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PALEOMAGNETIC EVIDENCE FOR ROTATION IN OPPOSITE SENSES OF ADJACENT BLOCKS IN NORTHEASTERN AEGEA AND WESTERN ANATOLIA.

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Abstract. Paleomagnetic data from western Anatolia and from the island of Lesbos demonstrate significant counterclockwise, clockwise or null rotations of coherent blocks which occurred during the neotectonic period. These results suggest that the brittle carapace of the lithosphere may not everywhere follow the motion of the ductile lower part but that its movement arises from adjustment to the extensional tectonic regime.

Introduction

As a result of the intracontinental convergence in Eastern Turkey, most of Turkey moved westward along the North and East Anatolian strike-slip faults. Since at least late Miocene, this motion is accompanied by large scale N-S extension in the Aegean and in Western Turkey with complementary E-W shortening (Tapponnier, 1977; Dewey and Şengör, 1979; Mercier et al., 1979; Le Pichon and Angelier, 1981; Angelier et al., 1981).

In this paper we report paleomagnetic data from northeastern Aegea showing that significant rotations of adjacent coherent blocks about vertical axes and in opposite senses have occurred in this region since at most 20 m.y. Although the data are still incomplete, the complicated rotational pattern in this area is easier to describe in terms of local rotations than in the framework of the general westward movement of the "Anatolian Plate" resulting from the Eurasia-Arabia collision (Tapponnier, 1977; Dewey and Şengör, 1979).

Geological Setting and Sampling

The studied area and the location of the sampling sites are shown in Figure 1.

The most striking structural and morphological features of this region are the E-W and NNE trending grabens (McKenzie, 1978; Dewey and Şengör, 1979). Focal mechanism solutions obtained from the Alaşehir and Gediz grabens, have shown that motion takes place on faults of listric geometry (Eyidoğan and Jackson, 1985). The NNE faults are probably partially inherited from Neo-Tethyan structures while the E-W fault system corresponds to a neotectonic structural direction. The complex pattern of faulting includes numerous other neotectonic faults of various orientations and displacements (Kaya, 1981), most of which are truncated by younger faults of different orientations. Slickensides indicating strike-slip movements in opposite senses and in different directions are also frequently observed in the field.

Widespread calc-alkaline volcanic products erupted during the first Aegean phase of

Oligo-Miocene age, which ended about 13 m.y. ago, and small volumes of lava with variable petrogenetic character are present in Central Aegea and Western Anatolia (Borsi et al., 1972; Fytikas et al., 1984).

In Lesbos, 25 sites were sampled mainly in lava flows of dacitic composition, ignimbrites and dykes dated between 15-20 Ma by K/Ar (Borsi et al., 1972) and two in blue-grey lacustrine marls of probable Pliocene age.

In Western Anatolia 28 sites were sampled in calcalkaline lava flows dated between 18 and 21 Ma and in alkali-basalts dated at about 10-11 Ma (Borsi et al., 1972; Fytikas et al., 1984). A few sedimentary and volcano-sedimentary formations were also sampled (12 sites).

For the volcanic formations, interbedded sediments have yielded in some cases precise bedding corrections. In others a local structural study gave a reasonable estimate. In the Çanakkale region the basement is unconformably overlain by Neogene lacustrine formations tilting northward with a shallow dip of about 15°. We have assumed that this general bedding attitude affects the sampled sites, which are devoid of local bedding criteria. Finally, when no precise correction for tilting was possible we had to rely on a subjective choice of "almost horizontal" lava flows based on the morphology of the flow itself.

At each site, the cores were obtained over at least a few tens of meters and were oriented with both magnetic and sun compass. A total of 800 cores from 67 sites were sampled and studied.

Laboratory Methods

Measurements have been done using a spinner or a cryogenic magnetometer. IRM acquisition in fields up to 1.6 T, followed by AC and/or thermal demagnetization of the SIRM, shows that magnetite is the main magnetic carrier, sometimes associated with a small amount of magnetic minerals of higher coercivity.

Both thermal and AF stepwise demagnetization were used. However the thermal treatment was generally preferred because it yielded overall more consistent results. Each single sample has been stepwise demagnetized with 12-15 steps between room temperature and at least 580°C. Both for volcanic and sedimentary samples, no significant changes in susceptibility values occur up to the highest temperatures showing that the magnetic minerals have not changed during the thermal treatment. Typical demagnetization diagrams are shown on Figure 2.

Results

The laboratory measurements have shown that some of the sampled lithologies are not suitable for a paleomagnetic study. In particular different sites in the ignimbrites and the dykes in Lesbos sometimes gave conflicting results and usually an unreasonable within-site scatter, although single samples are characterized by perfectly rectilinear demagnetization diagrams. This phenomenon is not fully understood, but we have considered reliable only the sites for which the Fisherian precision coefficient K was greater than 15. Ten sites in Lesbos and 15 sites in Western Anatolia, were rejected on this basis, leaving 42 trustworthy sites.

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Fig. 1. Schematic map of Northeastern Aegea showing (A) the most prominent structural characteristics (the E-W and NNE trending grabens) and (B) the location of the sampled paleomagnetic sites. Symbols: 1: Neogene continental basins; 2: Neogene volcanic and volcano-sedimentary formations; 3: Neogene plutonic formations; 4: Paleozoic basement.

All the reliable results are reported in Table I and on Figure 3, together with 3 sites (Çeşme 1, 2, 3) from the Karaburun peninsula reported by Lauer (1981). In each region the normal and reversed directions are antipodal, indicating a good magnetic stability and a satisfactory cleaning.

After bedding correction the inclination values from the different regions are quite consistent, with mean values around 50° , except for the one calculated from the 3 sites south of Bergama which is shallower.

The mean declinations from the different

Fig. 2. Typical demagnetization diagrams. Full circles: horizontal projection; open circles: vertical projection. The last step varies between 550° and 600°C . M_o (NRM intensity) is reported in 10^{-3} A/m unit.

regions are on the contrary quite divergent. In Lesbos and in the Çanakkale region they are aligned with the N-S direction. The Izmir region is characterized by a 35° westerly declination,

TABLE I. Paleomagnetic Data From Northeastern Aegea

Sites	Age Ma	n	before B.C		after B.C		K	α_{95}
			D	I	D	I		
<u>Çanakkale Region</u> ¹								
IZ50	----	8	194.0	-65.0	194.0	-50.0	24	10.0
IZ51	----	8	183.2	-70.4	183.2	-55.4	252	3.1
IZ52	----	8	176.6	-69.6	176.6	-54.6	165	3.8
IZ54	----	9	8.3	60.5	8.3	45.5	205	3.2
<u>Lesbos Island</u> ²								
LE249	----	10	8.0	37.0	11.2	27.0	280	2.6
LE252	----	8	0.2	49.0	4.8	40.2	153	4.0
LE253	----	9	13.6	59.5	17.2	49.7	196	4.0
LE255	----	11	----	----	11.3	53.3	704	1.6
LE256	16.9	11	----	----	340.5	55.0	229	2.8
LE257	16.9	10	----	----	350.0	69.0	262	3.0
LE263	18.0	9	----	----	177.8	-49.0	1333	1.3
LE269	18.0	8	----	----	146.0	-63.6	177	3.7
LE271	18.0	11	----	----	214.0	-20.0	15	10.0
LE272	18.0	10	----	----	191.7	-44.7	181	3.3
LE273	15.5	10	31.4	58.5	19.1	56.0	257	2.7
LE274	15.5	10	358.6	44.3	353.5	38.7	134	3.8
LE275	15.5	9	----	----	17.3	64.0	233	3.0
LE277	15.5	9	----	----	349.5	45.5	170	3.5
LE278	15.5	9	----	----	10.0	44.5	72	5.0
LE279	18.0	7	----	----	199.5	-20.0	144	4.4
LE280	18.0	7	----	----	191.0	-41.0	46	7.8
<u>Izmir-Bergama Region</u> ³								
IZ06	11.3	12	----	----	128.0	-47.0	158	4.2
IZ07	11.7	8	144.0	-34.0	141.0	-39.5	249	3.3
IZ09	7.0	12	169.0	-62.5	127.2	-41.0	93	4.2
IZ10	7.0	8	192.0	-55.0	144.0	-47.5	500	2.2
IZ24	----	7	----	----	348.0	64.0	56	7.0
IZ28	----	8	346.0	54.0	349.6	57.0	57	4.0
IZ44	18.2	9	----	----	342.0	71.4	828	1.6
IZ46	18.2	8	319.5	53.8	314.0	53.8	540	2.3
IZ57	----	9	328.0	36.6	325.0	14.7	35	8.0
IZ59	----	18	36.4	54.0	336.0	58.5	27	6.3
IZ60	----	10	50.6	58.2	331.0	67.5	76	5.0
IZ61	----	9	----	----	333.0	31.7	47	6.7
IZ64	----	10	----	----	165.2	-67.2	115	4.1
<u>South of Bergama</u> ⁴								
IZ22	17.5	11	----	----	190.0	-48.0	387	2.4
IZ47	17.5	9	----	----	7.2	34.8	45	7.0
IZ48	17.5	8	----	----	226.5	-28.8	12	14.0
<u>Karaburun Peninsula</u> ⁵								
IZ08	18.5	11	----	----	267.0	-34.5	23	8.5
IZ14	----	8	181.0	-51.0	182.0	-36.0	264	3.2
IZ15	17.0	5	----	----	226.0	-84.5	35	10.5
IZ16	21.3	6	----	----	43.5	16.3	97	5.8
IZ43	18.5	8	----	----	234.0	-53.5	450	2.6
Çeşme1	18.5	7	----	----	254.0	-51.9	189	4.4
Çeşme2	18.5	7	----	----	237.0	-51.5	52	8.4
Çeşme3	18.5	5	----	----	207.0	-59.5	132	6.7

Mean regional directions after bedding correction:

$$\begin{aligned}
 &^1 N = 4/6; D = 6; I = 54; K = 254; \alpha_{95} = 4.3 \\
 &^2 N = 17/27; D = 6; I = 49; K = 25; \alpha_{95} = 6.8 \\
 &^3 N = 13/23; D = 327; I = 52; K = 20; \alpha_{95} = 8.7 \\
 &^4 N = 3/4; D = 22; I = 39; K = 16; \alpha_{95} = 20.2 \\
 &^5 N = 8/10; D = 49; I = 51; K = 9; \alpha_{95} = 16.4
 \end{aligned}$$

The K/Ar ages refer to the sampled units but have not been determined on single sites.

Fig. 3. Stereographic projections of the stable paleomagnetic direction obtained for the reliable sites. Each stereogram corresponds to sites from a particular region. Symbols: 1: Çanakkale region; 2: Lesbos island; 3: Izmir-Bergama region; 4: south of Bergama; 5: Karaburun peninsula.

except for the 3 sites south of Bergama where a 20° easterly declination is observed. In the Karaburun peninsula the declinations are all deviated eastward (mean value 49°) with a large scatter. We have no explanation for this scatter which is not, in our opinion, related to erroneous declination values arising from the use of the usual tilt correction about the strike of the dip. Indeed all the measured dips in this region are of the order of 20° – 30° , so that very limited effects are to be expected in this case (McDonald, 1980).

Discussion

A recent examination of all the available paleomagnetic data from the Aegea leads to the conclusion that this entire domain has been linked to the African plate during most of its tertiary geodynamical evolution (Kissel and Laj, 1987). Using the Miocene African poles proposed by Westphal et al. (1986), the expected paleomagnetic direction in the studied region is $D = 5.8^\circ$; $I = 53.2^\circ$. Thus the observed inclination values are in good agreement with the expected ones. An examination of the observed declinations then indicates quite a complex pattern of rotations of adjacent blocks. Indeed, while Lesbos and the Çanakkale region have not undergone any significant rotation, the Karaburun Peninsula has been affected by a 44° clockwise rotation and the Izmir region has undergone a 37° anticlockwise rotation. The volcanic massif located south of Bergama has rotated clockwise with an angle of some 18° .

All the results are schematically summarized in Figure 4 which shows the amount of rotation and the inferred limits of the different blocks delineated by the paleomagnetic results. Two blocks, the Çanakkale region and the small block south of Bergama, are not defined by a sufficient number of sites. However, if their geographical limits are doubtful, we believe that the differences of their paleomagnetic directions from those of the surrounding regions are real.

The ages of the rotations are constrained by the ages of the volcanic and sedimentary rocks that underwent rotation. Therefore only lower limits may be provided. Whatever the age of the studied rocks, in each region, the measured

rotation is coherent indicating that the rotation post-dates the formation of the youngest studied rock. In the Izmir region, the youngest published data is a K/Ar age of 11.3 Ma (Borsi et al., 1972). However, we have recently obtained a K/Ar age of 7 Ma for a volcanic formation sampled near Foça.

Moreover, most of the neotectonic faults in the region were initiated during the late Miocene–Early Pliocene. The 7 Ma date for the Foça basalts indicates that the rotation of this region, quite coherent at all the sites, definitively belong to the neotectonic activity. The sites studied in the Karaburun peninsula are all situated in formations older than 16 Ma, so that the rotation cannot be directly time-bracketed. However, it seems unreasonable to us that the rotation of the Karaburun Peninsula has occurred during the pre-11 Ma activity and is thus not related to the other rotations of this area. The other sites exhibiting coherent rotations are all in rocks younger than 16 m.y..

Conclusions

The paleomagnetic data we have collected, between the North-Anatolian and the Alaşehir faults demonstrate significant clockwise and counterclockwise rotations of coherent blocks that took place during the neotectonic extensional regime. Such rotations are difficult to explain in the framework of the global geodynamical evolution of the Western Anatolian and Eastern Aegean regions and are most probably related to a local tectonic regime. In our opinion, these results show that the brittle upper part of the lithosphere does not

Fig. 4. Mean values of the declinations in the studied area. The reverse directions have been inverted through the origin. For the different regions (same numbers than in Fig. 3), the amount and the sense of the rotation are shown on a stereogram. The limits of the different rotating units are only intended as a visual support to identify zones of coherent rotation.

everywhere passively follow the motions of its lower ductile part or that the latter motions are more complex than hitherto assumed.

We think that the main characteristics of the observed rotational pattern can be explained by a recently proposed model for rotations in extensional zones in which there is no commensurate strike-slip faulting (Şengör et al., 1985, Fig. 18). An important feature of this model is the implication that large ($>20^\circ$) rotations arise from successive episodes of faulting, older faults being cut and rotated passively by younger ones. This feature explains the complex pattern of faulting seen in these regions.

A more detailed analysis of the structural and the paleomagnetic data is now under way to develop a better constrained geometrical model, as it has already been done in purely strike-slip context of deformation (Garfunkel et al., 1974; Ron et al., 1984; Brown and Golombek, 1986; Hornafius et al., 1986).

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