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Creeping along the Ismetpasa section of the North Anatolian fault (Western Turkey): Rate and extent from InSAR

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Abstract

Creeping along the North Anatolian fault (NAF) at Ismetpasa (Turkey) was discovered some thirty years ago, about a decade after the first observations of the phenomenon along the San Andreas fault in California. However, little is known about its lateral extent and rate. In order to study its three dimensional nature and rupture characteristics, we use Synthetic Aperture Radar Interferometry (InSAR) and elastic dislocation models compared also with field observations. Interferograms with temporal baselines ranging between 1.25 and 5 years show that the creeping section starts at the western termination of the 1943 (M=7.6) earthquake rupture. It continues about 70-km to the west, overlapping with the eastern part of the 1944 (M=7.3) earthquake rupture. Offsets along strike indicate a maximum creep rate of 11 ± 3 mm/year near the mid point of the creeping section decreasing gradually towards the edges. Near Ismetpasa, InSAR data yield 8 ± 3 mm/year of creep rate, consistent with recent instrumental (triangulation and creepmeter) measurements. Modeling of the InSAR and GPS data suggests that the fault-creep occurs most probably at a shallow depth (0-7 km). Our analysis combined with previous studies suggests that creeping might have commenced following the 1944 earthquake, and thus may be a long-lasting, but transient slip episode. © 2005 Elsevier B.V. All rights reserved.

Keywords: Fault creep; InSAR; Ismetpasa; North Anatolian fault

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1. Introduction

While the majority of active faults are locked, accumulating strain over a long period of time and hence producing earthquakes, some faults freely slip at the surface. This slow aseismic slip, called fault creep, may occur at varying scales and rates. In some

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cases, faults are thought to creep throughout the seismogenic layer at a rate comparable to the geologically determined slip rate and cannot therefore generate large earthquakes (e.g. central San Andreas fault; [1,2]). In other cases, fault-creep appears to take place within a shallow depth interval and/or at a rate slower than the overall slip rate, and hence does not prevent the fault from producing moderate-to-large size earthquakes (e.g. southern and northern Hayward fault; [3,4]). Therefore, the rate and extent of faultcreep along strike and depth are key parameters to assess seismic hazard, and to understand faulting behavior and the earthquake cycle [5,6].

Although creeping along the North Anatolian fault (NAF) at Ismetpasa (Fig. 1) was discovered over thirty years ago [7], about a decade after the first observation of the phenomenon in the U.S.A. [8], little is known about its three dimensional nature. To date, no observations indicative of fault creep at other sites along this section of the NAF have been reported. In this study, we use Synthetic Aperture Radar Interferometry (InSAR) with 10 years of data collected by the European Space Agency's ERS satellites to deduce the extent of the creep and its variation along strike in time and space. InSAR can map ground deformation at a high spatial resolution with sub-centimeter precision [9], and has been successfully used to study fault-creep along the San Andreas, Calaveras and Hayward faults [10-14]. The interferograms obtained in this study include atmospheric effects and have generally low coherence due to the vegetation cover and long temporal baselines necessary to monitor long-term surface changes [15]. Nevertheless, we are able to detect clear signals of the fault-creep and measure its rate all along the fault owing to numerous SAR images used. We model the InSAR data along with the available GPS data [16] using rectangular dislocations in an elastic half-space to determine the depth to which creep occurs. Finally, we discuss the relationship between fault segments, earthquake generation and the fault interactions.

2. Creep on the North Anatolian fault at Ismetpasa

The North Anatolian fault is one of the most seismically active structures in the eastern Mediterranean with a slip rate of 22 ± 3 mm/year [16]. With the

conjugate East Anatolian Fault, it accommodates the westward motion of the Anatolian block relative to Eurasia resulting from the collision between the Arabian and Eurasian plates and the trench pull along the Hellenic subduction zone in the Aegean (Fig. 1). A sequence of eight M > 7 westward-migrating earthquakes ruptured ~900 km of the North Anatolian fault from 1939 to 1999, beginning from the Karliova triple junction in the east, to the Sea of Marmara region, in the west. The creeping section of the NAF at Ismetpasa ruptured with surface breaks twice within 7 years; first in the M=7.3 1944 Bolu-Gerede earthquake and later in the M=6.9 1951 Kursunlu earthquake [7,17,18]. According to Ambraseys [7], the Ankara-Zonguldak railway at Ismetpasa was displaced by about 1.5 m during the 1944 earthquake. In the following 6 years, the fault at same site manifested aseismic surface slip of about 0.3 m before rupturing again during the 1951 earthquake [7]. Detailed surface slip distributions of these earthquakes are not known. However, it is thought that part of the ~50-km-long low slip section (<1.5 m) of the 1944 rupture to the east of Ismetpasa was re-ruptured by the 1951 earthquake [7,18,19,20].

Since the observation of an offset wall at the railway station in the town of Ismetpasa (Fig. 2), numerous measurements have been performed to deduce the rate of creep. Based on the measurement of this wall, Ambraseys [7] was the first to report a creep rate of about 20 mm/year for the period between 1957 (i.e. construction date of the wall) and 1969. Instrumental measurements (i.e. local triangulation networks and creep-meters) between 1982-1992 at this site have later shown that the creep rate is 7.7 ± 1.1 mm/year [17,21,22]. Data from another small triangulation network installed about 40 km west of Ismetpasa in Gerede (Fig. 1) indicate that no significant movement was taking place across the fault between 1982 and 1991 [12]. Therefore, fault-creep ceases to the west somewhere between Gerede and Ismetpasa. Except for the village of Ismetpasa, there is no urban site through which the fault runs. Thus, the extent and variation of creep along the fault cannot be deduced without instrumental measurements. Earthquake scaling laws [23], seismicity streaks [24], and repeating microearthquakes [4,25] may help one detect creeping sections of faults, but the present day seismic network is too sparse to study the microseismicity in this region.



Fig. 1. Map of the North Anatolian Fault (NAF) in the Sea of Marmara region [20] with the rupture segments of the large earthquakes that occurred in the last century. Arrows are GPS observed and modeled vectors relative to the Eurasian plate [16]. The dashed rectangle is the ERS image frame. The inset map shows the schematic plate configurations (Eu=Eurasia, Ar=Arabia, An=Anatolia, EAF=East Anatolian Fault).



Fig. 2. Photographs showing the warped and offset wall (40 cm) due to fault-creep in the Ismetpasa train station (September 2004, view towards the north). Note the extension of the wall due to the oblique cross cutting relationship between the wall and the fault in the inset photograph.

Dogan et al. [26] observed some fissures and cracks that show right-lateral slip of up to 6 cm at several new sites around the town of Ismetpasa after the 1999 Izmit earthquake. They conclude that a creep event was triggered by the distant 1999 Izmit earthquake (Fig. 1) as a result of passage of large-amplitude surface waves [27]. The effects of nearby earthquakes on a creeping fault have long been known [28] and have been confirmed by instrumental measurements such as creepmeters [29,30] and InSAR [11]. Therefore, creep events may also have taken place after the Mw 7.2, Düzce (November 12, 1999) and Mw 6.0, Orta (June 06, 2000) earthquakes. The epicenter of the latter event is very close (~25 km) to the Ismetpasa fault section and its coseismic fringes can be observed in several interferograms (e.g. Fig. 3a). Therefore, using InSAR we also aim to investigate the triggered slip inferred by Dogan et al. [26], and characterize the nature of creep and the effects of the recent nearby earthquakes. We shall later discuss the nature of creep inferred from the previous measurements and this study.

3. InSAR observations

We calculated more than 20 interferograms from SAR images acquired in the descending mode of ERS satellites between 1992 and 2002 using the SRTM 3-arcsecond (~90m) data for the removal of topographic phase. Of these, only seven interferograms have usable data (Fig. 4). One of the main restrictions on obtaining high-quality interferograms is the temporal decorrelation resulting from changes in the target scene due to erosion, vegetation, cultivation, seasonal fluctuation of water content, etc. For example, coherence is completely lost in the northwestern corner of all the interferograms due to the presence of a forest (Figs. 3 and 1). The other obstacle for obtaining high-quality interferograms is atmospheric water vapor. Most of the interferograms contain atmospheric effects due to turbulent mixing and stratification. Nevertheless, we were able to obtain useful interferograms with temporal baselines of up to 5 years to detect and measure the amount of aseismic slip (Fig. 4).

The sign of fault-creep in interferograms appears as a step or shift in phase at the surface trace of the fault [10,12]. In other words, fault-creep gives rise to a discontinuity in phase across the fault if it reaches to the surface. Therefore, the amount of phase shift defines the creeping rate. The uncertainty arises mainly from errors in phase unwrapping, and in some cases from atmospheric phase correlated with topography (i.e. when there is a significant difference in elevation across the fault). Atmospheric effects due to turbulent mixing are negligible as it is unlikely that such effects can sharply change across the fault. Phase residuals due to errors in the digital elevation model we use to remove the topographic phase, should also be minimal for the same reason. Furthermore, considering a vertical accuracy of 5–10 m for the SRTM 90-m data [31], artifacts remaining from topographic residuals in the interferograms (except interferograms 11145-01335 and 22377-28890) should be less then 1 mm of apparent range change (because the altitude of ambiguity heights of the interferograms are over 500 m). Discontinuity in phase across the fault can be observed in the interferograms shown in Fig. 3 although they are noisy and contain atmospheric effects. To better illustrate the discontinuity, a plane of fringes running orthogonal to the fault is added to one of the interferograms (Fig. 3d). Fringes are clearly offset along ~70 km-long fault



Fig. 3. a–c. Three of the interferograms used to measure the creep rate. Each fringe shows 2.83 cm of phase change along the radar line of sight. Black lines show the North Anatolian Fault zone. Note the concentric coseismic fringes of the 2000 Orta earthquake (focal mechanism from USGS). d. Same interferogram as in c but, a plane of fringe ramp is added perpendicular to the fault strike in order to better illustrate the discontinuity in phase across the fault as a result of fault creep. The extent of the creeping section of the fault is shown with a white dashed line. One of the profiles (i.e. P25) from which the creep rate was measured is shown with a solid white line.

section due to the fault creep. Although disturbed by atmospheric effects, bending of some fringes across the fault may also reveal a contribution of interseismic strain accumulation.

Phase profiles extracted from four independent interferograms across the fault east of Ismetpasa indicate a consistent phase step across the fault (Figs. 3d and 4b). Since InSAR measurements are in the radar line-of-sight (LOS) reference, we project them into the fault-parallel direction, assuming that surface deformation is purely horizontal strike slip. We then determine the rate of creep between 1992 and 2001 from fault-perpendicular profiles extracted from the interferograms every \sim 1.5 km along the fault (Fig. 4d). These measurements show that fault-creep initiates to the east at the western termination of the 1943 earthquake rupture and continues about 70 km to the west overlapping with the eastern



Fig. 4. a. Interferometric data used (ERS track 479; frame 2781). Bars represent the temporal baselines of the ERS interferograms with their orbit numbers on both sides and the altitude of ambiguity at the centre. A colored pattern is assigned to each interferogram with the exact dates of the images to facilitate comparison of the profiles and measurements shown below. b. LOS (line of sight) profiles from four independent interferograms yielding up to 12 mm/year of creep rate (see Fig. 3d for profile location i.e. P25). c. Modeling the data obtained after stacking the profiles of different interferograms shown in b (creeping depth = 6 km; locking depth = 14 km). d. Plot showing the creep rate measured from various interferograms along the fault, and variation of creeping depth obtained from elastic modeling. Locations of the encircled labels W and E are shown in Fig. 3d.

part of the 1944 earthquake fault segment (Figs. 3d and 4d). The maximum creep rate is 11 ± 3 mm/year approximately in the mid point of the creeping part of the rupture segment diminishing gradually

towards the edges. Near Ismetpasa, InSAR data yield 8 ± 3 mm/year of creep rate, comparable with those deduced from recent instrumental (triangulation) measurements [22]. Creep with an average rate

of 7 mm/year thus releases 30% of the tectonic loading $(22 \pm 3 \text{ mm/year}; [16])$. The error bar of ± 3 mm represents the variation of the creep rate from one interferogram to another at the same site (Fig. 4d), and the uncertainty in our measurements of creep rates from the profiles. The error will be much larger if there is any vertical motion (i.e. subsidence or uplift) along the fault as we assume the InSAR signal is due to horizontal motion only. The available data set do not allow us to deduce whether the variation in creep rate is episodic or otherwise time dependent [32].

We have two interferograms that span the Izmit, Düzce and Orta earthquakes (Fig. 4a). Fig. 4b illustrates that these interferograms do not yield relatively higher creep rates indicative of triggered slip. Triggered slip of 2 cm would be easily observed in the interferogram 22377-28890 spanning two years (Fig. 4) since it would double the inferred creep rate. Thus, if triggered slip occurred it must have been superficial and localized at a few points.

4. Modeling

In order to deduce the depth extent of the creep, we model the InSAR observations using elastic dislocations in a homogenous elastic half space [33]. We assume that a model of uniform slip from surface to some depth characterizes creep along the fault. Regional deformation due to secular loading is modeled by strike slip on buried dislocations below the NAF. However, as shown in Fig. 5, there is a tradeoff between the creeping depth and locking depth. Therefore, other sources of information (seismicity, GPS, etc.) are necessary to constrain the locking depth of the fault to confidently define the creeping depth [13]. Unfortunately, the GPS and seismic networks are too sparse in this region. Nevertheless, modeling the available GPS data suggests (Fig. 1) that the locking depth is somewhere between 10 and 17 km. The InSAR data near Ismetpasa favor a locking depth of 14 km (Fig. 5), consistent with seismic [34] and other GPS-based models [35].

To model the InSAR data, interferograms were filtered and then unwrapped. Because the coherent patches vary from one interferogram to another and atmospheric effects and orbital residuals result in



Fig. 5. RMS misfit (mm) between InSAR observations in Fig. 4c and models with varying locking depths and creeping depths. Star indicates the minimum misfit model parameters plotted in Fig. 4c. Shaded areas are minimum misfit plus 5%.

phase shifts, we were not able to stack the interferograms. Instead, we stack all the profiles of different interferograms at the same site after removing offsets between the individual profiles. Assuming a locking depth of 14 km and uniform slip, we then invert the resulting profiles using least square minimization (e.g. Fig. 4c). The results suggest that creeping occurs down to 6–7 km of the uppermost seismogenic crust (Fig. 4d).

5. Discussion and conclusions

It is not known whether or not the fault was creeping before the 1944 earthquake. However, as shown in Fig. 6d, the rate of creep appears to have exponentially decreased with time for the last ~50 years, implying that creeping may have commenced or accelerated after the 1944 event as postseismic deformation, and hence is transient. It is possible that a fast postseismic creep following the earthquake was coupled with a stable background creep, which could give rise to a creep rate higher than the far field velocity [36] as predicted by the exponential function shown in Fig. 6. If the fault was creeping before the 1944 earthquake, rupturing of the creeping section during these earthquakes would imply that the creeping zone must extend only to a shallow depth and that a strong asperity exists below. Otherwise, the slip deficit that led to the 1951 event could have been taken up at once by the 1944 event.



Fig. 6. Time-history of fault-creep at Ismetpasa as revealed by various measurements. Horizontal and vertical bars are the time window and error range of the measurements, respectively. Change in the creep rate with time is fitted to an exponential curve (heavy dashed line) using the function in the inset rectangle. The question mark corresponds to the unknown effect of the 1951 earthquake on the creep rate.

Modeling of the InSAR data also favors a shallow creep at present. However, as mentioned above, it is difficult to constrain the locking depths from geodetic data alone. There are conflicting results as to the extent of creep on the Hayward fault despite of the intensive studies with wide range of data sets [5,11,37,38]. Nevertheless, our next step will be to use other modeling strategies with more realistic variation of deep creep on the fault.

InSAR data indicate that creeping initiates around the western termination of the 1943 earthquake rupture (Fig. 3d), suggesting that the creeping section arrested the propagation of the 1943 earthquake rupture. Since detailed maps of surface ruptures of the 1943, 1944 and 1951 earthquakes are not available, it is not known if the creeping section was entirely ruptured during the 1944 event or if there was a gap between the 1944 and 1943 ruptures that was later broken by the 1951 event, overlapping with the 1944 rupture. If true, the latter case would explain why the creeping section of the fault at Ismetpasa ruptured twice within such a short time.

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