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Earth and Planetary Science Letters 141 (1996) 79–89

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Lower and Middle Jurassic paleomagnetic results from the south Lesser Caucasus and the evolution of the Mesozoic Tethys ocean

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Received 21 August 1995; accepted 18 March 1996

Abstract

We studied Lower Jurassic (Pliensbachian–Toarcian) basalts and tuffs and Middle Jurassic (Bajocian) limestones and marls from 9 sites in the southern part of the Lesser Caucasus (ca. 39.3°N, 45.4°E). A component showing rectilinear decay to the origin was reliably isolated from most volcanics. This characteristic component reveals nearly antipodal directions for both polarities and passes the fold test; the conglomerate test performed on lava boulders from the Aalenian basal conglomerates is also positive. We think that a primary remanence ($D = 20°$, $I = 38°$ $a95 = 5°$) was isolated from the volcanics. In contrast, Middle Jurassic sediments yielded controversial results, and the only reliably isolated intermediate-temperature component (ITC) does not pass the fold test. The ITC directions show a considerable improvement in data grouping during incremental unfolding, with a maximum at 40% unfolding. We argue, however, that the thus obtained mean direction does not correspond to any paleofield and is most probably an artefact.

When compared to reference data for the Eurasian and African plates, the Lower Jurassic mean inclination of 21°N ± 4° agrees well with the latter, thus implying that, in the Early Jurassic, the area studied belonged to Gondwana and was separated by the Tethys ocean from Eurasia, in agreement with paleontological data. We tried to locate the position of the boundary between the Eurasian and Gondwanian realms in the Caucasus region in the Early–Middle Jurassic; unfortunately, the available Jurassic paleomagnetic data from other tectonic units of the region did not reveal any clear pattern.

Keywords: Jurassic; paleomagnetism; Tethys; Lesser Caucasus

1. Introduction

Since the early fifties, one of the main goals of paleomagnetism has been to obtain reliable successions of paleomagnetic poles for major plates and thus establish their apparent polar wander paths (APWPs) which, in turn, have been used for tectonic reconstructions. Although many unsolved problems and controversies still remain, these APWPs seem to be established with a precision sufficient to create a variety of global paleogeographic reconstructions ([1–4], for review see [5]); at least from the Permian to the Present, all these reconstructions are rather similar.

One of the main results of these reconstructions is the recognition of the fact that the Tethys ocean, whose existence had earlier been proposed mainly on geological grounds [6,7], had really separated Gondwana and Eurasia. It also became clear that the

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PII S0012-821X(96)00056-8

existence of the Tethys implies a very complicated pattern of rifting and collision of numerous blocks and microplates, which are now welded together within the Alpine belt [8–10]. During the Mesozoic and Cenozoic, these microplates kept moving northward and finally collided with Eurasia, thus accounting for a complicated network of ophiolite sutures within the belt [11]. Many important details of the evolution of the Tethys, however, remain highly controversial.

Paleomagnetic data have provided many important insights into the evolution of the western Tethys.

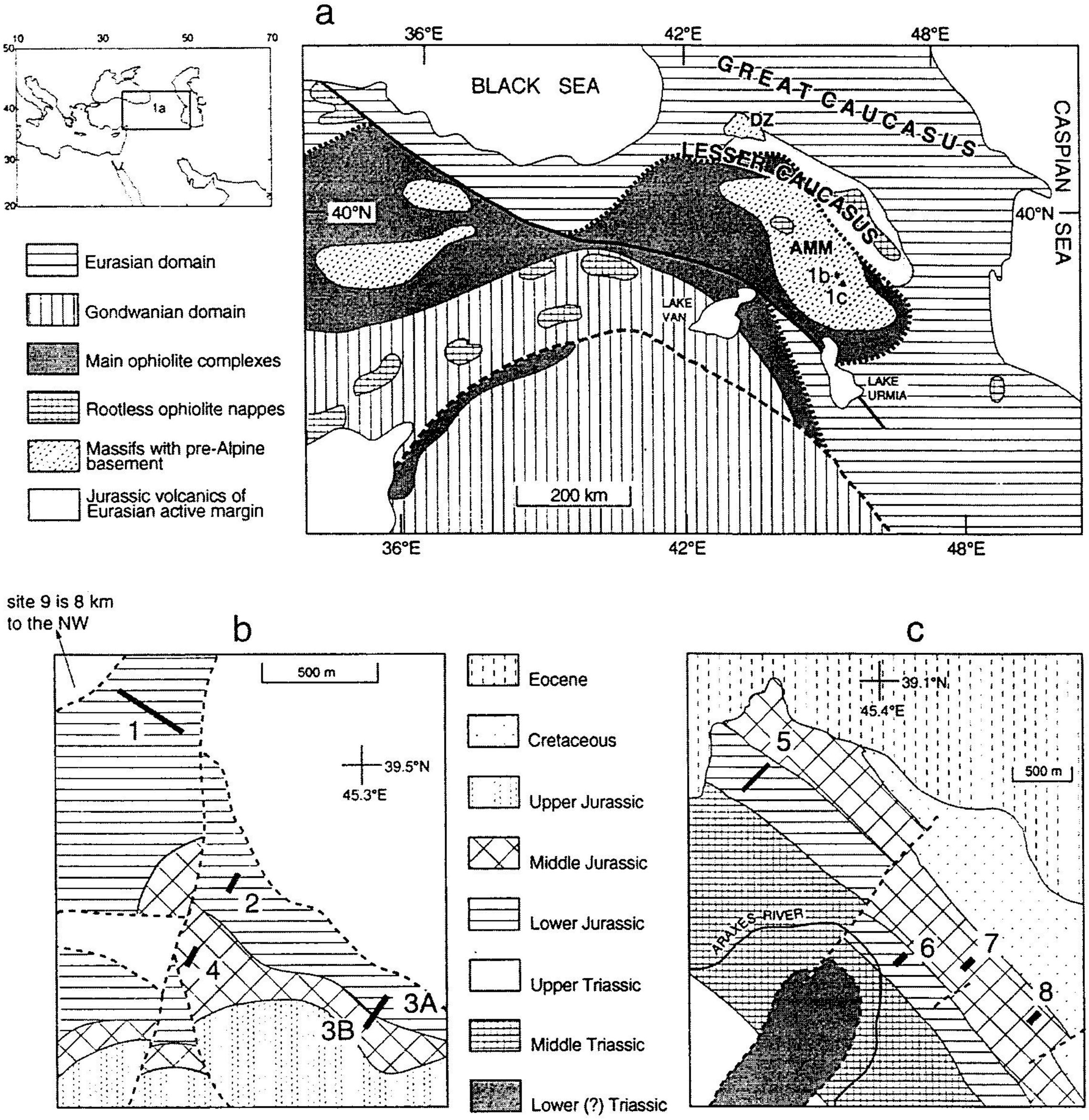

Fig. 1. (a) Schematic tectonic map of the Caucasus and adjacent regions simplified after [11] with the Meso-Tethys and Neo-Tethys sutures shown as thick dotted and dashed lines, respectively. The North Anatolian strike-slip fault is shown as thick solid line. *AMM* = Armenian Median Massif; *DZ* = Dzirula Massif. (b) and (c) Schematic geological maps of localities studied. Faults are shown as dashed lines. Sampling sites are numbered as in the text.

Unfortunately, the central and eastern parts of the paleo-ocean have been studied in much less detail and the data available are often of rather low quality. In particular, there is almost no data on northeast Turkey and northwest Iran. To the north, the data coverage for the Caucasus region appears to be adequate; most of the results, however, were obtained without an adequate demagnetization and component analysis [12], and their reliability is disputable. Paleomagnetic data from this region are needed to understand more clearly the convergence of Gondwana and Eurasia and the movements of intervening smaller blocks. Below, we present new results on Lower and Middle Jurassic rocks from the southern part of the Lesser Caucasus (now the territory of the Nakhichevan region of the Azerbadjan Republic) which may clarify the evolution of the Arabia–Caucasus segment of the Alpine belt.

2. Geological setting and sampling

The area studied belongs to the Armyanskoe Nagorie (Armenian Highlands), a rigid Armenian Median Massif (AMM) within the Alpine belt (Fig. 1a). The pre-Alpine AMM basement comprises (presumably) Precambrian metamorphic rocks and a Paleozoic–Middle Triassic platform sequence of Gondwana affinity. Ophiolite sutures almost surround this massif, suggesting that the AMM could have been a microplate in the early Mesozoic.

Lower Jurassic volcanics are known from both flanks of the Ararat Valley depression, in the south-central part of the AMM. The spatial distribution of volcanics is very limited. While the visible thickness of these rocks north of the Araxes River, on the southern flank of the Ararat depression, is about 200 m (Fig. 1c), they are absent altogether a few kilometres to the south in the Iranian Julfa region ([13]; A. Saidi, 1995, pers. commun.]. Volcanics of similar age and type are also found at a few localities on the northern flank of the Ararat depression but are not known from other parts of the AMM. These weakly differentiated, Al-poor, Ti-rich, alkali basalts are thought to result from the rifting of continental crust [14]. Much further to the north, thick piles of Jurassic volcanics (Somkhet–Agdam tectonic zone) belong to a quite different tectonic setting, tracing an Eurasian active convergent boundary (e.g., [15]). In addition, the main part of volcanic activity took place in the Middle–Late Jurassic, and not the Early Jurassic, as is our case.

The Lower Jurassic volcanics of the Ararat valley unconformably overlie Upper Triassic and older rocks and, in turn, are overlain unconformably by about 300 m thick, shallow-water limestones and marls of Middle Jurassic age; also noteworthy is the occurrence of a basal conglomerate, sometimes with lava debris, at the bottom of the Middle Jurassic. Belemnites of Pliensbachian–Toarcian affinities were found in a limestone layer in tuffaceous rocks on the northern flank of the depression (E.A. Uspenskaya, 1989, pers. commun.). Ammonites, pelicipodes and brachiopods point to an Aalenian age of the basal conglomerate member, whereas abundant ammonites in the marls and limestones define their age as Bajocian [16]. The Bajocian fauna belongs to the South Tethyan paleogeographical province [17], thus inferring a close proximity of the study area to the northern margin of Gondwana. The main deformation in the region studied took place in the Cenozoic, because Eocene rocks overlie the older formations with a major angular unconformity; much weaker Cretaceous folding events may be inferred from local angular unconformities.

Both Lower Jurassic volcanics and Middle Jurassic sedimentary rocks were sampled from two localities about 50 km apart. The northeastern one (Fig. 1b) is within the so-called Daralagöz Uplift (Range) north of the Ararat valley basin. Mainly tuffs with a few lava flows were sampled from Lower Jurassic rocks at sites 1 and 2. Site 3 encompasses the Lower–Middle Jurassic boundary; just one lava flow and 10 lava boulders from the basal conglomerate member were studied here (site 3A). Middle Jurassic limestones and marls were sampled from sites 3B and 4; in addition, the same rocks were studied at site 9, 8 km to the northwest of the area shown.

The southwestern locality (Fig. 1c) is about 50 km almost due south across the Ararat valley. Lower Jurassic volcanics, mainly lava, at sites 5 and 6 and Middle Jurassic limestones and marls at sites 7 and 8 were sampled from a NE-dipping monocline.

At each site one hand sample oriented with a magnetic compass was taken from a lava flow or a layer of sediments. Apart from site 3A, each site

Table 1
Paleomagnetic directions in Lower Jurassic volcanics

				IN SITU				TILT-CORRECTED				
S	N	T,m	B°	D°	I°	k	a95°	D°	I°	k	a95°	R
1	15/12	35	194/44	26.7	-3.1	35	7.4	30.5	39.3	40	6.9	0
2	32/21	175	152/30	2.2	17.4	19	7.5	12.4	42.4	15	8.5	2
3A*	6/6	2	192/47	18.1	27.2	9	23.8	33.2	75.0	7	28.2	0
5	17/13	200	32/69	247.4	71.1	15	11.2	18.5	36.1	12	12.3	6
6	8/6	50	37/71	277.3	78.0	56	9.0	26.0	24.1	40	10.7	0
Overall mean												
samples	72/52			2.3	38.8	3.2	13.3	20.0	38.2	16	5.1	
sites	4			359.3	51.1	2.5	75.4	22.1	35.7	63	11.7	
Four sites		$F_{(6,96)}=2.19$			f = 80.4				f = 2.88			
Without site 6		$F_{(4,86)}=2.47$			f = 92.2				f = 2.17			

* This site was omitted from computation of the overall mean. S = the number of site; N = the number of hand samples studied/accepted; T = true thickness studied; B = average dip direction/dip angle; D = declination; I = inclination; K = concentration parameter; a95 = the radius of confidence circle; R = the number of reversely magnetized samples; F = the critical value of F statistics with the number of degrees of freedom in brackets; f = calculated values of the same statistics [19].

covered a considerable stratigraphic interval, so hand samples were spaced a few meters apart along the sections over a true thickness of several tens to several hundred meters (Tables 1 and 2). Taken together, the sampling sites cover the entire Lower Jurassic and the main part of the Bajocian sections.

Table 2
Paleomagnetic directions in Middle Jurassic sedimentary rocks

				IN SITU				TILT-CORRECTED			
S	N	T,m	B	D°	I°	k	a95°	D°	I°	k	a95°
3B	25/16	120	206/57	40.7	44.1	20	8.4	163.8	74.1	17	9.1
7	12/12	80	26/65	43.1	84.6	80	4.9	28.1	20.1	66	5.4
8	14/12	60	36/69	157.4	84.9	46	7.2	41.3	23.8	56	6.5
9	8/8	20	51/16	91.0	61.3	31	10.1	78.2	47.6	37	9.2
Overall mean											
samples	48			56.3	71.8	9	7.3	50.2	52.6	4.6	10.8
sites	4			63.5	71.8	13	27.6	55.2	47.3	4.5	49.0
Stepwise unfolding											
samples*	48			50.4	64.9	21	4.6				
sites#	4			55.5	65.2	43	14.1				

* Maximum at 40% unfolding. # Maximum at 30% unfolding. Other notation as in Table 1.

3. Methods

Three or four cubic specimens were cut from each hand sample with a non-magnetic diamond saw. Two specimens per sample were subjected to step-wise thermal demagnetization in the laboratory-made oven with a residual field of about 10 nT in the Paleomagnetic Laboratory in Moscow. Alternating field (AF) demagnetization of pilot specimens was performed in a laboratory-made apparatus placed within a system of Helmholtz coils. All measurements of natural remanent magnetization (NRM) were made on a Czechoslovakian spin-magnetometer JR-4. Demagnetization data were analyzed with stereonets and orthogonal diagrams. Isolated components [18] from sister specimens were used for computation of sample means, which were in turn used for calculation of site means. Sample means were tilt-corrected using the bedding measurement closest to the sampling point; the within-site variation in bedding attitudes accounts for the differences in dispersions between in situ and tilt-corrected directions (Tables 1 and 2).

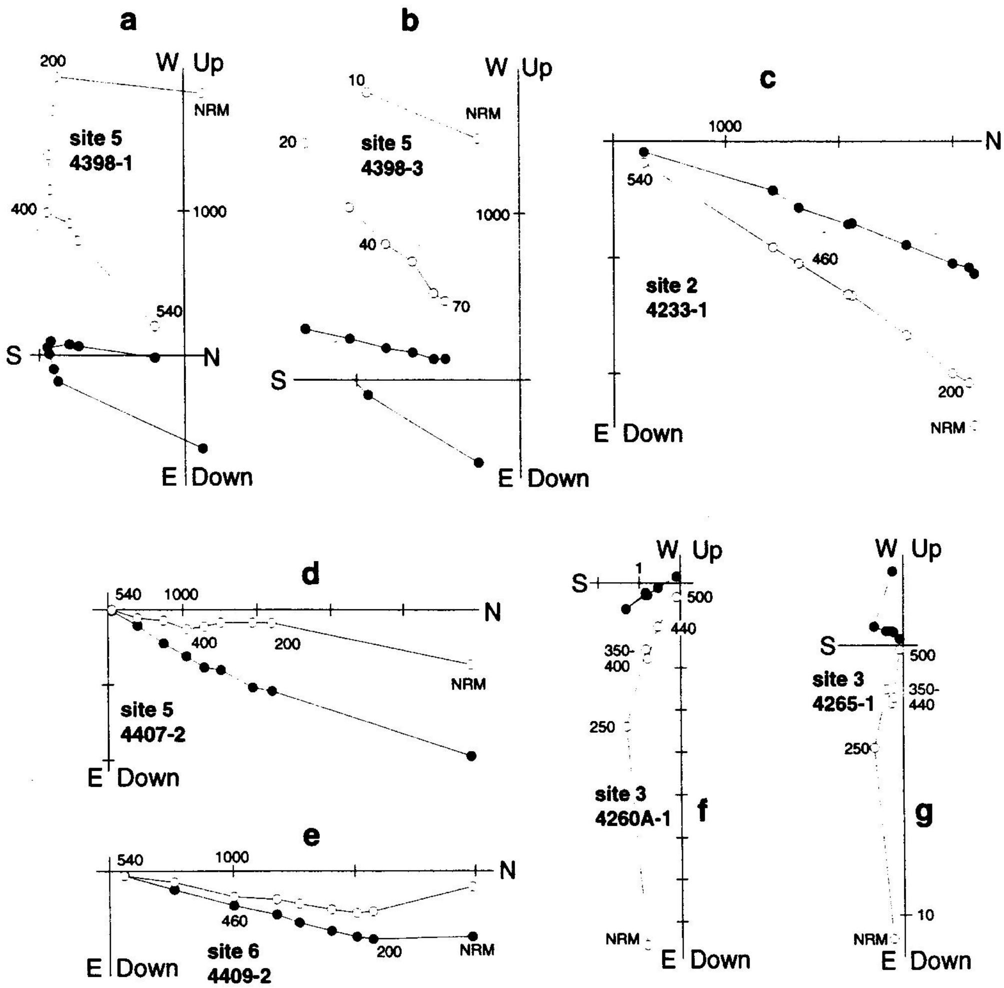

Fig. 2. Representative thermal (a, c–g) and AF (b) demagnetization plots of samples from Lower Jurassic volcanics. (a)–(c) basalts; (d) and (e) tuffs; (f) and (g) lava boulders. Data are plotted in stratigraphic coordinates. ● = vector end-points projected onto the horizontal plane; ○ = vector end-points projected onto the vertical plane. Steps are in degrees Celsius or millitesla. Magnetization intensities are in mA/m.

We used paleomagnetic software, written for an IBM PC by Randy Enkin and Stanislav Shipunov and for a Macintosh by Jean-Pascal Cogné.

4. Results

4.1. Lower Jurassic volcanics

NRM intensities of the volcanics range from 1 to 10 A/m. A pilot collection was subjected to thermal and AF treatments, and the former appeared to be more efficient for component isolation (Fig. 2a,b). The main collection was therefore thermally demagnetized. Apart from an unstable remanence of probably viscous origin removed at 200°C, a single characteristic component (ChRM) was present in most samples (Fig. 2c–e). Sometimes, another component was also isolated (Fig. 2a) or just suspected (Fig. 2b) within the 200–400° or 10–20 mT ranges; however, this intermediate component found in a few samples only is most likely to result from overlapping of unblocking spectra of the viscous and characteristic remanences and will not be considered further.

The ChRM is predominantly of normal polarity. However, at sites 2 and 5, approximately antipodal directions of reversed polarity were isolated (Fig. 3a,b). The ChRM directions from sister specimens usually differ by a few degrees. The ChRM sample means are very scattered at site 3A (Table 1), where a single lava flow just below the erosional boundary between Lower and Middle Jurassic rocks was studied. Moreover, the mean direction for site 3A deviates greatly from the other data on the volcanics in either coordinates (Table 1). It is likely that the basalt flow at this site was altered during the hiatus in the accumulation of the Jurassic sequence and later remagnetized. We decided to discard this result from computation of the formation mean.

In contrast, the within-site dispersion of ChRM directions from sites 1, 2, 5 and 6 is rather small, and the corresponding site means are much better grouped after tilt correction than in situ (Fig. 3c,d, Table 1). The fold test of McFadden and Jones [19] was applied, and the calculated F statistics in geographic coordinates are much larger than the 95% critical value, and somewhat exceed this value in stratigraphic coordinates as well (Table 1). This is likely to be due to incomplete averaging of paleomagnetic noise at the smallest site 6; without it, the fold test is positive at the 95% confidence level (Table 1).

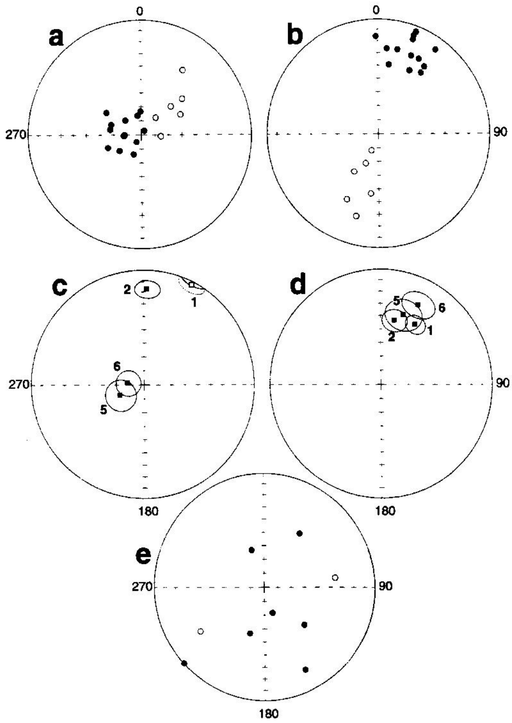

Fig. 3. Projection of ChRM directions from Lower Jurassic volcanics. (a) and (b) Sample means (dots) for sites 5 and 6 combined in situ (a) and after tilt correction (b). (c) and (d) Site means (squares) together with their circles of confidence from Lower Jurassic volcanics numbered as in the text and Table 1, (c) in situ and (d) after tilt correction. (e) ChRM directions (dots) from lava boulders. Open symbols = projected onto upper hemisphere; filled symbols = projected onto lower hemisphere.

NRM intensities in lava boulders from the basal part of the Middle Jurassic section are a hundred-fold less than in the underlying Lower Jurassic basalts. Optical observations on thin slices from the boulders, however, confirmed that they are indeed basalts, and rather fresh in appearance. Nevertheless, fine submicron magnetite particles might have been destroyed during the erosion and conglomerate accumulation, thus accounting for a sharp decrease in the NRM. Two specimens from each boulder were treated from the main collection. Of the 10 boulders studied, a ChRM was reliably isolated from 6 (Fig. 2f–g). In 3, both the intensity and direction of magnetization remained unchanged over a wide temperature interval and then the samples were completely demagnetized after the next 20° step; hence, the stable end-points were used for analysis. Both the ChRM directions and stable end-points from sister specimens agrees within a few degrees. In contrast, 9 boulder means are scattered (Fig. 3e), and the conglomerate test is positive; the calculated normalized length of vector (0.35) is much less than the critical 95% value of 0.529 of the Raleigh uniformity test [20].

The presence of nearly antipodal ChRMs of two polarities and the positive fold and conglomerate tests testify to an ancient, and most probably primary, age for the remanence isolated from the Lower Jurassic volcanics. There is no systematic difference between the results on tuffaceous rocks (sites 1 and 2) and lava flows (sites 5 and 6) (Table 1). As lava are thought to be faithful recorders of the ambient geomagnetic field, the overall mean inclination of

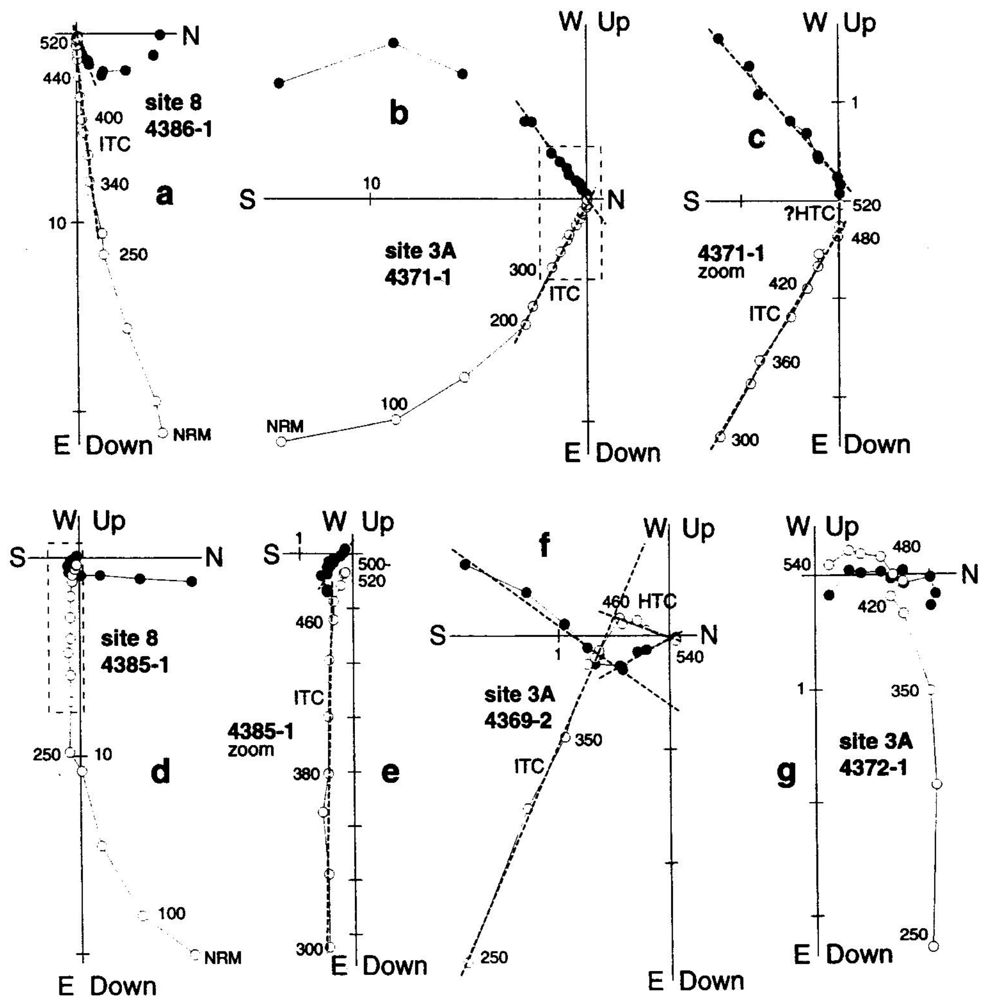

Fig. 4. Representative thermal demagnetization plots of samples from Middle Jurassic limestones and marls. Data are plotted in stratigraphic coordinates. ● = vector end-points projected onto the horizontal plane; ○ = vector end-points projected onto the vertical plane. Steps are in degrees Celsius. Magnetization intensities are in mA/m. Note that the low-temperature part of some plots are not shown for clarity.

38.2° ± 5.1°, being an unbiased estimation of the Early Jurassic geomagnetic field, corresponds to a latitude of 21.4°N ± 3.7°.

4.2. Middle Jurassic limestones and marls

NRM intensities in these rocks range from 1 to several tens of mA/m, and the main part of the NRM was often destroyed below 300° (Fig. 4). After removal of this unstable remanence, the remaining part of the NRM is mainly accounted for by a single component, persisting from 200° or 300° to up to 520°. This intermediate temperature component (ITC) of normal polarity sometimes decays to the origin (Fig. 4a), but usually misses it, and another high-temperature component (HTC) may be suspected (Fig. 4b–e). The isolation of the HTC, however, was severely hindered by the low magnetization intensity and the acquisition of spurious components above 500° or 520°, and it was recovered from just 9 samples out of the 68 studied (Fig. 4f). The HTC directions from sister specimens agree rather well, thus implying that this component is not an artefact. However, they are very scattered on the between-sample level. Judging by the permanently curved orthogonal plots of many specimens (Fig. 4g), unblocking spectra of the ITC and HTC strongly overlap at high temperatures. We suspect that the scatter of the HTC directions is also due to inadequate separation of these two components, and a few high-temperature rectilinear segments result from complete overlapping of these spectra. Thus, we preferred not to use the HTC data.

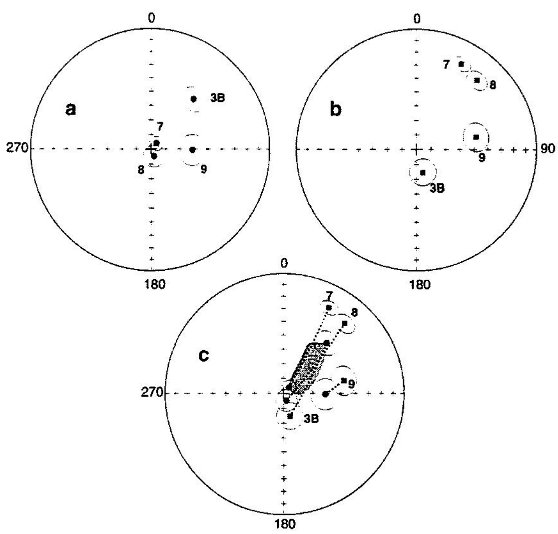

Fig. 5. Equal-area projection of the ITC site means from Middle Jurassic sediments together with their circles of confidence (a) in situ and (b) after tilt correction. (c) Same data pooled; ■ = site mean directions in situ; ● = site mean directions after tilt correction; dotted lines = trajectories of corresponding vectors during unfolding; shaded area = the part of the sphere where the mean direction of synfolding remanence should lie for various unfolding scenario (see text for explanation). All symbols are projected onto lower hemisphere.

In contrast, the ITC directions are calculated from long, well defined linear segments on orthogonal plots and most probably represent a true component of the NRM. The ITC directions are very scattered at site 4, and this site was discarded. For the other four sites, the ITC data of ubiquitously normal polarity are well grouped at the within-site level. The corresponding site means, however, are widely divergent both in situ and after tilt correction (Fig. 5, Table 2). During incremental unfolding, data grouping improves considerably and is the best at about 40% unfolding (Table 2); however, there are strong doubts as to its validity, as discussed below.

The main deformation in the study area started in the Eocene, so the ITC is clearly much younger than the rock age. The ubiquitously normal polarity of the Middle Jurassic sediments also points to their remagnetization because frequent polarity changes should be expected for the Bajocian [21,22]. The estimated reversal frequency for this stage ranges from 3 to 8 reversals per million years, which correspond to a duration for each polarity epoch of about 200,000 yr, on average. It is unlikely that the entire 300 m thick section of marine Bajocian sediments could have accumulated during such a short interval. It may be noted that the tilt-corrected Middle Jurassic site means from the southern locality (sites 7 and 8) closely resemble the results from the Lower Jurassic volcanics; nevertheless, the above reasoning infers that this agreement is fortuitous.

5. Interpretation and discussion

The predicted reference latitudes for the area studied recalculated from the APWP for the adjacent

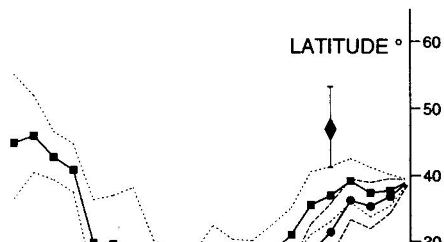

Fig. 6. Plots of latitude versus time for our data and reference values recalculated to the study area (39.3°N, 45.4°E). Our data: star; Early Jurassic result: diamond; mean inclination of the intermediate-temperature component in Middle Jurassic rocks at 40% unfolding. The latter result is arbitrary placed at 40 Ma as the main deformation in the study area started in the Eocene. As the reference we used the combined APWP [23] in the African (●) and European (■) frames, with their confidence intervals shown as dashed and dotted lines, respectively.

major plates, namely Africa and Eurasia [5], are different; the associated confidence limits, however, are rather large. For instance, the difference between the Eurasian and African Early Jurassic reference values is 17.3°, and the 95% confidence limits are 12.4° and 4.5°, respectively, so they almost overlap. Of course, this is due to large errors associated with mean poles for individual plates. Nevertheless, the observed Early Jurassic latitude of 21.5°N ± 3.7° is just slightly less than the corresponding African paleolatitude of 22.4°N ± 4.5°, the difference of about one degree being, of course, statistically insignificant. At the same time, the observed latitude is 18.3° ± 10.3° lower than that expected for stable Eurasia.

A more obvious pattern emerges when the master APWP, based on combined data sets for all major plates [23], is used for analysis. Due mostly to smaller error limits associated with mean poles, the African and Eurasian reference latitude curves are clearly distinct (Fig. 6). The observed latitude is higher by 3.7° ± 4.0° and 6.8° ± 3.4° than the 190 Ma and 180 Ma African reference latitudes, respectively. At the same time, the European reference latitudes are higher by more than 20°; for the 190 Ma value this difference is 24.4° ± 5.5°.

The good fit of the observed and African Early Jurassic latitudes implies that the area studied was close to the African plate (i.e., the northern margin of Gondwana) and was far away from the Eurasian land mass. This conclusion is in agreement with paleontological data indicating that this area belongs to the south Tethyan (Gondwanian) biogeographical realm [17]. Thus, the minimal width of the Tethys ocean was ca. 2700 ± 600 km in the Early Jurassic. The closure of this ocean can, of course, be deduced from the convergence of the African and Eurasian continents, as reflected by the latitude curves (Fig. 6). However, paleomagnetic data on younger rocks are needed to study the kinematics of the Armenian Median Massif within the Tethys. Moreover, the territory of eastern Turkey, western Iran and the Lesser Caucasus is an amalgamation of numerous small blocks and tectonic units which have definitely moved with respect to each other and major plates; some tectonic units might have been thrust over considerable distances. Thus, it is impossible to state that the entire territory to the south of the area studied belonged to Gondwana in the Early Jurassic, as is also demonstrated by the complicated relationship of the Eurasia and Gondwana units to the south of the study area (Fig. 1a).

The above interpretation implies that a considerable distance separated the study area from Eurasia. Paleontological data infer a Eurasian affinity of the Jurassic fauna for the Great Caucasus and several tectonic zones of the Lesser Caucasus, in particular the Middle–Late Jurassic volcanic sequence of the Somkhet–Agdam zone (Fig. 1a). Jurassic results over the entire Caucasus region are rather numerous but do not reveal a clear pattern. For instance, five locality mean inclinations (32° ± 15°, 42° ± 7°, 45° ± 8°, 48° ± 4°, and 54° ± 6°) have been reported from the northern piedmont of the Great Caucasus [24], which is the deformed margin of the East European platform [25]. The corresponding latitudes, ranging from 17°N to 34°N (26°N on average) fall considerably below the Early Jurassic Eurasian reference value of about 46°N. For the Dzirula Massif (Fig. 1a), which is to the south of the Great Caucasus but is thought to be an integral part of Eurasia in the

Jurassic [25], the same researchers calculated an overall mean latitude of about 29°N for three Middle Jurassic localities, whereas the Eurasian latitudes for 170 Ma and 160 Ma are 42°N and 31°N, respectively. Thus, a minor error in rock and/or magnetization age may bring the Dzirula result either into perfect fit or sharp disagreement with the Eurasian data. The ages of the rocks studied were often given only as Early or Middle Jurassic [25], thus contributing to the diffuse pattern. In general, the results for the entire Jurassic over the Caucasus region [12,24,26] fall in between the corresponding Eurasian and African reference values, thus excluding the precise tracing of the Eurasia–Gondwana boundary.

There may be several sources of this diffuse pattern. Most, if not all results are at least 10 years old and are mainly based on blanket cleaning at moderate temperatures and field intensities (as a rule 300° to 400°C or less than 40 mT), without component analysis. Although tilt correction usually decreases the dispersion, the statistically significant improvement in data grouping is observed in less than half the results. In addition, the main folding in the Caucasus is post-Oligocene in age and, hence, even a positive fold test does not constraint magnetization ages too well. At the same time, a reversal test is often positive. Nevertheless, it is quite likely that undetected secondary components may be present in at least some of the results, thus obscuring the true pattern.

The convergence of Eurasia and Gondwana might have been mainly accommodated between our study area and the Great Caucasus, but a smaller part of this convergence was compensated further to the north. It does not contradict paleontological data pointing to the Eurasian affinity of the entire north Caucasus, and available paleomagnetic data with expected direction much closer to Eurasian than to African ones. However, it does not fit altogether into geological data, which have revealed no structures able to accommodate any considerable horizontal movements north of the Caucasus.

The Early Jurassic formation mean declination of $20.0° \pm 6.5°$ is significantly rotated clockwise by $27.0° \pm 7.2°$ with respect to the 190 Ma African reference direction; at the same time, the difference of $-10.6° \pm 9.8°$ between the measured and Eurasian declinations is just marginally significant. Since the study area underwent a complicated tectonic evolution during the formation of the Caucasus segment of the Alpine fold belt, we can now neither date possible rotations nor evaluate their geological significance until paleomagnetic results on younger rocks are available.

The ITC mean inclination in Middle Jurassic sediments obtained at 40% unfolding corresponds to a latitude of $46.9°N \pm 6.0°$, which is higher than any Eurasian or African reference value for this area but still is rather close to the post-40 Ma data for the both plates (Fig. 6). It should be stressed that this result was obtained with the aid of incremental unfolding, which is based on an assumption of the exact proportionality of folding at all localities studied. This assumption, however, may be invalid for two localities about 50 km apart. The small circles outlined by the site mean directions during tilt correction are almost parallel for sites 3A, 7 and 8, whereas the mean for site 9 remains apart and actually moves away from the other directions during unfolding (Fig. 5c). Omission of the latter does not improve the reliability of the result, which still strongly depends on the assumed exact proportionality of unfolding. If the rocks at the northern and southern localities were deformed differently at the time when the ITC had been acquired, a better fit may be obtained. For instance, if site 3a, from the northern locality, is 20% unfolded and sites 7 and 8, from the southern locality, are 50% unfolded, the resulting overall mean inclination of about 56° will coincide with the 40 Ma Eurasian reference direction. Of course, this is not supported by any geological data; playing with various unfolding scenario, one can obtain quite different results (shaded area in Fig. 5c).

As a final remark, it is worth noting that the internal consistency of the Triassic–Jurassic unit poles for major plates is not always good, as evidenced, for instance, by the data from the East European platform, where two quite different mean poles for the late Middle Jurassic–Late Jurassic (145–176 Ma) were calculated [5]. For the Early–Middle Jurassic, the number of data are rather limited. In addition, some errors may be caused by a quick change in the expected inclination in both the Eurasian and African frames during the Jurassic (Fig. 6). If this change is real, any errors in rock and/or magnetization ages are likely to lead to large inclination discrepancies and, hence, to an erroneous tectonic interpretation. We think that the situation with paleomagnetic data from the Caucasus results from both the data scarcity and their often low quality, both on regional and global scales.

Acknowledgements

Thanks are due to Jean-Pascal Cogné, Randy Enkin and Stanislav Shipunov for the software used throughout this paper. Helpful remarks and suggestions by Stuart Gilder and two anonymous reviewers helped us to improve and clarify the article. This is IPGP contribution No. 1391. *[RV]*

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