Deciphering deformation along submarine fault branches below the eastern Sea of Marmara (Turkey): Insights from seismicity, strainmeter, and GPS data

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Context
Complex region where seismic and aseismic slip can interact

Location map: seismic activity during 2016, location of the GPS and strainmeter stations, GPS velocities averaged on 3-month periods from Jan. to Sep. 2016

GPS data
A slow transient recorded at one GPS station in April 2016

GPS station BOZT: a) Signal recorded between 2013 and 2017, corrected from seasonal variations. The slope represents the long-term trend (~1.8 mm/year) b) Zoom on 2016, signal corrected from seasonal variations, long-term trend removed. (Processed signal: courtesy of S. Ergintav, KOERI)

Strainmeter data - vbICA
Extraction of the seasonal component

Seasonal variations: signal reconstructed at BOZ1, ESN1, TEPE strainmeter stations using only the seasonal component. Comparison with meteorological data

Integration of the different data
A 2-step transient is visible in the GPS and strainmeter data. This transient is followed by an activation of the seismicity

Comparison of the available data during 2016: a) and b) Differential and shear strains recorded at BOZ1 and ESN1 stations. c) and d) East and North GPS components at BOZT station e) Temporal evolution of the seismicity on two clusters. The green curve corresponds to the seismicity in the green box on the Location Map, the blue curve to the one in the blue box, and the black curve to the seismicity in the whole region.

Coulomb modelling
2 consecutive events on 2 perpendicular faults

Coulomb modelling of the 2 transients: Left : 1st event, Right : 2nd event. Up : Differential strain, Down : shear strain

Conclusions
1. First slow event
2. Triggering of second slow event
3. Triggering of seismic activity
The North Anatolian Fault (NAF) is a strike slip fault that runs from Eastern to Western Turkey. During the 20th century, more than 1000km have been ruptured in a sequence of M>7 earthquakes propagating from East to west between 1939 and 1999. The last portion that did not rupture during this sequence is the one located in the Marmara Sea, South of Istanbul. In this study, we focus on the Eastern region of the Sea of Marmara, where the NAF is dividing in 3 sub-branches: the Main fault (NAF) north, a Middle Branch, and a Southern branch, that we will call «Armutlu Fault». This portion of the NAF may constitute a significant hazard for the region, but it is challenging due to the off-shore nature of the faults.

Possible slow transients have been reported in the Eastern Sea of Marmara:

- Repeating events have been found before a M4.2 earthquake in June 2016, suggesting that some aseismic slip took place before this earthquake (Malin et al. 2018)
- A transient signal has been observed at ESN1 strainmeter station mid-2016 (Martinez-Garzon et al. 2019)

This transient signal being observed on a single station, its origin could not be well constrained.

In this study, we combine strainmeter data from 2 stations with GPS and seismicity data to understand better the origin of this transient signal. We apply a vbICA technique to remove the seasonal variations from the strainmeter signals, and we perform Coulomb modelling to constrain the geometry and location of the fault(s) at the origin of the observed transient signal.
We corrected the GPS time series from seasonal variations and long-term trend estimated from a Trajectory Model (Bevis & Brown 2014). An acceleration towards south of the displacement recorded at BOZT station is visible between April and July 2016 (Fig.1). The cumulative displacement on these 3 months is ~ 2mm. Fig.2 shows the decomposition of the velocities on 3-month periods at 3 GPS stations (BOZT, DUM2 and TUZL). TUZL and DUM2 stations do not show any significant change on the 3 periods, whereas BOZT station shows an increase of the velocity towards South during the light blue period (i.e. from April to July 2016). The direction of the transient signal recorded at BOZT is coherent with an acceleration of the slip along the Armutlu fault, with a combination of strike-slip and normal motion, consistent with the tectonic setting of the region.
Strainmeter data

We use the 3 strainmeter stations that were working from 2016 to 2019. We correct them from offsets, tides and borehole trend (Hodgkinson et al. 2013), and we apply a vbICA decomposition (Gualandi et al. 2016) to extract and remove the seasonal variations from the signals.

The TEPE station being dominated by the seasonal variations, we analyze only the temporal evolution of the signals recorded at stations BOZ1 and ESN1, which are also closer to the area of interest, considering the location of the seismicity.

We highlight 2 strain transients in BOZ1 and ESN1 time series:

- A first one from April to July 2016 (light blue area on Fig.1). This transient is mainly visible on station BOZ1, on the differential and shear components.
- A second one from July to September 2016 (dark blue area on Fig.1), is clearly seen on ESN1 station, with a sharp change in the trend.

Both transients have an opposite sign on the two stations, suggesting that the source is located in between, potentially on the Armutlu fault. The change in amplitude evokes a migration from West to East.
We use the 3 strainmeter stations that were working from 2016 to 2019, and we apply a vbICA decomposition (Gualandi et al. 2016) to extract and remove the seasonal variations from the signals.

The method in brief:
- Multivariate statistic approach
- We use a matrix $X$ built with the data:
  - $T =$ number of epochs
  - $M =$ number of time series

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X = \begin{bmatrix} X_{11} & \cdots & X_{1T} \\ \vdots & \ddots & \vdots \\ X_{M1} & \cdots & X_{MT} \end{bmatrix} \]

- Data $X$ = a mix of a reduced number of sources (postseismic, seasonal, …)
- $A =$ weights to mix sources
- $\Sigma =$ Sources
- $N =$ Gaussian noise

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\begin{align*}
X &= A \Sigma + N \\
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\end{align*}
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Hypotheses:
- Statistical independence of the sources
- Linear mix of the sources

Output:
Temporal and spatial evolution of the sources that generated the signal

**Figure 1:** Strainmeter signals corrected from offsets, tides and borehole trend (Hodgkinson et al., 2013). The light blue area highlights the period where GPS data are available.

**Figure 2:** Seasonal component extracted using the vbICA decomposition.
After correcting for seasonal signal, TEPE station does not show any transient ⇒ we do not use this station for our analysis

On the contrary, BOZ1 and ESN1 stations are only slightly affected by the seasonal variations

The seasonal variations correlate with the temperature and pressure variations

**Figure 1:** Strainmeter signals corrected from offsets, tides and borehole trend (Hodgkinson et al., 2013). The light blue area highlights the period where GPS data are available

**Figure 2:** Comparison of the aerial strain reconstructed using only the extracted seasonal component at the 3 stations with meteorological data

**Figure 3:** Strainmeter signals after removing the seasonal variations extracted using a vbICA decomposition technique
Figure 1: a) and b) Strainmeter signals corrected from offsets, tides and borehole trend and from seasonal variations (vbICA). c) and d) BOZT GPS signal corrected from seasonal variations, long-term trend removed. (Processed signals: courtesy of S. Ergintav, KOERI). e) Temporal evolution of the seismicity in the whole region (black curve), and on the two clusters highlighted in Fig. 2 (green and blue curves). The vertical gray and black dashed lines indicate the occurrence in the region of $M>3.5$ and $M>4$ earthquakes, respectively.

The first strain transient (highlighted in light blue on Fig. 1), recorded at both strainmeter stations, is concomittent with the transient signal highlighted at the colocated GPS station BOZT.

The second part of the signal (highlighted in dark blue on Fig. 1) observed on the strainmeters is not recorded by the GPS. This, in addition to the fact that this second signal has an amplitude more than four times larger at ESN1 than at BOZ1, suggests that the cause of this second signal is located close to ESN1 station.

During the large signal recorded at ESN1 station in June-July 2016, a $M3.5$-$M4$ earthquake sequence occurred 30 km east, on the Middle Branch (highlighted by the green box on Fig. 2). However, we do not observe changes in the strain signal trend concomittent with the different earthquakes of this sequence.

A few weeks after the end of the strain transients, the seismic cluster located close to ESN1 station (blue box on Fig. 2) is showing the highest seismic activity in the region in 2016 (blue line in Fig. 1e), suggesting that this seismic activity has been inhaled by the previous transients.

Figure 2: Location map. The blue and green dashed boxes highlight the clusters shown in Fig. 1. The colored arrows show GPS velocities averaged on 3 month-periods from Jan. to Sep. 2016. The colors indicate the time.
We perform a forward modelling using Okada (1992) elastic dislocations to better constrain the location of the two transients. The strain and GPS variations due to the first event (April to July 2016) can be reproduced at both stations by simulating a M5.5 event occurring between 0 and 2km depth on an onshore fault between the two stations (Fault 1 on Fig.1). The geometry of this fault has been inferred from the InSAR data of Fig.2a.

The strain variation linked to the second event (July to September 2016) can be reproduced by a M5.5 event occurring between 0 and 6km depth on a perpendicular normal fault close to ESN1 station (Fault 2 on Fig.1). This fault has been defined using the seismic activity recorded by a temporary SMARTNET network (Martinez-Garzon et al., in review, SRL).

The second transient has increased the stresses at the location of the seismic cluster activated in October 2016 (blue rectangle on Fig.2b), suggesting that this second transient triggered the seismicity.
The detailed analysis of strainmeter, GPS and seismicity data allowed us to highlight the occurrence of two successive slow events on perpendicular faults. The first event occurs on a mainly strike-slip right-lateral fault that is little active seismically during the last 10 years. The second event occurs on a pure normal fault, that is activated by swarms during the last years. The first event, by changing the stress state on the perpendicular normal fault, triggered the second slow event. This slow shallow event, in turn, changed the stress state in the surrounding, and triggered the largest increase of seismicity in the region during the year 2016, activating the deepest part of the normal fault (between 4 and 10km). This activation initiated with two earthquakes of M>3.5 in two hours.

We present in this study forward models that are supporting our hypothesis. To perform an inversion for the slip distribution on these two faults, we need either more GPS and strainmeter stations or/and the capability to reliably extract transient signal from noisy InSAR time series. We cannot neither determine if the slip on the first fault continues to propagate eastward, because of the lack of stations in the region.

This study shows the importance of combining different type of deformation data and seismicity data to analyze and understand the distribution of seismic and aseismic slip and their interactions, in particular in a seismic region moderately active.