The fault breaks of the 1999 earthquakes in Turkey and the tectonic evolution of the Sea of Marmara: a summary

Rolando Armijo[1], Bertrand Meyer[1], Aykut Barka[2], Jean-Bernard de Chabalier[1], Aurélia Hubert-Ferrari[1] and Ziyadin Cakir[2]

(1) IPG, Paris (UMR 7578 CNRS), 4 Place Jussieu, 75252 Paris Cedex 05, France
(2) ITU, Eurasia Earth Sciences Institute, Ayazaga, 80626 Istanbul, Turkey

Abstract

We discuss the main features of the 1999 earthquake's breaks within the framework of relevant tectonic information at a larger scale, specifically the observations concerning the process of propagation of the North Anatolian fault across the Sea of Marmara and the Aegean. Using a long-term fault kinematic model of the Marmara pull-apart we can assess the total slip, the block rotations near Izmit and Düzce and explain the distinct fault bend observed near Akyazi. Finally, we briefly present some aspects of the fault segmentation and slip heterogeneity seen in the field and in the SAR interferograms.

Introduction

The August 17, 1999 Izmit (Mw=7.4) and November 12, 1999 Düzce (Mw=7.2) earthquakes are the latest of a sequence of eight large earthquakes that ruptured progressively the North-Anatolian fault (NAF) in the 20th century. Unlike their predecessors, which broke along the uniform eastern trace of the NAF between Erzincan and Mudurnu, the 1999 events ruptured a fault splay in the more complicated Sea of Marmara region, where the NAF divides into a number of branches, before entering westwards into the Aegean (Fig. 1) [e.g., Barka and Kadinsky-Cade, 1988]. To clarify the significance of these branches in relation with the development of the NAF, we use a critical revision of the regional geology that provides new constraints on the long-term slip and on the structural evolution of the Sea of Marmara [Armijo et al., 1999; 2000]. A first-order model of this evolution suggests that the structure is dominantly a pull-apart, and that extension in the Sea of Marmara is associated with dextral displacement across two main segments of the NAF. Stretching in Marmara thus appears to be independent of extension related to the Aegean, in contrast with earlier views [e.g., Sengör et al., 1985]. A few rigid blocks moving coherently seem appropriate to describe, over the past 5 m.y., the regional kinematics, and are consistent with the shorter-term description of the displacement field that comes out from GPS measurements [Straub et al., 1997; McClusky et al., 2000]. However, steady deformation localized on the larger faults appears to be the dominant mechanical process; an inference that contrasts with the more distributed shear across western Anatolia commonly advocated [e.g., Taymaz et al., 1991]. The progression of large earthquakes in the 20th century [Barka, 1996; Stein et al., 1997] mimics the apparent westward propagation of the NAF over the past 10-15 m.y. As for the earthquake sequence, the observation of long-term fault propagation -over 2000 km from the Arabia-Eurasia collision zone in eastern

From: A. Barka, Ö. Kozacı & S. Akyüz (eds) *The 1999 Izmit and Düzce Earthquakes: Preliminary results.* Istanbul Technical University Press, Istanbul, p.55-62.

Anatolia to the Corinth Rift in Greece [Armijo et al., 1996]- suggests elastic behavior, at the scale of the continental lithosphere. In this paper we first examine the occurrence of the 1999 earthquakes within the framework of the long-term kinematics. Then, we compare the tectonic observations of the 1999 surface breaks with the SAR interferometry data to briefly discuss the fault segmentation and slip heterogeneity.

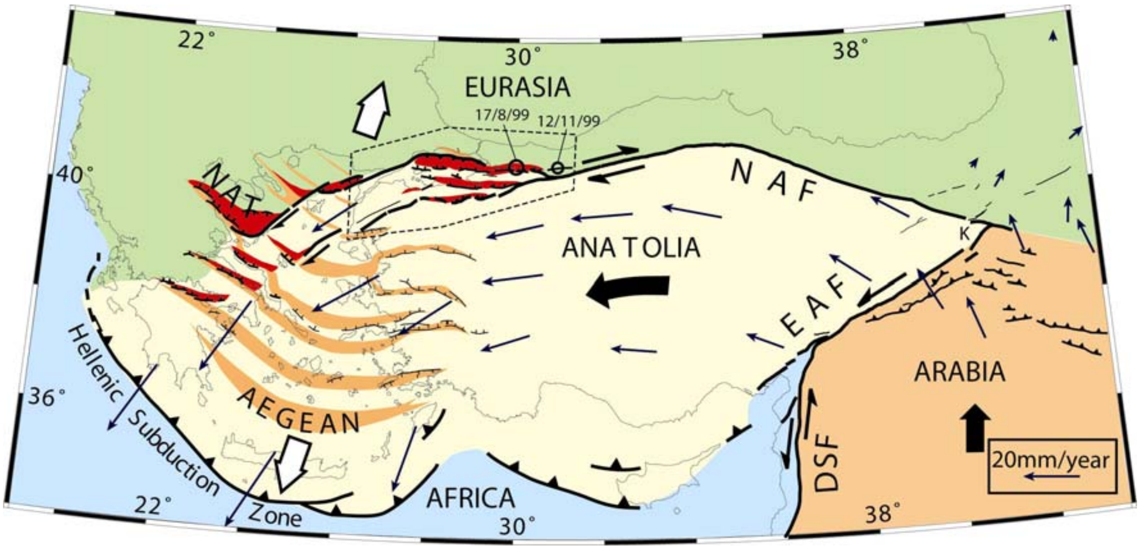

Figure 1. Tectonic setting of the 1999 earthquakes within the frame of continental extrusion in the eastern Mediterranean [from Armijo et al., 1999]. Anatolia-Aegea block escapes westward from the Arabia-Eurasia collision zone, toward Hellenic subduction zone. The August 17 and November 12 events occurred where the North Anatolian fault (NAF), at the boundary between Anatolia/Eurasia, splays westward into a number of branches associated with extensional basins (red). Current motion relative to Eurasia (GPS (Global Positioning System) and SLR (Satellite Laser Ranging) velocity vectors, in mm/yr, from Reilinger et al. [1997]). In Aegean, two deformation regimes are superimposed [Armijo et al., 1996]: a widespread extension starting earlier (orange stripes, white diverging arrows) and a more localized transtension associated with later, westward propagation of NAF (red). EAF - East Anatolian fault, K - Karliova triple junction, DSF - Dead Sea fault, NAT - North Aegean Trough. Box outlines Marmara pull-apart region.

The 1999 breaks and the long-term kinematics

The 1999 earthquake breaks occurred east of the Sea of Marmara, where two previous earthquakes had already ruptured in 1957 and 1967 contiguous segments south of the Almacik block (Fig. 2). 32 years later the Izmit and Düzce earthquakes ruptured along other branches of the NAF, following a sinuous fault trace that includes the Karadere and Düzce segments, north of the Almacik block. The Almacik block is now completely surrounded by recent breaks. However, the 1999 breaks form a prominent bend in the area separating the Almacik and the Armutlu blocks, near the city of Akyazi. The long-term perspective provides insight for a better understanding of these features.

Restoring the original shape of distinct geological markers on both sides of the Sea of Marmara pull-apart helps to constrain its kinematics and long-term evolution. Critical to this reconstruction is the observation of shortening in the Dardanelles, which affects sedimentary sequences of Eocene to Quaternary age and appears to be associated with a restraining bend along the North Anatolian fault

[Armijo et al., 1999; 2000]. Despite minor complexities, the Ganos and the Gelibolu folds appear to be two large anticlines that are truncated by the NAF. A significant unconformity suggests that propagation of the NAF across these folds took place at about 5 Ma. However, different descriptions and differing structural interpretations have been proposed for the Dardanelles area (e.g., Sengör et al., 1985; Barka and Kadinsky-Cade, 1988; Barka, 1992; Sümengen and Terlemez, 1991; Yaltirak, 1996; Yaltirak et al., 2000; Görür et al., 1998; Tüysüz et al., 1998; Okay et al., 1999). Neither of these integrates specifically the very apparent offset of the two large anticlines (Ganos and Gelibolu anticlines) nor their fairly well constrained age.

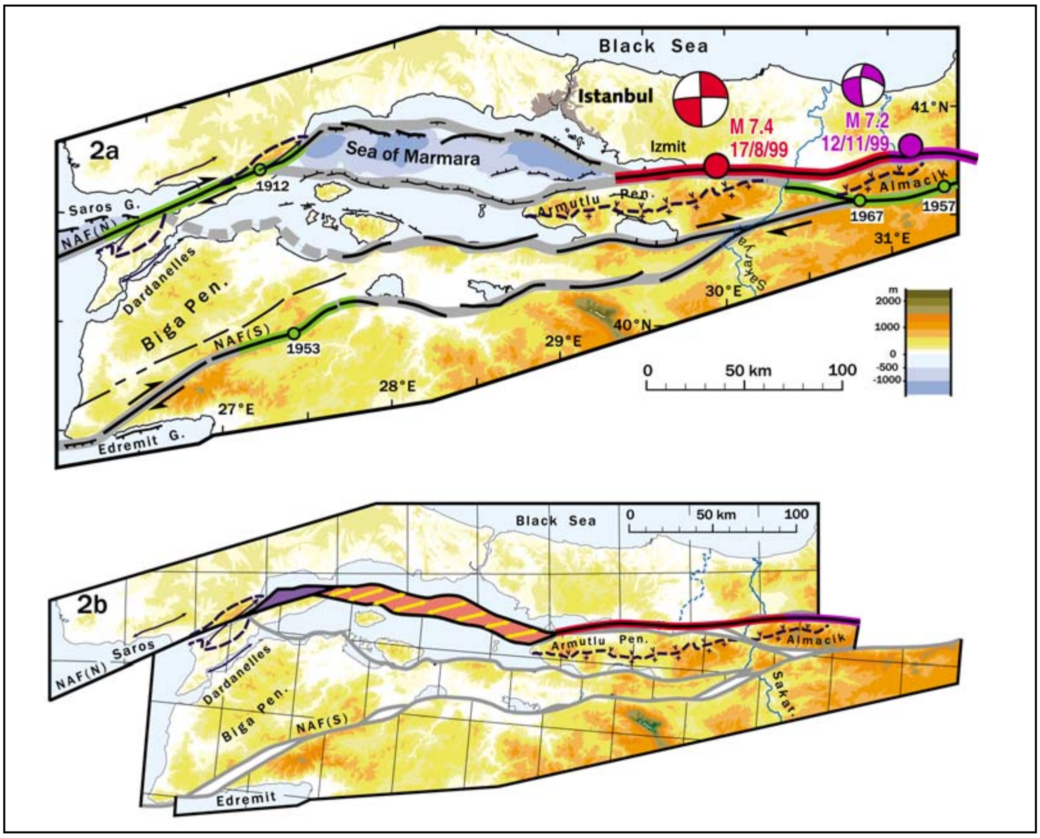

Figure 2. Surface breaks associated to the 1999 earthquakes and fault kinematics in the Sea of Marmara region [from Armijo et al., 1999]. **a.** The NAF splays westward into two main branches 100 km apart. Northern branch (N), cutting Dardanelles structure connects the Sea of Marmara with the Gulf of Saros (Aegean). Within Marmara pull-apart, slip may be partitioned between strike-slip faults and faults with normal-slip component, such as those that bound the deep northern basins. Normal faulting is also seen in southern shelf and margin. Sinuous southern branch (S) bypasses pull-apart. Outlined in purple and red are the breaks of the 1999 earthquakes; in green four previous earthquake breaks. Almacik block is completely surrounded by recent breaks. Outlined in gray are the cuts used for restoring slip (Fig. 2b). Contact between Sakarya metamorphic rocks (+) and Eocene volcanic rocks (v), nearly coincident with Intra-Pontide suture, is represented in Armutlu Peninsula and in Almacik block (from Yilmaz et al., 1997). **b.** Kinematic model for Sea of Marmara region (see Armijo et al. [1999] for details). Geometry of the 1999 fault breaks is schematically restored from Fig 2a. Reconstruction is at ca. 5 Ma with Dardanelles anticline (70 km slip on northern branch of NAF) and original contact between Armutlu Peninsula and Almacik block restored. Counterclockwise rotation of southern block (Anatolia) relative to Eurasia is 5°, consistent with models derived from GPS measurements [Reilinger et al., 1997, McClusky, 2000]. Total right-lateral slip on NAF at eastern side of model is about 85 km, with 15-20 km shortening across fault zone. More rotation of Almacik block (10°) is predicted to absorb compression and to produce the observed bend of the northern fault near Akyazi (see Fig. 4). The northern basins of Sea of Marmara have undergone average stretching of 300% (extensional region in red with yellow arrows). Compressional gap east of Dardanelles anticline is outlined in violet.

Another critical observation concerns the amount of offset and differential rotation between the Armutlu and Almacik blocks, east of the Sea of Marmara (Fig. 2). Structural observations at small-scale and paleomagnetic measurements lead earlier to conflicting interpretations of the geology of this area [Saribudak et al., 1990; Michel et al., 1995]. Specifically, Saribudak et al. [1990] suggested a large clockwise rotation of 212° of the Almacik block since Eocene times, associated with very substantial shear along the NAF. However, both in the Armutlu and the Almacik blocks a similar contact is seen, over 150 km, between the metamorphic rocks belonging to the northern edge of the Sakarya terrain [Yilmaz et al., 1997] and the steeply, north-dipping, sedimentary and volcanic rocks of Eocene age that unconformably overlay them. Assuming initial continuity of this marker across the fault supports very modest (≈ 5°) counterclockwise rotation of the Almacik block relative to the Armutlu block since the Eocene, suggesting total right-lateral displacement along the NAF consistent with that observed in the Dardanelles.

The reconstruction in Fig. 2b represents the likely situation of the Marmara Sea region at 5 Ma. It restores both the right-lateral offset of 70 km between the Ganos and Gelibolu anticlines in the Dardanelles and the continuity of the Eocene marker mapped in the Armutlu and Almacik blocks. About 20-30 km of right-lateral slip is required, over the long term, across the Karadere and Düzce segments, north of the Almacik block. The southward bend of the 1999 fault breaks, near Akyazi, appears reasonably explained by the long-term kinematics. This requires accommodation of about 50 km of right-slip across the Mudurnu-Sapanca segment, between the Almacik and Armutlu blocks, associated with counterclockwise differential rotation of 5°.

Segmentation of the 1999 breaks

After occurrence of the 1999 events, the earthquake sequence of the 20th century is no longer suggestive of westward tapering of slip along the NAF (Fig. 3). However, the most apparent feature is slip heterogeneity. Narrow peaks of cumulative slip (over 6 m) are clear in at least two areas where slip is partitioned into two or more faults. One is where the 1939 rupture superposes with those of the 1942 and 1943 events (Niksar-Erbaa area); the other is where the 1957 and 1967 events superpose with the 1999 earthquakes (Almacik block).

At a more detailed level, combining tectonic observations of the 1999 surface breaks and the SAR interferometry data allows us to assess more precisely than for previous earthquakes the fault segmentation and slip heterogeneity. Together the Izmit and Düzce earthquakes ruptured about 180 km along the NAF (Fig. 4). However, the August surface break consists of four distinct segments with variable right-lateral slip reaching 5 m. Using the observed fault trace and the measurements of surface offsets gathered in the field, a synthetic interferogram can be created by forward modeling of a dislocation in elastic half-space and assuming, for instance, uniform vertical distribution of slip down to a depth of 15 km (Fig. 5a). Despite the strong assumptions (and possible atmospheric artifacts in the interferogram), our simple first-order model seems to reproduce reasonably well the details of the segmentation observed in the SAR interferogram (Fig. 5b). See, for instance, the fringes oblique to the fault southwest of Sapanca lake. Nonetheless, the correspondence between our simple model and the main features of the interferogram suggests that detailed observations of earthquake breaks gathered at the surface are enough to assess reasonably well the overall coseismic slip distribution.

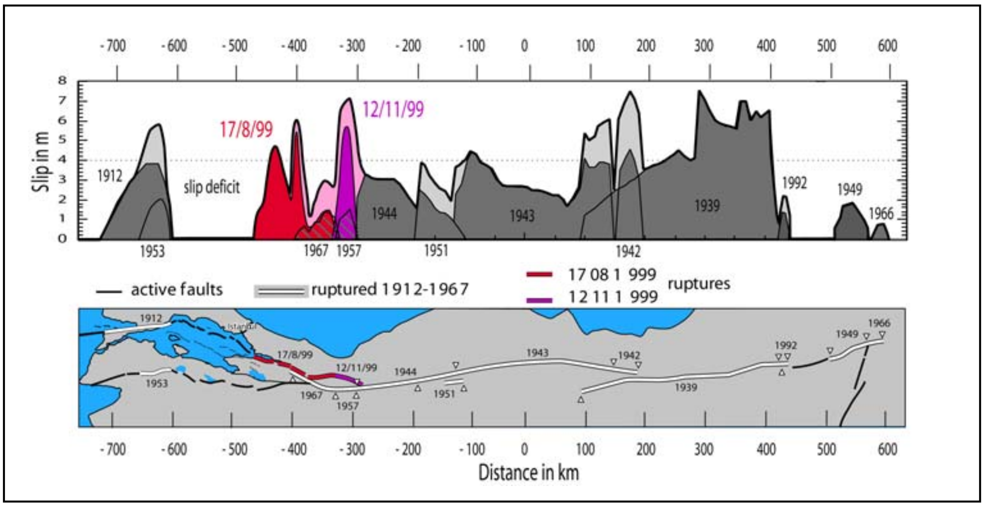

Figure 3. Large earthquakes along the North Anatolian Fault in the 20th century (modified from Stein et al. [1997]). Top represents earthquake slip as a function of distance along the NAF. Dark grey is for events prior to 1999; red and purple for the last two events in 1999. Thick line and lighter colors indicate cumulative slip. The 1999 events contributed to fill the region with slip deficit along the northern branch of the NAF, between the large 1944 and 1912 events. The zone of slip deficit remaining on this branch across the Sea of Marmara has strong potential for future earthquakes [e.g., Hubert-Ferrari et al., 2000; Parsons et al., 2000]. Bottom shows extent of surface breaks along the trace of the NAF.

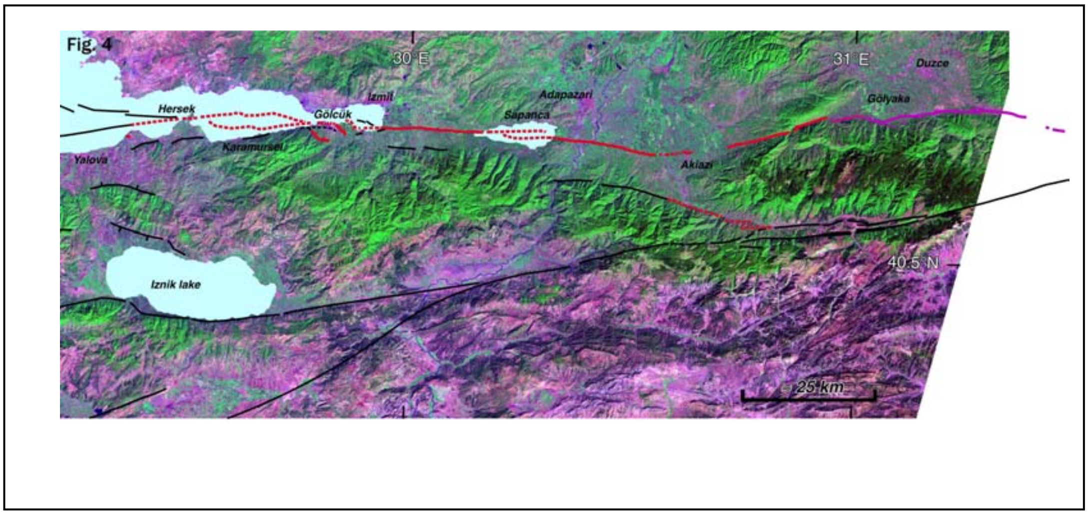

Figure 4. Active faults in the eastern Marmara region superimposed on Landsat TM color composition. Red and purple lines correspond to the Izmit (17/8/99) and Düzce (12/11/99) fault breaks, respectively. The August break has 110 km length onland from Gölcük to southwest of Gölyaka but secondary features suggest that it probably extends westwards offshore Karamursel and beyond, toward Yalova (dashed red lines). Smaller surface breaks and fissures were observed south of Gölyaka, where significant slip occurred during the November (Düzce) event. Similar features were seen along the Mudurnu fault near Tasburun (south of Akyazi); a segment that had broken already in 1967.

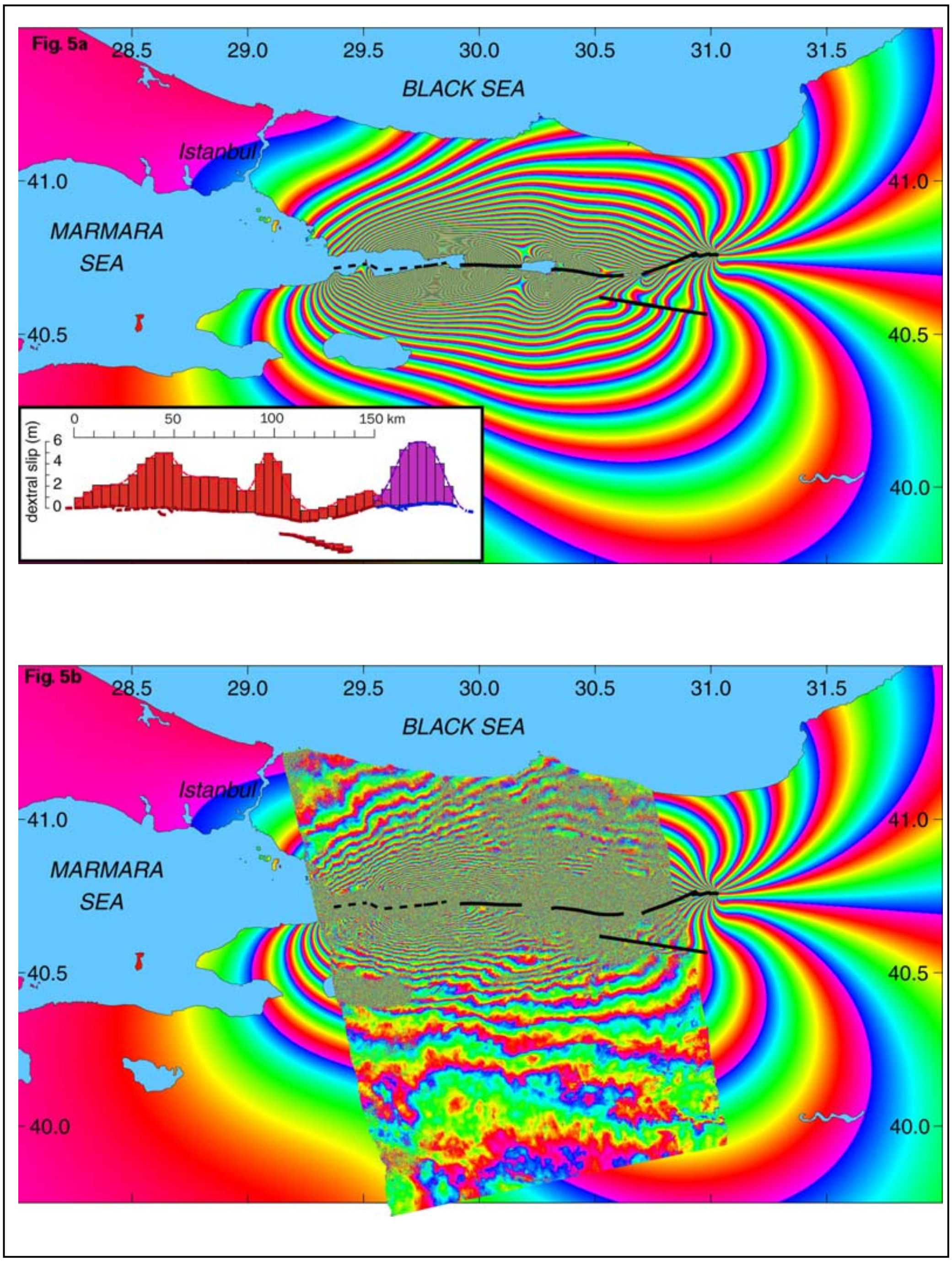

Figure 5. Surface deformation associated with the Izmit (17/8/99) earthquake. **a.** First-order forward modelling of deformation as it would be seen by satellites ERS (ascending tracks). Fault rupture in black. Synthetic interferometric fringes are obtained using elastic dislocation model in half space and fault slip distribution as observed in the field. Corresponding seismic moment is 1.7 x 10^{20} Nm. Inset shows slip measured along the two surface breaks (August earthquake, red; November event, purple). **b.** Observed interferogram (track 157, ERS2 images of 13/08/99 and 17/09/99) superimposed on model. Each fringe represents 2.8 cm change in length in the line of satellite sight (or about 7 cm of righ-lateral slip along the fault). The fit to our first-order model suggests rupture of the offshore fault west of Gölcük, beyond Hersek delta, and reactivation of the Mudurnu fault south of Akyazi (see fig. 4).

West of the city of Gölcük the rupture goes offshore into the Gulf of Izmit and its western end cannot be observed directly. The coseismic SAR displacement field implies that a fifth offshore segment ruptured, bypassing 10 km the Hersek delta to the west, towards Istanbul. Besides, a new set of fissures were observed along the fault trace that had already ruptured in 1967, in the Mudurnu valley. The corresponding discontinuity observed in the SAR imagery is modeled with 40 cm right-lateral slip on a steeply north-dipping fault. Finally, the subsequent Düzce earthquake added to slip heterogeneity by breaking a 35-km-long segment with slip reaching 5.5 m.

References

Armijo, R., B. Meyer, G.C.P. King, A. Rigo and D. Papanastassiou, Quaternary evolution of the Corinth Rift and its implication for the late Cenozoic evolution of the Aegean, *Geophys. J. Int.*, *126*, 11-53, 1996.

Armijo R., B. Meyer, A. Hubert, and A. Barka, Westwards Propagation of the North Anatolian Fault into the Northern Aegean: Timing and kinematics, *Geology*, *27*, 267-270, 1999.

Armijo, R., B. Meyer, A. Hubert and A. Barka, Westward propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics: Reply, *Geology*, *28*, 188-189, 2000.

Barka, A., The North Anatolian fault zone, *Annales Tectonicae*, *6*, 164-195, 1992.

Barka, A., Slip distribution along the North Anatolian Fault associated with the large earthquakes of the period 1939 to 1967, *Bull. seism. Soc. Am., 86*, 1238-1254, 1996.

Barka, A. and K. Kadinsky-Cade, Strike-slip fault geometry in Turkey and its influence on earthquake activity, *Tectonics*, *7*, 663-684, 1988.

Hubert-Ferrari, A., A. Barka, E. Jacques, S. Nalbant, B. Meyer, R. Armijo, P. Tapponnier and G.C.P. King, Seismic hazard in the Marmara Sea following the 17 August 1999 Izmit earthquake, *Nature*, *404*, 269-272, 2000.

McClusky, S., S. Balassanian, A. Barka, C. Demir, S. Ergintav, I. Georgiev, O. Gurkan, M. Hamburger, K. Hurst, H. Kahle, K. Kastens, G. Kekelidze, R. King, V. Kotzev, O. Lenk, S. Mahmoud, A. Mishin, M. Nadariya, A. Ouzounis, D. Paradissis, Y. Peter, M. Prilepin, R. Reilinger, I. Sanli, H. Seeger, A. Tealeb, N. Toksöz and G. Veis, Global Positioning System constraints on the plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *J. Geophys. Res.*, *105*, 5695-5719, 2000.

Michel, G.W., M. Waldhör, J. Neugebauer and E. Appel, Sequential rotation of stretching axes, and block rotations: a structural and paleomagnetic study along the North Anatolian Fault, *Tectonophysics, 243*, 97-118, 1995.

Okay, A., E. Demirbag, H. Kurt, N. Okay and I. Kuscu, An active, deep marine strike-slip basin along the North Anatolian fault in Turkey, *Tectonics*, *18*, 129-147, 1999.

Parsons, T., S. Toda, R.S. Stein, A. Barka and J.H. Dieterich, Heightened odds of large earthquakes near Istanbul: An interaction-based probability calculation, *Science, 288*, 661-665, 2000.

Reilinger, R.E., S.C. McClusky, M.B. Oral, R.W. King, M.N. Toksoz, A.A. Barka, I. Kinik, O. Lenk and I. Sanli, Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, *J. Geophys. Res.*, *102*, 9983-9999, 1997.

Saribudak, M., M. Sanver, A.M.C. Sengör and N. Görür, Palaeomagnetic evidence for substantial rotation of the Almacik flake within the North Anatolian fault zone, NW Turkey, *Geophys. J. Int., 102*, 563-568, 1990.

Sengör, A.M.C., N. Görür and F. Saroglu, Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study, in Strike-slip faulting and basin formation, edited by K.T.a.C.-B. Biddle, N., *Society of Economical Paleontologists and Mineralogists*, *Special Publication 37*, 193-230, 1985.

Stein, R.S., A.A. Barka and J.H. Dieterich, Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering, *Geophys. J. Int.*, *128*, 594-604, 1997.

Straub, C., H.-G. Kahle and C. Schindler, GPS and geologic estimates of the tectonic activity in the Marmara Sea region, NW Anatolia, *J. Geophys. Res.*, *102*, 27587-27601, 1997.

Taymaz, T., J.A. Jackson and D.P. McKenzie, Active tectonics of the north and central Aegean Sea, *Geophys. J. Int.*, *106*, 433-490, 1991.

Tüysüz, O., A. Barka and E. Yigitbas, Geology of the Saros graben: Its implications on the evolution of the North Anatolian fault in the Ganos-Saros region, NW Turkey, *Tectonophysics*, *293*, 105-126, 1998.

Yaltirak, C., Tectonic history of the Ganos fault system, *Bulletin Turkish Association of Petroleum Geologists*, *8*, 137-156, 1996.

Yaltirak, C., M. Sakinç and F.Y. Oktay, Westward propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics: Comment, *Geology, 28*, 187-188, 2000.

Yilmaz, Y., Tuysuz, O., Yigitbas, E., Genc, C., and Sengör, A. M. C., 1997, Geology and tectonic evolution of the Pontides, *in* Robinson, A. G., ed., Regional and petroleum geology of the Black Sea and surrounding regions: American Association of Petroleum Geologists Memoir 68, p. 183-226.