Palaeomagnetic evidence for substantial rotation of the Almacik flake within the North Anatolian Fault zone, NW Turkey

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SUMMARY
Palaeomagnetic data on Eocene rocks from within the ‘Almacik Flake’, bounded by two strands of the North Anatolian right-lateral fault indicate that the flake has undergone an apparent counterclockwise rotation of about 148° on average. We interpret this as a real 212° clockwise rotation, because the Almacik flake is entirely delimited by the right-lateral North Anatolian Fault strands, the only dominant post-Eocene structure in the area, and because areas surrounding the flake do not show the same rotation. This rotation must have occurred since the North Anatolian Fault originated in the late medial Miocene (late Serravallian: 11.5 Ma) and, if so, may imply either a larger total slip along it than hitherto estimated or that the Almacik flake is the surface expression of a flower structure rotating above a shear zone narrower than the present width of the flake.

Key words: fault block, North Anatolian Fault, rotation, Turkey.

1 INTRODUCTION
In the last decade and a half, numerous palaeomagnetic studies have led to the recognition of significant fault-bounded block rotations within strike-slip fault zones or broad shear zones [see Beck (1988), Lamb (1988), and McKenzie & Jackson (1983) for brief review]. Block rotations found in the shear zone associated with the San Andreas strike-slip fault in southern California are the best-known examples of this kind of rotation (Beck 1976, 1980; Luyendyk, Kamerling & Terres 1980; Luyendyk et al. 1985; Kamerling & Luyendyk 1985; Carter, Luyendyk & Terres 1987). Some of these reported rotations, inferred from palaeomagnetic data are very large, exceeding 45°; some values approach 100°, and some may have gone through 360°. This implies that rapid rotation of blocks occurs in the deforming zones of a strike-slip environment: blocks bounded by left-lateral faults rotate anticlockwise, those bounded by right-lateral faults rotate clockwise (Gallo et al. 1980; Garfunkel 1988). This study represents the first recognition of a substantially rotated block along the North Anatolian strike-slip zone by using the declination of the primary remanent magnetization of the rocks affected by the rotation.

2 GEOLOGY AND SAMPLING
The Almacik flake is an 80 km long and 20 km wide spindle-shaped block bounded by two local strands of the North Anatolian fault (Fig. 1). This block consists of Palaeozoic to Eocene metamorphic, sedimentary and volcanic rocks bisected by a N-S striking piece of the Intra-Pontide suture (Yilmaz et al. 1981; Şengör, Görür & Saroğlu 1985). The fragments of this suture, being represented by two prominent 025° striking and steeply ESE-dipping narrow zones of ophiolites including ultramafic rocks, gabbros and meta-mafic volcanics (Fig. 1b), deviate considerably in their orientation from the rest of the suture zone, which has a strike of about 083°. Sungurlu (personal communication, 1984) has suggested that the rocks lying to the west of the suture trace within the Almacik flake (S in Fig. 1b) resemble those that make up a part of the Sakarya Continent (normally located to the south of the Intra-Pontide suture: Fig. 2) and those to the east of the suture (I in Fig. 1b) resemble those forming a part of the Palaeozoic of the Istanbul nappe (normally located north of the suture: Fig. 2). The Almacik flake was previously interpreted by Şengör et al. (1985) from structural relationships as having undergone 110° clockwise rotation and it was suggested that the flake is a positive flower structure probably detached from its roots by this rotation.

To check this rotation we sampled the Eocene volcanics and sedimentary rocks located along the northern margin of the Almacik flake for palaeomagnetic analysis. Fig. 1 shows a simplified geological map of the flake and our palaeomagnetic sites.

Sampling sites were chosen in outcrops of known structural and stratigraphic position. Interbedded sediments
Figure 1. (a) Location map of the Almacık flake (modified from Honkura & Işikara 1988) and the trace of the Intra-Pontide suture. (b) Simplified geological map of the Almacık flake and palaeomagnetic sampling sites. Geological map is after Abdüsselamoglu (1959); S: Sakarya Continent fragment; I: Istanbul Nappe fragment.

occur at all the volcanic sites and provide precise bedding corrections. Ten sites, evenly distributed throughout the flake, were collected by hand-sampling and drilling methods. Four sites (ALM01-04) were located in the central part of the flake, in the vicinity of the village of Abazayatağ. Five sites (ALM05-09) were sampled between the township of Dikmen and Hendek near the western end of the flake. These sites are located in Eocene volcanics and marls. Finally, in the east, only one site ALM10 was sampled near the village of Muratbey from andesites.
3 PALAEOMAGNETIC ANALYSIS AND RESULTS

Each specimen was demagnetized either by alternating (AF) demagnetization steps of 5 to 40–50 mT or by heating to 550°C in steps of 50°C. Representative AF and thermal demagnetization results and the decay of the remanence intensity during progressive demagnetization are shown in Fig. 3. Best-fit method on Zijderveld plots is used to obtain cleaned remanence directions. Samples required thermal demagnetization revealing that the remanence has blocking temperatures up to 550°C. This blocking temperature and the fact that the remanent magnetization showed intermediate coercivity (as shown by AF demagnetization) suggest that this magnetization is carried by magnetite and/or titanomagnetite. The NRM of the samples was measured on a spinner magnetometer. The noise level of the equipment is $1 \times 10^{-4}$ A m$^{-1}$. Results of five out of 10 sites are presented in this paper: two sites taken from marls (ALM06-07) were rejected because of their low intensity ($0.5-1 \times 10^{-3}$ A m$^{-1}$) of magnetization. One site (ALM01) from the central part of the flake was also discarded because within-site scatter was too large. One volcanic site (ALM04, basaltic pillow lava), again from the central part of flake, shows intensive alteration on the basis of field observation and petrographic analysis. For this reason a detailed demagnetization procedure will be applied to this site and its results, therefore, are not available at present. In the eastern part of the flake, the only available site (ALM10) was rejected because of its low intensity of magnetization. The measured NRM intensities of the sampled volcanic rocks range from 0.13 to 3.80 A m$^{-1}$. Furthermore, thermal demagnetization was not as successful as AF treatment in eliminating

Figure 3. Typical demagnetization diagrams. Full circles: horizontal projection; open circles: vertical projection. The plots show tilt corrected magnetization vectors. The unit on the vector plot scales is $1.5 \times 10^{-1}$ A m$^{-1}$. 
secondary components at the three volcanic sites (ALM02, ALM05, ALM08). Thus alternating field demagnetization was favored for these sites. Thermal demagnetization was found to define the same vectors as AF treatment.

The two sites from the central part of the flake have reverse polarity and a mean declination of approximately 15°. One site on the western part of the flake is also of reverse polarity with a declination of 28°. Two sites in the same region yield normal polarity vectors with a mean declination of 232°, although grouping is not tight. These normal and reverse directions taken altogether indicate a significant rotation of the flake (Fig. 4a and b). Site mean directions are given in Table 1.

4 DISCUSSION AND CONCLUSION

It has been shown in the preceding section that the rocks sampled are magnetically stable, and their directions are palaeomagnetically reliable.

The tectonically corrected palaeomagnetic results of this study indicate a counterclockwise rotation of the Almacik flake at approximately 148°. This rotation must be post-Eocene since the rocks collected are Eocene in age. Outside the Almacik flake, around the Bolu province and northeast of it, a consistent pattern of declination direction indicating 20° counterclockwise has been observed (Sarbudak 1989). This suggests that the rotation of the Almacik flake has occurred independently from that of the surrounding regions.

A 212° clockwise rotation is favoured, rather than 148° anticlockwise because the block is completely surrounded by strands of the right-lateral North Anatolian Fault which originated in the late middle Miocene. A post-Eocene but pre-middle Miocene large-scale counterclockwise rotation of the block seems inconsistent with the geological evolution of the area. The dominant structure of post-Eocene age in this area is the right-lateral North Anatolian strike-slip fault (Fig. 5). As the separation of the Almacik flake occurred

### Table 1. Palaeomagnetic results from the Almacik flake.

<table>
<thead>
<tr>
<th>Site</th>
<th>Rock type</th>
<th>Before Correction</th>
<th>After Correction</th>
<th>Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALM02</td>
<td>Dacite</td>
<td>57.0 -66.1</td>
<td>348.2 -51.0</td>
<td>4.3</td>
</tr>
<tr>
<td>ALM03</td>
<td>Basalt</td>
<td>2.8 -37.8</td>
<td>42.8 -50.4</td>
<td>9.1</td>
</tr>
<tr>
<td>ALM05</td>
<td>Andesite</td>
<td>262.2 50.8</td>
<td>229.9 64.0</td>
<td>13.3</td>
</tr>
<tr>
<td>ALM08</td>
<td>Andesite</td>
<td>245.0 39.7</td>
<td>235.6 53.3</td>
<td>23.4</td>
</tr>
<tr>
<td>ALM09</td>
<td>Andesite</td>
<td>13.6 -10.5</td>
<td>28.2 -47.6</td>
<td>12.9</td>
</tr>
</tbody>
</table>

* Mean site direction after bedding correction (reverse directions are inverted through the origin); N = 5, D = 212°, I = 55.8°, K = 22.9, 95% = 16.3°. N is number of sites.
Substantial rotation of the Almacik flake

Figure 5. Schematic map showing the mean observed rotation ($D = 212^\circ$) within the Almacik flake indicated in the circle with number of sites ($N = 5$). Geological map is simplified from MTA, 1961–1964.

post-Miocene, bounded by two local strands of the right-lateral North Anatolian fault, it could only have rotated in a clockwise direction under the influence of the right slip of the North Anatolian fault (Fig. 5). This observation is consistent with recent theoretical models predicting substantial rotation along strike-slip zones (McKenzie & Jackson 1983; Sonder, England & Houseman 1986; Lamb 1987, 1988).

The narrower the zone taking up a given amount of strike-slip, the faster will be the associated rotations (Sonder et al. 1986). In our area of study the strike-slip zone is narrow and may thus have given rise to very substantial rotation (i.e. 200'). This implies here a rate of rotation of about 18° Ma$^{-1}$. This is a high rate, but seems very plausible in view of theoretical calculations suggesting rates similar to those measured in the southern Alps of New Zealand which could lead to rotation by 90° in 4 Ma (Englal 1988). This is an exciting conclusion that may have wide-ranging implications for the amount of total slip along the North Anatolian Fault zone which may be substantially larger than the 100 km so far suspected (Sengör et al. 1985), assuming that the Almacik flake has rotated rigidly about a vertical axis as a consequence of the vorticity of the underlying and continuously deforming lithosphere.

Applying the equations derived by McKenzie & Jackson (1983, see Appendix) we get $D = 2a\Phi$ ($D$, the total displacement along the shear zone; $\Phi$, rotation angle; $a$, width of the North Anatolian shear zone). We assume 'a' is equal to the spacing of the northern and the southern boundary strands of the Almacik flake, which is approximately 20 km, and $\Phi$ is 3.7 radians (212°). Thus the displacement $D$ is 148 km. However, this analysis is only valid for a rotating block with an equidimensional shape in plan view. Lamb (1987) has shown that if the rotating blocks have elongate shapes in plan, rotations take substantially longer. Applying this to the Almacik flake, which is longer than it is wide, the calculated displacement of 148 km must be an absolute minimum. This conclusion, however, seems to us an unrealistic figure since all the available geological data along the North Anatolian Fault zone suggest a total displacement of about 100 km (Sengör 1979) which decreases westward (Sengör, Burke & Dewey 1982).

We suggest that the model of McKenzie & Jackson (1983) may be inapplicable here and that the rotation may have been caused by the movement of the Almacik on a much narrower shear zone underneath, as suggested by the model of Gallo et al. (1980) implying a flower structure beneath the Almacik flake. We think that the regional geology, which shows thrust faults partially bounding the Almacik flake, is more consistent with such an interpretation.

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The equation \( D = 2\alpha \Phi \) was derived on the basis of the 'floating block' model of McKenzie & Jackson (1983). Blocks of crustal material of a size smaller than the width of the shear zone (width of shear zone = \( a \)), in which they are located, are modelled as isolated and rigid circular objects floating on a highly viscous fluid. If deformation is simple shear, then let \( W \) equal the rate of shear strain in the shear zone, across which the relative velocity is \( u \). Therefore \( W = u/a \). Under these circumstances McKenzie & Jackson (1983) and Lamb (1987) have shown that the rate of rotation about a vertical axis of the circular rigid object will be \( W/2 \). If deformation continues for a time \( t \), then the object will rotate through an angle (in radians) \( Wt/2 \), which equals \( \Phi \). The total displacement across the shear zone is \( ut \), which equals \( 2\alpha \Phi \).