Bouchon et al. (2011) VS Ellsworth et al. (2018)

Pre-slip or cascade of earthquakes before the M_w7.6 1999 Izmit earthquake?

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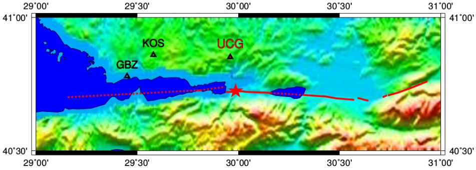

Outline

Introduction: Pre-slip vs cascade of foreshocks

Bouchon et al. (2011): Pre-slip observations before the M_w7.6 1999 Izmit earthquake.

Nucleation of the 1999 Izmit earthquake by a triggered cascade of foreshocks

Two points of view

Pre-slip model

Foreshocks are triggered by aseismic slip over an area surrounding the mainshock hypocentre.

Consequences:

The underlying aseismic slip might be a precursor to the earthquake.

Cascade model

Foreshocks might occur by neighbour-to-neighbour stress transfer between them without an aseismic slip component.

Consequences:

The foreshocks are no different than any other set of clustered earthquakes.

The mainshock is just a random outcome of triggering.

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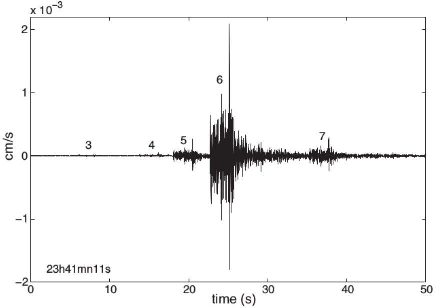
Waveform similirity: coincidence or same source?

All of the well-distinguished events share nearly the same waveforms:

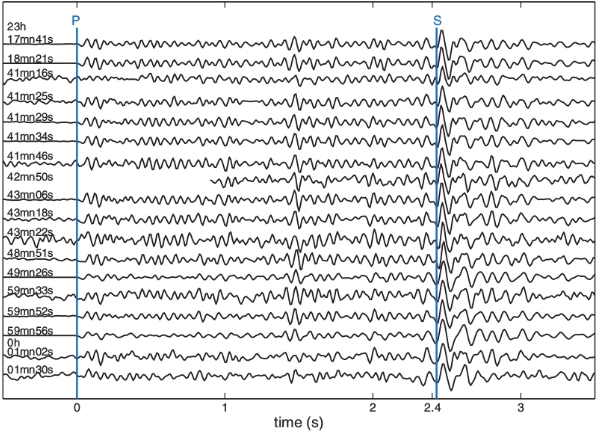
- 7 foreshocks well identified with a receiver $<$14 km epicenter offset.
- $\approx$ 40 events were found using cross-correlation with a template.

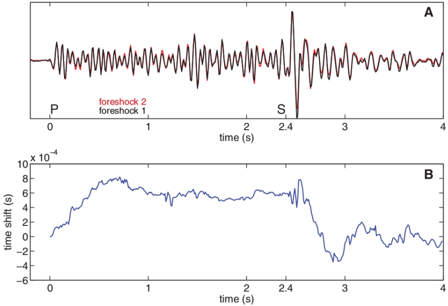


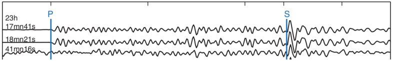
18 foreshocks visually identified

Surprising features:

- S-minus-P traveltime of 2.4 (s).
- Some of them separated by 5 (s) between them.
- Magnitudes ranging from $[0.3, 2.7]$.
- Very similar waveforms.







Cross-correlating the 1st and 2nd foreshocks:

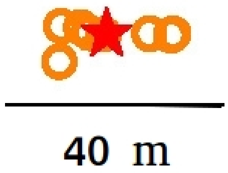
- S-minus-P travel times differ ≈ 0.0006 s.
- ≈ 5 m distance from one each other.

The distance of ≈ 5 m is not between the sources but the projection of the source distance projected to the ray path.

Applying the same cross-correlation analysis for all the possible P and S couples:

Any of the events differs in S-minus-P travel time by less than 0.0024 s from the majority of the other events

This implies that any one shock is located within 20 m or less from the majority of the other events.



⟶ **All of the events originate from an area of the fault that is no larger than the size of the largest events.**

Activity accelerated

How?

- 4^{th} largest event occurred 43 min before the mainshock
- 3^{th} largest event occurred 20 min before the mainshock
- 2^{nd} largest event occurred 12 min before the mainshock
- 1^{st} largest event occurred 1 min 45 s before the mainshock

Acceleration increase again 1 min before the earthquake:

- One shock occurred 0.14 s before the mainshock (magnitude $\approx$2.0).
- Another shocked 0.07 s later (P-pulse bigger than previous ones).

Questions related to the acceleration

Magnitude is not increasing in that critical one minute before??
but in the others yes??

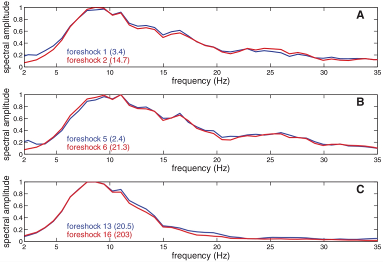
why we can not see this phenomena for other earthquakes??
there are receivers closer than 14 km nowadays!

Why do they look so similar:

Their spectral corner frequencies is higher than the maximum frequency displayed (35 Hz):
(seen as false point sources)

Or, the two events may have nearly the same corner frequencies, because spectral amplitude drops off rapidly beyond an event corner frequency.

Same patch, same length ($\approx$ 300 m) but different slip:
1st a little less than 1 cm (0.8 cm)
2nd a little less than 1 mm (0.8 mm)
1st stress drop of 2.6 MPa
2nd stress drop of 0.3 MPa



(A to C) Comparison of the S-wave ground-velocity spectra of some events. The peak recorded amplitude of each event is given in parenthesis and is expressed in micrometers per second.

Creep loading surrounding areas?

Repetive earthquake due to creep:

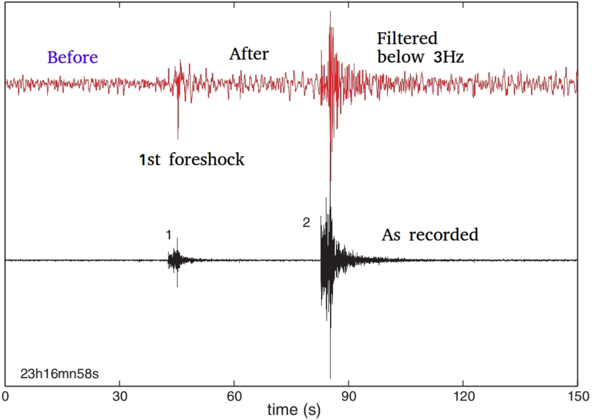
They usually have recurrent times of months or years and similar magnitudes.

In this case, separated by minutes!

A possible reason for the magnitude difference observed here is that the interevent time of the pre-Izmit shocks is extremely short, possibly forcing the response of the patch.

patch responds not only to the loading but also to the loading rate, which may be highly irregular.

After first the foreshock, the seismic gound motion content at low-frequencies increased significantly. **Its energy is at least below 2Hz.**



No location can be provided for this increase in the low-frequency content.

Hypothesis: Maybe it is the signature of the creep happening around the hypocentral area.

Summary

These observations show that this particular earthquake was preceded by a phase of slow slip occurring at the base of the brittle crust.

This observations (long duration nucleation phase) and similarity between foreshocks and mainshock are encouraging for early-warning systems...

but

other well-recorded earthquakes, 1999 Chi-Chi (Taiwan) or 2004 Parkfield (California), o not show evidence for similar foreshocks or nucleation events.

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- The foreshocks form a contiguous series of ruptures that progressed systematically from west to east towards the mainshock hypocentre,
- The Izmit foreshock sequence occurred as a triggered cascade in which one foreshock loads the adjacent fault patch causing it to fail.
- We find no evidence to support a hypothesized precursory aseismic driving process.

A big problem of the theory

The transition from a locked state to a dynamically growing rupture due to pre-seismic growth of slip instability occurs at a reduced area ($\approx$ decimeters) $\longrightarrow$ small strain amplitude essentially impossible to detect at the surface (hypocenter at 5–15 km depth)

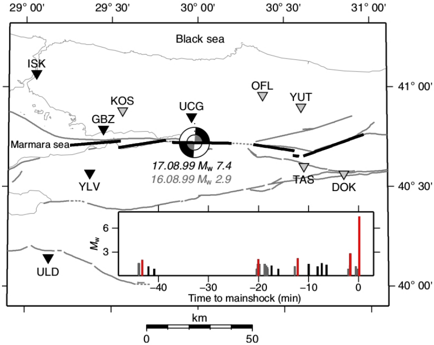
Arguments:

Similarity of foreshock waveforms only implies close proximity in space, not repeating rupture

(Comment: Not sure about this!)

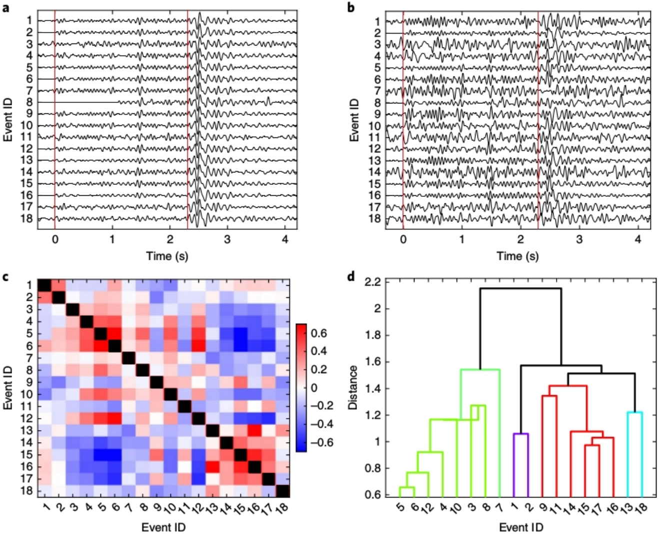
Analysis of seismograms from nine additional stations to identify, precisely locate and quantify the foreshocks, and interpret their progression toward the mainshock.

The location of foreshocks and stress changes suggest a sequence of triggered earthquakes.



Cluster analysis

- 4 episodes of foreshocks
- each episode has a M≥2.0 principal shock
- Difference between depths (foreshock-mainshock) is ± 30 m



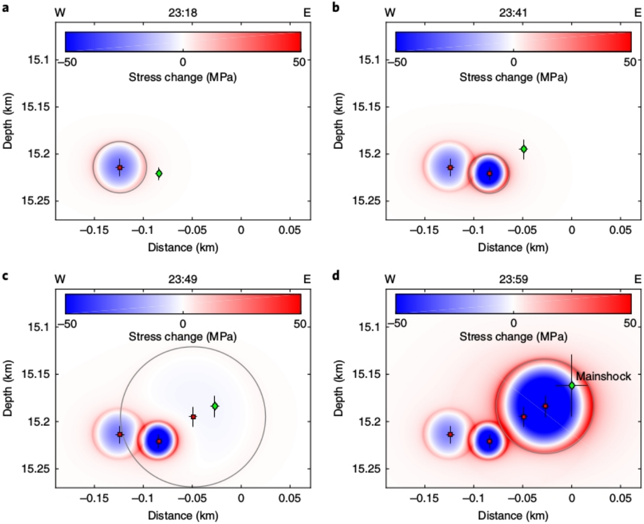
a Foreshocks

b Residual after removing common mode.

c Pairwise cross-correlation of residuals

d Event family tree correlation based

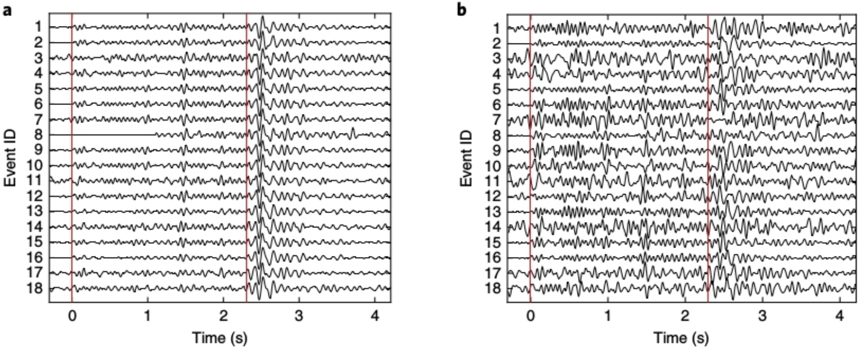
Evolving shear stress changes on the fault plane during the foreshock sequence



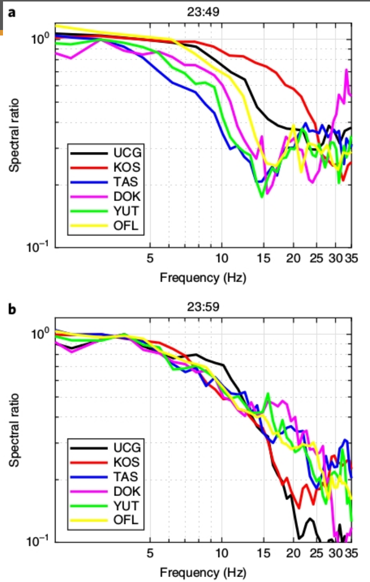
1st: 17 mm 2nd: 39 mm and 4th 100 mm, while 3rd: 4mm

3rd produced the smallest stress drop

Because the foreshock waveforms are slightly dissimilar from one another, it is unlikely that any are repeating earthquakes.



The 23:49 foreshock exhibits rupture directivity not seen in the other foreshocks (corner frequency measurements varying with azimuth).



P wave spectral ratios for the 23:49 and 23:59 foreshocks computed using event 23:41 as the denominator and normalized at 1 Hz.

The available seismic recordings presented here can neither confirm nor refute whether the noise originated in the foreshock zone or was unrelated to the earthquake.

One feature of the foreshocks that we can be confident in is the spatial roughness of slip and stress distribution in each earthquake.

The nucleation of the Izmit earthquake and its foreshock sequence can be mostly explained as a cascade of triggered events.

While aseismic slip (unobservable) or fault-valve behaviour (at best weakly supported by the evidence) are possible contributors.