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THE 1999 EARTHQUAKE ACTIVITY IN IZMIT, NW TURKEY AN OPPORTUNITY FOR THE STUDY OF ACTUALISTIC STRIKE-SLIP RELATED TECTONIC FORMS

E.L.LEKKAS[1]

ABSTRACT

The 1999 earthquake activity in the area of Izmit – Bolu, Turkey, which included two major shocks, on the 17th Aug. and 12th Nov. 1999, was caused by the reactivation of fault segments that belong to NAFZ. Field research was focused on fault geometry and slip characteristics, and allowed us to distinguish seven successive right-stepping reactivated segments and the related oversteps. Investigations showed that there is good match between the observed structures and those produced by experimental modelling. Finally, an estimation is made as to the percentage of seismic and aseismic slip on the reactivated segment of the fault zone.

KEY WORDS: Izmit, earthquake, strike slip, fault

1. INTRODUCTION

On August 17, 1999 (03:01:37 local time), a major earthquake hit NW Turkey. The epicentre was located at 40.702N, 29.987E (USGS), the magnitude was Mw=7.4 and the focal depth was h=15-17 km (USGS). The earthquake caused considerable damage to numerous population centres including Adapazari, Izmit, Gφlcόk and Yalova, all lying along an E-W axis. The main bulk of damage was within a 140 by 15 km zone, which also included the surficial occurrence of the seismic fault, which belongs to the NAFZ (Fig. 1).

About three months later, on 12 November 1999 (19:57:21 local time), the area was hit anew by a Mw=7.1 earthquake (h=10 km), located at 40.768N, 31.148E (USGS), approximately 100 km east of the August shock. The towns of Bolu, Dόzce, Hendek, Cφlyaka and Adapazari, among others, were severely damaged. All of them lay on a E-W trending zone, 80 km long and 10 km wide. That zone also hosted the surficial occurrence of the seismic fault, located on the eastward prolongation of the 17 August rupture.

Both earthquakes were accompanied by a suite of earthquake-related effects such as lateral spreading, soil fractures, liquefaction, settlement, coastline change, tsunamis and so on. On top of all these, the fires that broke out completed the picture of devastation (LEKKAS et al., 1999).

The 150 kilometres of surficial faulting in the Izmit and Dόzce earthquakes gave us the chance to study the real-time deformation in strike-slip zones. This is a rare opportunity because the study of strike-slip deformations is mainly based either on laboratory, analogue or numerical experiments (MANN et al. 1983, SYLVESTER 1988, etc.), or on the examination of tectonic structures formed in the geological past (Fig. 2).

In the following sections we shall give first a brief outline of the regional seismotectonic – geodynamic setting; the earthquake faults and related events will also be presented. Next, we shall focus on the reactivated fault segments

2. GEODYNAMIC SETTING – GENERAL DESCRIPTION OF SEISMIC FAULTS

The Middle East region corresponds roughly to the Arabian Plate, which moves northwards, towards the Eurasian Plate, squeezing out and to the west the Anatolian Plate, while a portion of eastern Turkey, Armenia, Azerbaijan and northern Iran are driven eastwards (Oral 1994, Reilinger et al. 1997). The westward extrusion of the Anatolian Plate is mainly accommodated through the NAFZ, which has a mean E-W trend, running from Armenia to the Sea of Marmara. It is a 1st-order tectonic structure within the Eurasian Plate (Ambraseys 1970, Sengor 1979, Sengor et al. 1985, Barka et al. 1984, Barka 1992). The right-lateral strike-slip motion of the NAFZ has given birth to a series of major earthquakes, many of them exceeding magnitude 7 (Barka 1996, Barka et al. 1988). Ten such large earthquakes have occurred since 1939 (Fig. 1), causing considerable damage to the popu-

1. Department of Geology, University of Athens, Panepistimioupoli, 15784 Athens

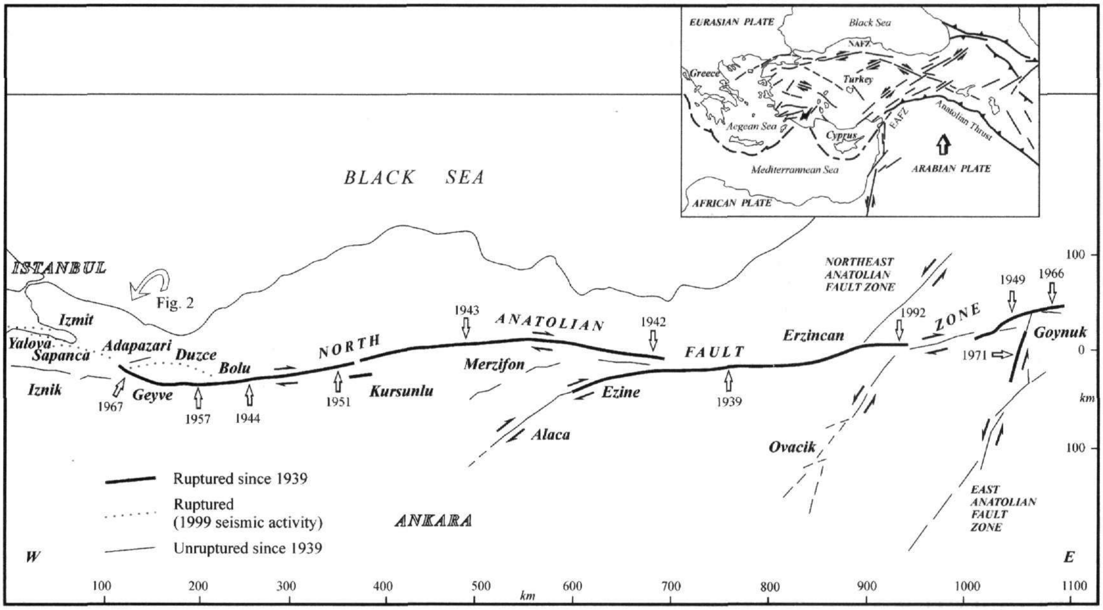

Fig. 1 Tectonic sketch map to show the parts of the NAFZ reactivated since 1939 (heavy lines), according to Stein et al. (1997). The Bolu, Dózce, Adapazari, Sapanca, Izmit and Yalova segments (dotted lines) ruptured in the 17 August and 12 November 1999 earthquakes.

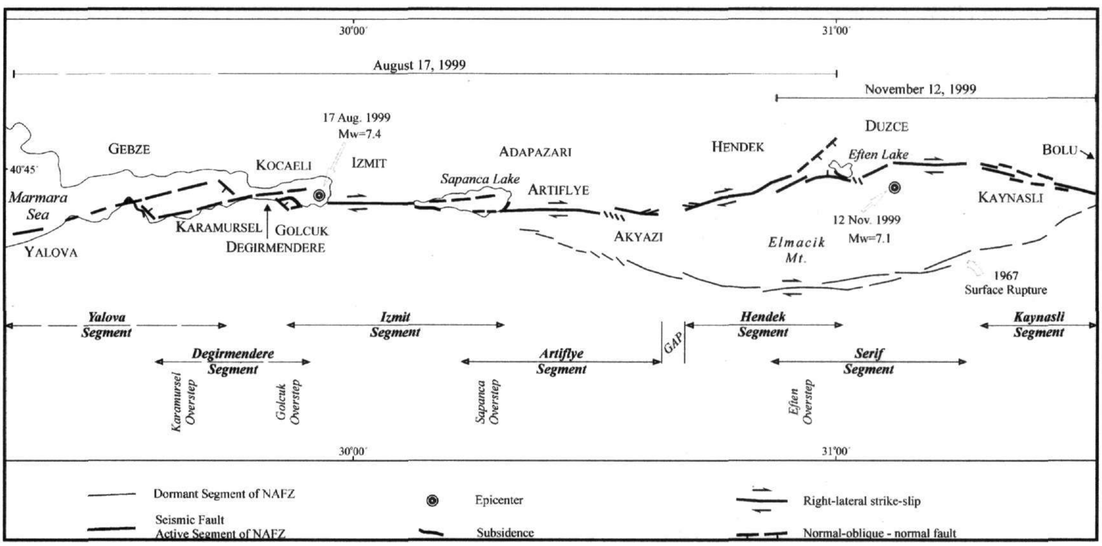

Fig. 2 The traces of the segments reactivated in the 17 August and 12 November 1999 earthquakes.
and associated structures. Finally, a comparison between our observations and the results of previous studies will be attempted.

lation centres lying on fault traces (Stein et al., 1997).

The existence of the NAFZ is also evident in the modification it has caused on the relief and drainage (Chorowicz et al., 1999). Strike-slip deformation has created, among others, a series of depressions, or pull-apart basins, such as the Sapanca and Izmit lakes; another example is the Sea of Marmara (Wong et al. 1995, Armijo et al. 1999) which, according to more recent research, is characterized as an escape basin with co-linear symmetrical flower structures above a single buried master fault (Aksu et al., 2000).

The part of the NAFZ that gave rise to the 17 August 1999 earthquake had not ruptured in the 20th century

(Stein et al., 1997). GPS surveys had detected aseismic movement on this part, in the order of 10-15 mm/yr (Straub et al. 1997, Armijo et al. 1999). It has also been suggested that earthquake fractures were produced in the 1719 and 1754 earthquakes that were located in the same area. USGS has reported that the rupture plane was almost vertical, oriented E-W and the slip vector was right-lateral (NP1: strike 92, dip 68, slip 178; NP2: strike 183, dip 88, slip 22).

Field reconnaissance and mapping showed that the surface faulting occurred between Lake Eften and Gφlcók, for an overall distance of 100 km; the maximum observed offset was locally more than 5 m. Additionally, there is evidence that faulting continued offshore to the west of Gφlcók and in the Sea of Marmara, for another 50 km (Youd et al., 1999).

The epicentre of the 12 November 1999 earthquake was located south of Dózce. The shock was also caused by a part of the NAFZ that had not ruptured in the 20th century (Stein et al., 1997). GPS measurements have also found a 10-15 mm/year aseismic movement on this part of the fault (Straub et al. 1997, Armijo et al. 1999). The focal mechanism solution calculated by the USGS gave an E-W trending rupture plane with steep southerly dip (NP1: strike 265, dip 65, slip -158; NP2: strike 166, dip 70, slip -27).

Post-earthquake field mapping showed that surface faulting occurred between Lake Eften in the west and Kaynasli-Bolu in the east, for a distance of over 50 km and a maximum right-lateral offset that exceeded locally 4.5m.

3. DETAILED DESCRIPTION OF FAULT SEGMENTS

The reactivated fault zone in the 17 August earthquake was 100 km long; about 50 km less was the rupture caused by the 12 November shock, which means that a total of 150 km were affected by surficial faulting onshore (Fig. 2), while within the Sea of Marmara faulting may have continued for a few km (Youd et al., 1999).

The surficial ruptures are distinguished in segments, which are characterized by their own geometry and kinematics (Fig. 2, 3). Our description is based on field observations along the seismic fault as well as on other papers (AWATA et al., EMRE et al. 2000).

Yalova segment. It is located within the Sea of Marmara (Youd et al., 1999). Its strike is N70°-80°E, parallel to the coastline, which is probably cut by the fault NE of Yalova. At this particular site, there are abundant soil fractures and lateral spreading in the formations that outcrop on the coastal zone, giving rise to ENE-WSW (N70°-80°E) gaps that display horizontal (right-lateral) offset that does not exceed 15 cm. It cannot be confirmed, however, whether these cracks are dynamically related to the Yalova segment or have resulted from seismic shaking. At any rate, the Yalova segment is estimated to be more than 25 km long.

Degirmendere segment. The occurrence of this segment is more certain than of the previous one, since it marks several parts of the coastline between Karamursel and Gφlcók. Its overall strike is N75°-85°E and its length is approximately 20 km. Coseismic slip amounted to 20 cm. The separation distance between this segment and the Yalova one is 4 km, with the Karamursel overstep developing between these two segments.

Karamursel overstep. A 16 by 4 km pull-apart basin has formed within this extensional overstep. However, its occurrence within the Sea of Marmara obstructed further more detailed observation.

Izmit segment. It has a general E-W trend, a length of 27 km, and stretches between Gφlcók in the west and Lake Sapanca in the east. At its western end, close to Gφlcók (Ford factory) there is a N45°W, 2 km long surficial trace with 2.3 m vertical throw (NE side down) and 1.7 m of dextral offset. Towards the east and for the next 4 km, fault strike is N85°E and strike-slip offset reaches 2.8 m. The fault then enters the sea, to be found again south of Izmit at the eastern flank of the gulf; at this location the strike-slip offset reaches its maximum value of 4.6 m and the trend is N85°-90°E, with minor only deviations. The segment can be traced up to Lake Sapanca and its continuation within the lake is deemed highly possible.

Gφlcók overstep. A second releasing overstep with the northern part of it lying under sea level, between the Izmit and Artiflye segments. Its length is ´ 6 km and its width is ´ 2 km.

Artiflye segment. It can be traced from the southern coast of Lake Sapanca up to Akyazi, where the fault trace splays into numerous minor sub-parallel to each other fractures. It maintains a more or less constant E-W trend for a total length of 37 km. Throughout its length the right-lateral component is predominant, amounting to 5.2 m, while the vertical offset rarely exceeds 20-40 cm. This segment can be distinguished into two constituent faults: the western one displays the maximum, 5.2 m horizontal offset, accompanied by several en echelon fractures; and the eastern one, with smaller displacement (>4 m). Towards the east, the displacement decreases and the fault trace breaks up into 5 en echelon fractures with gradually decreasing throw. Note also that a gap exists between the termination of this segment and the adjacent one in the east (Hendek segment).

Sapanca overstep. It develops between the Izmit and Artiflye segments. This transform-parallel strike-slip basin has a length (overlap distance) of 8 km and a width (separation) of 2.5 km.

Hendek segment. It has a length of ´35 km and an initial N80°E trend at its western part, bending eastwards to N60°E. It is traced from Akyazi up to Lake Eften, where it forms the northern flank of the lake. It displays a certain variety in its kinematic characteristics: at the western, N70-80°E trending part, the right-lateral component amounts to 2.6 m and the vertical one does not exceed 0.5 m. At the eastern part, the horizontal offset gradually decreases and the vertical throw reaches 0.5 m, with the southern block downthrown.

Eften overstep. It corresponds roughly to Lake Eften, developing between the Hendek and Serif segments that overlap for ´13 km, being offset by 1-5 km.

Serif segment. It was reactivated in the 12 November earthquake. Its length is 33 km and strikes N85°-90°E. The strike-slip offset in this segment reaches up to 4.6 m, while locally we measured 0.6 m of vertical throw. Its western part must have also moved in the 17 August event, with a right-lateral offset of less than 0.5 m.

Kaynasli segment. It is the easternmost fault reactivated in the 12 November earthquake. It stretches between the town of Kaynasli up to Bolu and is characterized by predominant dextral strike-slip offset (maximum observed: 2.8 m) and secondary dip-slip (max: 0.5 m). Its length is 17 km and has a mean E-W trend. This segment is also characterized by the existence of a broad deformation zone, especially at the locations where it cuts loose surface deposits. At these sites, the width of the deformation zones, which include suites of sub-parallel to each other minor fractures, is up to 200 m. Its throw steadily decreases towards the E.

The distinction of the segments that ruptured in the 1999 earthquakes is an approach towards the deformation along the NAFZ on the macro-scale; and this has shown that the mean trend of these segments was E-W and their average length was 40 km. The maximum strike-slip displacement (Fig. 3) was more than 5 m, but it was significantly smaller on the NW-SE or NE-SW trending parts, where dip-slip component reached its maximum value (´1.5 m). The distinction of the surficial traces is also in good accordance with the observed displacements, which invariably decrease towards the edges of the mapped surficial fault traces.

All segments are consistently right-stepping and the pull-apart basins that have developed have a W/L ratio of 1/3 to 1/4, a figure indicative of a mature stage of strike-slip deformation (Mann et al., 1983).

It should also be noted that there is another branch of the NAFZ in the area, lying to the south of the reactivated segments, passing from Mudurnu. This arc-shaped branch that meets the reactivated fault between Artiflye and Bolu (Fig. 3) remained dormant in the 1999 earthquakes although it was activated in 1967 (Ambraseys & Zatopec, 1969).

4. DISCUSSION - CONCLUSIONS

The 1999 earthquake activity in NW Turkey, which culminated in the two major shocks of 17 August and 12 November (Izmit and Dózce earthquakes), was caused by the reactivation of two consecutive parts of the NAFZ that had not ruptured in the 20th century; however these segments were expected to break (Stein et al., 1997). This reactivation produced surficial faulting for over 150 km. The sense of slip was predominantly strike-slip (dextral) and locally exceeded 5 m, while the mean trend was E-W. The data collected from the observations are in good accordance with the instrumental recordings and focal mechanism solutions which, in turn, comply with the kinematic and dynamic setting that controls the NAFZ. Certain deviations in the geometry and kinematics of some fault segments are due to localized transtension or transpression. Additionally, it seems that the 12 November earthquake was caused by the 17 August event, which triggered the adjacent eastern non-reactivated part of the fault zone. It should be also noted that the Mudurnu branch, which lies south of the reactivated segments and had ruptured in the 1967 event, was not reactivated in the 1999 activity (Fig. 2, 3).

Observations showed that the overall 150 km of surficial faulting can be broken into seven right-stepping segments. This distinction is in good accordance with the observed slip distribution (Fig. 3).

The W/L ratio of the oversteps is in the range of 1/3 to 1/4. This is indicative of strike-slip deformation that has reached a mature stage and has formed pull-aparts that were either well-defined and bounded on all sides by faults (i.e Gφlcók pull-apart basin) or were of transform-parallel type (e.g Lake Sapanca).

The onset of strike-slip deformation is placed at 5 Ma BP (Armijo et al., 1999). The finite deformation has reached a mature stage and this is confirmed by the comparison of the W/L ratio of the pull-apart basins (W/L= 1/3 to 1/4) with the existing from literature models (Aydin & Nur, 1982). In addition, the overall strike-slip displacement is more or less equal to the length of the Sapanca pull-apart basin, which is 16 km. The average annual displacement is thus estimated at 32 mm/yr (16 km/ 5 Ma), which is at least double the figure estimated by GPS measurements (Straub et al. 1997, Armijo et al. 1999). It seems that the 10-15 mm/yr correspond to the aseismic movement and the 'extra' 10-20 mm/yr are accommodated by seismic slip.

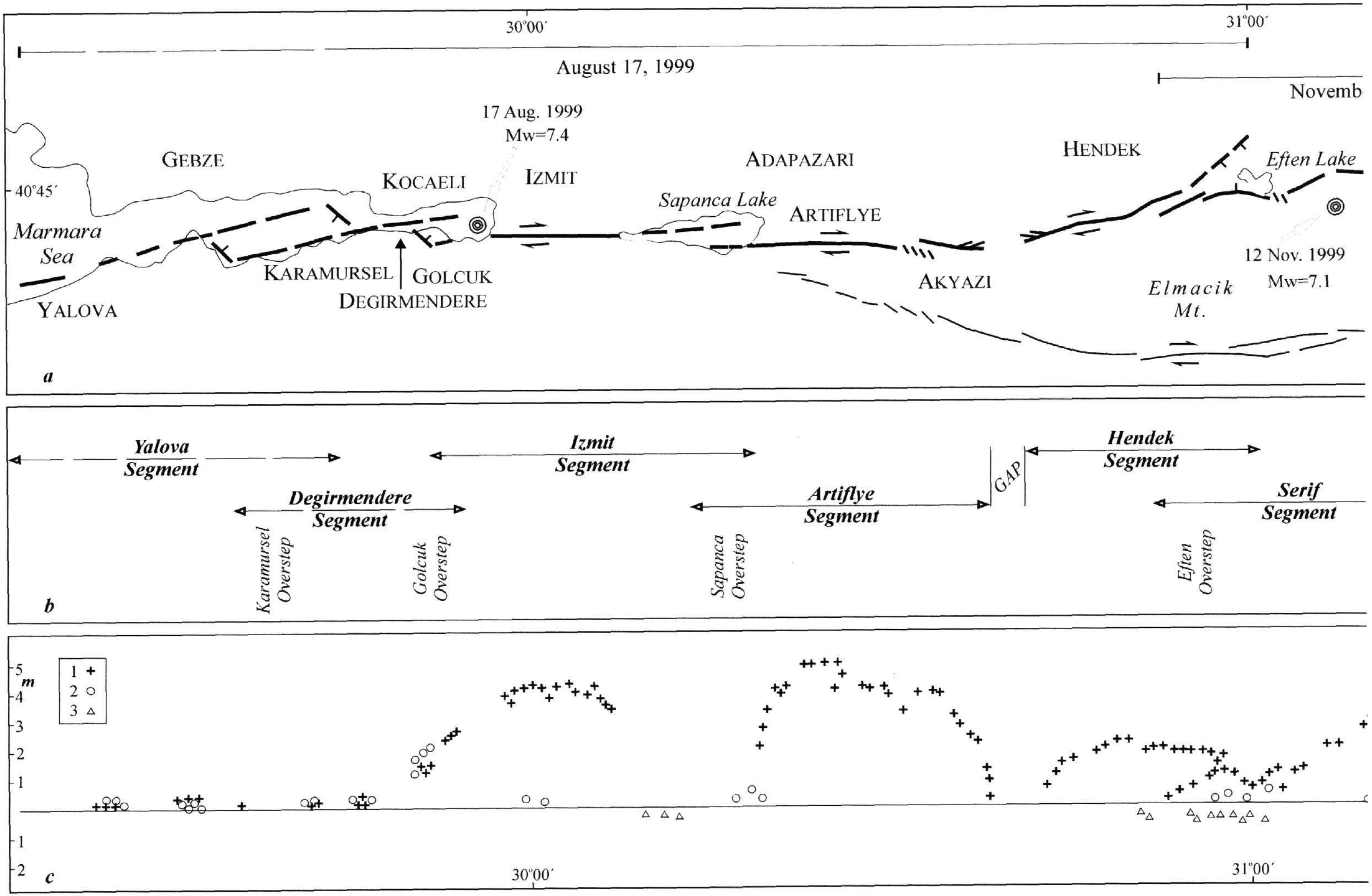

Fig. 3. a. Slip map of the surface ruptures associated with the 17 August and 12 November 1999 earthquakes; b. Segment and overstep names; c. Along strike-slip distribution (also informed by AWATA et al. 2000). 1: strike-slip, 2: dip-slip (northern-side-down), 3: dip-slip (southern-side-down).

Taking into account that the last (prior to 1999) reported surface faulting at this part of the NAFZ was in the events of 1719 and 1754, we can estimate that in this 250+ year interval the cumulative residual deformation that had not been accommodated by creep was between 2.5 – 5 m (10-20 mm/year). This figure matches the mean displacement measured along the reactivated parts of the NAFZ.

The amount of subsidence within the Sapanca pull-apart can be approximated (Sylvester, 1988) and this should be more or less equal to the offset length, which is 5 km. Of course, this value reflects the displacement of the substratum formations and not the picture we get from the local morphology: sediments have accumulated in depressions and ridges have been eroded, which tends to eliminated the surficial expression of the actual tectonic displacement.

On the macro-scale and regardless the localized deviations, caused by secondary factors, it is the existence of the seven consecutive segments that has controlled coseismic deformation. These segments must meet the master fault at a depth of 2-5 km, which is inferred from the overall width of the deformation zone (Sylvester, 1988).

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