamic evolution of those areas, which are situated at the southern margin of the East European Platform. To correct for the inclination error in sedimentary rocks, we aimed at taking a large sample set for a new statistical model [1]. In North Dobrogea, Middle-Late Triassic sections were sampled. Results indicate an unrealistic paleolatitudinal position, which is too far north (~60°N) from what can be expected. Probably, this is caused by a component that could not be sufficiently removed. Similarly, in Triassic to Lower Jurassic rocks from Crimean sections, an unresolved component remained in the samples at higher demagnetisation steps. On the contrary, Late Jurassic (Early Kimmeridgian-Tithonian) Crimean data give very good, but rather unexpected results. They indicate a position of Crimea at near-equatorial latitudes (3.7°N) at that time. Those data support a recently published scenario [2], wherein Eurasia and Africa underwent a large southward drift and clockwise rotation in Middle-Late Jurassic times, causing Crimea to move to low latitudes.

1. Introduction

The southern margin of the East European Platform (EEP), and especially the area surrounding the Black Sea consisting of the North Dobrogea Orogen (NDO), Crimea and the Greater Caucasus (GC) is characterized by a long history of deformation caused by the closure and opening of the Tethys oceans from Devonian (~400 Ma) to Neogene times (Fig 1). The area is therefore very suitable to study the behaviour of large-scale lithospheric faults. The behaviour of those faults can be described by two contrasting scenarios. One scenario considers the continuous accretion of continental terranes to the southern margin of Eurasia, accompanied by the opening and closure of back-arc basins and marginal seas and/or wider oceans, with the successive southward jumping of subduction zones e.g. [3] (Model 3 in Fig. 2). The other scenario considers the repeated opening and closure of back-arc basins behind a long-lived subduction zone, with partial or total inversion of the sedimentary basins e.g. [4, 5] (Model 1 in Fig. 2). These two scenarios have large, but very different implications for the behaviour of suture zones and inverted basins over a long period of time. In the former, suture zones are considered to be stable through time whereas in the latter they are unstable zones of lithospheric weakness.

Many different scenarios for the Mesozoic geodynamic reconstruction of the North Dobrogea Orogen, Crimea and Greater Caucasus have been proposed in literature [6]. North Dobrogea, Crimea and the Greater Caucasus are assumed to be part of the thinned margin of the East European Platform (EEP): the Scythian Platform (Fig. 1). Deformation is caused by subduction of the Tethys oceans and by the accompanied collision of the Cimmerian terranes [7], comprising parts of Turkey, Iran and South Tibet, and of Africa with the Eurasian margin (Fig. 3). It is of great interest here to note that the many (oceanic) back-arc basins and/or intra-continental rifts that formed along the Eurasian margin could have transported the North Dobrogea-Crimea-Greater Caucasus deformed corridor far southward with respect to the Eurasian margin. Therefore, knowledge of the paleolatitudinal positions of the different blocks and plates through time is a crucial prerequisite to discriminate between different scenarios and hypotheses. Published paleomagnetic data from these areas, however, appear to be sparse.

The aim of this study, therefore, is to obtain new Mesozoic paleomagnetic data from Crimea and North Dobrogea. Firstly, the obtained data are compared to the established apparent polar wander paths (APWPs) of the Eurasian and African continents to provide results that may allow us to distinguish between conflicting geodynamic scenarios. Secondly, our approach was aimed at correcting for the well-known inclination error in sediments that results in the determination of too low latitudes. The inclination error is mainly caused by compaction due to burial. We used the newly developed statistical field model of [1] to correct the inclination error of the paleomagnetic data, which earlier proved successful (e.g. [8, 9]) in an improved estimate of paleolatitude. Since use of this model requires a large dataset (n > 100) to be statistically significant, we have performed a dense sampling of the sections.

2. Mesozoic history

The Paleo-Tethys ocean separated Eurasia and Africa until late Paleozoic times, when the Cimmerian terranes, assumed to include parts of Turkey, Iran and Tibet (Fig. 3), drifted away from the African margin, and the Paleo-Tethys started to close. The rifting between the Cimmerian terranes and Africa in Late Paleozoic times accounted for the opening of the Neo-Tethys ocean [5]. There are different models on the development of Neo-Tethys. Some authors consider the opening of a distinctive Northern and Southern Neo-Tethys, separated by relatively small continental fragments [5, 6]. Others consider the opening of a single Neo-Tethys, separated from the Paleo-Tethys by a strip of Cimmerian terranes [3]. The Paleo-Tethys fully subducted by Late Triassic to Early Jurassic [4] (Fig. 2). The polarity of subduction of Paleo-Tethys however, is still a matter of debate [6], as well as which continental fragments are part of the Cimmerian terranes. The subsequent closure of Neo-Tethys underneath Eurasia, initiating in Cenozoic times, finally resulted in the collision of the African continental margin with the Eurasian margin.

The deformational phases in the North Dobrogea-Crimea-Greater Caucasus corridor from Late Paleozoic to Late Mesozoic times were dominated by successive collisions of Gondwana derived Cimmerian terranes to the Eurasian margin [10, 11]. The subsequent cycles of collision, formation of back-arc basins or intra-continental rifts and inversion of the basins, enables us to mark three distinct Cimmerian deformational events: the ***Eo-, Mid-, and Neo-Cimmerian inversion*** (Fig. 4) [4].

In general, North Dobrogea, Crimea and the Greater Caucasus were suffering extension from Early to Middle Triassic times, probably in a back-arc extensional setting north of the subducting Paleo-Tethys [3]. Mid-oceanic ridge basalts (MORB) were extruded in North Dobrogea, but the extrusional setting is a matter of debate. Even a small oceanic basin might have opened, implying formation and subduction of an oceanic plate [12]. The margin of the East European Platform (EEP) was separated from the (Eurasia derived) Pontides and the Transcaucasus by the oceanic Küre basin (Fig. 3) [3]. In the Greater Caucasus, a compressive event has been reported in Late Triassic times: the ***Eo-Cimmerian*** event, causing inversion of Permo-Triassic basins [10]. In Crimea and North Dobrogea, evidence for the Eo-Cimmerian event is less well documented. The Eo-Cimmerian event results from the collision of the Cimmerian terranes with the Eurasian margin, with Iran (Elborz) at the collisional front [4]. The collision causes the closure of the Küre-South Crimean basin and the accretion of the Pontides and Transcaucasus to the EEP [4]. The Eo-Cimmerian compressional event is followed by extension, possibly caused by back-arc spreading behind the northwards subducting Neo-Tethys [4].

From Early to Middle Jurassic times another compressional pulse is recorded: the ***Mid-Cimmerian*** orogeny. In the Greater Caucasus, this is inferred from an unconformity between Middle and Upper Jurassic strata at the northern margin of the basins. In the deepest part of the basins, the sedimentation is continuous, which suggests the possibility that the characteristics of the strata are not caused by inversion, but are caused by post-rift subsidence of the basin [13]. The Mid-Cimmerian orogeny caused the intense folding of the Triassic to Early Jurassic Tauric - flysch like- series on Crimea [11]. The Mid-Cimmerian orogenic belt prolonged westwards into the NDO where Middle Jurassic flysch-like deposits documented the inversion of the basins [12]. The timing of initiation and termination of Mid-Cimmerian inversion is a matter of debate and has large implications for the explanation of calk-alkaline magmatism that occurred in the Greater Caucasus and Crimea in Bajocian times (early Middle Jurassic). Difference in timing of the Mid-Cimmerian inversion implies that in one explanation the calk-alkaline signature of volcanics was caused by subduction-related arc volcanism [4, 5]. Nikishin et al. and Sengor [4, 5] propose the presence of a subduction zone along the Greater Caucasus. Indications for the formation and subduction of an oceanic basin in the Greater Caucasus, however, like remnants of an accretionary prism, high pressure (HP) metamorphism or ophiolitic fragments are practically absent [10]. According to [4] the Mid-Cimmerian orogeny was followed by a new rifting cycle. Following a second explanation, the Bajocian calk-alkaline volcanics could alternatively have been extruded in a back-arc extensional setting just after Mid-Cimmerian inversion [10]. The timing of metasomatism of the calk-alkaline signature of the volcanics has never been analysed and has possibly been caused by a much earlier event [10, 11]. Indeed, knowledge of paleolatitudinal positions of the Greater Caucasus and Crimea is an important prerequisite here and will help to solve the existing controversies. Comparing paleomagnetic data to Eurasian paleolatitudes might enable us to determine whether an oceanic basin accounted for the southward drift of Crimea and/or the Greater Caucasus with respect to the Eurasian margin.

The back-arc setting of the North Dobrogea-Crimea-Greater Caucasus deformed corridor in Mid-Jurassic finally ended in an inversion in Late Jurassic-Early Cretaceous times, the ***Neo-Cimmerian*** inversion. This inversion was reported in Crimea and North Dobrogea. In the Greater Caucasus, this compressional event is sparsely documented [10, 14, 15]. The Greater Caucasus probably experienced extension until Tertiary times, when basins were inverted.

As a result of ongoing convergence between Eurasia and Africa, the Black Sea back-arc basins were opened from Middle-Late Cretaceous times onwards, which significantly complicates reconstructing the Mesozoic setting in the area [4]. Many of the Mesozoic strata are covered by the Black Sea or, on land, by younger strata. The absence of the Black Sea before Middle-Late Cretaceous also implies the attachment of the Pontides in North Turkey to the North Dobrogea-Crimea-Greater Caucasus deformed corridor belt before opening of the basin. This implies that comparison of data from the North Dobrogea-Crimea-Greater Caucasus deformed corridor to published results from the Turkish Pontides will be valuable.

3. Regional geology

The wedge-shaped ***North Dobrogea Orogen*** (Fig. 5) is a Cimmerian orogenic belt that is located between the Moesian plate and the southern margin of Eurasia [12]. To the north it is bounded by the Sfantu Gheorghe Fault (SGF), which is probably the continuation of the Tornquist-Tesseire line that is marked by the Danube river. The Tornquist-Tesseire line is the boundary between the Phanerozoic West- and Middle-European crust and the Precambrian EEP [16]. The Peceneaga-Camena Fault (PCF) separates the North Dobrogea Orogen at its southern boundary from Moesia. Its eastern margin is delimited by the Black Sea.

The pre-Mesozoic basement rocks are mainly exposed in the western part of the orogen: the Macin nappe. This part is substantially uplifted with respect to the eastern parts: the Niculiţel and Tulcea nappes. Preceding Eo-Cimmerian inversion, MORB-basalts of the Niculitel formation were extruded in Middle Triassic (Fig. 4). Those basalts of the Niculitel formation are intercalated with Anisian and Ladinian (Middle Triassic) carbonate deposits. Extrusion of those basalts might be caused by an intracontinental rift, but the hypothesis that in Middle Triassic times a (small) oceanic basin was developed and closed cannot be rejected [12]. As mentioned in the introduction, there is little evidence for an Eo-Cimmerian pulse in North Dobrogea. The evidence is based on the onset of synorogenic siliciclastic turbidites from the late Carnian Alba formation in the Niculitel nappe and a slight unconformity between Triassic and Jurassic strata. The Alba formation overlays the Anisian and Ladinian carbonates and changes laterally into marly basinal facies: the Cataloi formation. Even more to the southeast these facies change into Carnian and Norian platform carbonates [12]. An extensional phase in the Early Jurassic is not recorded in NDO. Therefore, Seghedi [12] considers the Eo- and Mid-Cimmerian events as one continuous event. The Middle Jurassic Mid-Cimmerian event is recorded in flysch-like deposits. In Oxfordian-Kimmeridgian times (Late Jurassic) the inversion of the basins was temporarily interceded when carbonates were deposited in the remnant basins. Kimmeridgian basalt flows were probably extruded along the PCF. The following inversion, the Neo-Cimmerian event, has been recorded from Berriasian to Aptian (Early Cretaceous). Late Jurassic carbonate platforms were destroyed and North Dobrogea derived sediments were transported and deposited on the South Dobrogea Platform and in the Black Sea area [12, 17].

The ***Crimean*** (Fig. 6) peninsula is located in southern Ukraine, along the northern margin of the Black Sea coast. It is part of the thinned margin of the EEP: the Scythian Platform. The Paleozoic basement of Crimea is almost completely covered with Mesozoic-Cenozoic sediments. The pre-Mesozoic history of Crimea is not very well known because of bad age constraints, the limited amount of lithological data (that are only inferred from boreholes) and the severe overprint that was the result of Mesozoic orogenic activity [4].

In Triassic to Early Jurassic times, a thick Tauric flysch-like series was deposited in an extensional setting [4] (Fig. 4). Those deposits are an alternation of shales and turbidites. The lateral equivalent of this unit can be found in the Küre unit in the Turkish Central Pontides. Extension probably developed in a back-arc setting that was caused by the subduction of Paleo-Tethys [3]. The Eo-Cimmerian event in Late Triassic times is sparsely recorded on Crimea. It is recorded in a slight unconformity between Triassic and Jurassic strata that is sometimes absent [13]. The extensional Triassic-Early Jurassic period was followed by the Mid-Cimmerian inversion in Hettangian times, resulting in the intense folding of the Tauric series [4]. A Sinemurian to Toarcian (Lower Jurassic) deep-water basin unit with clastic turbidites, shallow-water conglomerates and some volcanics unconformably overlies the Tauric succession. The Aalenian to Early Bajocian (Middle Jurassic) units are mostly sandy. The Late Bajocian to Callovian comprises a volcanic complex, with shallow to deep-water volcanoclastics and Bathonian shales and siltstones. These are covered by late Callovian red beds, that change gradually into Upper Jurassic platform carbonates [11]. According to Nikishin et al. [4], the first signs of Mid-Cimmerian inversion are not Hettangian but late Aalenian in age. According to Saintot et al. [10] the Bajocian calk-alkaline magmas have been extruded in a back-arc extensional setting after the end of the Mid-Cimmerian compressional event. Nikishin et al. [4] date the end of inversion, and thus initiation of an extensional phase as Callovian. The ambiguous explanation of the tectonic setting during extrusion of the calk-alkaline, mainly Bajocian volcanics, has been described in the previous sections. The shallow marine carbonate platform that developed in west Crimea during extension in Middle-Late Jurassic, laterally changes into relative deep water conglomerates and flysches, indicating a possible deepening of the basin eastwards. The Neo-Cimmerian inversion in Berriasian times caused deformation of these Upper Jurassic sequences [4].

4. Sections and sampling

The sections that were sampled in ***North Dobrogea*** are both located in the Triassic part of the Tulcea nappe. The ***Agighiol section*** is situated in Anisian to Carnian limestones of the Niculitel formation. The age has been determined on the basis of ammonoids [18]. The Anisian to Carnian limestones [18] of the Agighiol section were sampled in a continuous section of 123 meters in stratigraphic thickness. The lower part of the section contains post-depositional reddish fluid-flow patterns. In total, 160 cores were drilled regularly spaced throughout the section.

The Dobrogean ***Dunavaţ section*** is Anisian to lower Ladinian in age [18]. It consists of shallow water limestones that are probably partly recrystallized. Parts of the strata are tidal flat deposits that sometimes contain algae and cyanobacteria. The younger part of the section contains more mud, indicating that the basin became deeper through time. The section near the village of Dunavaţ is also situated in the Niculitel formation and is Anisian to Lower Ladinian in age. The ages were determined on the basis of calcareous algae [18]. The section covers ~100 meters in stratigraphic thickness and was sampled regularly spaced throughout the section. In total, 218 cores were drilled.

One of the sampled sections in ***Crimea*** is situated in the Triassic-Early Jurassic Tauric series. The exact age of this ***Tauric section*** is very poorly determined [19]. The Tauric section is situated in the Bodrak river and covers part of the Triassic to Lower Jurassic Tauric series. The stratigraphic thickness of the section is 21 meters. In total, 211 samples were drilled regularly spaced through the section. Half of the samples were drilled in turbiditic, sandy layers and half of the samples were drilled in shaly layers.

The Crimean ***Ai Petri Plateau section*** is located in the Upper Jurassic platform carbonates. The age of the strata is Upper Jurassic, and recently they were dated palynologically as Early Kimmeridgian to Tithonian in age (S. Vincent, pers. comm.). The Upper Jurassic strata of the Ai Petri Plateau were sampled near the city of Yalta. The sampled section has a thickness of 6 meters. This thickness and the number of samples (N=97) are large enough to filter out secular variation and to determine paleolatitude and enable correction for the inclination error.

5. Paleomagnetic results

The natural remanent magnetisation (NRM) was measured on a horizontal 2G Enterprises DC SQUID cryogenic magnetometer (noise level 3×10^{-12} Am^2). All samples were demagnetised with stepwise alternating field (AF) and/or thermal demagnetisation, with a minimum of 9 steps and a maximum of 17 steps. Typically, small temperature steps were used (20-30°C). AF steps ranged from 2.5 mT to a maximum of 100 mT in the last step. Examples of characteristic demagnetisation diagrams of the NRM are plotted in orthogonal vector diagrams [20]. Principal component analysis was carried out [21] to determine the characteristic remanent magnetization (ChRM). Samples with a maximum angular deviation (mad) exceeding 15° were rejected from determination of mean Fisherian [22] ChRM directions, as well as samples that exceeded the maximum cut-off angle determined with the Vandamme method [23], which was carried out before and after tectonic correction separately. Inclination error correction with the statistical method developed by [1] was only carried out on the Crimean Ai Petri Plateau section, because of the large number of successful samples that is required.

From the ***Agighiol section*** 52 samples were measured for determination of the natural remanent magnetization (NRM). Samples were demagnetised by alternating field (AF) (N=42) and thermally (N=10). One sample had an anomalously high intensity and was probably struck by lightning and therefore excluded. Intensities of the samples ranged from ~10-150 mA/m at 100°C. A viscous component was removed from 20°C to 100°C. Samples were thermally demagnetised to a maximum temperature of ~480°. AF demagnetisation was carried out (after thermal demagnetisation to 150°C) to ~100-300 mT. Characteristic examples of the NRM are shown in Appendix 1. A low temperature (LT)/low coercive force (LC) component that is statistically indistinguishable (Fig. 7) from the present day field was observed, mostly in the AF demagnetised samples (n=22) (Table 1). This component was fully removed at 40 mT. We determined the ChRM at higher temperatures and coercivity ranges at 4 or more successive temperature steps, to a maximum of 480°C) or ~100-300 mT. The maximum angular deviation determined from principal component analysis was in 96% of the samples smaller than 7°. Only 2 samples were rejected (mad > 15°). Nine samples exceeded the Vandamme cut-off angle before tilt correction and 8 samples exceeded the Vandamme cut-off angle after tilt correction, and were also rejected.

A final set of 40 samples fit the criteria to calculate the mean ChRM directions. Before bedding tilt correction the mean direction is D=13.4°, I=57.8°, with a distribution that is uncomfortably close to the direction of the geo-axial dipole (GAD) field in Dobrogea (Fig. 7). After bedding tilt correction the mean direction is D=79.6°, I=73.1° (Table 1; Fig. 7), which would imply a high paleolatitude. The α_{95} and k-values before and after tilt correction direction vary as a result of changing bedding orientation throughout the section, but the bedding orientation does not vary enough for a fold test. The paleolatitude calculated from the inclination after tilt correction is 54.8°<58.7°N<65.6°.

From the ***Dunavaţ section*** 52 samples were demagnetised for determination of the NRM; 42 samples were demagnetised with AF and 10 thermally. Intensities were ranging from ~0.3-9.0 mA/m at 90°C, after the removal of a viscous component from 20°C to 90°C. Samples were thermally demagnetised up to 300°C or 400°C. AF demagnetised samples were first thermally demagnetised to 150°C and then AF demagnetised to 60mT or in exceptional cases to 110 mT (Appendix 1). A first, low coercive force (up to 15-30 mT) component that is close to the GAD field in Dobrogea (I=63.5) was present in 6 samples that were demagnetised with AF. A high temperature (HT)/high coercive force (HC) component at 4 or more temperature or AF steps was used to determine the ChRM at higher temperatures and coercivity ranges, to a maximum of 390°C or ~110 mT. Seven samples exceeded the allowed mad of 15° and were therefore rejected. Another 7 ChRM directions were rejected (before and after tilt correction), because of exceeding the Vandamme cut-off angle. The mad in 71% of the samples is less than 10°.

The set of 38 samples that fit the criteria for calculation of the mean ChRM direction, give the direction D=357.2, I=57.3, before bedding tilt correction. The distribution is again uncomfortably close to the GAD field in Dobrogea (Fig. 7), but statistically distinguishable from it. After correction for bedding orientation the mean direction becomes D=14.7, I=75.5, again implying a high paleolatitude (Table 1; Fig. 7). The paleolatitude inferred from the direction with bedding tilt correction is 57.5°<62.7°N<68.2°.

In total, 71 samples from the ***Tauric section*** were demagnetised. Starting intensities range between ~1-15 mA/m in the sands (20°C) and between ~0.5 to several mA/m (20°C) in the shales. Samples were thermally and alternating field (AF) demagnetised, as well as mixed thermally and AF demagnetised. A first batch of the samples was thermally demagnetised to a maximum of 260°C; at higher temperatures the NRM showed erratic behaviour. Therefore, a second batch was first thermally demagnetised to 260°C and afterwards with alternating field to a maximum of 60 mT. A third batch was stepwise thermally heated to 140°C and afterwards demagnetised with alternating field to a maximum of 60 mT. Characteristic examples of AF demagnetisation of the NRM are shown in Appendix 2. A viscous component was fully removed after heating to 90°C. Only one directional component was observed up to 260°C in the orthogonal vector diagrams. There is a component at higher temperatures that cannot be resolved, but that clearly tends to go to reversed polarity. The ChRM was determined using 4 or more successive temperature or AF steps. Out of 71 measured samples, 14 samples exceeded the maximum allowed mad of 15°. There is no clear distinction in direction between the turbiditic and sandy layers, although directions in the sandy beds seem to cluster more.

A mean direction was calculated on the basis of 52 samples. The calculated direction before tilt correction is D=33.5°, I=61.1°, with a distribution that is uncomfortably close to the GAD field in Crimea (Table 1; Fig.8). Importantly, the orientation of the fold axis of the isoclinal folds was not determined, meaning that only the inclination after bedding tilt correction could be determined. We concluded that the GAD field mainly determines this direction, as the directional component at higher temperatures could not be determined, and therefore this direction was not calculated.

All drilled samples of the ***Ai Petri Plateau section*** (N=97) were demagnetised. Intensities at 90°C are several mA/m. Samples were thermally demagnetised to a maximum of 360° (Appendix 2). In total, 91 samples show clearly a low temperature component that persists up to 210°C with a direction that is similar to the GAD field direction in Crimea (I=62.9) (Fig. 8; Table 1). The NRM was determined at temperatures of 210°C or higher at 4 or more temperature steps. The ChRM has a very low inclination and shows a small counter clockwise rotation. Of all samples, 87% has a mad lower than 5°, and 94% of the samples have a mad lower than 7%; only 4 ChRM directions were rejected that exceeded the Vandamme cut-off angle.

The remaining 93 samples fit the criteria to calculate a mean direction. Before tilt correction, the direction is: D=351.8°, I=21.8° (Fig 8; Table 1). After tilt correction, the direction is: D=354.5°, I=7.3°. The inferred paleolatitude, calculated from the inclination after bedding tilt is: 2.7°<3.7°N<4.6°.

The high number of samples allowed correction for the inclination error, using the TK03.GAD model of [1]. The correction is almost negligible, and inclination changes from 7.3° to 6.0°<7.8°N<10° (Fig. 9). The uncorrected value thus falls within the uncertainty range of the corrected value.

6. Discussion

Triassic North Dobrogea

In Fig. 10 (a) the position of North Dobrogea is indicated in an age versus latitude plot. This age vs. latitude plot indicates the position of North Dobrogea through time using APWPs of Europe [24] [25]. Comparing our data to these APWPs, we can infer that the paleolatitude (~60°N) for the Agighiol and Dunavat sections is much farther north than what would be expected, from any geodynamic scenario. We must therefore conclude that we have not been sufficiently able to isolate a reliable primary component.

The Triassic Deslicaira section, part of the Agighiol formation, has been studied by Gallet et al. (pers. comm.). The determined paleolatitude from this section is also higher than expected for this region, although significantly lower (~33°N) than in our study. Gallet et al. (pers. comm.) deduced both normal and reversed polarities from their samples, whereas we found only normal polarities. The Deslicaira section has been proposed by M. Orchard as a golden spike (Global Boundary Stratotype Sections and Points (GSSP)) for the Lower-Middle Triassic boundary [26], but a good biostratigraphic zonation on the basis of ammonoids was never obtained here (Gallet et al. pers. comm.). Galbrun et al. [27] also sampled the section Agighiol. They did find reversed polarity intervals with shallow inclination, again in contrast with the data presented here, but also their normal data show very steep inclinations. The normal and reversed polarities of Galbrun et al. [27] are not antipodal and clearly fail a reversal test. The section they sampled was located only a few hundreds of meters from the Agighiol section in our study. The discrepancy between Galbrun et al.'s study [27] and our study might be attributed to the fact that our samples did not endure temperatures higher than 360°C in the Dunavat section and 480°C in the Agighiol section; we found erratic behaviour above these temperatures. The samples that were AF demagnetised could not be completely demagnetised, even in a strong field (300 mT). This is likely caused by the presence of hematite in the samples, which is also suggested by the reddish colour of the sediments. No rock magnetic properties have yet been determined to verify this. The large difference in rotation between the Agighiol (D=79.0°) and Dunavaţ (D=14.7°) sections after tilt correction, both from the same age interval and the same tectonic and sedimentary unit, further indicates that the determined directions are unlikely to be primary.

Mesozoic Crimea

The samples of the Triassic-Lower Jurassic Tauric section clearly contain an unresolved component (Appendix 2), which might represent an unknown primary direction. In addition, the Tauric series are intensely folded, and therefore we suggest that the determined direction of the Triassic-Early Jurassic Tauric section is caused by an overprint.

The data for the Late Jurassic Ai Petri Plateau suggest a very low, equatorial position. The correction for inclination error of the Late Jurassic section is therefore negligible. Furthermore, the age versus latitude plot (Fig. 10 (b)), illustrating the variation of paleolatitude through time of Crimea [24, 25], shows that Late Jurassic Crimea is situated south of the Eurasian margin or in the vicinity of the African margin.

A position of Crimea so far south of the Eurasian margin in Late Jurassic times, or even at the African margin is rather controversial. It would not only imply a considerable detachment of Crimea and the southward adjacent Pontides from Eurasia, it also implies a difference in time and space for the position of the Cimmerian terranes. The Cimmerides are assumed to have been accreted to the Eurasian margin long before Late Jurassic times [3, 4]. Therefore, we compare our new data and published paleolatitudinal data from the Global Paleomagnetic Database (GPMDB) in age vs. latitude plots for Crimea, the Pontides and the remaining, southern part of Turkey, since it was mostly part of the Cimmerian terranes. The APWPs from Van der Voo and Torsvik, and Besse and Courtillot [24, 25] for Africa and Eurasia were used for the age versus latitude plots (Fig. 10). The only datasets in the GPMDB from Crimea that are accessible in literature are from Pechersky and Safonov [28]. Their results imply an indistinctive position of Crimea at latitudes between the Eurasian and African margins. Contrary to our study, however, the sites from the study by Pechersky and Safonov [28] contain only a few samples. In addition, AF and thermal demagnetisation was mostly carried out in only a few steps; directional analysis included the use of demagnetisation great circles. The age vs. latitude plot for the Pontides (Fig. 10 (c)) shows an ill-determined position of the Pontides through time. The age vs. latitude plot of southern Turkey (Fig. 10 (d)) shows that data between 0 and 60 Ma range between ~10° and 60° north. Well-determined Triassic results from [29-33] in the GPMDB suggest a position of continental fragments that are found today in southern Turkey, to have been close to the African margin in Triassic times. A striking feature is the absence of data in the GPMDB between 60 and 200 Ma for southern Turkey. From the GPMDB data, we cannot make any comparison between paleolatitudes of the Pontides and southern Turkey and the low, equatorial latitudes that were found in this study for the Late Jurassic Crimean limestones. An equatorial position of Late Jurassic Crimea can therefore not yet exclude or confirm one of the possible scenarios for the position of Crimea through time, with respect to Eurasia. The scattered paleomagnetic data of Turkey in combination with our data neither enable us to reject nor confirm any scenario.

An explanation for the unexpected southern position of Crimea is that the Eurasian and African continents were positioned further south in the Late Jurassic than is suggested by the APWPs. Jurassic poles for Europe as well as for Africa are poorly constrained [34, 35]. European Jurassic rocks (mainly limestones) often contain a low magnetic signal, and both African and Eurasian rocks are often remagnetised. Data that are used in APWPs from Besse and Courtillot [25] and also from Schettino and Scotese [36] do show some very low latitudes for Middle-Late Jurassic Europe and Africa, but rapid plate motions are underestimated in the established APWPs, caused by the usage of averaging procedures. Recently, however, Muttoni et al. [2] provided evidence for a very fast southward drift and large clockwise rotation of Eurasia and Africa in Jurassic times (Fig. 11) with culmination in the Late Jurassic. Muttoni et al.'s [2] results include formerly published data on radiolaritic cherts and new paleomagnetic data from radiolaritic cherts and pelagic limestones collected in the Lombardian basin, Italy. Deposition of radiolaritic cherts in between periods of deposition of pelagic limestones was formerly explained by deepening of a basin, causing the ocean floor to decrease below the carbonate compensation depth (CCD). Since modern oceans sediments below the CCD are not necessarily radiolaritic, another explanation was given by new paleomagnetic data. Those data suggest that Adria drifted towards, and subsequently away, from a near-equatorial upwelling zone of high biosiliceous productivity, causing sedimentation of radiolaritic cherts and subsequently pelagic limestones. A compilation of all presented data by [2] suggests the southward drift and clockwise rotation of Eurasia and Africa that accounts for the northward rotation of Western Europe and for the southward rotation of Eastern Europe. This fast plate motion of Eurasia and Africa is in excellent agreement with our new position for East-European Crimea at equatorial latitudes in Late Jurassic (Fig. 11).

7. Conclusions

The Triassic latitudinal position of the North Dobrogea Orogen inferred from the Agighiol (~60°N) and Dunavat (~62°N) sections is in both cases much higher than expected from APWPs [25]. Previous work done by Gallet et al. (pers. comm.) on comparable sections, resulted in the determination of shallower inclinations (~33°N). An explanation for the obtained high inclinations is that demagnetisation could not resolve the primary component, caused by erratic behaviour of thermally demagnetised samples above 360°C (Dunavat section) or 480°C (Agighiol section) as well by the probable presence of a high coercivity mineral (e.g. hematite) that is resistant to AF demagnetisation (max. 300 mT).

In the Triassic-Early Jurassic Tauric section, an unresolved component is left in the samples. The determined magnetic signal is close to the present day field in Crimea. The Late Jurassic (Early Kimmeridgian to Tithonian) Crimean Ai Petri Plateau section yielded very good paleomagnetic results that are consistent and robust. The inferred paleolatitude is much lower (equatorial northern hemisphere) than formerly expected for a position close to Eurasia. The Late Jurassic position of Crimea can be explained by two scenarios: (a) the position of Crimea was far south of the Eurasian margin. This implies that the position of the Pontides and the Cimmerian terranes must therefore also have been much further south; (b) the Eurasian and African continent were located at a much more southern position in Late Jurassic times. Scenario (a) can neither be confirmed nor rejected with presently known paleomagnetic data, as paleolatitudinal positions of the Pontides and the Cimmerides are very poorly determined, allowing widely different geodynamic scenarios for the region. Instead, scenario (b) from Muttoni et al. [2] is in excellent agreement with the Late Jurassic Crimean data from this study that support this scenario. Clearly, the averaging procedures used in construction of APWPs may strongly underestimate rapid plate motions.

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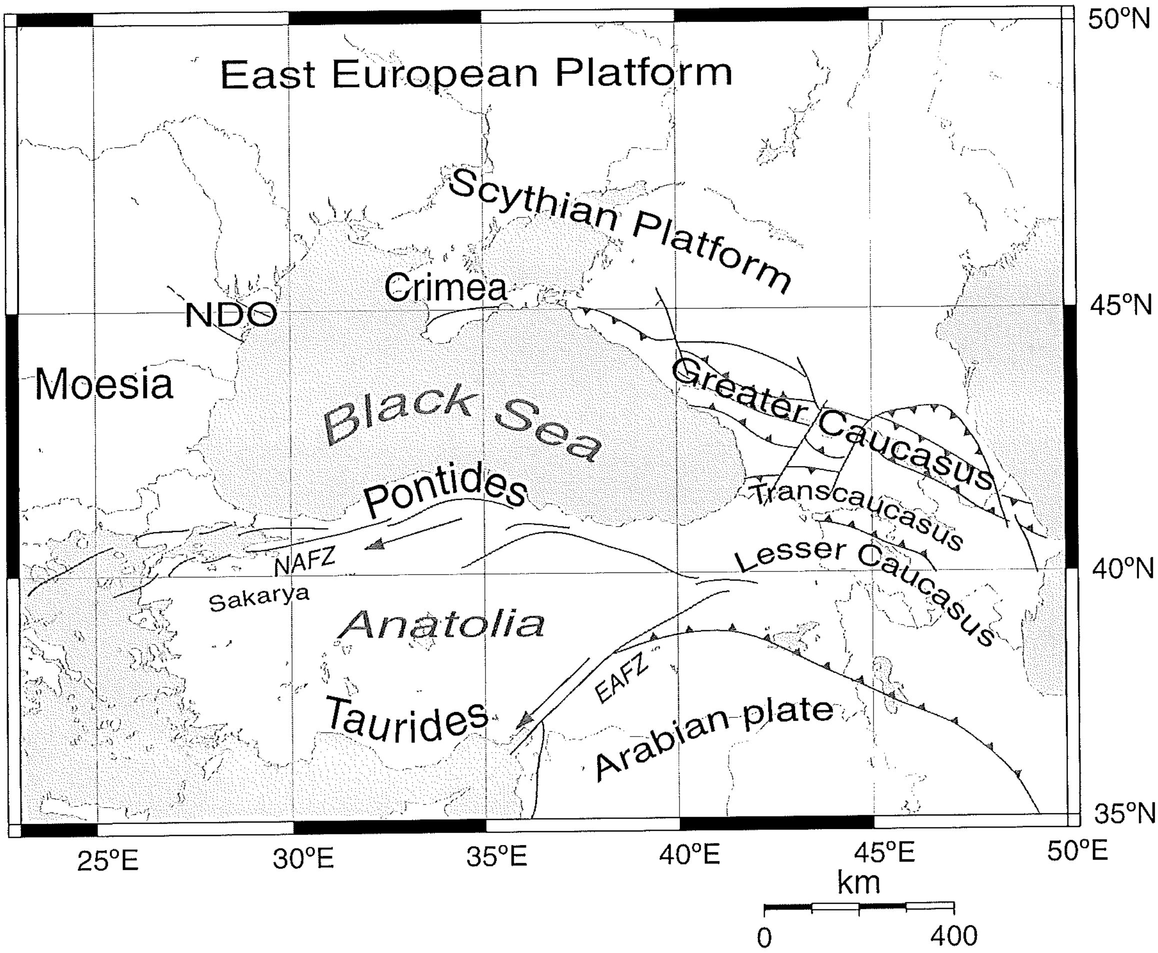


Fig. 1. Map of the study area with indication of the main faults, thrust zones and subduction zones. NDO: North Dobrogea Orogen, NAFZ: North Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone

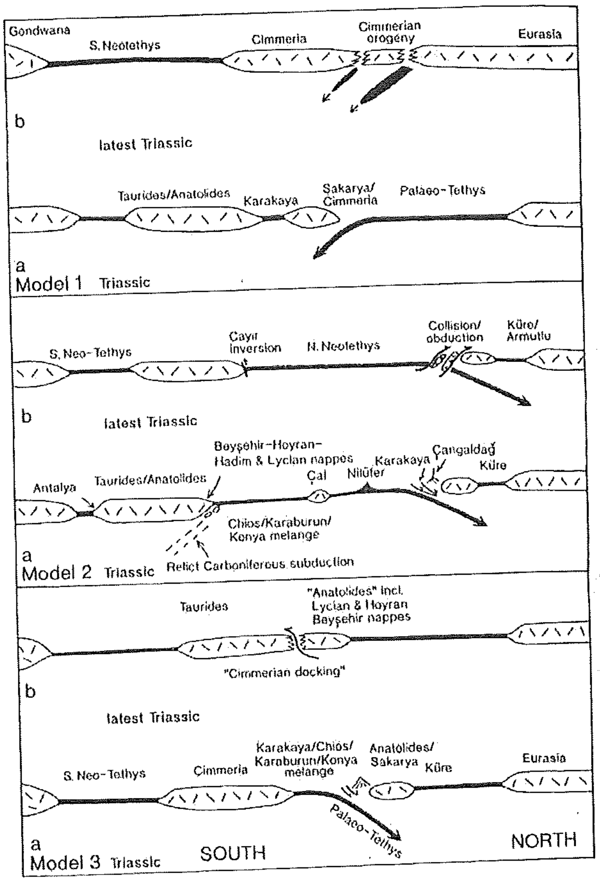


Fig. 2. After [6]. Alternative models for the Triassic tectonic setting of Western Turkey (a) Model 1 by [5], (b) Model 2 by [38], (c) Model 3 by [3] For explanation see text.

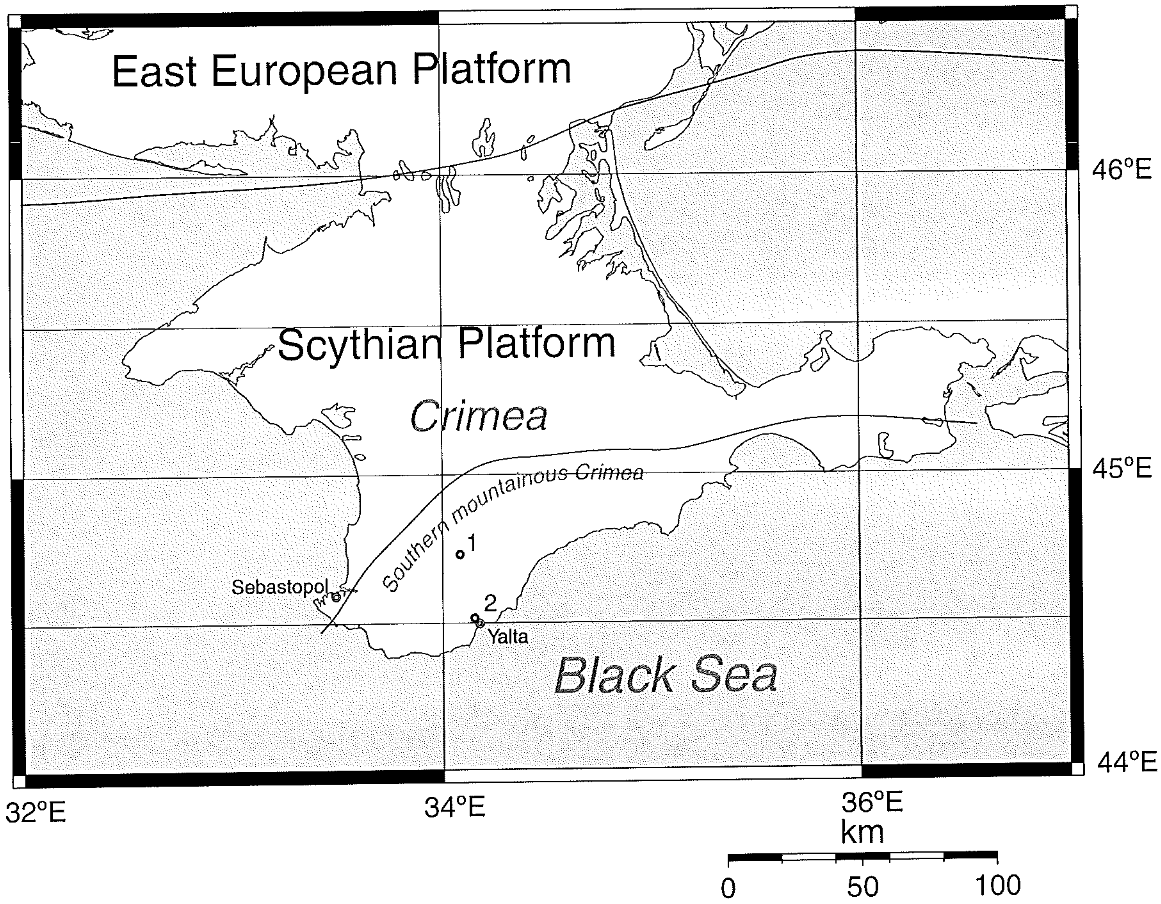


Fig. 6. Map of Crimea with indication of the main geological regions. Southern mountainous Crimea is mainly characterised by Mesozoic-Cenozoic thrusting and folding during the Alpine stage: the Crimean Belt. 1: Tauric section, 2: Ai Petri Plateau section

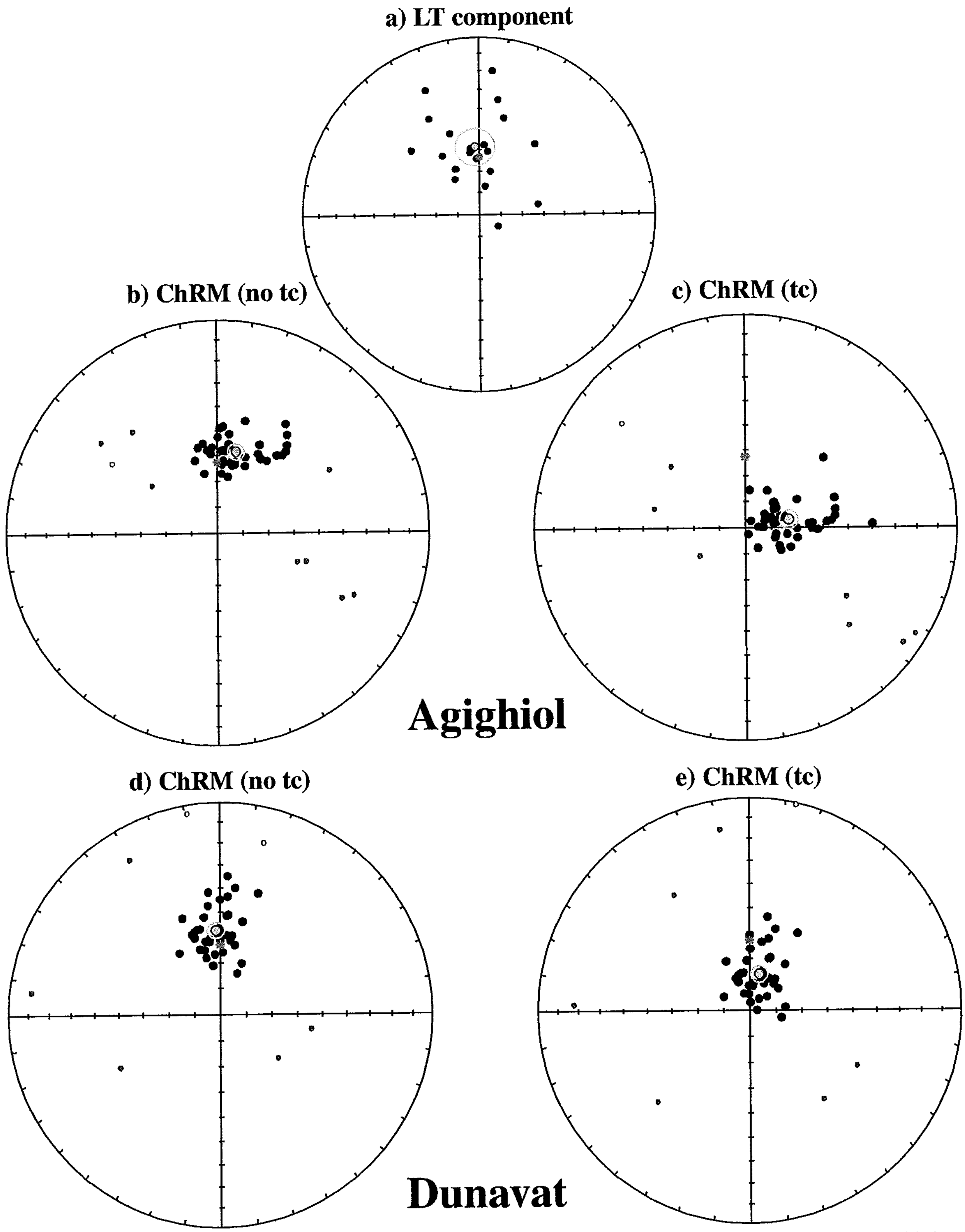


Fig. 7. Equal area plots of NRM components and their Fisherian mean for the Middle-Late Triassic Agighiol section (North Dobrogea) (a) low temperature component without tilt correction and (b) high temperature component without tilt correction, and (c) high temperature component with tilt correction. For the Middle-Late Triassic Dunavat section (North Dobrogea) (d) high temperature component without tilt correction and (e) high temperature component with tilt correction. Open (closed) symbols denote projections on upper (lower) hemisphere. Red asterix indicates GAD field at site locality. Blue circles denote a95, large blue symbols are mean directions. Small grey symbols were rejected after determination of the Vandamme cut-off angle.

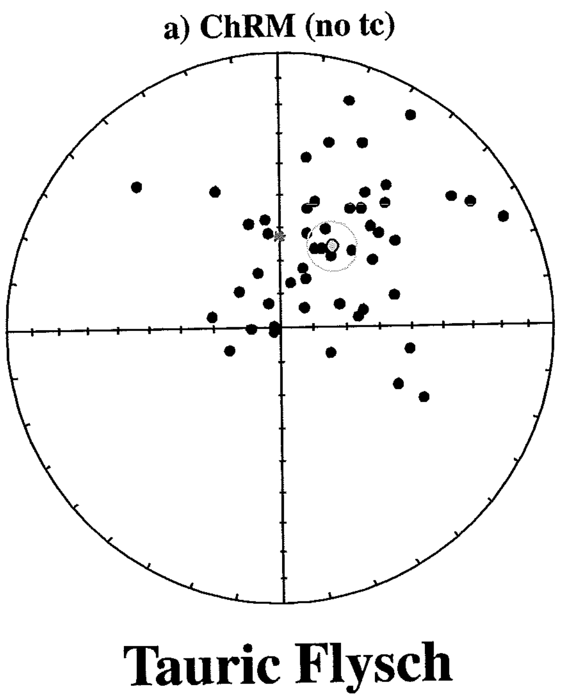
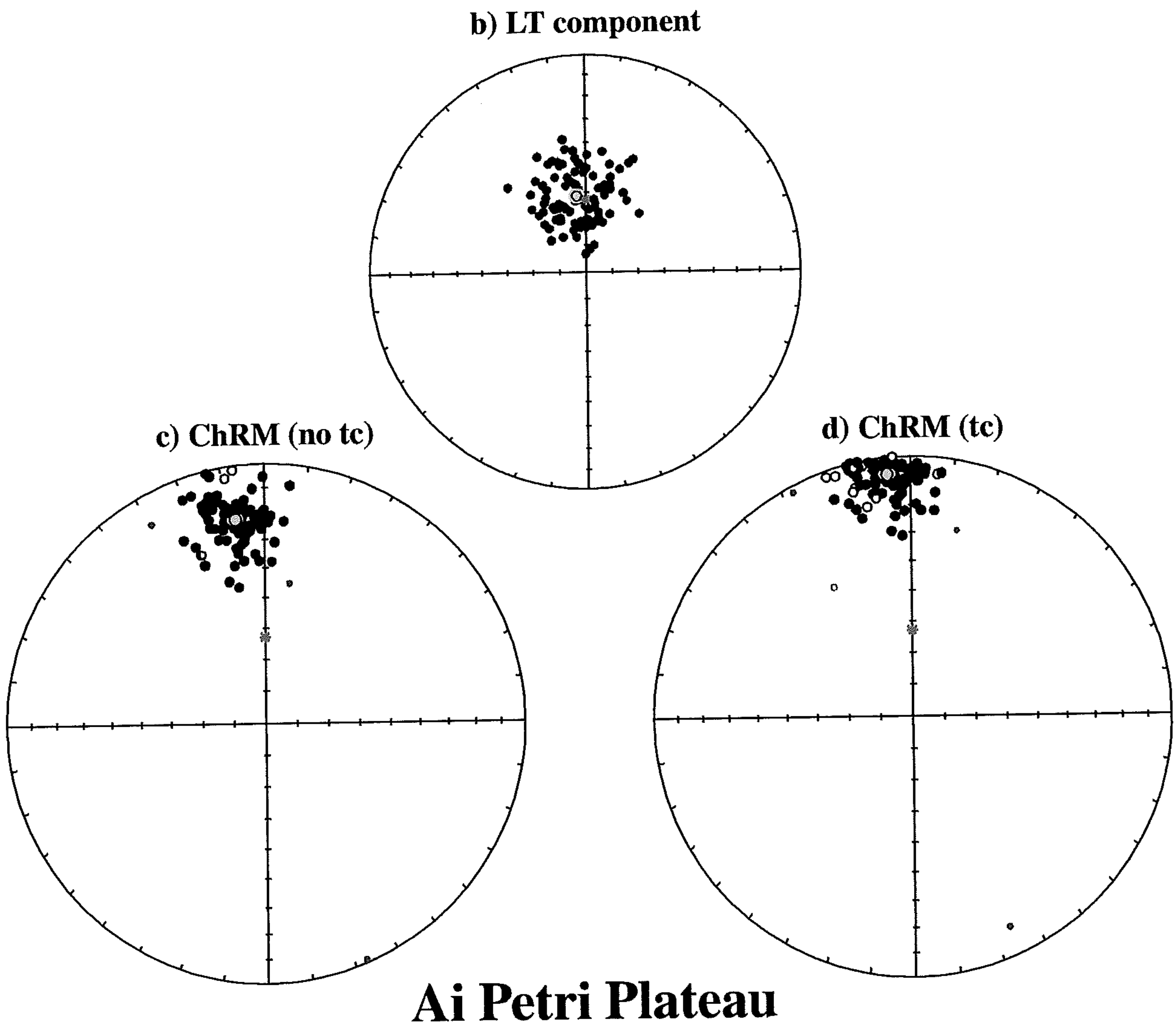


Fig. 8. Fisher equal area plots. Triassic-Lower Jurassic Tauric section (Crimea) (a) without tilt correction. Late Jurassic limestones of the Ai Petri Plateau section (Crimea), (b) the low temperature component without tilt correction (c) high temperature component without tilt correction, (d) high temperature component with tilt correction. Open (closed) symbols denote projections on upper (lower) hemisphere. Red asterix indicates GAD field at site locality. Blue circles denote a95, large blue symbols are mean directions. Small grey symbols were rejected after determination of the Vandamme cut-off angle.



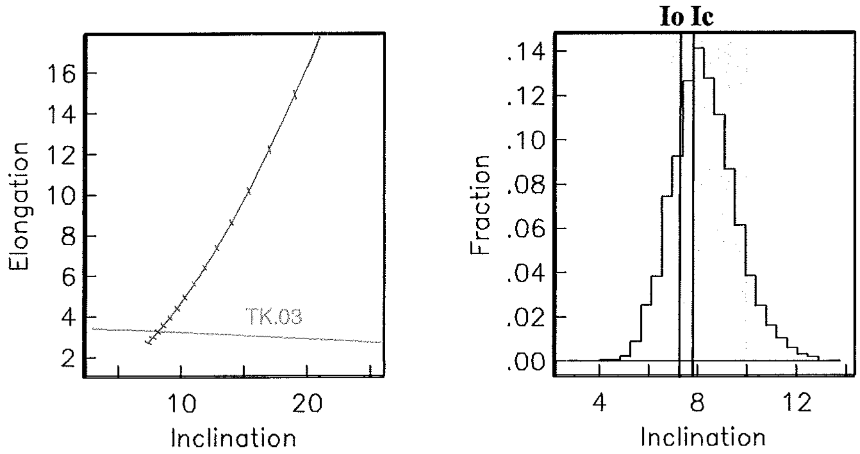


Fig. 9. Correction of inclination error using the method developed by [1]. On the left diagram, the barbed line shows variation of the elongation of the dataset distribution with respect to mean inclination when affected by a flattening factor ranging from 0.3 to 1.0; yellow curves are the same for generated datasets from bootstrap analysis. The corrected inclination is given by the intersection with the green curve (expected elongation from geomagnetic model of [1]). Right diagram indicates distribution of corrected inclinations with 95% confidence interval (grey area); Io is the mean observed inclination, Ic the mean corrected inclination.

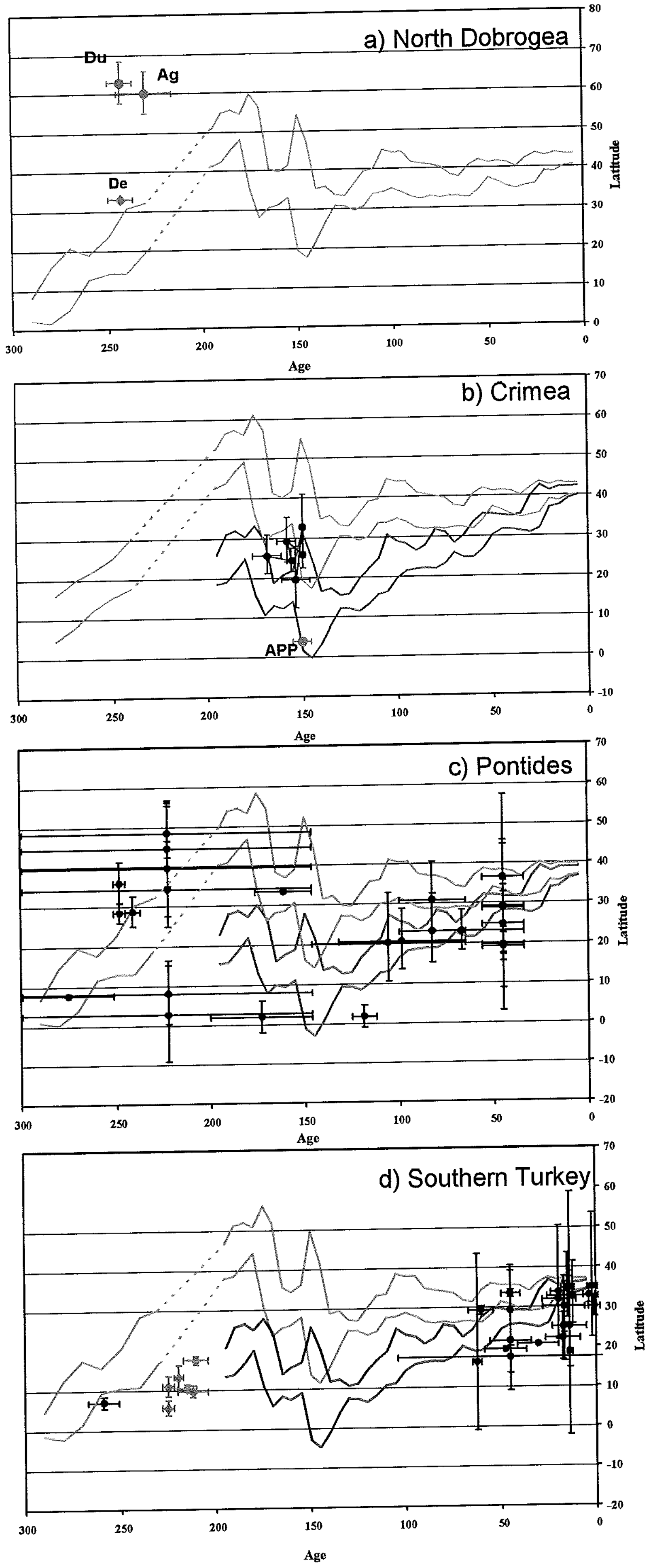


Fig. 10. Age versus latitude plots with APWPs from Besse and Courtillot (2002) (0-200 Ma) and Van der Voo and Torsvik (2004) (230-290 Ma), calculated with three-point moving averages. (a) North Dobrogea, (b) Crimea, (c) Turkish Pontides, (d) Southern Turkey. Blue lines show envelope of paleolatitude when assuming that the area was attached to Eurasia, brown lines for Africa. (a) In red: paleolatitude of Agighiol section (Ag) and Dunavat section (Du); in green: paleolatitude of Deslicaira section (De) (Gallet et al., pers. comm.). (b) In red: paleolatitude of Ai Petri Plateau section (APP); in black: paleolatitudinal data from the GPMDB of [28]. (c) & (d) In black: data from the GPMDB. (d) In green: data from [29-33]. Vertical error bars show 95% confidence limits, horizontal error bars show age uncertainty.

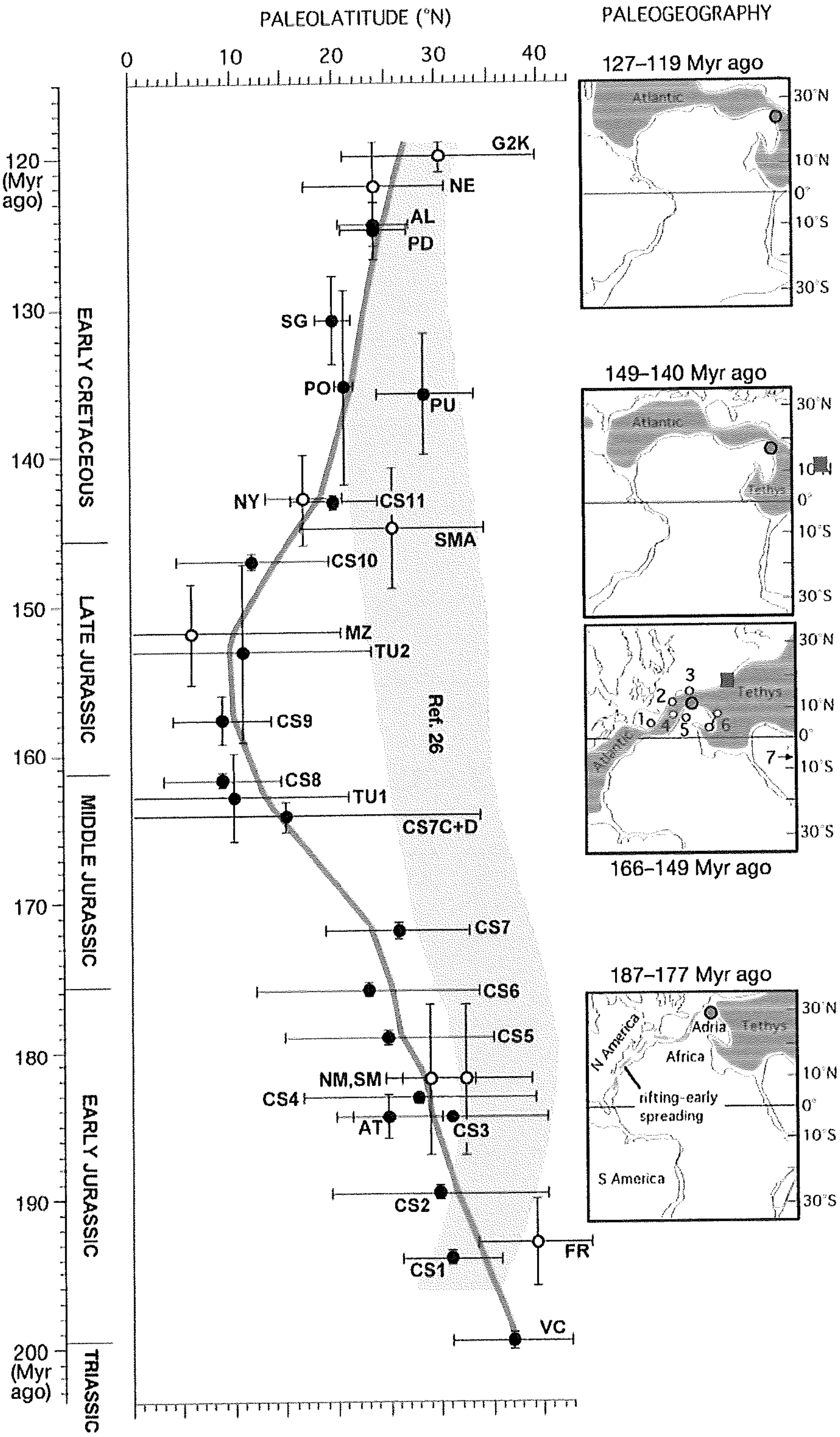
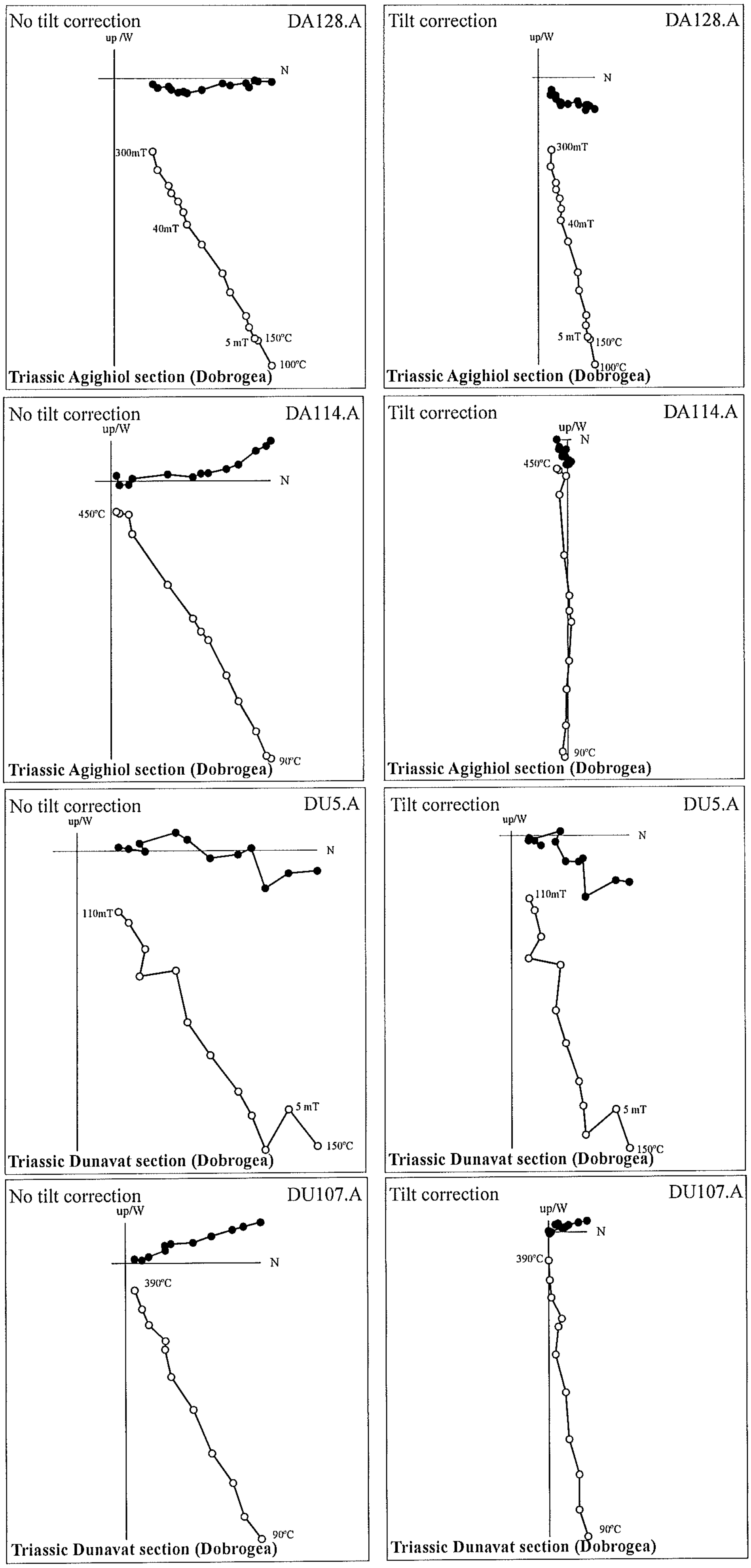


Fig. 11. After [2]. Left panel: Constructed latitude versus age curve for Adria in red from [2]. In yellow: Latitude versus age curve constructed for Adria from APWPs of [25]. Right panel: position of Europe and Africa in Jurassic-Early Cretaceous times. Red circle: position of Adria; red square: position of Crimea

		High temperature/ High coercive force component										Palolatitude
		n/N samples	Dec (°)	Inc (°) before tilt correction	a95 (°)	k	n/N samples	Dec (°)	Inc (°) after tilt correction	a95 (°)	k	(°)
North Dobrogea												
Agighiol	Anisian to Carnian	40/52	13.4	57.8	3.2	52.1	41/52	79.0	73.9	3.3	46.8	54.8°<60.0°N<65.6°
Dunavat	Anisian to lower Ladinian	38/52	357.2	57.3	3.2	53.3	38/52	14.7	75.5	3.2	53.3	57.5°<62.7°N<68.2°
Crimea												
Tauric series	Triassic to Lower Jurassic	52/71	33.5	61.1	7.4	8.1						
Ai Petri Plateau	Early Kimmeridgian to Tithonian	93/97	351.8	21.8	1.9	60.7	93/97	354.5	7.3	1.9	60.7	2.7°<3.7°N<4.6°

		Low temperature/Low coercive force component				
		N samples	Dec (°)	Inc (°) before tilt correction	a95 (°)	k
North Dobrogea						
Agighiol	Anisian to Carnian	22	356.6	58.5	8.8	13.5
Dunavat	Anisian to lower Ladinian	6	6.9	55.0	15.0	20.9
Crimea						
Tauric series	Triassic to Lower Jurassic					
Ai Petri Plateau	Early Kimmeridgian to Tithonian	91	353.1	62.9	2.5	35.1

Table 1. Mean paleomagnetic directions of North Dobrogean and Crimean sections.



Appendix 1. Characteristic orthogonal vector diagrams of both North Dobrogean sections. Closed (open) symbols denote projection on the horizontal (vertical) plane; numbers refer to temperature or alternating field demagnetisation step.

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Datum: 28 juli 2005
Onderwerp: Resultaat na toekenning subsidie-aanvraag

Geachte leden van het Bestuur,

Hierbij treft U het verslag aan van onderzoek dat mede mogelijk gemaakt werd door toekenning van een subsidie uit het Molengraaff Fonds in 2004. Zonder bijdrage van het Molengraaff Fonds was het niet mogelijk geweest om mee te gaan op beide veldwerken (in Roemenie en de Ukraine). Een deel van het onderzoek is mondeling gepresenteerd op het jaarlijkse EGU congres, dat dit jaar plaats vond in Wenen (zie bijgevoegd Abstract). Bovendien zijn we allebei zodanig in de wetenschap geïnteresseerd geraakt dat wij beiden in januari zullen beginnen aan een promotie onderzoek,

Hartelijk dank,

Maud Meijers (tevens namens Martijn Deenen)

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Paleomagnetic evidence for large-scale northward terrane translation of Crimea since the Jurassic

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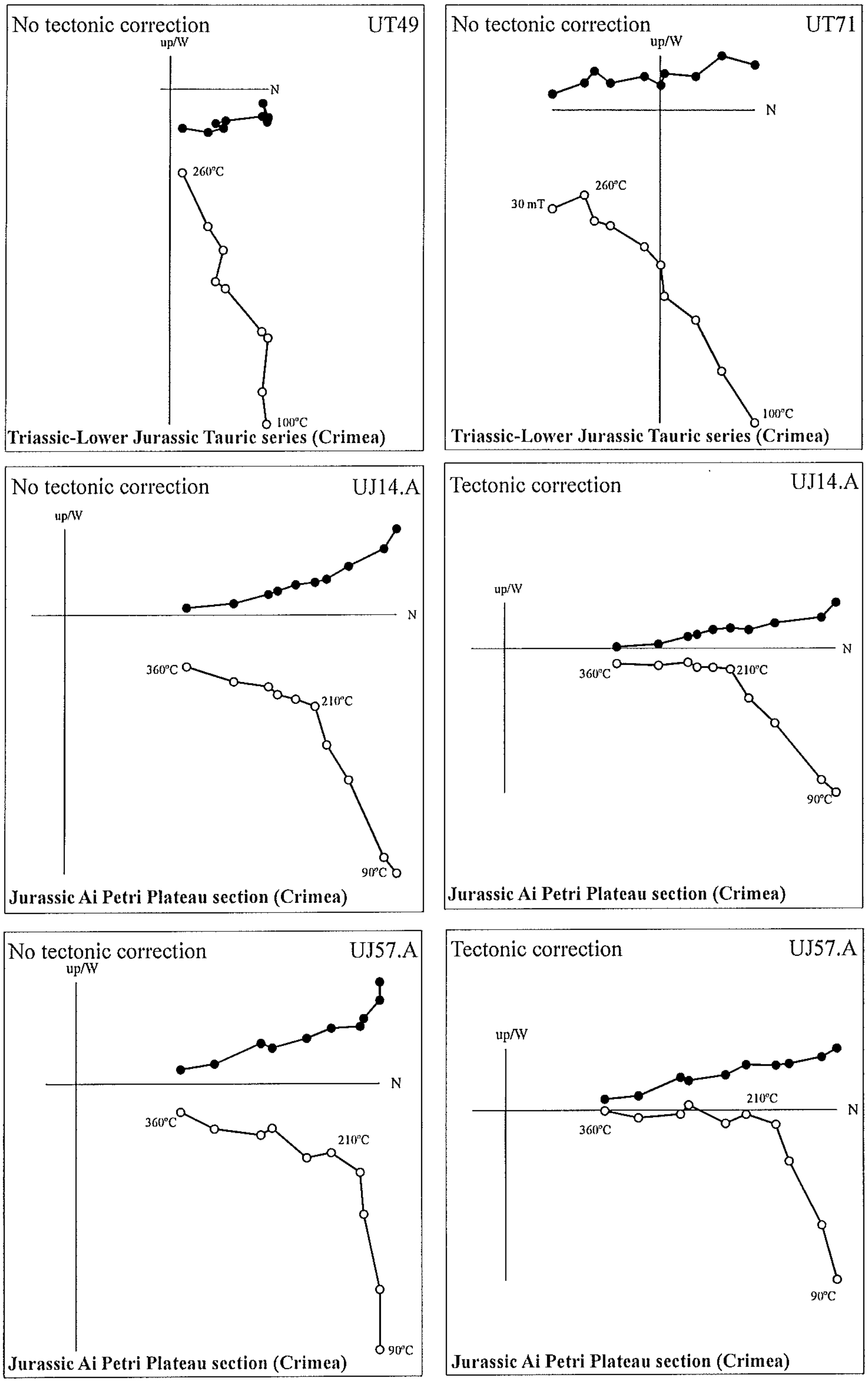
The East European Platform, and especially the area surrounding the Black Sea (North Dobrogea, Crimea, Caucasus), is a very suitable region to study the behaviour of large-scale (lithospheric) fault zones, because subduction processes have continuously been taking place over a 400 Myr period (Devonian-Neogene). However, major controversies exist on the mechanisms that have caused fault activity, back-arc spreading or even continental rifting. Knowledge of the paleolatitudinal positions of the different blocks and plates through time is a crucial prerequisite to discriminate between the different models and hypotheses. This can be established by detailed paleomagnetic reconstructions of well-dated lithological sequences. In this context it is of importance that paleomagnetic results from sediments can show too low inclinations, caused by sedimentary processes (e.g. compaction) that cause so-called "inclination errors". However, a new model was recently developed by Tauxe and Kent, which can be used to predict distributions of paleomagnetic field vectors as a function of paleolatitude, but only when a large data set ($N > 100$) is available. We measured and analysed a high number of paleomagnetic samples from several sedimentary sequences of Triassic and Jurassic age on the Crimean Peninsula and the North Dobrogea Orogen to determine the paleolatitudinal position of these regions through time. These results are corrected by the elongation/inclination method of Tauxe and Kent, to overcome the fundamental problem of inclination error in sediments. We conclude that the Triassic and Jurassic rocks from South Crimea have originally been formed at very low equatorial latitudes. This suggests that Crimea was certainly not part of Eurasia and that a position close to the Cimmerian terranes is more likely. Results from Triassic sections in North Dobrogea show systematically very high inclinations, but we are not certain here that we



Appendix 2. Characteristic orthogonal vector diagrams of both Crimean sections. Closed (open) symbols denote projection on the horizontal (vertical) plane; numbers refer to temperature or alternating field demagnetisation step.