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Determination of the 30-year creep trend on the Ismetpaşa segment of the North Anatolian Fault using an old geodetic network

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The Ismetpaşa segment of the North Anatolian Fault was ruptured during both the 1944 ($Mw = 7.2$) Gerede and 1951 ($Mw = 6.9$) Kurşunlu earthquakes. The field studies carried out in the aftermath of these two major earthquakes showed that the Ismetpaşa segment had experienced a creep movement. To monitor the surface creep, a geodetic network with six control points was established on the segment. This network was observed three times—in 1972, 1982 and 1992. Based on our evaluations of those observations, the creep on the segment was geodetically determined to be 1.02 cm/year (1972–1982) and 0.93 cm/year (1982–1992) respectively. In 1999, the North Anatolian Fault experienced two major shocks—the $Mw = 7.4$ Gölcük and $Mw = 7.2$ Düzce earthquakes—both on the western part of the Ismetpaşa fault. Using the global positioning system, our surveying team observed the network one more time in 2002 to assess whether these earthquakes affected the creep of the Ismetpaşa segment, or not. The evaluation of the observations revealed a creep of 0.78 cm/year for the period 1992–2002. This result reveals that the creep of the segment has decreased in a linear fashion between 1972 and 2002 and that it had not been triggered by the Gölcük and Düzce earthquakes.

Key words: Crustal movement, earthquake, geodetic networks, geodetic surveys.

1. Introduction

Turkey is located at a tectonically very active region which frequently experiences destructive earthquakes. In this region, the activity is due to a squeezed wedge between the Arabian and African tectonic plates moving northward and the relatively stable Eurasian plate. The wedge, which is known as the Anatolian block and which incorporates much of Turkey, is being squeezed westward. On a large scale, this movement is controlled by the collision of the Arabian and Eurasian plates (McKenzie 1972; Sengör, 1979; U.S. Geological Survey, 1999).

The boundaries of the Anatolian block with the Eurasian plate are formed in the north by the North Anatolian fault (NAF) (Fig. 1). This fault, which runs from the border of Iran to the Marmara Sea, a length of about 1200 km, is one of the most active strike-slip faults (2.2 cm/year slip rate; McClusky *et al.*, 2000) in the world and has experienced 12 major earthquakes ($Mw > 6.7$) since 1939 (Stein *et al.*, 1997). However, the Anatolian motion and, most likely, the NAF slip rate are not constant along the length of the fault. Recent large-scale studies based on global positioning system (GPS) measurements indicate velocities varying from 1.7 to 2.7 cm/year across the different branches of the NAF (McClusky *et al.*, 2000; Reilinger *et al.*, 2000; Provost *et al.*, 2003). The reason for this discrepancy is the progressive deformations that can be experienced at the surface points approaching the fault line. It is well known that while the majority of active faults are locked, some faults creep throughout the seismogenic layer or within a shallow depth (Cakir *et al.*, 2005). In this respect, data obtained from both near-field studies and large-scale ones are very crucial to our understanding of fault behaviors and, hence, to an accurate assessment of seismic hazards (Malservisi *et al.*, 2003; Bilham *et al.*, 2004). Such investigations on the NAF were first initiated on the Ismetpaşa fault segment, which had been ruptured by two major earthquakes, the 1944 $Mw = 7.2$ Gerede earthquake in its western tail and the 1951 $Mw = 6.9$ Kurşunlu earthquake in its eastern tail (KOERI, 2004). During the course of these investigations, it was realized that the wall of the train station in Ismetpaşa, a small town located 350 km east of Istanbul and 100 km northwest of Ankara, was showing an offset. This offset was subsequently determined to have been caused by the creep movement, which is an aseismic fault slip. Measurements taken between 1957 and 1969 revealed that the wall showed a 2 cm/year offset during this period (Ambraseys 1970). This value was compatible with the movement rate of Anatolian block given above. Following these initial measurements, offset in the period of 1969–1978 was determined to be 1.1 cm/year, which is one order of magnitude smaller than the yearly motion rate of the Anatolian block, based on data obtained from a triangulation network on which angular measurements are conducted (Aytun 1982). The General Command of Mapping of Turkey then established a second geodetic network across the Ismetpaşa fault to determine surface creep by means of the trilateration method based on distance measurements between the network points. The three successful observations on this network were carried out by different survey groups in 1972, 1982 and 1992 (Ugur, 1974; Deniz *et al.*, 1993). Based

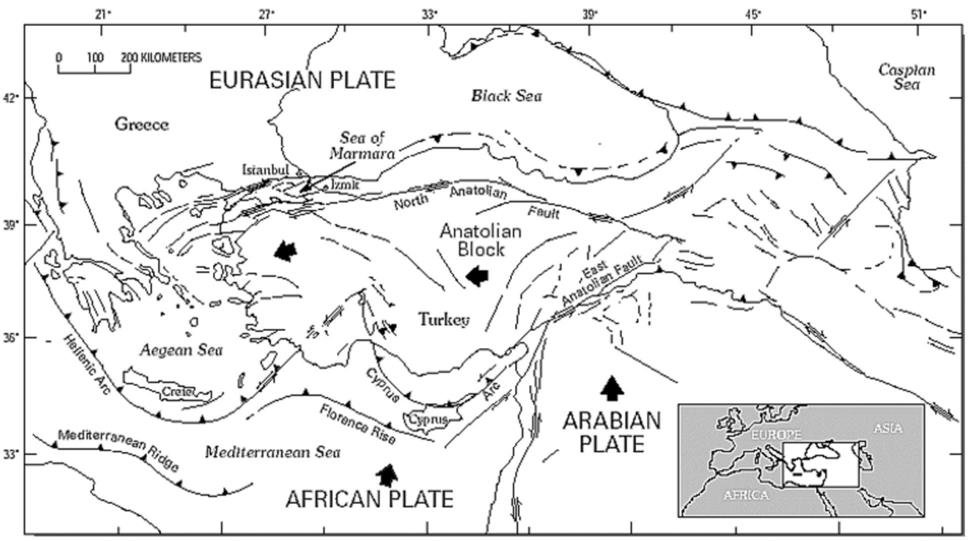

Fig. 1. Tectonic map of Turkey (Barka and Kadinsky-Cade, 1988).

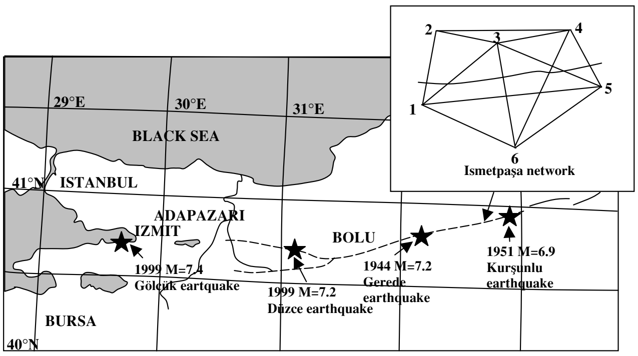

Fig. 2. Map of the NAF around the Marmara and the Northern Black Sea region (adapted from Deniz *et al*., 1993). The inset map shows the Ismetpaşa geodetic network. Scale of the inset map: the distance between the points 1 and 5 represents 1.2 km in the field. The dashed line is the trace of the NAF. The stars locate the major earthquakes that occurred in the last century.

on those observations, the average offsets on the segment were determined to be 1.1 cm/year and 0.9 cm/year for the periods of 1972–1982 and 1982–1992, respectively. All of these studies showed that the fault creep on the Ismetpaşa fault had progressively slowed down with time.

In 1999, two major earthquakes, Gölcük ($Mw = 7.4$) and Düzce ($Mw = 7.2$), occurred west of the Ismetpaşa segment (Fig. 2). These earthquakes were judged to be capable of changing the creep trend on this segment and, consequently, it was decided to resurvey the network established by the General Command of Mapping. This decision was based on two rationales: (1) information on the creep history of the segment was available since 1972; (2) the computational strategy applied in each period was well known and as such, a new period of observations could be readily integrated with previous ones. On the basis of these rationales, any possible variation could be deduced by a new surveying campaign on this network. Two important studies were carried out by other research groups during the period of the resurvey. In those studies, a triggered creep on the Ismetpaşa segment was claimed by Dogan *et al*. (2002), but refuted by Cakir *et al*. (2005) on the basis of InSAR observations. Those conflicting deductions presumably attracted attention to our study, re-affirming the desire of the General Command of Mapping to confirm whether a triggered creep exists or not.

Within this framework, the study reported here evaluates the observations made in 2002 carried out in the network in the same manner as in the previous observation periods in 1972, 1982 and 1992. By comparing the results from the consecutive periods, we were able to model changes in the offsets of the network points by means of a regression analysis to determine whether the last two earthquakes affected the segment, or not. Based on the offsets of the network points, the amount of surface creep on the Ismetpaşa segment was determined by means of extrapolation. We then compared the result with those obtained from other studies carried out in the different time intervals.

2. Periodical Observations on the Geodetic Network and their Evaluations

Creep is an aseismic fault slip which may be stable and continuous, or temporally and spatially episodic (Yamashita, 1973; Evans *et al*., 1981). It can occur in a shallow depth from the earth surface or all the way to the bottom of the brittle crust. Its rate is proportional both to the depth at which it occurs and to the rate at which shear stress is applied to the fault (Bilham*et al*, 2004). The amount of offset at the surface trace of the fault due to this creep movement can be determined by applying geodetic measurements.

In order to monitor the horizontal offsets across the Ismetpaşa segment of the NAF, a micro-geodetic network, named the Ismetpaşa trilateration network, was established with six control points, three of which are on the Eurasian plate and the remaining three are on the Anatolian block (Fig. 2). The first period of observations on this network were performed in 1972 by measuring the slope distances between the network points using the technique of electromagnetic distance measurement (EDM) which is a classical (terrestrial) surveying method. These slope distances were reduced onto the sea level (i.e. geoid), which is the common reference surface, using the height information of the network points. These elevations were available from previous campaigns, possibly obtained by altimeter observations since elevations approximated to meter accuracy are usually adequate for the reduction of slope distances to sea level. The reduced distances were then projected onto the Gauss-Krüger projection plane, which had been chosen as the horizontal computation surface (Bomford, 1965; Kuang 1996). Since this process requires approximate point coordinates, a local coordinate system in which the coordinates (y, x) of the point 1 were taken to be 1000 and 1000, respectively, was defined on the Gauss-Krüger projection plane. In order to weight the observations, the function $p_i = 1/s_i^2$ (p_i = weight of ith observation, s_i = distance in kilometers), which is the most common function used for trilateration networks, was taken into account as the stochastic model (Ugur, 1974). Using the observation equations and the weights obtained in this fashion, the horizontal coordinates of the network points were estimated by the least squares adjustment. During the adjustment process, the network datum was defined by inner constraints with respect to the points on the Eurasian plate. The reason for doing so was to monitor the offsets at the points on the Anatolian block relative to the Eurasian plate (Ugur, 1974).

Two subsequent observations, in 1982 and 1992, respectively, were carried out on the network. It is well-known fact that a rigorous deformation analysis requires that the same computational procedures be followed in all the periods of observations—i.e. the adjustment has to be carried out on the same surface, using the same approximate coordinates for the network points to enable that all the solutions refer to the same datum, thereby providing comparable stochastic characteristics for the observations, among other parameters. Therefore, the computation procedure used in the first period was followed exactly for the observations in the 1982 and 1992 periods (Deniz *et al.*, 1993; Eren, 1984). The only difference between the 1992 and 1982 observations was that point 5 had to be taken out of the former surveying plan because it had been destroyed during this time interval. Since point 5 was the object point—i.e. it was not used in the inner constraint of the adjustment to define the network datum—its absence did not constitute a problem with respect to the consistency of the solutions from the different observation periods.

Following the Gölcük and Düzce events, one more observation campaign was planned for the available points in the Ismetpaşa network and performed by our surveying team in 2002, but this time using a different and modern surveying technique—GPS. For the GPS campaign, 1-hour site occupation in static mode of relative positioning was regarded to be adequate to obtain sufficient precision in order to monitor the offsets of 10 years. Using the relative positioning technique of GPS, absolute and relative coordinates and slope distances can be determined on the earth surface. Absolute and relative coordinates from GPS refer to GPS's own coordinate system (World Geodetic System 1984). However, the slope distances in three-dimensional space are independent of datum and can therefore be evaluated in any local terrestrial coordinate system. In this respect, the GPS-defined slope distances given in Table 1 can be adjusted in the same surface and the same datum as was done in the previous periods.

Table 1. Slope distances from GPS campaign of 2002 and their precision.

From_to	Slope distance (in meters)	Precision (in milimeters)
1_2	467.0006	2.1
1_3	636.0370	3.9
1_6	697.3051	2.4
2_3	394.6544	3.8
2_4	849.5194	3.4
2_6	914.1582	3.0
3_4	464.4200	4.1
6_3	703.2374	4.6
6_4	827.1253	3.9

In order to eliminate the possible scale difference caused by applying a different surveying method, the Helmert transformation was applied to the results after the adjustment. Accordingly, we have reached a common solution for the network over a period of the 10 years since 1972. Table 2 lists the horizontal coordinates obtained in the period of 2002 together with those obtained from the previous periods.

3. Analysis of the Results

As seen from Table 2, significant offsets are present in the coordinates of points 1 and 6, which are located on the Anatolian block. The magnitudes of these offsets are given in Table 3 and are visualized in Fig. 3.

It is clear from Table 3 and Fig. 3 that the directions of the offsets in each period are parallel to the fault and westward in accordance with the movement characteristics of the NAF. The magnitudes of the offsets that have occurred since 1972 were found to be 26.6 cm for point 1 and 25.3 cm for the point 6. However, it is quite apparent that the magnitudes tend to decrease drastically in each period. Using the values in Table 3, we deduced the following equations for the magnitudes of the offset at points 1 and 6 using regression coefficients of 99.6 and 100%, respectively:

$$d_{1(\mathrm{cm})} = 12.12 - 0.162\Delta t \qquad (1)$$

$$d_{2(\mathrm{cm})} = 13.16 - 0.237\Delta t \qquad (2)$$

where $t = (t - t_0)$, t is time in years and t_0 is the reference epoch for which the year 1972 has been taken.

It is known that unless the fault creeps freely to the bottom of the brittle crust (i.e. no frictional resistance), the amount of the offset across a creeping fault will decrease naturally as one goes away from the fault. As seen from Table 2 and the above equations, the offset at point 6 remains systematically smaller than that at point 1, implying that surface creep is superficial. In this case, we can estimate the magnitude of surface creep by extrapolating the offsets of these two points to the fault trace. In this way, the surface creep for the Ismetpaşa segment is extrapolated

Table 2. Horizontal coordinates of the Ismetpaşa geodetic network points from the periodical observations.

	Points on the Eurasian plate					
	2		3		4	
Period	$y \pm m_y$ $[m] \pm [mm]$	$x \pm m_x$ $[m] \pm [mm]$	$y \pm m_y$ $[m] \pm [mm]$	$x \pm m_x$ $[m] \pm [mm]$	$y \pm m_y$ $[m] \pm [mm]$	$x \pm m_x$ $[m] \pm [mm]$
1972	1457.098 ± 1	905.474 ± 1	1568.853 ± 2	1283.825 ± 2	1825.609 ± 1	1670.274 ± 2
1982	1457.098 ± 1	905.474 ± 1	1568.852 ± 2	1283.823 ± 2	1825.605 ± 1	1670.266 ± 2
1992	1457.098 ± 2	905.474 ± 2	1568.854 ± 3	1283.825 ± 3	1825.609 ± 3	1670.274 ± 3
2002	1457.100 ± 1	905.473 ± 1	1568.850 ± 1	1283.827 ± 1	1825.610 ± 1	1670.273 ± 1

	Points on the Anatolian block			
	1		6	
Period	$y \pm m_y$ $[m] \pm [mm]$	$x \pm m_x$ $[m] \pm [mm]$	$y \pm m_y$ $[m] \pm [mm]$	$x \pm m_x$ $[m] \pm [mm]$
1972	999.936 ± 2	1000.007 ± 3	999.937 ± 2	1697.193 ± 2
1982	999.870 ± 4	999.926 ± 4	999.879 ± 3	1697.102 ± 3
1992	999.811 ± 3	999.858 ± 4	999.821 ± 3	1697.041 ± 4
2002	999.763 ± 1	999.804 ± 3	999.778 ± 2	1696.999 ± 2

Table 3. Offsets at the network points on the Anatolian Block.

Periods	Point No	$dy \pm m_{dy}$ [cm]	$dx \pm m_{dx}$ [cm]	$d = \sqrt{dy^2 + dx^2}$ [cm]	$= \arctan(dx/dy)$ [°]
1972–1982	1	-6.6 ± 0.5	-8.1 ± 0.5	10.4 ± 0.5	230.83
	6	-5.8 ± 0.4	-9.1 ± 0.4	10.8 ± 0.4	237.49
1982–1992	1	-5.9 ± 0.5	-6.8 ± 0.6	9.0 ± 0.6	229.05
	6	-5.8 ± 0.4	-6.1 ± 0.5	8.4 ± 0.5	226.44
1992–2002	1	-4.8 ± 0.3	-5.4 ± 0.5	7.2 ± 0.4	228.52
	6	-4.3 ± 0.4	-4.2 ± 0.5	6.1 ± 0.5	224.39

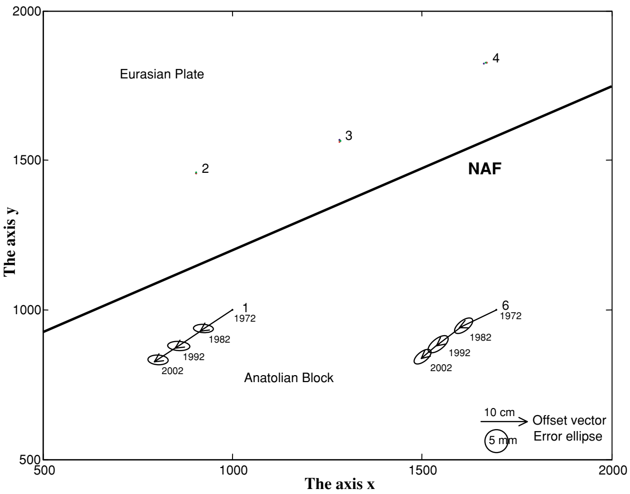

Fig. 3. Surface displacements at points 1 and 6 relative to Eurasian plate since 1972. The axes are plotted on the Gauss-Krüger projection plane. The arrows and ellipses are the offsets and the error ellipses of the offsets, respectively. The scales are shown at the right lower corner. The solid line is the NAF.

to 10.2 ± 0.6 cm for the period 1972–1982, 9.3 ± 0.7 cm for the period 1982–1992 and 7.8 ± 0.5 cm for the period 1992–2002. Using these values, we can provide the following linear equation with the regression coefficient of 98% for the surface creep between 1972 and 2002:

$$d_{s(\mathrm{cm})} = 11.50 - 0.120\Delta t. \tag{3}$$

All of these findings show that surface creep at the Ismetpaşa segment has been decreasing in a linear trend since 1972. If the creep started in the aftermath of the 1944 or 1951 earthquake, this trend may continue until the creep ceases. However, this may not be the case if the creep was already present before these earthquakes and its rate was increased by either of these events.

4. Discussion and Results

In this study, the surface creep on the Ismetpaşa segment of the NAF after both major earthquakes in 1999 was determined on the basis of periodical observations of an old trilateration network. The GPS observations of the network, conducted in 2002, were successfully evaluated in the same datum as that of the previous observation periods, 1972, 1982 and 1992. When the results obtained from the analyses were compared to those in 1992, the offsets of 0.72 ± 0.04 cm/year and 0.61 ± 0.05 cm/year were derived for the points on the Anatolian block. Even though these values are rather smaller than the Anatolian motion rate given in Introduction of this paper, they are very consistent with those obtained for the previous periods, such that the offsets can be expressed by the linear equations given by Eqs. (1) and (2). In this respect, it can be said that the creep rate on the Ismetpaşa segment has not changed after the 1999 earthquakes, thereby confirming the deductions of Cakir *et al*. (2005).

Based on the results presented in detail in the previous section, the size of the offset is smaller at the farther point from the fault—i.e. at point 6—than at the other point. This signifies that the fault creep occurs at a shallow depth, which is in agreement with the inference of Cakir *et al.* (2005). In this respect, the surface creep rates for the periods of 1972–1982, 1982–1992 and 1992–2002 can be estimated to be 1.02 ± 0.06, 0.93 ± 0.07 and 0.78 ± 0.05 cm/year, respectively, by an extrapolation using the offsets at network points 1 and 6. These values denote a linear decrease in the creep rate which has been going on since the 1970s. As shown in Fig. 4, this event is verified by other studies (Aytun, 1982; Altay and Sav, 1991; Cakir *et al*., 2005). The isolated exception is encountered in the first report on the creep by Ambraseys (1970), which is represented by a solid circle in the figure. The fault slip rate after an earthquake decreases logarithmically with time (Smith and Wyss, 1968; Wallace and Roth, 1968; Harsh, 1982; Ergintav *et al*., 2002). In this respect, as the time at which observations are conducted on faults approaches the breakout of an earthquake, creep rates of faults are presumed to be larger. This may explain why the creep rate obtained from the first study on this segment by Ambraseys (1970) is much different from the other rates in the figure. Nonetheless, long after the earthquake, the change in creep rate may appear to decrease linearly. The creep rate at the Ismetpaşa fault that is shown in Fig. 4 indicates that it has been in its linear decreasing phase since 1970s.

Being in the linear decreasing phase does not necessarily mean that the creep will cease in the future. If the fault creep started after the 1944 or 1951 earthquake it might be transient (scenario 1), or if the creep on the fault was already present and increased as a result of any of these earthquakes it might now be decreasing down to its pre-earthquake rate (scenario 2). In addition, Sylvester (2004) suggests that the long-term rate of creep may vary before or after earthquakes along the creeping fault segment. Since the studies at the Ismetpaşa segment were first started in

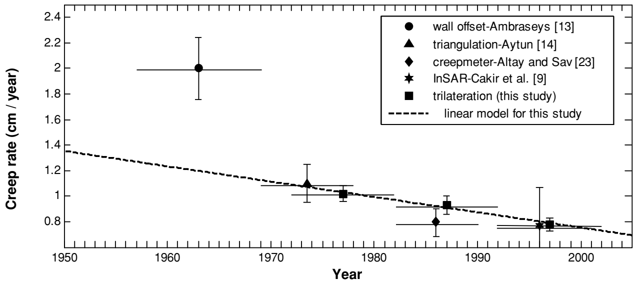

Fig. 4. Creep rates for the Ismetpaşa segment obtained from different studies (adapted from Cakir *et al*., 2005). Horizontal bars represent the time window. Vertical bars show the error ranges.

1957, we are not certain which scenario will turn out to be the right one. Therefore, it is crucial to monitor the creep using this geodetic network in order to understand how the fault mechanism will progress.

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