Magnetic Anomalies Related to Active Folds in the North Anatolian Fault Zone

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(Received April 27, 1990; Revised July 4, 1991)

Measurements of the geomagnetic total intensity were carried out in the western part of the North Anatolian Fault Zone. In particular, profile measurements were made across some fold structures in the graben. The data show anomalies presumably related to active folds, although fold structures are not necessarily accompanied by magnetic anomalies. The anomalies are similar to those found along the active faults in the North Anatolian Fault Zone, and they could be interpreted in terms of a dike-like structure model as was the case for the anomalies associated with the active faults. This implies that folding may be a surface manifestation of faulting at depth.

1. Introduction

The North Anatolian Fault Zone (NAFZ) is a 1500 km long transform fault, and many right-lateral strike-slip faults exist in the zone. Its overall activity has been considered as direct evidence of relative motion between the Anatolian block and the Black Sea plate. Large destructive earthquakes have occurred repeatedly in the past along this fault zone (AMBRASEYS, 1970). The westward extension of NAFZ branches off at 30.6°E into two active fault zones, the northern and southern branches (e.g. DEWEY and ŞENGÖR, 1979; BARKA and HANCOCK, 1984; HERCE, 1985; BARKA and KADINSKY-CADE, 1988).

The northern branch constitutes a graben-like structure which is filled with Cenozoic sediments and is characterized by an extensional tectonic stress regime. As will be shown in the next section, many active fold structures have been found in the graben, although fold structures obviously imply compressional stress and disagree with the extensional stress regime (IKEDA *et al.*, 1989).

The magnetic anomalies found near the active fault constituting the southern branch could be well interpreted in terms of a dike-like structure, which in turn provided information on the surface extension of the fault plane as well as its dip angle (HONKURA *et al.*, 1985; IŞIKARA *et al.*, 1985). Folding may also disturb the subsurface magnetic structure and yield a magnetic anomaly to be observed at the Earth's surface.

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This is the motivation of our measurements of the geomagnetic total intensity in the northern branch of NAFZ.

2. Tectonic Setting

Tectonic characteristics of the northern branch of NAFZ have been discussed frequently by many authors (e.g. ŞENGÖR *et al.*, 1982; SİPAHIOĞLU and MATSUDA, 1986; IKEDA, 1988; IKEDA *et al.*, 1989). The Izmit-Sapanca fault zone, the northern branch of NAFZ as shown in Fig. 1, is a sedimentary trough as wide as 5–8 km. This portion of NAFZ is believed to be a transition zone from dominantly transcurrent motion in the east to the extensional tectonic regime in western Turkey and the Aegean Sea (DEWEY and ŞENGÖR, 1979; MCKENZIE, 1972; EVANS *et al.*, 1985). Focal mechanism solutions for microearthquakes occurring in the Izmit-Sapanca fault zone suggest that transtensional movements are dominant (EVANS *et al.*, 1985).

Fig. 1. Tectonic sketch map showing main characteristics of the westernmost portion of the North Anatolian Fault Zone (NAFZ). NAFZ west of 30.6°E branches into two fault zones; the Izmit-Sapanca fault zone and the Iznik-Mekece fault. Surface ruptures along the Mudurnu fault in association with the earthquakes of May 26, 1957 and July 22, 1967 are indicated by small dots (after AMBRASEYS and ZAPOTEK, 1969; AMBRASEYS, 1970). Focal mechanisms of these two earthquakes and the largest aftershock (July 30, 1967) of the July 22, 1967 earthquake are also shown (after MCKENZIE, 1972).

In the meantime, IKEDA *et al.* (1989) found some lines of evidence showing that the sediments filling the trough have been subjected to compressional deformation.

Fig. 2. Distribution of active folds and faults in the Izmit-Sapanca fault zone (eastern half). Note that the westward extension of the Mudurnu Valley fault is traceable along the basin margin from Almedie to Kizilirmaci (shown by a thick dashed line), but is not active in the late Quaternary. Slip on this portion of the Mudurnu Valley fault is likely to have been transferred to the folds and faults to the north.

Fig. 3. Distribution of active fold axes in the southeastern part of the Izmit-Sapanca fault zone. Measurements of the geomagnetic total intensity were made along profiles A-B and C-D. Topographic contours are given in 10 m.

Figures 2 and 3 show the distribution of active faults and folds. In particular, we should note many active folds in the Izmit-Sapanca fault zone, although we will not enter into details; more discussions are beyond our present scope and geomorphological information will be given elsewhere (Ikeda *et al.*, in preparation). Contradiction between compressional stress as implied by the geomorphologically inferred fold structures, and extensional stress as indicated by focal mechanism solutions, and also by the overall geological structure, should have a very important bearing on tectonics in this region. Information on the subsurface structure must be one of the essential points in this problem.

3. Measurements of the Geomagnetic Total Intensity

Figure 3 also shows two profiles, along which the geomagnetic total intensity was measured, in the area east of the Sapanca Lake, whereas Fig. 4 shows a profile in the area west of the Sapanca Lake. We selected these profiles simply because magnetic measurements seemed to be easily made along a nearly straight line crossing the fold axis. Total intensity values are shown in Fig. 5; these values are relative to the total intensity at one of the continuous stations which have been in operation in the southwest of the present area, and daily variations are almost completely removed.

Fig. 4. Profile E-F for magnetic measurements and a fold axis at Rahmiye. Topographic contours are given in 10 m.

In order to interpret these anomalies, we consider a two-dimensional inclined dike-like body. The two-dimensional treatment would be justified, because we deal with the fold structure which can be approximated by a two-dimensional feature. We used the method of calculation, originally proposed by TELFORD *et al.* (1976), which is also described in WON (1981) and IŞIKARA *et al.* (1985). For calculations, we first made cubic-spline interpolation for the data gap due to power lines and a bridge and then took nine-point moving averages for C-D (Kizilbayır) and E-F (Rahmiye) profiles because small-scale fluctuations for these profiles obscure the overall trend.

For these data, we applied a vertical dike model with appropriate parameter values and obtained an approximate model. Starting with this approximate model, we derived the best fit model by an iterative inversion scheme (WATANABE, 1984). Parameters to be determined are the magnetic susceptibility, the dip angle, the depth, the thickness, and the location of a dike relative to the profile. The normal value of the total intensity in the area is also taken as a parameter. Portions surrounding a dike-like structure is regarded as being non-magnetic and also the direction of magnetization is assumed to be the same as that of the ambient magnetic field of the Earth; in this region the inclination is about 55° .

Fig. 5. The distribution of the geomagnetic total intensity along profiles A-B, C-D and E-F.

3.1 Analysis of the magnetic anomaly observed at Küçücek

The geomagnetic total intensity was measured along the profile A-B as shown in Fig. 3. In the southeast, a topographic feature indicative of a fold structure was observed and the profile is likely to cross the fold axis. The data obtained at Küçücek are shown in Fig. 5. The distribution of the total intensity shows a positive peak and its location is close to the fold axis as shown in Fig. 4. The result of the iterative

inversion analysis for this profile is seen in Fig. 6. The rms error for the model which can best explain this anomaly is about 10 nT. It turns out that a magnetic body having a susceptibility of $6.37 \times 10^{-4} \text{ emu/cm}^3$ exists at a depth of about 300 m and dips to the southwest with the angle of 54° . The thickness is insignificant and the northeastern boundary can extend further to the northeast.

Fig. 6. Geomagnetic total intensity values (dots) observed at Küçücek and the distribution of the total intensity (solid line) derived from the best fit 2-D magnetic dike-like structure model. The arrow indicates the fold axis.

We examined the reliability of the estimated parameters by changing one specific parameter value with the others fixed at the values for the optimum model. If a residual twice as large as the one for the optimum model is considered allowable, a change of 20~30% is acceptable for the susceptibility, $10\sim 15^\circ$ for the dip angle, 100~200 m for the boundary location. The depth is not well constrained if the optimum depth is greater than a few hundred meters. The dip angle is fairly reliable and hence useful for discussing the fault structure. The boundary location is also well constrained, since misfits for models deviated from the optimum model are overall shifts and such models are hardly acceptable as reliable ones. The extension of the southwestern boundary of the magnetic body to the surface seems to correspond to the fold axis shown by the arrow in Fig. 6. We here interpret the southwestern boundary as indicating a fault plane and then the fold structure at the surface can be considered to be a manifestation of undulatory deformation, caused by fault displacement, in a rather thick sedimentary layer.

3.2 Analysis of the magnetic anomaly observed at Kizilbayir

The total intensity was measured along the profile C–D as shown in Fig. 3, about 3.5 km west of Küçücek. The data obtained at Kizilbayir are shown in Fig. 5. The model derived from the iterative inversion analysis for this profile is shown in Fig. 7. For this profile, the rms error is about 1.3 nT. The magnetic body is located at the depth of about 360 m, but this estimate is not well constrained. Its susceptibility is fairly low amounting only to 1.13×10^{-4} emu/cm³. It dips to the northeast with the angle of 67°. The thickness of the body is also determined from the inversion scheme, but the southwestern boundary is obviously of little significance.

In this case, the northeastern boundary of the magnetic body coincides with the fold axis shown by the arrow in Fig. 7. This is another example showing a possible association of a surface fold structure with a fault at depth.

Fig. 7. Nine-point running averages of the geomagnetic total intensity (dots) observed at Kizilbayir and the distribution of the total intensity (solid line) derived from the best fit 2-D magnetic dike-like structure model. The arrow indicates the fold axis.

3.3 Analysis of the magnetic anomaly observed at Rahmiye

The total intensity was also measured along the profile E–F shown in Fig. 8. The geomagnetic total intensity data obtained along the profile crossing the fold axis, which runs in the northeast-southwest direction, are shown in Fig. 5. The result of the iterative inversion analysis for this profile is shown in Fig. 8 together with the running average data. The rms error is about 5.6 nT. The magnetic body having a susceptibility of 5.05×10^{-4} emu/cm³ is located at the depth of about 130 m and dips to the northwest direction. Again the southeastern boundary is meaningless.

In Fig. 8, the relation between the fold axis shown by the arrow and the north-western boundary of the magnetic body is not very obvious, but a discrepancy of only a few hundred meters can be ascribed either to slight modification of surface topography or to poor resolution in magnetic modeling, or to both.

Fig. 8. Nine-point running averages of the geomagnetic total intensity (dots) observed at Rahmiye and the distribution of the total intensity (solid line) derived from the best fit 2-D magnetic dike-like structure model. The arrow indicates the fold axis.

4. Discussion and Concluding Remarks

We have shown the results of geomagnetic total intensity measurements in the northern branch of the North Anatolian Fault Zone. In this area, some magnetic anomalies seem to be related to fold structures. However, fold structures are not necessarily accompanied by magnetic anomalies; in fact, no notable magnetic anomaly was found from measurements of the geomagnetic total intensity which were made along a profile crossing many fold axes shown in the northwest corner of Fig. 3. We can easily attribute such a case to weak magnetization of basement rocks. They are unlikely to yield a significant magnetic anomaly even if they are affected by faulting or folding.

At first we may ascribe the magnetic anomalies to an undulatory magnetic layer associated with folding, but the typical scale length is different and this possibility is ruled out. Magnetic anomalies observed at Küçücek, Kizilbayir and Rahmiye were all interpreted rather in terms of a dike-like structure, although one of the boundaries of the model structure is insignificant and may be extended further away. We further interpret the boundary as indicating a fault plane. In order for a fault displacement beneath the sedimentary layer to result in a fold structure at the surface of the layer, the topographically lower side should be upheaved; fold structures shown in Figs. 3 and 4 can all be interpreted in such a way.

If the above condition is applied to the three fault models, the fault plane shown in Fig. 6 should represent normal faulting, whereas the planes shown in Figs. 7 and 8 should correspond to thrust faulting. Usually, surface folding can be associated with

thrust faulting at depth (STEIN and KING, 1984; STEIN and YEATS, 1989). The three cases shown above may not be an example of such a large-scale structure but rather a local phenomenon reflecting secondary deformation of sediments caused by faulting below the sediments.

Our interpretation of the magnetic anomalies related to surface fold structures indicates the existence of thrust faulting as well as normal faulting in the İzmit-Sapanca area. This interpretation agrees partly with the extensional stress regime and also partly with the compressional stress regime. This apparent contradiction may be understood if vertical displacement is secondary and a dominant feature is strike-slip movement. This is only a possibility and more studies are obviously needed to confirm this possibility.

We are thankful to the anonymous referees for their valuable comments. This work was supported by the Ministry of Education, Science and Culture, Japan, under International Scientific Research Program Nos. 61041029, 62043026, 63041054 and by Boğaziçi University under Project 88T0255.

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