SHORT-TERM AND LONG-TERM SLIP RATE ESTIMATIONS ALONG THE GANOS FAULT USING STREAM OFFSETS AND PALEO-CLIMATIC CHANGES (NORTH ANATOLIAN FAULT, TURKEY)

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Abstract

The Ganos fault, is the westernmost segment of the right-lateral North Anatolian Fault (NAF) located west of the highly populated Istanbul and Marmara region of Turkey. This fault generated a large and destructive earthquake (Ms=7.3) in 1912 and hence plays a significant role in the hazard of the region. Recent crustal deformation along the Ganos fault is expressed by typical structures of strike-slip faulting; i.e. step-overs, pull-aparts, bends, pressure ridges, sag-ponds, offset ridges, shutter ridges and stream displacement. We use DEM, aerial photography and DGPS field investigations to document the fault zone and infer the long-term and short-term active deformation in the Marmara region. Our observations describes 69 right lateral cumulative displacements ranging from 8 to 575 m and include streams, ridges and partly ancient roads. The classification of stream offsets shows 5 distinct classes of cumulative slip that can be correlated to different episodes of stream formation due to climatic fluctuations and hence to periods of high precipitation. The sea level change and paleoclimatic fluctuation curves of the Black Sea allow us to constrain the timing of high rainfall periods and determine 5 subsequent sea level rise episodes at 4 ka, 10.2 ka, 12.5 ka, 14.5 ka and 17.5 ka. The slip rate estimations provide 17.9 mm/yr constant slip rate during the last 20.000 years and a variable slip rate of 17.7 mm/yr, 17.7 mm/yr, 17.9 mm/yr and 18.9 mm/yr for the last 10.2 ka, 12.5 ka, 14.5 ka and 17.5 ka, respectively. This indirect dating method provides an average slip rate for the Ganos fault which is similar to slip rates obtained from paleoseismic trenching sites (17 - 27 mm/yr) of the region and other studies along the NAF (15 to 25 mm/yr). We notice that geodetic methods applied over the whole NAF suggest slightly higher strain accumulation values (22 - 26 mm/yr), but they represent the deformation over a significantly larger area. The discrepancy between geodetic and geological results can be due to the complex lithospheric structure and earthquake rupture characteristics along the NAF.

1- Tectonic Setting

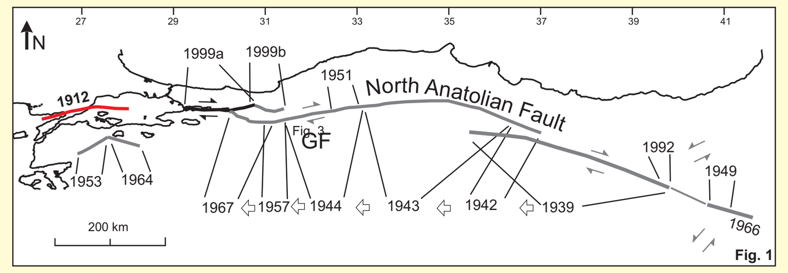
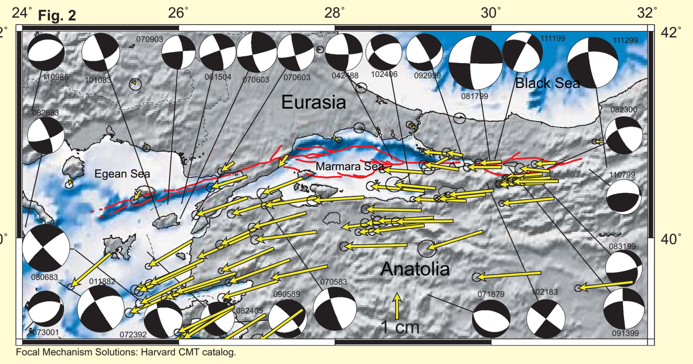
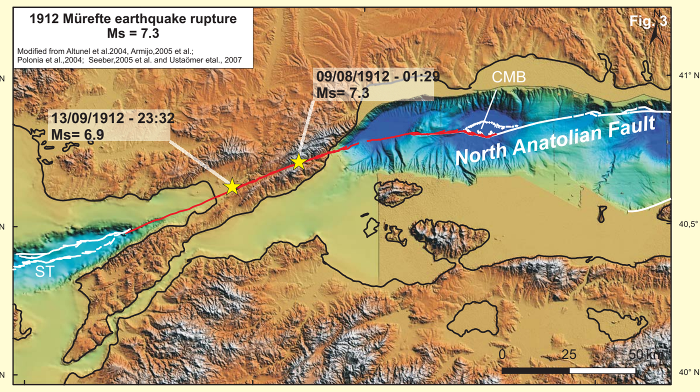


Fig 1 - The Ganos fault is an earthquake segment that ruptured in 1912, prior to an earthquake sequence starting from 1939 to 1999 along the NAF (Barka, 1996).

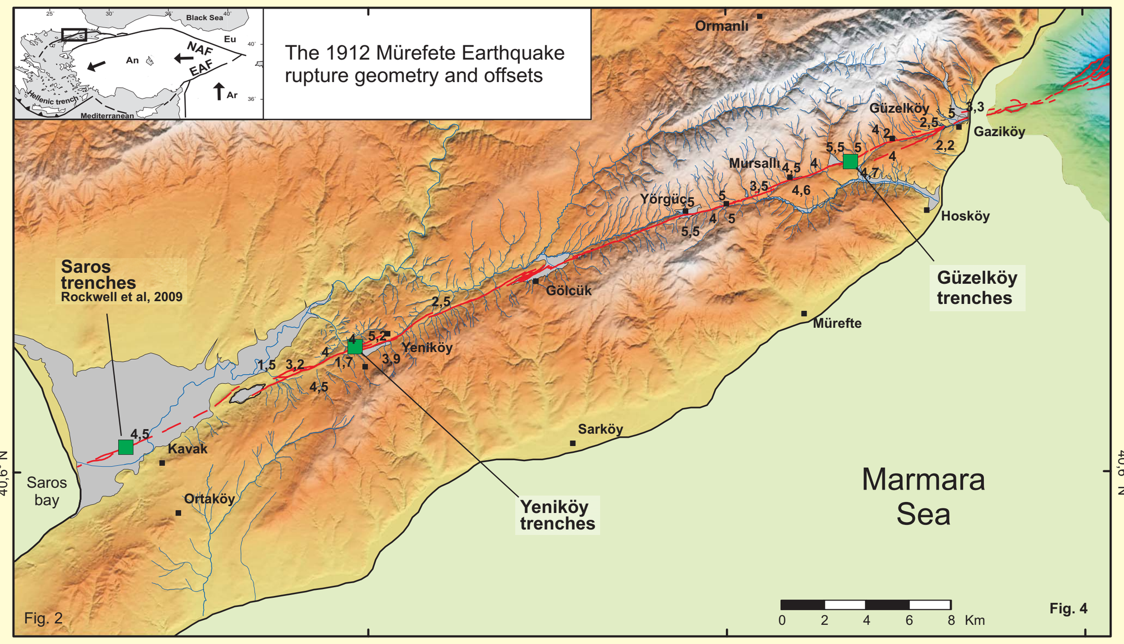




The Ganos fault (GF) is the westernmost segment of the North Anatolian Fault (NAF) which exposed a westward propagating earthquake sequence in the 20th century that last ruptured east of the Sea of Marmara in 1999 (Fig. 1, 2). The GF segment is located west of the Marmara pull-apart basin and ruptured in 1912, prior to this earthquake sequence (Aksoy et al., 2010, Altunel et al., 2004; Fig. 2,3). Today, the two ends of the 1912 and 1999 earthquake ruptures define the seismic gap in the Sea of Marmara. Understanding the active deformation along the GF segment is essential to evaluate the earthquake behaviour of the segment, hence assess the hazard in the Marmara region. During this study we used field observation, quantitative geomorphology, earthquake geology, paleoseismology and paleoclimatology in order to investigate the tectono-morphic characteristics of the GF and constrain a short-term and long-term slip-rate estimation for this section of the

Detailed mapping of the 1912 earthquake rupture and related offsets provides a good basis to understand the co-seismic slip behaviour of the fault, that in fact produces the short-term and long-term deformation in the region. Figure 4 illustrates the detailed morphology, drainage pattern, 1912 surface rupture and the right-lateral co-seismic displacement (Aksoy et al., 2010).

Paleoseismic investigation at three sites were conducted in order to constrain slip history and geologic slip-rates of the Ganos fault (Fig. 4).



2- Prominent strike-slip morphology

The NAF is apparent as a linear narrow valley, trending approximately N70°E in the Ganos region. This valley is in general less than 1.5 km wide between two topographic highs (Fig.4,5). Most of the deformation of the NAF is localized in this narrow zone. The dominant strike slip motion is well expressed by abundant morphologic structures along the entire onland section, (e.g. pressure ridges, shutter ridges, stream offsets, step-overs with right or left stepping jogs, releasing and restraining bends, back-tilted slopes and sagponds). Rectilinear valleys and pressure ridges reach a length up to 4 km with cumulative displacements of streams that vary from 10 to 1000 meters (Aksoy, 2009).

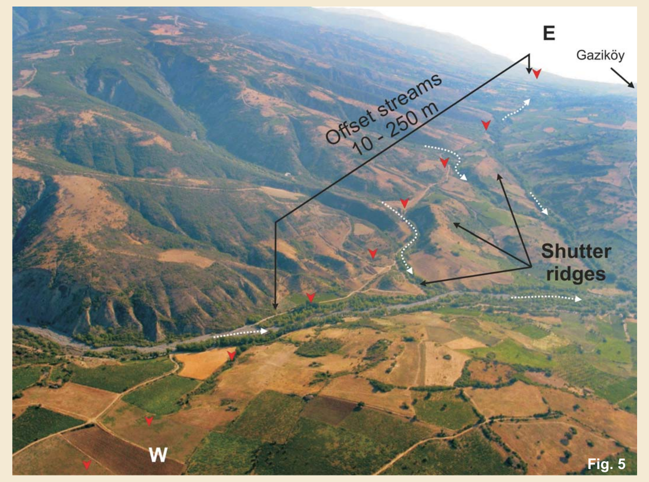


Fig. 5 - The aerial photo of the eastern part of the Ganos fault shows the rectilinear fault geometry associated with shutter ridges and stream offsets ranging from 10 to 250 m (Gaziköy-Güzelköy; Photo by Stefano Pucci).

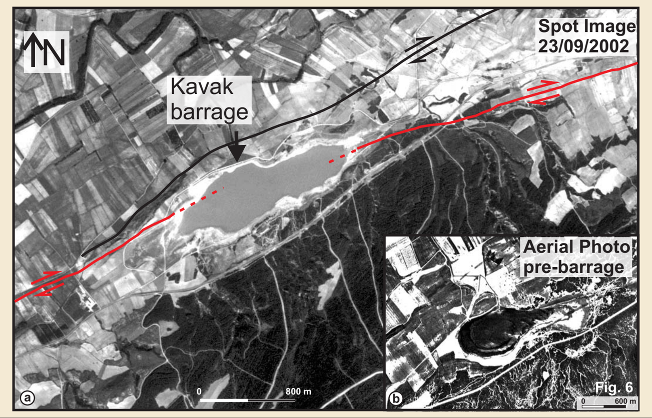


Fig. 6 - The spot image shows a barrage lake near Kavak built in 1989 and located along the fault (a). The aerial photo taken prior to the dam construction documents the original morphology of the structure which represents a typical sag pond common along strike-slip faults(b).

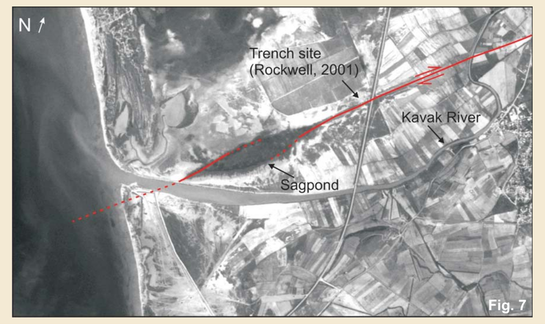


Fig. 7 - Shows another sagpond, 300 x 1400m in size, located 8 km west of the Kavak Lake.

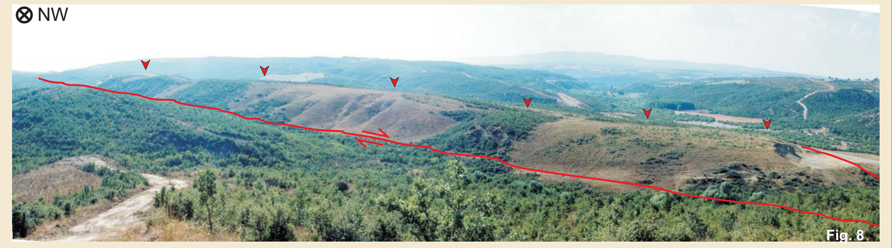
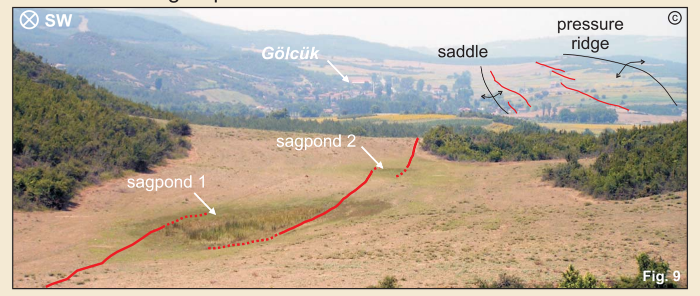


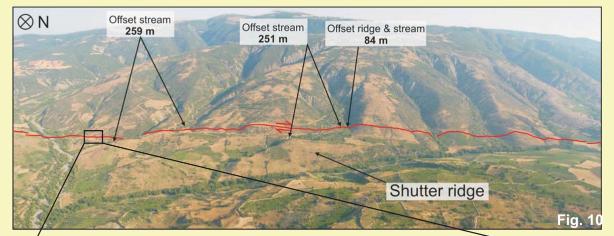
Fig. 8 - A linear pressure-ridge west of Gölcük oriented 18° oblique to the GF. It is bounded by strike-slip faults and rises as a push-up structure.

Fig. 9 - The central section of the GF (east of Gölcük) is expressed as uplifted terraces associated with two sagponds. The surface is tilted against the main slope direction. West of Gölcük the fault strikes along the southern margin of a pressure ridge and smoothes the slope with several releasing step-overs.



3- Cumulative stream offset examples and distribution

Cumulative offset are prominent markers of the short- and long-term deformation of a fault system. Therefore we studied the cumulative displacements along the 45-km-long onland section of the Ganos fault (Aksoy, 2009). Most offsets were measured on streams; however significant displacement were also recorded on ridges, paleo-channels and man made structures (e.g. roads). Digital Elevation Model (DEM), SPOT5 and Google Maps images were used as a base to determine significant slips. Remote observations were afterwards verified by field investigations. At some sites we used total station or DGPS system to obtain more precise measurements. The analysis of the entire onland fault section allowed to document 77 right-lateral cumulative displacements. Most of our measurements resulted in slip values less than 100 m; nonetheless even if sparse, higher measurements were present.



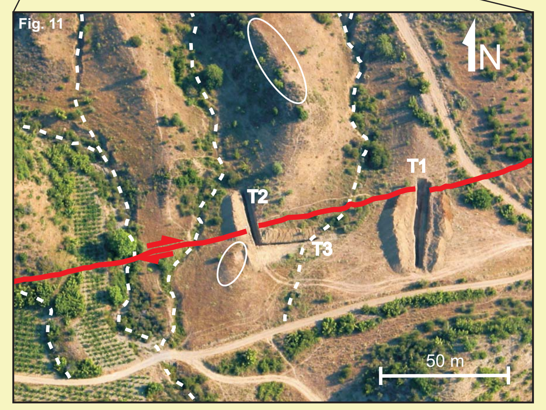


Fig. 10 - Between Gaziköy and Güzelköy, several streams are displaced up to 260 m (see also Fig. 5). Streams on the steep slopes of the Ganos Mt. form deep incisions orthogonal to the fault strike. This orientation allows a good correlation of displaced structures on each side of the fault.

Fig. 11 - At the Güzelköy trench site, using total station survey we measured 11 m and 19 m of offsets on the stream west and east respectively, to trench T2. The ridge offsets, indicated as ellipses is 29 m. The two streams west of T2 show a good example of how stream bed capturing may occur by successive right-lateral motion.

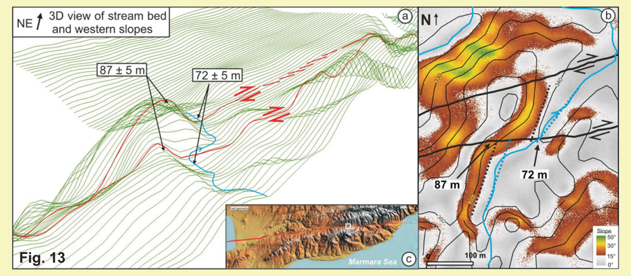


Fig. 13 - A right-lateral offset on a stream and relevant ridges west of Yörgüç. The stream is offset by 72 m. a) The wireframe 3D view of the site, visualizes the displaced channel wall. b) is a slope map from which the 87 m ridge offset was measured.

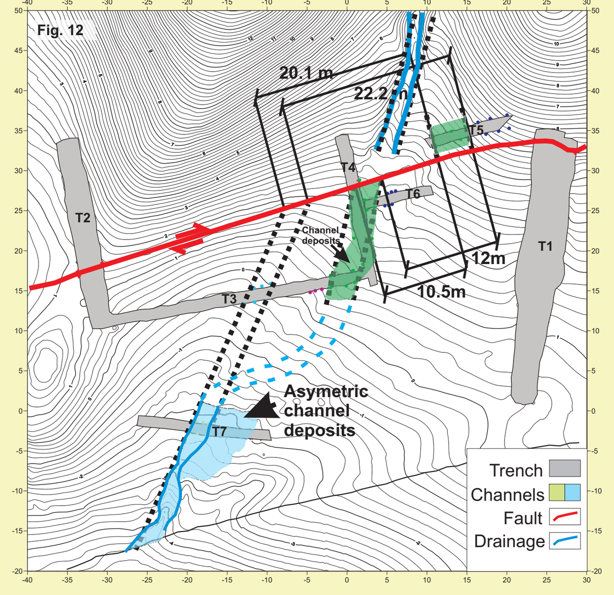
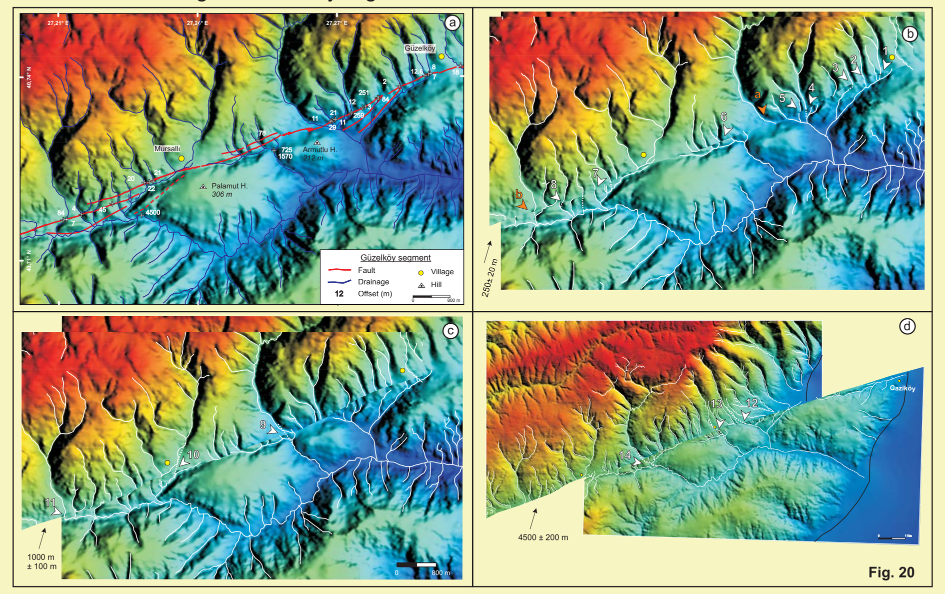


Fig. 12 - Microtopograpic map of Yeniköy trench site. Stratigraphic and morphologic comparisons yield 11 m and 21 m of right-lateral offset which by dating the channel yield a geologic slip-rate of 22 mm/yr for the last ~700 years and 27 mm/yr for the last ~781 years, respectively..

Fig. 20 - Cumulative offset measurements show a distinct group of 200 - 250 m. The reconstruction of 250 m, 1000 and 4500 m on the left figure shows the fit in the drainage network along the Güzelköy segment.



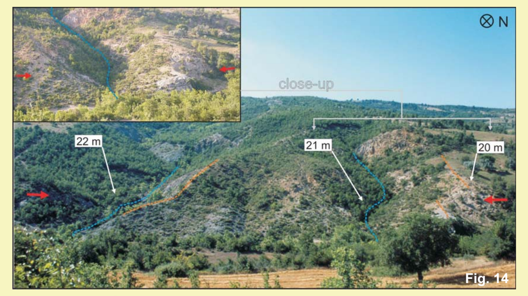


Fig. 14 - Shutter ridges and displaced streams at Mursallı measured with total station yield ~21 m right-lateral displacement.

Fig. 15 - At the Yeniköy trench site, using DGPS we measured 46 m and 96 m of displacement on the stream and shutter ridge, respetively.

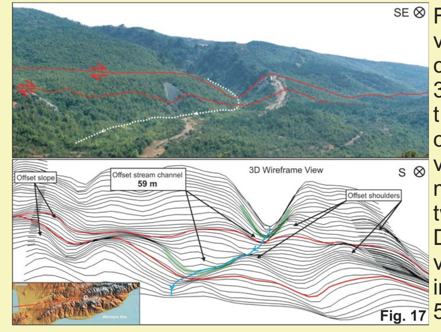


Fig. 17 - A “V” shaped valley is deflected after crossing the fault. The 3D view (b) exposes the northern continuation of the valley. 59 m offset is measured between the two valley sections. Displaced ridges are visible on the 3D image, with less than 50 m displacement.

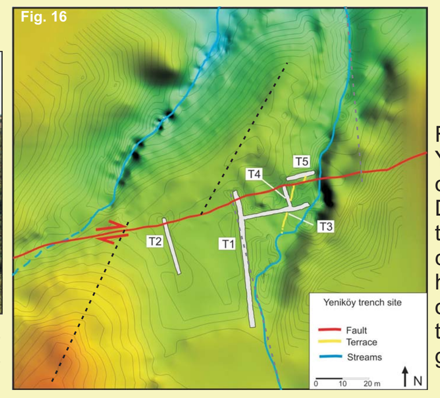


Fig. 16 - DEM of Yeniköy site, obtained from 5500 DGPS data points. 5 trenches allowed to constrain earthquake history and dating the offset fluvial channel that yield a 19 mm/yr geologic slip-rate.

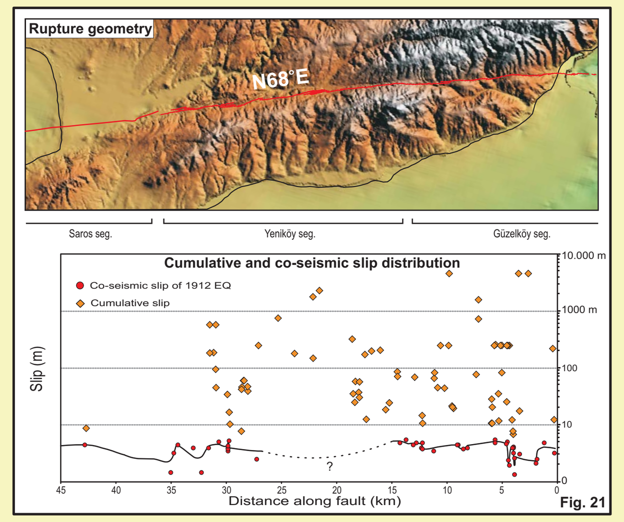


Fig. 21 - The distribution of 77 cumulative offset measurements vary from 10 to 9000 m. Offsets correspond to streams, ridges and other structures. Most offsets range between 10 and 100 m. The largest offset we suggest is 9 km corresponding to the largest two incisions North and South of the GF (see in Fig 4.). Two gaps are distinct (near 25. and 40. km) which correspond to extensional basins were the fault runs through the low land. The lower line and red dots represent the co-seismic displacement of the 1912 Mürefte earthquake.

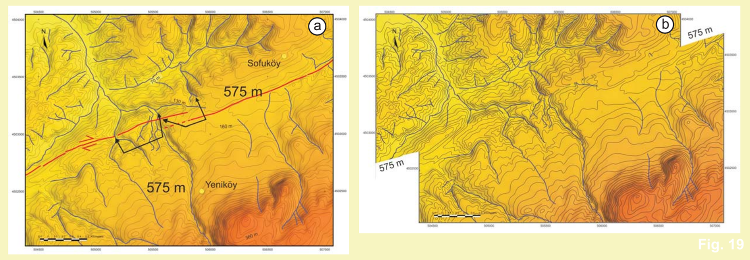


Fig. 19 - Near Yeniköy a deep V shaped incision is distinct north of the GF, however the incision lacks of a relevant stream source. A reconstruction of 575 m demonstrates an earlier stage of the drainage system. Two streams show well correlation with other drainage catchments and the reconstructed morphology.

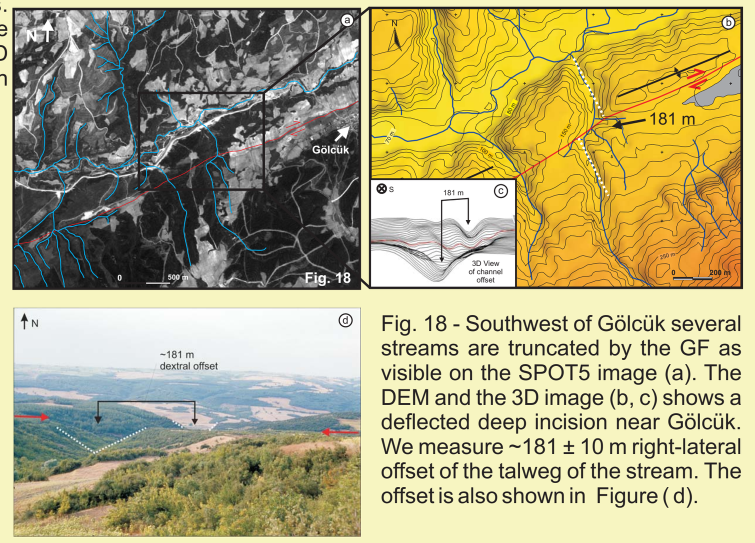


Fig. 18 - Southwest of Gölcük several streams are truncated by the GF as visible on the SPOT5 image (a). The DEM and the 3D image (b, c) shows a deflected deep incision near Gölcük. We measure ~181 ± 10 m right-lateral offset of the talweg of the stream. The offset is also shown in Figure (d).

4 - Climatic control on stream development & slip-rate estimations

69% of the measurements correspond to stream channel offsets. In the Ganos region stream channels are dominantly formed on the steep slopes, North and South of the GF (Fig.5,10). Here, rainfall is the dominant force on channel incision, therefore incision is dependend on climatic events. High precipitation periods continuously create new stream channels on both sides of the fault. Streams flowing across the fault function as counters recording co-seismic slip. Each new channel starts recording cumulatively the displacement (Fig. 22). This process leads to gaps within the slip record, since no new counters (streams) are formed. Here we present an method first applied by Ferry et al. (2008) for the Death Sea and related DS fault. We analyze stream offsets and use paleoclimatology to determine possible periods of high rainfall and aridity.

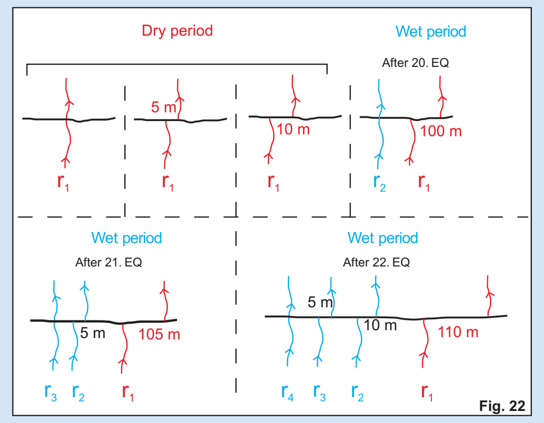
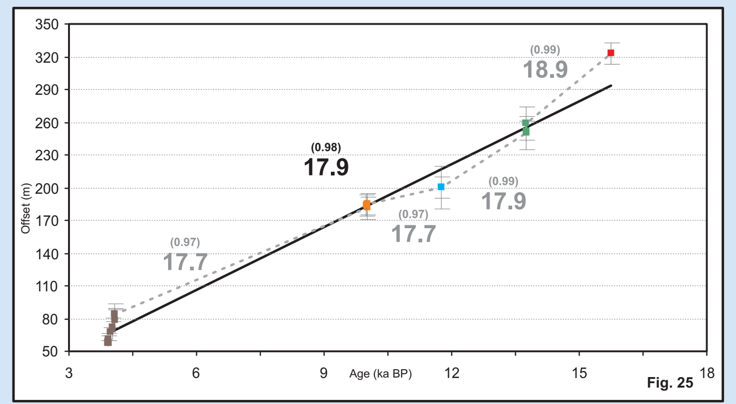


Fig. 22 - The development of displaced stream groups occurs with changes in climate. Streams form during high precipitation periods. At dry periods, existing streams accumulate slip (r_1) and new streams do not form. The duration of the dry period defines the size of the gap. When precipitation starts new streams form continuously and record slip (r_2, r_3, r_4).



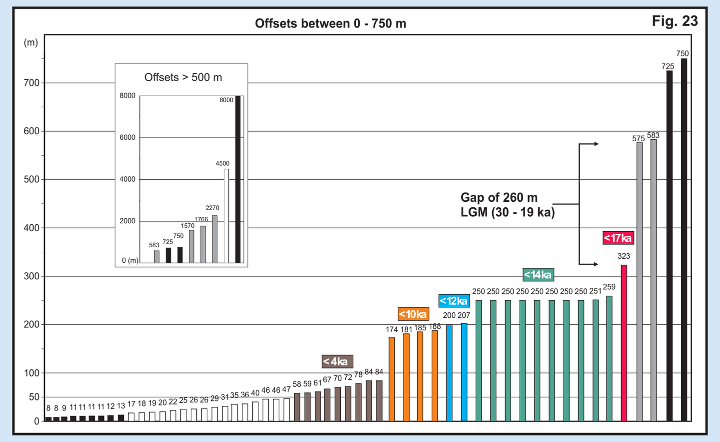


Fig. 23 - The histogram of cumulative stream offsets demonstrates several groups. A comparison with climatic studies allows to date these groups.

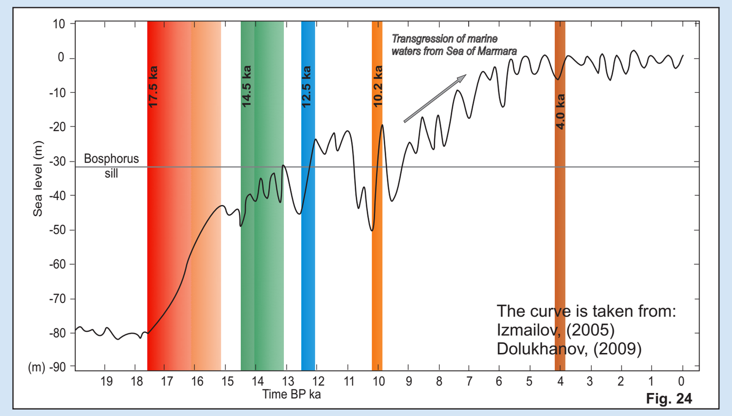


Fig. 24 - Since the Black Sea was a closed lake until 9 ka BP. Earlier sea level fluctuations indicate climatic changes. Four consequent periods of sea level rise (wet climate) are correlated with five offset groups (Fig. 23).

Slip-rate estimation: The correlation of offset groups and high precipitation periods from sea level fluctuations allows to obtain slip-rates; an average slip-rate of **17.9 mm/yr** for the last **20k yr** and variable slip-rates of 17.7 mm/yr, 17.7 mm/yr, 17.9 mm/yr and 18.9 mm/yr for the last 10.2 ka, 12.5 ka, 14.5 ka and 17.5 ka, respectively.(Fig. 25).

Comparison with other studies:

These results are very comparable with slip-rate estimations from three trench sites along GF and other estimations along NAF:

1- Güzelköy trench site: **22 mm/yr** for the last **~700 years** and **27 mm/yr** for the last **~781 years**.

2 - Yeniköy trench site: **19 mm/yr** for the last **2840 years**.

3 - Saros trench site *(Rockwell et al, 2009):* **15.8 mm/yr** for the last **~1700 years**.

4- Offset anticline (Armijo et al, 1999): **14 mm/yr** for the last **5 m.y.**.

Geodetic measurements (**GPS**) give a plate velocity of **22-24 mm/yr** for this part of the NAF.

Conclusion

- Prominent strike-slip morphology was evident by lateral stream and ridge offset, shutter ridges, linear depressions (saddle), sagpond and pressure ridges.
- 77 cumulative offset measurements expose the long-term and short-term fault behaviour of the western most section of the North Anatolian Fault.
- 5 cumulative slip groups (from 70 to 300 m) show well correlations with subsequent sea level rise periods and yield a constant slip rate of 17.9 mm/yr for the last 20.000 years and a variable slip rates ranging from 17.7 to 18.9 mm/yr.
- Two trenching studies provided geologic slip-rates comparable to the climate-offset comparison.
- The Güzelköy site yield a slip-rate of 22 mm/yr for the last ~700 years and 27 mm/yr for the last ~781 years, respectively.
- The Yeniköy site yield a geologic slip-rate of 19 mm/yr for the last 2840 years.
- All slip-rate estimation are comparable with values obtained at other section of the NAF and with related geodetic plate velocities for the Anatolian block.

ACKNOWLEDGMENTS

This work was supported by the RELIEF project (EC Contract EVG1-2002-00069). M.E. Aksoy benefited from a fellowship from the French Embassy in Ankara and CROUS - France. Besides, the work was partly founded by ITU Scientific Research Program. In memory to Prof. Aykut Barka and Prof. Pavel Markovich Dolukhanov.

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