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Slip history of the 1944 Bolu-Gerede earthquake rupture along the North Anatolian fault system: Implications for recurrence behavior of multisegment earthquakes

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[1] Recent research shows that active fault systems produce multisegment earthquakes; however, we have yet to understand the faulting behavior of various spatial patterns of segments. We conducted a three-dimensional trenching survey to reconstruct the detailed slip history of a fault segment that ruptured as one of the multisegment ruptures along the North Anatolian fault system. The trench site, on the Gerede segment, recorded a maximum right-lateral slip of up to 6 m that was associated with the 1944 Bolu-Gerede earthquake ($M 7.4$). Fault exposures show evidence of four paleoearthquakes. Radiocarbon dates, a refined probability density distribution, and correlation with historical earthquakes place the mean repeat time at ~ 330 years. Four discrete paleoslips yield a slip per event of 5.0 ± 0.8 m with a coefficient of variation of 0.2. Our research suggests that multisegment earthquakes exhibit various spatial patterns, regardless of recurrence with quasiperiodicity and characteristic slip. Coincidentally, the fault geometry exhibits extremely linear traces, suggesting simple stress accumulation and release through earthquake cycles. Furthermore, the 1944 event did not occur in a single segment, and the Gerede segment probably ruptured within a slip-pulse-like rupture during a multisegment earthquake. A comparable geological slip rate of $\sim 17 \text{ mm a}^{-1}$ based on a GPS-based strain rate supports the persistence of macroscopic asperity through recent geological time. Therefore we conclude that a segment with simple fault geometry along a strike-slip fault system plays an important role in forecasting the timing of future multisegment earthquakes, but the spatial extent of such earthquakes needs to be explored further.

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1. Introduction

[2] Determining the manner in which large earthquakes repeat on an active fault system is a fundamental question in assessing future seismic potential and related hazards. Recent discoveries about large earthquakes generated from strike-slip fault systems show that fault systems are generally segmented and that the activation of plural fault segments, or multisegments, produces surface-rupturing earthquakes throughout the world [e.g., Sieh *et al.*, 1993; Sekiguchi *et al.*, 2000; Barka *et al.*, 2002; Eberhart-

Phillips *et al.*, 2003]. The evidence concerning the occurrence of such multisegment earthquakes is, often, associated with a complex history of paleoearthquake events with various spatial patterns or different combinations of fault segments over several earthquake cycles [Rockwell *et al.*, 2000; Weldon *et al.*, 2005]. Numerical models describing the recurrence of large earthquakes have recently been developed; however, they are still deterministic, and it remains necessary to improve their heterogeneities and physical properties, mainly those related to fault friction [e.g., Tse and Rice, 1986; Rice and Ben-Zion, 1996; Ward, 1997]. In contrast, a paleoseismology-based substantial recurrence model has provided the basis for practical seismic hazard analysis [e.g., *The Headquarters for Earthquake Research Promotion*, 2005; *Working Group on California Earthquake Probabilities (WGCEP)*, 1988, 1995]. The assessments of future seismic sources on active fault systems are highly dependent on the repeatability of surface slip associated with large earthquakes. For example, the characteristic earthquake model [Schwartz and Coppersmith, 1984] assumes that similar slip distributions occur during similar size large earthquakes repeating on the fault system and fault segments.

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Figure 1. Index map of the North Anatolian fault system (NAFS) and the 1944 Bolu-Gerede earthquake rupture. (a) Spatial distribution of large earthquakes in the 20th century along the NAFS. The relative motion of $<24 \pm 1 \text{ mm a}^{-1}$ between the Eurasian plate and the Anatolian micro plate is after McClusky *et al.* [2000] and Reilinger *et al.* [2006]. (b) Detailed fault geometry of the 1944 earthquake rupture zone. Bold lines denote active faults that ruptured in the 1944 event identified by Kondo *et al.* [2005]. The Demir Tepe trench site in this article is located near the middle section, where a maximum slip of $\sim 6 \text{ m}$ was measured. The Ardicli trench site where eight paleoearthquake events were identified by Okumura *et al.* [1993, also presented paper, 2004] is 1 km east of the Demir Tepe site.

However, such repeatability of surface slip has not been greatly examined, particularly in the case of multisegment earthquakes. The reasons are due not only to the difficulties in reconstructing several paleoslips but also to uncertainties of the extent of past ruptures and earthquake magnitudes. Because the amount of surface slip is basically a function of earthquake magnitude [e.g., Wells and Coppersmith, 1994; Biasi and Weldon, 2006] or of interevent time, as in a slip-predictable model [Shimazaki and Nakata, 1980], we need to reconstruct, to the fullest extent possible, a detailed slip history with fewer uncertainties regarding both past rupture extents and interevent time, plus the geological slip rate.

[3] The North Anatolian fault system (NAFS), which extends approximately 1200 km, is a major continental transform fault system, and it offers great advantages in revealing details about paleoseismic sources. The NAFS produced several serial large earthquakes exceeding $M \sim 7$ in the 20th century, and the earthquakes' epicenters generally migrated from east to west (Figure 1) [e.g., Barka and Kadinsky-Cade, 1988; Barka, 1996; Stein *et al.*, 1997]. Surface-rupturing earthquakes provide slip distributions along the faults associated with the large earthquakes [Barka, 1996] and instrumental records that imply the size

of the earthquakes, the rupture propagation directions, and static fault parameters [Dewey, 1976; Ambraseys and Finkel, 1988]. Furthermore, historical earthquake records of the last millennium [e.g., Ambraseys, 1970; Ambraseys and Finkel, 1988, 1995] in the literature give us a limited idea of the rupture extent as well as the precise timing of events correlating with geological evidence. In this context, the fault section that ruptured during the 1944 earthquake is one of the best earthquake segments on the western central NAFS. Kondo *et al.* [2005] recently reported that the 1944 rupture is divided into fault segments, and they presumed that these segments produced historical multisegment earthquakes in different combinations with the 1944 event. The question thus arises: how is repeated surface slip associated with those historical earthquakes?

[4] To address these fundamental questions, we excavated a three-dimensional (3-D) trench at the Demir Tepe site on the 1944 Bolu-Gerede earthquake rupture [Barka and Kadinsky-Cade, 1988; Kondo *et al.*, 2004] to simultaneously reveal the timing and slip of past multisegment earthquakes on the NAFS. In this paper, we describe the results of the 3-D trenching survey, discuss how surface slip actually repeated with distinct spatial characteristics during

Figure 2. (a) Surface slip distribution associated with the 1944 earthquake and (b) proposed segmentation model by Kondo *et al.* [2005], based on the slip distribution and fault discontinuities. The 1944 earthquake rupture is divided into five main fault segments. The Demir Tepe trench site is located on the Gerede segment, and it recorded the maximum slip during the 1944 earthquake.

past multisegment earthquakes and explain the implications for recurrence of multisegment earthquakes and practical seismic-hazard analysis.

2. Demir Tepe Trench Site

[5] The site is located on the main central segment of the 1944 earthquake rupture. Kondo *et al.* [2005] proposed dividing the 1944 earthquake rupture into five main segments

based on the revisited slip distribution, the detailed fault geometry mapped in 1/25,000 scale, and the extent of surface ruptures associated with historical earthquakes (Figure 2). Along the main central segment, the Gerede segment, systematic right-lateral offsets up to ~6 m were measured by aerial photograph interpretation, field measurements, and interviews with eyewitnesses [Kondo *et al.*, 2005]. The İsmetpaşa segment, next to the Gerede segment, probably reruptured during the 1951 earthquake [Kondo *et al.*, 2005;

Figure 3. Geomorphological map around the Demir Tepe trench site. The rectangle with thick lines represents the detailed geomorphic map shown in Figure 4. Active fault traces that ruptured in the 1944 earthquake extend straight and cut fluvial terraces, alluvial fan surfaces, and marshy lowlands. The faults form tectonic geomorphic features on the scale of a few tens of meters, such as the systematic right-lateral offset, sag ponds, and push-up structures. The trench site was where thick fine sediments deposited close to the composite outer fan.

Figure 4. Detailed geomorphological map and plan view of 3-D trenches. Contour interval is 0.2 m. The fault traces shown in bold thick lines cut fan surfaces and exhibit a right step 5-m wide, forming a linear fault depression. The fan surfaces are divided into higher and lower surfaces according to their relative height differences. Three fault-crossing and eight fault-parallel trenches were sited for detection of paleoearthquakes and for burial offset measurements, respectively. We expected fine sediments to be trapped inside the depression, and buried channels flowed perpendicularly across the fault traces from north to south. At the ground surface, an offset tree line of 4.0 m to 5.0 m during the 1944 earthquake and cumulative offset gullies of ~10 m were measured by *Kondo et al.* [2005].

Çakir et al., 2005]. Fault creeping has been reported at İsmetpaşa, but recent surface slip measurements and interviews of eyewitnesses by *Doğan et al.* [2003] and interpretation of Interferometric Synthetic Aperture Radar (InSAR) over a wider space by *Çakir et al.* [2005] indicate that most cumulative slip reported as creeping can be explained by the after-slip of the 1944 earthquake, the surface slip of the 1951 earthquake, and remotely triggered surficial slip by recent large earthquakes.

[6] The trench site (GPS coordinates: 40.82°N, 32.32°E) is located near the middle of the Gerede segment; several offsets between 4 and 5 m remain on the tree lines and field boundaries near the site (Figures 2 and 3). One kilometer east of the Demir Tepe site, as described in previous works by *Okumura et al.* [1993] and K. Okumura et al. (Slip history of the 1944 segment of the North Anatolian fault to quantify irregularity of the recurrence, paper presented at Annual Meeting, Seismological Society of America, Palm Springs, Calif., 2004) revealed the precise chronology of eight paleoearthquakes based on fine sediments exposed in the trenches at the Ardicli site, suggesting a mean recurrence time of 250 to 300 years during the last millennium.

[7] The Demir Tepe site is situated on the alluvial fan, where the fault traces exhibit a right step and form a linear depression (Figures 3 and 4). The fault traces striking at N80°E cut through the lower alluvial fan surfaces. At the northern side of the fault traces, the older fan surface remains as a remnant of a higher level, and the almost N-S trending erosional scarp constrains the spatial distribution and flow direction of braided channels while the lower fan surface was forming (Figure 4). The linear depression is 50 m in length and 4 m in width, suggesting the depth of the depression is shallow and filled with relatively fine sedi-

Figure 5. Summarized schematic geologic column at the Demir Tepe site. Most of the sediments consist of alluvial fan deposits, such as mudflow deposits, fluvial braided channel deposits, and flood loam deposits, in addition to modern topsoil at the ground surface. Inside the depression, fine sediments composed of clay, silt, and fine to medium sand composed the depression fill deposits. As a result, four paleoearthquake events including the 1944 earthquake were identified at the site. See also the detailed descriptions in the text.

Figure 6. Representative logs for the fault-crossing DTC2 trench. The western wall is flipped. The index of each unit is shown in Figure 5. Red bold lines denote faults, and solid triangles in black represent paleoearthquake horizons. We identified four paleoearthquake events based on the upward termination of faults, unconformities, and fissures.

ments that may help determine the high-resolution event chronology.

[8] We excavated 11 trenches to identify faulting events in three fault-crossing trenches and to reconstruct the spatial distribution of buried channels in eight fault-parallel trenches. We named the trenches DTA-1 to DTA-4 and DTD-1 to DTD-4 for the fault-parallel trenches and DTB, DTC, and DTE for the fault-crossing trenches. The size of the fault-parallel trenches is 0.7 m wide, 1 m deep, and 3 m to 5 m

long. The size of the fault-crossing trenches is 0.7 m to 4 m wide, 1 m to 2.5 m deep, and 3.5 m to 8 m long for the DTB and DTE trenches. The DTC trench, which was 0.7 m wide and 3 m long, was the best fault exposure for identifying faulting events. It was later deepened up to 2.5 m and named the DTC2 trench. We present a summary of the stratigraphy and its relation with faulting events in Figure 5. The logs for the DTC2 trench walls are shown in Figure 6 to explain the event identification. Two walls of the fault-parallel trenches

Figure 7. Representative logs for fault-parallel trenches, including the northern wall of the DTA1 trench and the northern wall of the DTD1 trench. The DTA1 trench is excavated at the northern side of the fault traces, and the DTD1 trench is at the southern side. The piercing points for reconstruction of buried channels in unit 6b and unit 8 are shown. For the offset reconstruction, we used the eastern margin of unit 6b and the western margin of unit 8 because they had better spatial continuation and preservation. See also the main text and Figure 9 for the spatial distribution of the buried channels.

on both sides of the fault zone are shown in Figure 7. Detailed individual logs for the other walls are presented separately in the auxiliary material for interested readers (Figures S1–S9).¹

3. Stratigraphy and Identification of Paleoseismic Events

[9] The stratigraphy at the site is mainly marked by alluvial fan deposits exposed near the bottoms of the trenches, then fluvial channel deposits covering the fan deposits, flood loam, fine silt to clay sediments in the fault depression, and flood loam deposits and recent topsoil near the surface (Figure 5). Fault strands with almost vertical angles appear in the fault-crossing trenches. We divided them into 12 stratigraphic units based on lithological characteristics, spatial distributions, and stratigraphic relations. In Table 1, we summarized the characteristics of each unit from top (Unit 1) to bottom (Unit 12).

[10] On the basis of the stratigraphic relations among faults and individual units, especially the upward truncation of faults and the displacement and deformation differences, we identified four paleoseismic events. Here we describe specific features used to recognize faulting events and summarize the characteristics of each event. We named the events Event I to IV, from the youngest to the oldest faulting events.

3.1. Event I

[11] Faults cut through all sediments exposed on the walls of the fault-crossing trenches. The upper terminations of the

faults disappear in the recent soil horizon A (Figure 6). Soil horizon A appears to be active and to grow continuously. Local eyewitnesses say the trench site was ruptured just after the 1944 earthquake and a small pond appeared inside the fault depression. Event I corresponds to the 1944 earthquake.

3.2. Event II

[12] The upward termination of faults cutting strata through Unit 4 is covered with Unit 2 (Figure 6). Unit 2 is a silty clay unit with slight humus that is distributed only inside the fault depression. Therefore the unit probably was deposited and filled after the depression-forming associated with Event II. Unit 3, the channel fill deposit inside the gullies, does not show a direct stratigraphic relation with this event horizon. However, judging from the larger offsets of the gullies (~10 m) than that of the 1944 earthquake (i.e., Figures 4 and 5), Unit 3 is below this event horizon and was deposited before the event. Thus we conclude that Event II most probably occurred after the deposition of Unit 3 and before the deposition of Unit 2.

3.3. Event III

[13] The upward termination of faults cutting through Unit 6b is covered with Unit 5b (Figure 6). Inside the fault depression, Unit 6 inclines toward the southern fault trace at approximately 45° and is abutted by the upper part of Unit 5. As both Units 6 and 5 consist of relatively fine sediments only distributed inside the depression, the original depositional surface should have been almost flat. This means that Unit 6 is more deformed than Unit 5b and other younger units. Additionally, the top of Unit 6a contains patchy humus and remnants of roots. This indicates that Unit 6a had been close to the ground surface and was affected by soil

¹Auxiliary materials are available in the HTML. doi:10.1029/2009JB006413.

Table 1. Lithological Description of Stratigraphic Unit

Unit	Description
1	Recent soil horizon just below the ground surface, exposed on all trench walls. The thickness is around 10 cm on the fan surfaces, and 10 to 20 cm inside the fault depression.
2	Weak humic silty clay filling the fault depression. The thickness is 10 to 25 cm and gradually thickens toward the southern margin of the depression. The spatial distribution is intersected by southern fault traces. On the walls of the fault-crossing trenches, this unit unconformably overlies Unit 4, flood loam deposit.
3	Channel fill deposit consisting of fine sand granules along gullies flowing through the lower fan surfaces. This layer is exposed only on the walls of the DTA, DTB, and DTC/DTC2 trenches. The geometry on the walls exhibits the trough shape of typical channel deposits. The thickness is at maximum 5 cm.
4	Flood loam deposit is exposed on all trench walls. This unit is composed of massive silt and fine sand with rare granules. Its thickness is 40 to 50 cm and almost constant in every trench, suggesting the site was nearly flat when the unit was deposited. On the lower fan surfaces, the unit overlies Unit 6a, composed of braded channel deposits with unconformity (Figure 7: north wall of DTD trench). In the fault depression, the stratigraphic boundary between this unit and below Unit 5a, which is fine sandy silt, shows transitional contact, implying a smaller time gap of sedimentation (Figure 6: DTC2 trench). Additionally, the top of Unit 4 inside the depression indicates weak soil development with granules.
5	Depression filled with fine sediment consisting of two subunits: upper yellowish fine sandy silt (Unit 5a), and lower grayish clay (Unit 5b). Judging from its lithological characteristics and spatial distribution, the unit was deposited in a pond-like environment. Its thickness increases up to 50 cm on the southern margin of the depression in the fault-crossing trench (Figure 6: DTC2 trench). The unit clearly abuts Unit 6a, which is more deformed as described below.
6	Braded channel deposits composed of clean sand and gravel, divided into two subunits: upper silty clay with fine sand (Unit 6a), and several channel deposits (Unit 6b). Unit 6a was observable only in the DTC2 trench. The top of the unit contains patchy humus and the remnants of roots. The facies indicate that the environment changed from a shallow water table that was close to braded channels to an area of soil development after the deposition of Unit 6a. Additionally, the stratigraphic contact with the clayey unit above it, Unit 5b, indicates a sharp and recognizable rapid environmental change. Unit 6b is composed of well-sorted fine to medium sand alternating with well-sorted coarse sand and granules. The lateral variation in grain size is distinct and reverse grading is partly observed. This unit covers almost all trenches and its thickness varies from 5 cm to 30 cm. Judging from these characteristics, this unit is deposited in braded channels covering most area of the trench site.
7	Clay with granules inside the fault depression. Its thickness increases toward the south, and the southern margin of this distribution is cut and limited by faults. The depositional surface of the unit is inclined south at 45°S and indicates monoclinical deformation near the faults, whereas the bottom of the unit is inclined at 60°S and is cumulatively deformed (Figure 6).
8	Channel deposits only appeared in the fault-crossing trenches (DTA, DTD trenches; Figure 7). The unit is composed of subangular cobbles from 10 to 20 cm and its facies are distinctive and unique in the trench site. The geometry of the unit's cross section on the wall indicates a typical channel deposit (Figure 7). The width of the channel is between 3 and 6 m. No exposure affected the fault-crossing trench; therefore, the unit flowed straight forward from north to south across the fault depression, almost perpendicular to the fault traces.
9	Sand and gravel exposed only in the DTC2 trench. The unit consists of granules of up to 2 cm, and it has a matrix filled mainly with silt and medium to coarse sand.
10	Alluvial fan deposit composed of silt and subangular gravel divided into two subunits: upper dark brown and dark purple developed soil (unit 10a), and lower dark brown soil (unit 10b). Both units consist of poorly sorted subangular and angular cobbles from 0.5 cm to 10 cm filled with a matrix of silt. Between these two subunits, the alternation of clay and medium sand deposits implies dormancy in the alluvial fan development and a deposition in a low-energy environment. The upper unit 10a indicates the effect of soil development and contains numerous pieces of brick and pottery.
11	Debris flow deposit that appears only in the DTE trench. The thickness is about 90 cm, and the unit is composed of very poorly sorted cobbles and boulders. The unit contains fragments of pottery in a matrix of silt.
12	Grey-green clay with poorly sorted subangular cobbles exposed only at the southern side of the faults. The thickness is more than 100 cm. The top of the unit is intersected by an alluvial fan deposit (Unit 10).

development after its deposition. In contrast, Unit 5b, abutting Unit 6a, reflects low-energy sedimentation with a relatively stable water state, and this implies that the environment around the site suddenly changed from a high-energy state like a braded channel to low-energy sedimentation. Judging from these observations, Event III occurred and deformed Unit 6a and Unit 5b, then filled the lower part of the fault depression. Thus, Event III, which deformed Unit 6a, occurred before the deposition of the material filling Unit 5b.

3.4. Event IV

[14] Faults cutting through Unit 7 are clearly truncated by a sand and gravel layer, Unit 6b (Figure 6). The faults cut through from Unit 10a near the trench bottom to the lower part of Unit 7. On the western wall, Unit 7 stratigraphically contacts Unit 9 toward the southern fault strands at 60°, indicating more deformation than upper Unit 6a, which is cut by the younger Event III. Because Unit 7 consists mainly of clay which deposited horizontally, it is apparent that Unit 7 experienced an older event. The upward termination

of faults inside Unit 7 is not clear, however, so it is obvious that the faults do not cut through the bottom of Unit 6b and the laminated sand layer inside the unit. Therefore Event IV occurred between the deposition of Unit 7 and Unit 6b.

4. Chronology of Paleoseismic Events and Historical Earthquakes

[15] The radiocarbon ages of 25 accelerator mass spectrometry (AMS) samples constrain the timing of the four paleoseismic events. In order to refine the timing further, we first adopted stratigraphic-order constraints on calendar ages for each unit and events as proposed by *Biasi and Weldon* [1994] and *Biasi et al.* [2002] using the OxCal 3.1 program developed by *Ramsey* [2000]. Because three of the four paleoseismic events, excluding Event III, can be correlated with historical earthquakes with stratigraphic-order constrained ages, we attempted a further age constraint of Event III using the historical event constraint in the OxCal program. Therefore we first describe the original radiocarbon age for

Table 2. Radiocarbon Dates and Summary of Paleoseismic Event Timing^a

Unit ^b	Sample Name	Lab Code ^c	Material	¹³ C (‰)	Conv. ¹⁴ C (years B.P.)	Calibrated Age (1 sigma)
<i>Event I (1944)^d</i>						
02	DTC2W113	B-188778	humic silt	-27	160 ± 40	A.D. 1675–1950
02	DTCE02	B-180990	charcoal	-28	200 ± 40	A.D. 1656–1947
<i>Event II (1640–, 1668)^e</i>						
04 (middle)	DTE2S42 ^f	L-105565	charcoal	-25.0	80 ± 35	A.D. 1695–1953
04 (middle)	DTCN01	B-192589	charcoal	-26	170 ± 40	A.D. 1660–1950
04 (middle)	DTE2S42 ^f	B-192588	charcoal	-24	200 ± 50	A.D. 1650–1950
04 (lower)	DTCE05	B-180991	charcoal	-24	370 ± 40	A.D. 1452–1627
04 (lower)	DTA3N01	B-180987	charcoal	-25	410 ± 40	A.D. 1440–1487
<i>Event III (1210–1460, unknown)^e</i>						
05a	DTC2W115	L-105559	charcoal	-25.0	120 ± 35	A.D. 1680–1951
05b	DTC2E100	L-105560	charcoal	-25.0	1145 ± 35	A.D. 785–963
06a	DTC2W110	B-192590	wood	-27	880 ± 40	A.D. 1060–1210
06a	DTC2E106	B-192591	wood	-28	920 ± 40	A.D. 1030–1180
06a	DTC2W109	B-188780	charcoal	-26	1070 ± 40	A.D. 980–1020
06a	DTC2W111	L-105561	charcoal	-25.0	1560 ± 35	A.D. 431–541
06b (upper)	DTE2S41	L-105566	charcoal	-25.0	1055 ± 35	A.D. 978–1019
06b (lower)	DTA3N04	B-180989	charcoal	-26	1320 ± 40	A.D. 661–765
06b	DTC2E104	B-192592	plant	-27	1350 ± 40	A.D. 650–690
06b (bottom)	DTC2W119	L-105562	charcoal	-25.0	1360 ± 35	A.D. 653–683
<i>Event IV (840–960, 1035 ?)^e</i>						
07	DTC2W120	L-105563	charcoal	-25.0	1200 ± 35	A.D. 777–889
07	DTC2E101	B-191844	charcoal	-25	1700 ± 40	A.D. 240–370
07	DTC2E103	B-192593	humic silt	-25	1770 ± 40	A.D. 230–330
08	DTA2N15	L-105558	charcoal	-25.0	1270 ± 35	A.D. 687–777
09	DTC2W121	L-105564	wood	-25.0	1290 ± 35	A.D. 675–774
10a (upper)	DTA3N03	B-180988	charcoal	-24	1510 ± 40	A.D. 535–603
10a (upper)	DTE2S39	L-105567	charcoal	-25.0	1530 ± 35	A.D. 443–598
11 (lower)	DTFE67	B-188781	charcoal	-26	2480 ± 40	B.C. 770–425

^aCalibrated ages were determined using the OxCal 3.5 program of Ramsey [2000] and data from Stuiver *et al.* [1998]. Italic font represents stratigraphically contradictory samples, which are excluded from further age constraint. Modeled calendar years are refined date ranges derived from the OxCal program as shown in Figure 8.

^bInformation in parentheses gives unit part.

^cB, Beta Analytic, Inc.; L, Lawrence Livermore National Laboratory.

^dYear in parentheses is the historical earthquake.

^eYears in parentheses are modeled calendar years (1 sigma), historical earthquakes.

^fSplit samples for cross check in different laboratories.

each event and the possibility of correlation with historical earthquakes, and then we demonstrate the results of the combined chronology for the four past earthquakes. The dating results are summarized in Table 2 with the original radiocarbon dates and the modeled dates. The final probability distribution functions (PDFs) for each unit and event derived from both stratigraphic and historical constraints are presented in Figure 8.

4.1. Event I (A.D. 1944 Earthquake)

[16] This event occurred during the most recent soil development; therefore it most probably corresponds to the 1944 earthquake. Judging from the results of radiocarbon dating from Unit 2, this event is loosely constrained to have occurred after 160 ± 40 y.B.P (Sample DTC2W113; Table 2) and after A.D. 1675, very close to the modern calendar age.

4.2. Event II

[17] Event II occurs after the deposition of the flood loam deposits of Unit 3. The unit did not contain carbon samples, but we could obtain samples from Unit 4 to provide an older limit for the event. Three samples collected from the middle part of Unit 4 are close to modern, at 80 ± 35 y.B.P (DTC2S42: split sample), 170 ± 40 y.B.P (DTCN01), and

200 ± 50 y.B.P (DTC2S42: split sample), whereas samples from the lower part of the unit are from 370 ± 40 y.B.P and 410 ± 35 y.B.P (Table 2). Because the unit consists of massive flood loam deposits, the depositional time period should have been fairly short and probably occurred during one flood sequence. On the other hand, the results of dating show two clusters of younger ages: close to modern and ~400 y.B.P. To solve this contradiction, we used modeled calendar dates based on the stratigraphic-order constraint of the OxCal program [Ramsey, 2000]. On the basis of the stratigraphic-order constraint, the recalculated calendar dates show that Unit 4 was deposited after A.D. 1640. We thus consider the event to be correlated with the A.D. 1668 earthquake described in historical records [Ambraseys and Finkel, 1988].

4.3. Event III

[18] The timing of this event is constrained between A.D. 1210 and A.D. 1460 by the stratigraphic-order constraint and the correlation of historical earthquakes to the other three events (Table 2 and Figure 8). The unit 5 posterior deposit associated with this event was not well constrained because of the reworked charcoal it contained and because of samples it contained that were inconsistent with stratig-

Figure 8. Summary of calendar dates and probability distributions of the last four events and stratigraphic units. The original radiocarbon dates and details are shown in Table 2. Two recent events are assumed to correspond to the 1944 earthquake and the historical 1668 earthquake. The calculation was carried out using OxCal 3.5 [Ramsey, 2000]. Outlines indicate the probability distributions of calibrated radiocarbon ages prior to running the model. Grey areas represent posterior limits placed upon the distributions by constraints including stratigraphic order and historical earthquakes. Black areas show probability distributions inferred for the paleoearthquakes.

raphy (i.e., samples DTC2-W115 and DTC2-E100). On the basis of the radiocarbon dates (Table 2), the timing of the event is loosely constrained between 370 ± 40 y.B.P (DTCE05 from Unit 4) and 880 ± 40 y.B.P (DTC2E100 from Unit 6a). In order to further constrain the estimate, we assumed that the other three events correspond to historical earthquakes. Then, we recalculated the calendar age for Event III and obtained modeled calendar dates between A.D. 1210 and A.D. 1460 (Table 2 and Figure 8). Because of the shortage of dating samples from Unit 6a and the existence of soil development at the top of the unit, the actual timing of the event could be nearer the younger end of the modeled date range. No earthquake was recorded during this period, whereas results from the Ardicli trench site 1 km east of our site indicates that the paleoseismic event EV 3 occurred between the 11th and 13th centuries [e.g., Okumura *et al.*, 1993, also presented paper, 2004]. These data imply that

Event III at the Demir Tepe site is correlated with EV 3 at the Ardicli site, and it might have occurred in the 13th century.

4.4. Event IV

[19] The timing of this event is constrained between A.D. 840 and A.D. 960 (Table 2). Radiocarbon ages place the date between 1055 ± 35 y.B.P (DTE2S41) and 1200 ± 35 y.B.P (DTC2W120); however, these samples are derived from only one representative for each unit because chances to collect carbon-containing material here were limited. All other samples from both units are reworked charcoal that is just a few hundred years older. Thus the actual depositional ages for each unit are possibly younger; therefore the timing of the actual event could be younger than the modeled calendar dates between A.D. 840 and A.D. 960. At the Ardicli site, Okumura *et al.* (presented paper, 2004) recognized that EV 4 occurred between the 10th and 13th centuries, and it can be correlated with Event IV of our study. From this cross correlation, Event IV is possibly correlated with EV 4 of the Ardicli site and the historical earthquake of A.D. 1035. Ambraseys [1970] mentioned that this event occurred along the North Anatolian fault, and surface ruptures seem to have appeared between the town of Gerede and at least as far as İsmetpaşa, ~20 km east of the site. We thus assume in the following interpretation and discussion that Event IV at the Demir Tepe site corresponds to the 1035 historical earthquake.

5. Slip Measurement for Discrete Four Paleoeearthquakes

[20] Here we present interpretations of offset measurements of the surface and buried channels for the four paleoseismic events. We obtained four discrete offsets for individual paleoearthquakes based on stratigraphic relations among event horizons and reference deposits for the offset measurements. The slips associated with the two recent earthquakes are adopted from Kondo *et al.* [2005] as explained below; therefore we present the manner of measurement and the detailed piercing lines for the older buried channels in Figure 9. Cumulative offsets after the occurrences of Events III and IV are interpreted based on Figure 9. The reconstructed paleoenvironment inferred from lithological characteristics, spatial distribution of deposits, and detailed slip histories during individual paleoearthquakes are summarized in Figure 10.

5.1. Offset of Event I (A.D. 1944 Earthquake)

[21] The right-lateral offset associated with the 1944 earthquake near the site is measured at 4 to 5 m using the tree line. The amount is not very accurate or reliable because the reference tree line is curved, the fault trace crosses it at a low angle, and the fault trace is not perpendicular. However, offset measurements along the 1944 rupture within 10 km around the site were between 4.5 m and 5.5 m [Kondo *et al.*, 2005]. We thus believe that the 4.5 ± 0.5 m offset of the tree line at the site is reliable, and we used this for older slips by event subtraction.

5.2. Offset of Event II (A.D. 1668 Earthquake)

[22] Two shallow gullies incising into the alluvial fan surface exhibit cumulative right-lateral offsets of 10.5 ± 0.5 m

Figure 9. Plan view map of reconstructed buried channels for cumulative offset measurement. The buried channel in unit 6b exhibits a best-estimate slip amount of 15.3 ± 0.1 m, and in unit 8 it shows a best-estimate slip amount of 19.9 ± 0.5 m. Judging from observations of the fault-crossing trenches, unit 6b is cut by faults three times, and unit 8 is cut four times. Subtracting these cumulative slips yielded slip per event for individual earthquakes.

and 10.8 ± 0.2 m (Figure 4). These were originally measured and reported by Kondo *et al.* [2005] as 9.2 ± 1.3 m and 9.7 ± 1.2 m. The best estimate made in this report is similar, but the previous measurement had a large degree of uncertainty resulting from inappropriately putting the reference lines on the gullies in different directions on both sides of the fault zone. In this article, we reexamined the measurement to precisely determine the amount of slip based on more geomorphologically reliable reference lines. Then, we obtained the revised slip amounts as follows.

[23] The gullies incise into Unit 4 flood loam, which is clearly cut by faults associated with the 1944 and 1668 earthquakes. The amount of slip of the gullies is much larger than that of the 1944 event; therefore these gullies record the cumulative slips of the two most recent events. It is thus reasonable to reconstruct the sedimentation history that the site was once covered with Unit 4 flood loam, gullies developed at the surface, and then the 1668 earthquake occurred (Figures 9 and 10). In this case, it is important to assess whether the gullies originally developed linearly prior to the 1668 event

because this would especially affect the fault depression formed by prior events. The fault depression was formed during Event III and is covered by Unit 5 clay and silt and by Unit 4 (Figure 4). The thickness of Unit 4 inside the depression is very slightly larger than that on the alluvial fan surface, so it is apparent that the site was almost flat just after the deposition of Unit 4. Judging from these observations, the gullies originally flowed linearly on the fan surface and were not affected by the fault depression.

[24] Thus the cumulative offsets of 10.5 ± 0.5 m and 10.8 ± 0.2 m were produced by the 1944 and 1668 events. These measurements yield the best estimate of 10.6 ± 0.4 m for cumulative offsets at the site. Subtracting the 1944 offset from these cumulative offsets yields the amount of offset associated with the 1668 event: 6.1 ± 0.7 m.

5.3. Offset of Event III (No Historical Records)

[25] The cumulative right-lateral offsets of Unit 6b are 14.5 ± 0.8 m. Unit 6b is a braded channel deposit and is distributed widely at the site. On the walls of the fault-parallel trenches, DTA1 and DTD1, the eastern channel margins of Unit 6b are clearly visible (Figures 7 and 10). Meanwhile, the distribution of Unit 6b away from the fault zone is widely spread, and the channel margins are not continuously identifiable. On the walls of the fault-crossing trench DTC2 and the fault-parallel DTA1, DTA2, and DTD1 trenches, which are close to the fault zone, Unit 4 directly overlies the Unit 10 fan deposit unconformably, and there is no sedimentation of Unit 6b. Thus the channel margin exposed on the fault parallel trenches was originally deposited as one continuous channel of several braded channels (Figure 9).

[26] In the fault-parallel DTD1–4 trenches at the southern side of the fault, Unit 6b erodes the eastern margin of the lower buried channel deposit of Unit 8 (e.g., Figure 7). The contact between those units is almost linearly distributed in the plan view map (Figure 9). Correlation of the individual channels comprising Unit 6b is difficult, but it is clear that one of channels flowed southward linearly and eroded the lower channel of Unit 8.

[27] On the basis of these observations, we attempt to reconstruct the spatial distribution of Unit 6b and measure the associated right-lateral offsets. We set the most reliable reference lines for measurement at the eastern margin of channel in the DTA1 and DTD1 trenches, and the linearly distributed contact between Unit 6b and Unit 8 was exposed in the fault-parallel trenches. The amount of cumulative offset is measured at 15.3 ± 0.1 m (Figure 7). Subtracting the cumulative offset of the recent two events from this value, we resolved an offset associated with Event III of 4.7 ± 0.4 m.

5.4. Offset of Event IV (A.D. 1035 Earthquake)

[28] Unit 8, beneath the Event IV horizon, consists of subangular gravel in cobble to boulder size and shows distinctive facies for correlation from wall to wall in the fault-parallel trenches (Figure 11). In the fault-crossing trenches and inside the fault depression, no exposure of Unit 8 was obtained.

[29] The reconstructed spatial distribution of the unit indicates that the channel of Unit 8 flowed almost perpendicular to the fault strike and was clearly cut right-laterally

Present

Figure 10

Figure 11. A photograph of the piercing point of buried channel unit 8, looking northwest in the DTA1 trench. The channel margin is clearly identified and shows a distinct trough-shape channel margin. The spatial distribution of the channel margin gives a cumulative slip of 19.9 ± 0.5 m, shown in Figures 9 and 10.

by faults (Figure 9). Judging from the absence of the unit inside the fault depression, the channel originally flowed linearly across the fault trace and was not affected by the fault depression.

[30] Piercing lines through Unit 8 set on the western margin of the channel allowed us to measure cumulative offsets of 19.3 ± 0.5 m. The eastern margin of the channel is eroded by the younger Unit 6b. We assumed the trend of the piercing line at the northern side of fault is the same as at the southern side. Because Unit 8 is not exposed in the fault-crossing trenches, the number of events forming cumulative offsets is not definitive. Judging from the estimation that Unit 8 is indirectly below the Event IV horizon and is the age of the older Unit 9, the four paleoearthquakes most probably produced the cumulative offset of Unit 8. Thus the offset associated with Event IV is 4.6 ± 0.6 m.

6. Discussion and Conclusions

6.1. Quasiperiodic and Characteristic Recurrence Behavior on the Gerede Segment

[31] A time-slip diagram based on reconstructed data indicates quasiperiodic characteristic behavior at the Demir Tepe site (Figures 12 and 13). Assuming the timing of individual events can be correlated with historical earthquakes as described above, the average interevent time is calculated to be 330 years. The slip per event associated with the last four events is summarized as 4.0 ± 0.5 m (A.D. 1944 event), 6.1 ± 0.7 m (A.D. 1668 event), 4.7 ± 0.4 m (13–15th century event), and 4.6 ± 0.6 m (A.D. 1035 event).

Figure 12. Reconstructed slip per event for the last four events at the Demir Tepe site. The mean slip is 5.0 m for individual earthquakes. The COV of 0.2 indicates that the repeated slip at the site was highly characteristic during the recent four earthquakes.

The average amount of slip per event during the last four events is 5.0 ± 0.8 m with a coefficient value (COV) of 0.2.

[32] This recurrence behavior can be interpreted as a representative characteristic of the main portion of the Gerede segment. Kondo *et al.* [2005] presented detailed data and pointed out that measurements of the cumulative slips exhibit double to quadruple multiple slips for the 1944 slip at each locality (Figure 14). The cumulative offsets along the segment were twice as large as the 1944 offset at four measurement sites, three times as large at two sites, and four times as large at another two sites, all within the errors of measurement. Combining these cumulative slip data with the Demir Tepe trench data shows that it is reasonable to believe that the main portion of the Gerede segment has ruptured with quasiperiodic and characteristic slip through the four recent multisegment earthquakes.

[33] The repetition of similar slip is inconsistent with physics-based theoretical models. Several physical models predict complex slip repetition in accord with power law frequency-size distributions of seismicity [e.g., Shaw and Rice, 2000; Parsons, 2006]. However, our data do not support such highly irregular and chaotic random repetitions of slip on a given segment. The repetition of surface slip distributions on the fault segment supports the hypotheses of geology-based recurrence models such as the characteristic slip model [Schwartz and Coppersmith, 1984], the uniform slip model [Sieh, 1981], or the slip patch model [Sieh, 1996]. Similar surface slip repetition of up to 8 m is reported at the Wallace Creek site on the San Andreas fault [Liu-Zeng *et al.*, 2006]. This may imply that a segment that produces surface slip larger than ~ 5 m constantly repeats through multiple earthquake cycles, if the tectonic loading rate on the segment is stable.

[34] In addition, historical records indicate that the Gerede segment was active during some of the past multisegment earthquakes. In the earthquake cycle of the 10th to 11th centuries, the five segments comprising the 1944 rupture activated separately: the Bolu and Yeniçağa segments during

Figure 10. Reconstruction of slip history combined with deposition of individual stratigraphic units and individual amount of slip per event at the Demir Tepe site, showing the start of the reconstruction, soon after the deposition of unit 8 buried channel (Event IV image) and the current topography and the displaced trench with a summary of three distinct cumulative slips (present image).

Figure 13. Time-slip diagram at the Demir Tepe site. The timing of three out of four events is assumed to be correlated with historical earthquakes in 1944, 1668, and 1035. Grey rectangles indicate uncertainties in time and amount of slip. Thin gray lines denote geological slip rate inferred from 3-D trench data. The diagram indicates that repeat events have a highly characteristic slip and are quasiperiodic. In addition, the data support a more slip-predictable, rather than a time-predictable, recurrence as shear stress τ_2 falls on the same level for each event. See details in text.

the 967 earthquake and the Gerede, İsmetpaşa, and possibly the Bayramören segments during the 1035 earthquake [Kondo *et al.*, 2005]. No historical records suggest that the rupture terminated between the Gerede segment and the next eastern İsmetpaşa segment and a segment boundary exists between them. But the faulting behavior on the İsmetpaşa segment is characterized by after-slip following the 1944 event [Doğan *et al.*, 2003; Çakır *et al.*, 2005], hence, it is unique and different from the Gerede segment. Moreover, the 1668 earthquake was accompanied by a surface rupture >600 km, encompassing the 1939, 1942, 1943, and 1944 earthquake ruptures [Ambraseys and Finkel, 1988] and even the 1967 rupture zone [Ikeda *et al.*, 1991]. Thus historical data and our segmentation model indicate that different combination patterns of fault segments, including the Gerede segment, have produced various sizes of large earthquakes with distinct rupture lengths through the recent earthquake cycles. Nevertheless, trench and historic data indicate that during the last millennium, four earthquakes associated with different total rupture lengths have ruptured the Gerede segment of the NAFS with approximately uniform slip and recurrence intervals.

6.2. Role of the Gerede Segment During Repeated Multisegment Ruptures and Its Persistence

[35] A comparison of the detailed fault geometry and seismic instrumental data recorded during the 1944 earthquake shows that the rupture initiated close to the eastern end of the 1944 rupture and propagated westward. The epicenter was located at 41.10° N, 33.22° E around the border between the 1944 rupture and the eastern next 1943 Tosya earthquake rupture [Dewey, 1976; Ambraseys, 1988]. The easternmost segment of the 1944 rupture, the Bayramören segment, recorded a relatively small surface slip, up to ~2 m, associated with the 1944 event. A few aftershocks of magnitudes >5.0 occurred around the Bolu town region, close to where the 1944 rupture terminated [Dewey, 1976], in accord with the westward rupture propagation.

[36] Judging from these instrumental records and surface geometry characteristics, the five fault segments likely ruptured in sequence from east to west, as in a slip-pulse rupture pattern (Figure 15a). The downdip width of the fault plane is assumed to be 15–20 km, describing the general dimensions of the fault plane along the NAFS [e.g., Stein *et al.*, 1997]. If the entire 1944 rupture simply occurred on a single segment as described by the L-model [Scholz, 2002] from east to west, the surface slip distribution of the rupture would have appeared as shown in Figure 15a. However, the surface slip distribution measured in the field does not in fact fit the profile of the L-model which is like a rupture mode derived from a single-segment model. Furthermore, the constant size of the repeated slip on the Gerede segment apparently does not scale with the rupture length of individual historical earthquakes (Figure 15b). The amount of slip on the Gerede segment saturated and did not proportionally increase with the longer rupture length of >600 km during the 1668 event, nor did it decrease with the shorter rupture length of ~70 km during the 1035 earthquake. This is in accordance with the large earthquake scaling laws that were recently modified because the amount of slip saturates during long rupture on

Figure 14. Cumulative slip distribution with slips during the 1944 earthquake along the Gerede segment. Modified from Kondo *et al.* [2005]. The x axis represents eastward distance along the Gerede segment. The cumulative slip distribution shows two to four slips for the 1944 event, suggesting that a similar amount of discrete slip distribution recurred along the segment for the last four events. This implies that the repeatability of the Demir Tepe site can be reasonably applied as a representative recurrence for the Gerede segment.

Figure 15. (a) Proposed rupture pattern associated with the 1944 earthquake and (b) multiple-rupture length through historical earthquakes. The measured surface slip distribution is not consistent with the slip distribution of a single segment model such as the L-model [e.g., Scholz, 2002] but rather with a segmented model in which each segment ruptured in sequence from east to west. Judging from historical records, the Gerede segment has experienced multisegment ruptures with different total rupture lengths or earthquake magnitudes. Although there is a great variance in rupture length for each event, the Gerede segment likely ruptured in a highly characteristic way that was quasiperiodic. This implies that a macroscopic asperity segment regularly repeating in multisegment earthquakes exists along active fault systems such as the NAFS.

active fault [e.g., Shaw and Scholz, 2001; Manighetti et al., 2005].

[37] In contrast, in the case where the five segments have their own slip distributions and they ruptured in one sequence during the 1944 event, a slip-pulse-like rupture pattern provides a better fit to the actual surface slip profile. No detailed slip data around each segment boundary were available; therefore it is difficult to discuss whether the actual slip distribution completely fits a W-model [e.g., Romanowicz, 1992]-like slip pattern. But, the slip-pulse-like distribution is apparently more appropriate than the single-segment slip pattern, as several slip gaps and abrupt changes in the amount of slip exist, corresponding to our proposed segment boundaries. We thus speculate that the rupture pattern during the 1944 event would have been a slip-pulse-like propagation from east to west. Judging from the relatively simple surface fault traces and the small magnitudes of fault discontinuities along the entire 1944 rupture, the rupture process might have been relatively smooth [Kondo et al., 2005]. In these seismological contexts, the Gerede segment behaves as an asperity in the relatively large slip patch on the fault plane. A reestimation of the detailed rupture process would provide more concrete and quantitative seismic source information.

[38] Furthermore, the Gerede segment has an extremely linear surface geometry, suggesting a simple fault structure at depth, and it has persistently repeated its faulting behavior through recent geological time. The surface geometry of the Gerede segment shows extremely linear and simple traces without any kilometer-scale discontinuities such as fault steps, bends, gaps, or bifurcations (Figure 2; more details in

the work of Kondo et al. [2005]). This is in accord with the simple recurrence behavior that indicates a relatively simple strain accumulation and release process through earthquake cycles. Our best estimate of the slip rate in this study is 17 mm a^{-1} based on the oldest offset buried channel and its age (Figure 13). Assuming a characteristic slip of $\sim 5 \text{ m}$ and a recurrence interval of ~ 250 years estimated at the Ardicli site in longer periods [e.g., Okumura et al., 1993], the slip rate would possibly be $\sim 20 \text{ mm a}^{-1}$. It is thus comparable with a GPS-based geodetic rate of $<24 \pm 1 \text{ mm a}^{-1}$ along the NAFS [McClusky et al., 2000; Reilinger et al., 2006]. Kozaci et al. [2009] argued that the slip rate derived from a 3-D trench within a 5-m width of the fault zone may be an underestimate. However, as Rockwell and Ben-Zion [2007] pointed out, the primary slip zones of active faults are highly localized on the order of millimeters to centimeters, as we can observe in these trenches at depths of a few meters as well as at seismogenic depths. The facts we observed and the slip rate estimate support the idea that the primary fault zone is highly localized enough to represent a strain-release mechanism from the ground surface to a significant depth. This also suggests that the recurrence behavior of the segment is able to reflect the downdip behavior on the fault plane; therefore it is likely that the Gerede segment has generally been active as an asperity with a relatively large slip patch at depth during multisegment earthquakes. It is thus apparent that the recurrence behavior on the Gerede segment has persisted through recent geological time as suggested by its repetition during historical earthquakes in addition to its geological slip rate.

6.3. Implications for Seismic Hazard Analysis

[39] The characteristics of recurrence behavior on the 1944 rupture imply valuable information for the seismic hazard analysis of multisegment earthquakes derived from a strike-slip fault system. The evidence for the mechanical simplicity of long-term faulting supports the idea that surface data provide a long-term forecast of the timing of multisegment earthquakes produced by an active fault system [e.g., Wallace, 1970; Schwartz and Coppersmith, 1984; WGCEP, 1995]. This implies that surface slip data, recurrence intervals, and slip rate data contribute practically to predicting the location and size of asperities on a fault system before the occurrence of multisegment earthquakes. On the other hand, we probably need to pay more attention to estimating the total rupture length and the final size of an earthquake based on single-point surface slip data. A simple reconstruction of slip for each event at the site would have not been useful in distinguishing the total rupture length of each historical earthquake. Additionally, recurrence behavior on the Gerede segment cannot be adapted to anywhere else on any segment [e.g., Weldon et al., 2004; Kondo et al., 2009]. The characteristics of recurrence behavior would naturally be different from segment to segment all along the fault system, probably reflecting fault strength contrasts and other physical properties on the fault planes [e.g., Wesnousky, 1988].

[40] Turning back to Figure 13, further analysis of the time-slip diagram indicates that the slip-predictable behavior fits slightly better with the recurrence of such a macroscopic asperity during multisegment ruptures, rather than the time-predictable model. Both time- and slip-predictable models [Shimazaki and Nakata, 1980] show fairly good agreement, but the slip-predictable model best fits the actual data. This implies that the type of segment may be generally triggered and involved as a part of multisegment ruptures, not single segment rupture, over earthquake cycles. The stress changes resulting from the activation of neighboring segments might have influenced the timing of the Gerede segment faulting, but the Demir Tepe site is situated almost at the middle of the segment and far enough from the segment boundaries where static stress concentration generally occurs [e.g., Stein et al., 1997]. Because the amount of slip is basically controlled by the stress drop built up due to the stress rate on a segment and the elapsed time since the last event, in addition with dynamic rupture effects, better fitting to the slip-predictable model suggests that the segment may be affected by simple stress accumulation and mostly dynamic stress changes.

[41] Furthermore, the various rupture lengths associated with historical earthquakes, between several tens of kilometers to hundreds of kilometers, raise a question about the final size of multisegment earthquakes. Because the 1944 earthquake initiated around the eastern edge of the 1944 rupture, the rupture propagated unilaterally, although it may have been relatively smooth and brief. This rupture pattern indicates that the easternmost segment ruptured first and triggered the next western segment sequentially during the 1944 event. This suggests that when the 1944 earthquake initiated, the rupture at the initiation stage could not determine where the terminus of the total rupture would be, or when the earthquake rupture would stop. In fact, the rupture terminated at the westernmost segment which is located

~180 km far west from the epicenter. If any segments inside of the 1944 rupture were not ready to be triggered and not participated in the multisegment rupture, the size of the 1944 earthquake would have been smaller and the event would have terminated at a different place. In this context, the data imply quantitatively how close an individual segment is close to failure is important, and this would be helpful in estimating the final size of the multisegment earthquake as well as in fault discontinuity analysis [e.g., Wesnousky, 2006] and dynamic rupture simulation [e.g., Harris and Day, 1993; Kase and Kuge, 1998]. Hence knowing the past recurrence behavior from a time-slip history on given segments is needed to forecast the final size of multisegment earthquakes on the strike-slip fault system.

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References

- Ambraseys, N. (1970), Some characteristic features of the Anatolian fault zone, *Tectonophysics*, **9**, 143–165, doi:10.1016/0040-1951(70)90014-4.
- Ambraseys, N. (1988), Engineering seismology, *Earthquake Eng. Struct. Dyn.*, **17**, 1–50, doi:10.1002/eqe.4290170101.
- Ambraseys, N., and C. Finkel (1988), The Anatolian earthquake of 17 August 1668, in *Historical Seismograms and Earthquakes of the World*, edited by W. H. K. Lee, H. Meyers, and K. Shimazaki, pp. 173–180, Academic, San Diego, Calif.
- Ambraseys, N., and C. Finkel (1995), *The Seismicity of Turkey and Adjacent Areas: A Historical Review, 1500–1800*, 240 pp., Muhittin Salih Eren, Istanbul, Turkey.
- Barka, A. (1996), Slip distribution along the North Anatolian fault associated with the large earthquakes of the period 1939 to 1967, *Bull. Seismol. Soc. Am.*, **86**, 1238–1254.
- Barka, A., and K. Kadinsky-Cade (1988), Strike-slip fault geometry in Turkey and its influence on earthquake activity, *Tectonics*, **7**, 663–684, doi:10.1029/TC007i003p00663.
- Barka, A., et al. (2002), The surface rupture and slip distribution of the 17 August 1999 İzmit earthquake (M 7.4), North Anatolian fault, *Bull. Seismol. Soc. Am.*, **92**, 43–60, doi:10.1785/0120000841.
- Biasi, G., and R. Weldon II (1994), Quantitative refinement of calibrated C-14 distributions, *Quat. Res.*, **41**, 1–18, doi:10.1006/qres.1994.1001.
- Biasi, G., and R. Weldon II (2006), Estimating surface rupture length and magnitude of paleoearthquakes from point measurements of rupture displacement, *Bull. Seismol. Soc. Am.*, **96**, 1612–1623, doi:10.1785/0120040172.
- Biasi, G., R. Weldon II, T. Fumal, and G. Seitz (2002), Paleoseismic event dating and the conditional probability of large earthquakes on the southern San Andreas fault, California, *Bull. Seismol. Soc. Am.*, **92**, 2761–2781, doi:10.1785/0120000605.
- Çakır, A., M. Akoglu, S. Belabbes, S. Ergintav, and M. Meghraoui (2005), Creeping along the İsmetpaşa section of the North Anatolian fault (Western Turkey): Rate and extent from InSAR, *Earth Planet. Sci. Lett.*, **238**, 225–234, doi:10.1016/j.epsl.2005.06.044.
- Dewey, J. (1976), Seismicity of northern Anatolia, *Bull. Seismol. Soc. Am.*, **66**, 843–868.
- Doğan, A., H. Kondo, Ö. Emre, Y. Awata, and S. Özalp (2003), Triggered slip on the İsmetpaşa segment of 1944 Bolu-Gerede surface rupture by the 1999 İzmit earthquake, North Anatolian Fault, Turkey, *Geophys. Res. Abstr.*, **5**, EAEm1-A-11520.
- Eberhart-Phillips, D., et al. (2003), The 2002 Denali Fault earthquake, Alaska: A large magnitude, slip-partitioned event, *Science*, **300**, 1113–1118, doi:10.1126/science.1082703.

- Harris, R., and S. Day (1993), Dynamics of fault interaction: Parallel strike-slip faults, *J. Geophys. Res.*, **98**, 4461–4472, doi:10.1029/92JB02272.
- Ikeda, Y., Y. Suzuki, E. Herece, F. Saroglu, A. M. Isikara, and Y. Honkura (1991), Geological evidence for the last two faulting events on the North Anatolian fault zone in the Mudrunu Valley, western Turkey, *Tectonophysics*, **193**, 335–345, doi:10.1016/0040-1951(91)90342-P.
- Kase, Y., and K. Kuge (1998), Numerical simulation of spontaneous rupture processes on two non-coplanar faults: The effect of geometry on fault interaction, *Geophys. J. Int.*, **135**, 911–922, doi:10.1046/j.1365-246X.1998.00672.x.
- Kondo, H., V. Özaksay, C. Yildirim, Y. Awata, Ö. Emre, and K. Okumura (2004), 3-D trenching survey at Demir Tepe site on the 1944 earthquake rupture, North Anatolian fault system, Turkey (in Japanese with English abstract and figure captions), *Geol. Surv. Jpn.*, **4**, 231–242.
- Kondo, H., Y. Awata, Ö. Emre, A. Doğan, S. Özalp, F. Tokay, C. Yildirim, T. Yoshioka, and K. Okumura (2005), Slip distribution, fault geometry, and fault segmentation of the 1944 Bolu-Gerede earthquake rupture, North Anatolian Fault, Turkey, *Bull. Seismol. Soc. Am.*, **95**, 1234–1249, doi:10.1785/0120040194.
- Kondo, H., A. Kurcer, S. Ö. Zalp, and Ö. Emre (2009), Non-characteristic recurrence behavior on the 1942 Nıksar-Erbaa earthquake rupture along the North Anatolian fault system, Turkey, *Geophys. Res. Abstr.*, **11**, EGU2009-7712.
- Kozaci, Ö., J. Dolan, and R. Finkel (2009), A late Holocene slip rate for the central North Anatolian fault, at Tahtakopru, Turkey, from cosmogenic ¹⁰Be geochronology: Implications for fault loading and strain release rates, *J. Geophys. Res.*, **114**, B01405, doi:10.1029/2008JB005760.
- Liu-Zeng, J., Y. Klinger, K. Sieh, C. Rubin, and G. Seitz (2006), Serial ruptures of the San Andreas fault, Carrizo Plain, California, revealed by three-dimensional excavations, *J. Geophys. Res.*, **111**, B02306, doi:10.1029/2004JB003601.
- Manighetti, I., M. Campillo, C. Sammis, P. M. Mai, and G. King (2005), Evidence for self-similar, triangular slip distributions on earthquakes: Implications for earthquake and fault mechanics, *J. Geophys. Res.*, **110**, B05302, doi:10.1029/2004JB003174.
- McClusky, S., et al. (2000), Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *J. Geophys. Res.*, **105**, 5695–5719.
- Okumura, K., T. Yoshioka, and I. Kusu (1993), Surface faulting on the North Anatolian fault in these two millennia, *U.S. Geol. Surv. Open File Rep.*, **94-568**, 143–144.
- Parsons, T. (2006), *M* 7.0 earthquake recurrence on the San Andreas fault from a stress renewal model, *J. Geophys. Res.*, **111**, B12305, doi:10.1029/2006JB004415.
- Ramsey, B. (2000), OxCal Program Ver. 3.5, Radiocarbon Accelerator Unit, Univ. of Oxford, U.K., *Radiocarbon*, **40**, 1041–1083. (Available at <http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html>.)
- Reilinger, R., et al. (2006), GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions, *J. Geophys. Res.*, **111**, B05411, doi:10.1029/2005JB004051.
- Rice, J., and Y. Ben-Zion (1996), Slip complexity in earthquake fault models, *Proc. Natl. Acad. Sci. U. S. A.*, **93**, 3811–3818, doi:10.1073/pnas.93.9.3811.
- Rockwell, T. K., and Y. Ben-Zion (2007), High localization of primary slip zones in large earthquakes from paleoseismic trenches: Observations and implications for earthquake physics, *J. Geophys. Res.*, **112**, B10304, doi:10.1029/2006JB004764.
- Rockwell, T., S. Lindvall, M. Herzberg, D. Murbach, T. Dawson, and G. Berger (2000), Paleoseismology of the Johnson Valley, Kickapoo and Homestead Valley faults of the Eastern California Shear Zone, *Bull. Seismol. Soc. Am.*, **90**, 1200–1236, doi:10.1785/0119990023.
- Romanowicz, B. (1992), Strike-slip earthquakes on quasi-vertical transcurrent faults: Inferences for general scaling relations, *Geophys. Res. Lett.*, **19**, 481–484, doi:10.1029/92GL00265.
- Scholz, C. (2002), *The Mechanics of Earthquakes and Faulting*, 2nd ed., 439 pp., Cambridge Univ. Press, New York.
- Schwartz, D., and K. Coppersmith (1984), Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas fault zones, *J. Geophys. Res.*, **89**, 5681–5698, doi:10.1029/JB089iB07p05681.
- Sekiguchi, H., K. Irikura, and T. Iwata (2000), Fault geometry at the rupture termination of the 1995 Hyogo-ken Nanbu earthquake, *Bull. Seismol. Soc. Am.*, **90**(1), 117–133, doi:10.1785/0119990027.
- Shaw, B. E., and J. R. Rice (2000), Existence of continuum complexity in the elastodynamics of repeated fault ruptures, *J. Geophys. Res.*, **105**, 23,791–23,810, doi:10.1029/2000JB900203.
- Shaw, B. E., and C. H. Scholz (2001), Slip-length scaling in large earthquakes: Observations and theory and implications for earthquake physics, *Geophys. Res. Lett.*, **28**, 2995–2998, doi:10.1029/2000GL012762.
- Shimazaki, K., and T. Nakata (1980), Time-predictable recurrence model for large earthquakes, *Geophys. Res. Lett.*, **7**, 279–282, doi:10.1029/GL007i004p00279.
- Sieh, K. (1981), A review of geological evidence for recurrence times of large earthquakes, in *Earthquake Prediction: An International Review*, Maurice Ewing Ser., vol. 4, edited by D. Simpson and P. Richards, pp. 181–207, AGU, Washington, D. C.
- Sieh, K. (1996), The repetition of large-earthquake ruptures, *Proc. Natl. Acad. Sci. U. S. A.*, **93**, 3764–3771, doi:10.1073/pnas.93.9.3764.
- Sieh, K., et al. (1993), Near-field investigations of the Landers Earthquake sequence, April to July 1992, *Science*, **260**, 171–176, doi:10.1126/science.260.5105.171.
- Stein, R., A. Barka, and J. Dietrich (1997), Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering, *Geophys. J. Int.*, **128**, 594–604, doi:10.1111/j.1365-246X.1997.tb05321.x.
- Stuiver, M., P. Reimer, E. Bard, J. Beck, G. Burr, K. Hughen, B. Kromer, F. McCormac, J. van der Plicht, and M. Spurk (1998), INTCAL98 Radiocarbon age calibration, 24,000–0 cal BP, *Radiocarbon*, **40**, 1041–1083.
- The Headquarters for Earthquake Research Promotion (2005), Methods of evaluating active fault for fundamental survey and observation (August 24, 2005) (in Japanese), 46 pp., Tokyo.
- Tse, S., and J. Rice (1986), Crustal earthquake instability in relation to the depth variation of frictional slip properties, *J. Geophys. Res.*, **91**, 9452–9472, doi:10.1029/JB091iB09p09452.
- Wallace, R. (1970), Earthquake recurrence intervals on the San Andreas Fault, *Geol. Soc. Am. Bull.*, **81**, 2875–2890, doi:10.1130/0016-7606(1970)81[2875:ERIOTS]2.0.CO;2.
- Ward, S. N. (1997), Dogtails versus rainbows: Synthetic earthquake rupture models as an aid in interpreting geological data, *Bull. Seismol. Soc. Am.*, **87**, 1422–1441.
- Weldon, R., K. Scharer, T. Fumal, and G. Biasi (2004), Wrightwood and the earthquake cycles: What a long recurrence record tells us about how faults work, *GSA Today*, **14**, 4–10, doi:10.1130/1052-5173(2004)014<4:WATECW>2.0.CO;2.
- Weldon, R. J., T. E. Fumal, G. P. Biasi, and K. M. Scharer (2005), Past and future earthquakes on the San Andreas Fault, *Science*, **308**, 966–967, doi:10.1126/science.1111707.
- Wells, D. L., and K. J. Coppersmith (1994), New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc. Am.*, **84**, 974–1002.
- Wesnousky, S. (1988), Seismological and structural evolution of strike-slip faults, *Nature*, **335**, 340–343, doi:10.1038/335340a0.
- Wesnousky, S. (2006), Predicting the endpoints of earthquake ruptures, *Nature*, **444**, doi:10.1038/nature05275.
- Working Group on California Earthquake Probability (WGCEP) (1988), Probabilities of large earthquakes occurring in California along the San Andreas fault, *U.S. Geol. Surv. Open File Rep.*, **1978**, 388–398.
- Working Group on California Earthquake Probabilities (WGCEP) (1995), Seismic hazards in southern California: Probable earthquakes, 1994–2024, *Bull. Seismol. Soc. Am.*, **85**, 379–439.

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