Zakynthos 25/10/2018, Mw 6.8 earthquake: Superposition of strike-slip and thrust?

Report to EMSC

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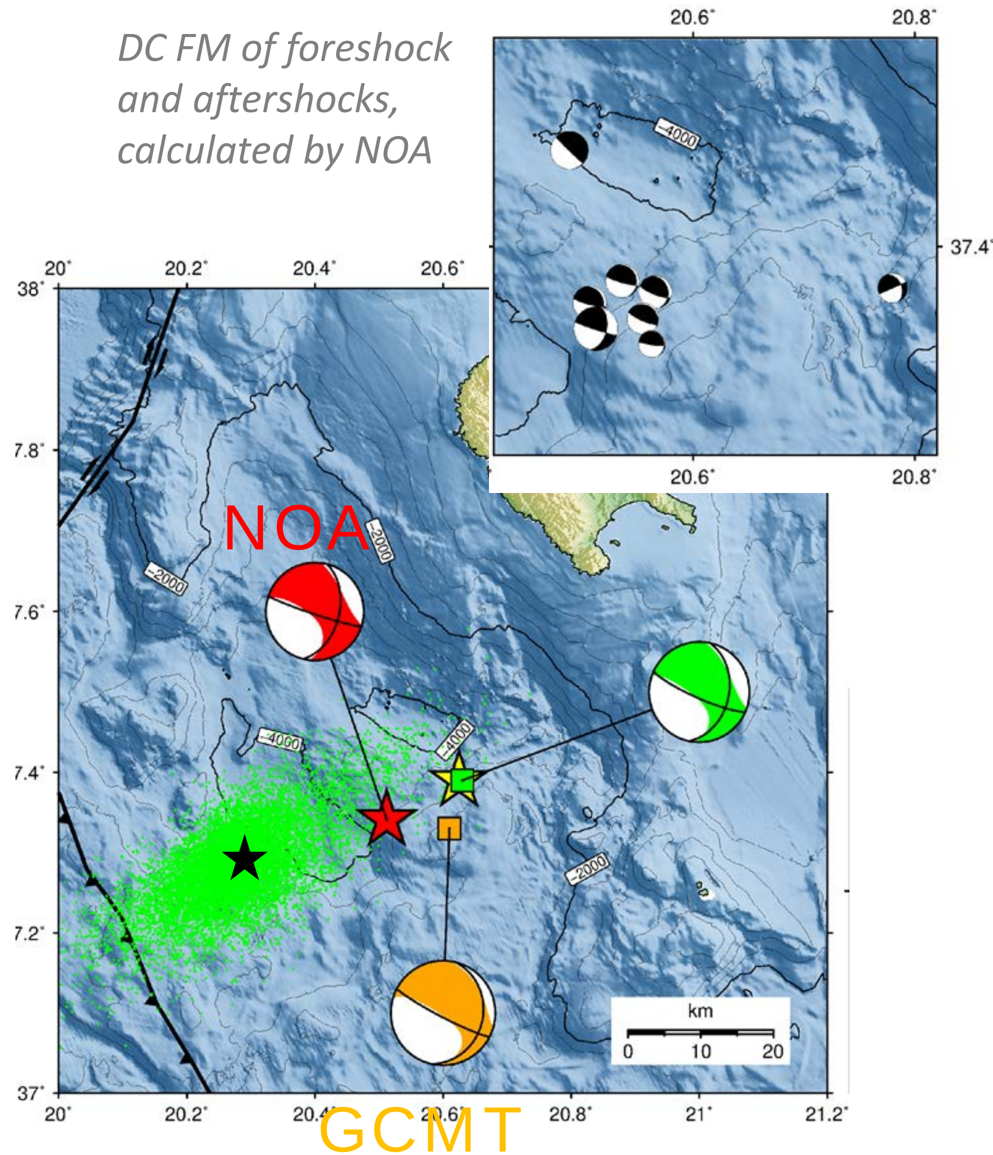
Epicenter and Centroid solution

- **Location**
  - NonLinLoc (Lomax et al., 2004) – manual P wave picks from BB stations in Greece and a few stations in Italy
  - Lat(°) 37.30, Lon(°) 20.29

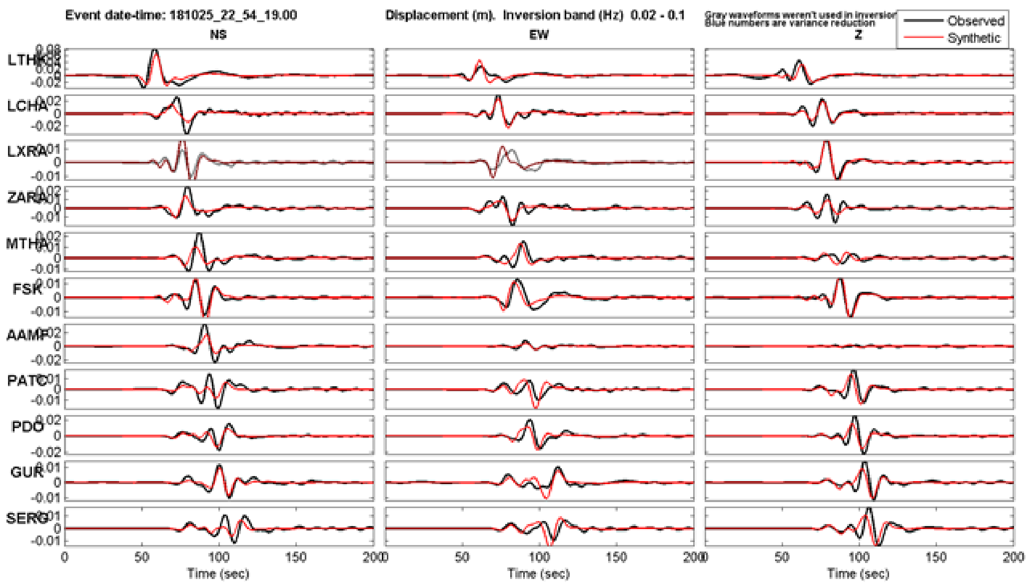
- **Centroid**
  - ISOLA (Sokos and Zahradník 2008)
  - BB stations (270-630km)
  - Frequency range (0.01-0.02 Hz)
  - Centroid position close to epicenter of AUTH (37.39, 20.63)
  - strike = 12°, dip = 41°, rake = 165°
  - **DC% ~40, CLVD% ~ -60**
  - Analogous s/d/r angles and low DC% was obtained by using only local SM stations in the frequency range of 0.02-0.05 Hz

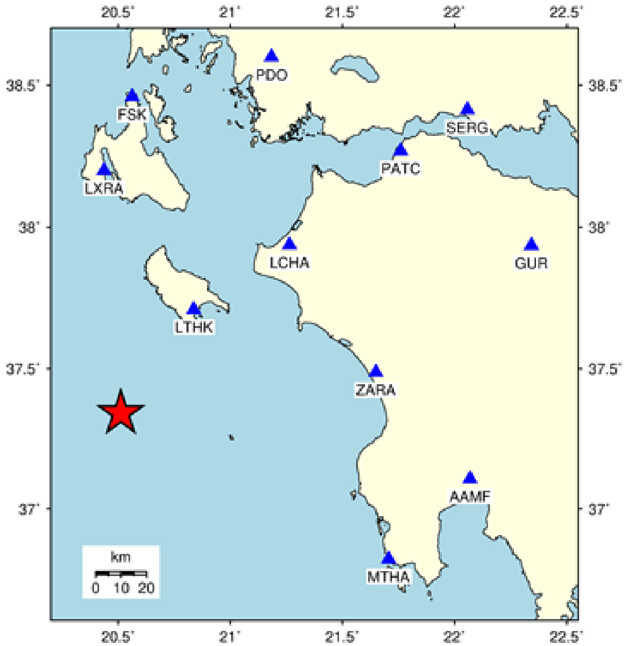


Major Subevent (sub1)

i.e. a dominant moment release point-source

- local SM stations of western Greece
- frequency range of **0.02-0.10 Hz**
- horizontal grid search was performed at **trial depths of 15, 20, 25, 30 and 35 km**
- seeking a **DC-constrained** (i.e. a DC% 100) moment tensor

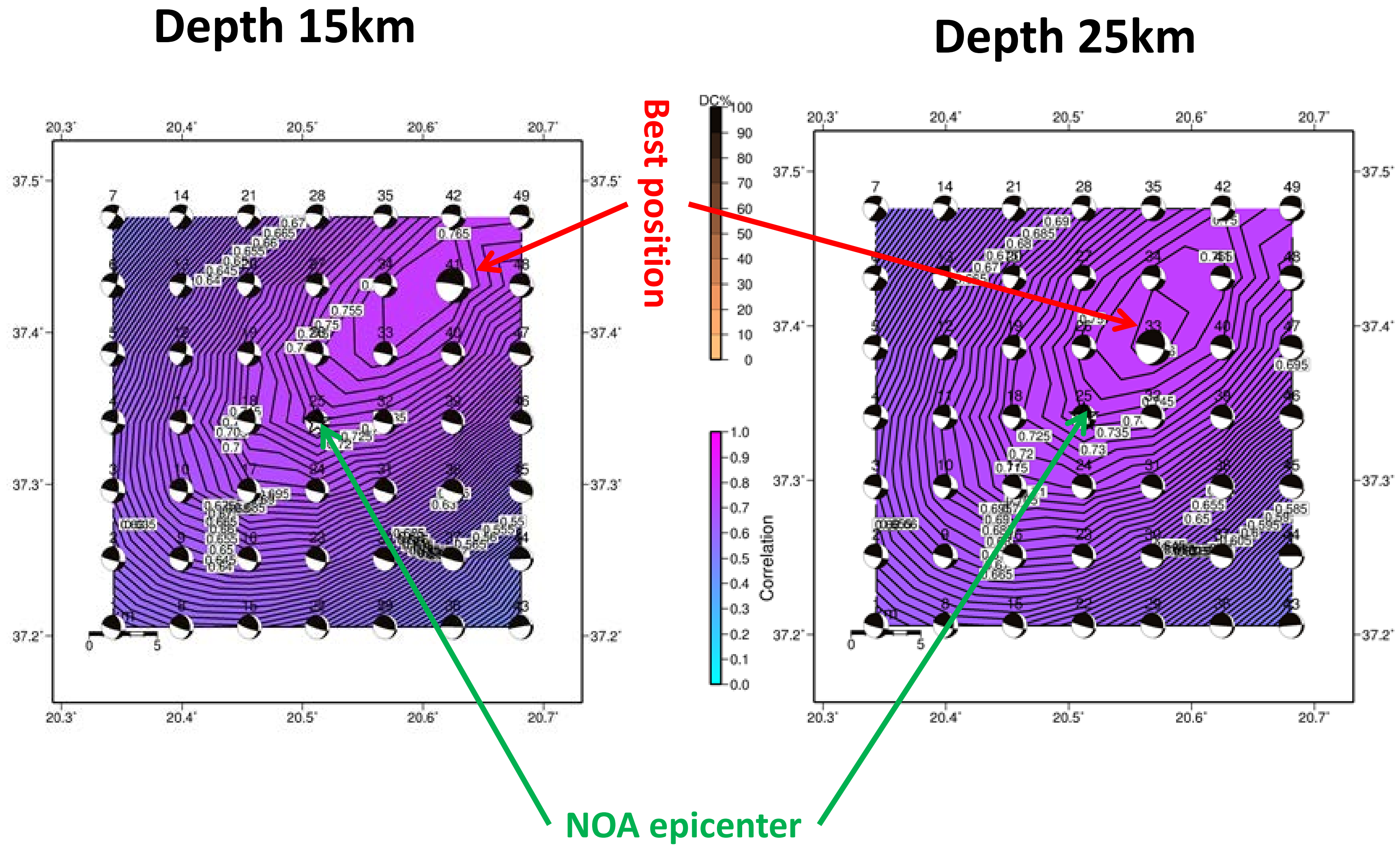




Waveform fit, VR ~ 0.6
the best-fit solution at depth of 25 km
strike = 20°, dip = 40°, rake = -170°

Major Subevent (sub1)

horizontal grid search for a DC-constrained major subevent.



Major Subevent (sub1)

horizontal grid search for a DC-constrained major subevent.

Partial results:

- **The SW-NE elongation** of the isolines - azimuthal gap of the local SM stations towards SW.

- **Source depth**:
  - Can be hardly be precisely resolved
  - With increasing depth sub1 moves closer to the NOA epicenter, and Mo increases also.
  - Depth 35-km would be already too large (Mw > 6.8)
  - the source angles are stable s/d/r ~ 20/40/-170

- Centroid and major subevent position can hardly be distinguished from each other => fault rupture was spatially and temporally compact. Supported by global back-projections [IRIS].

- **non-DC component of centroid** can be caused by **complexity of the source**.

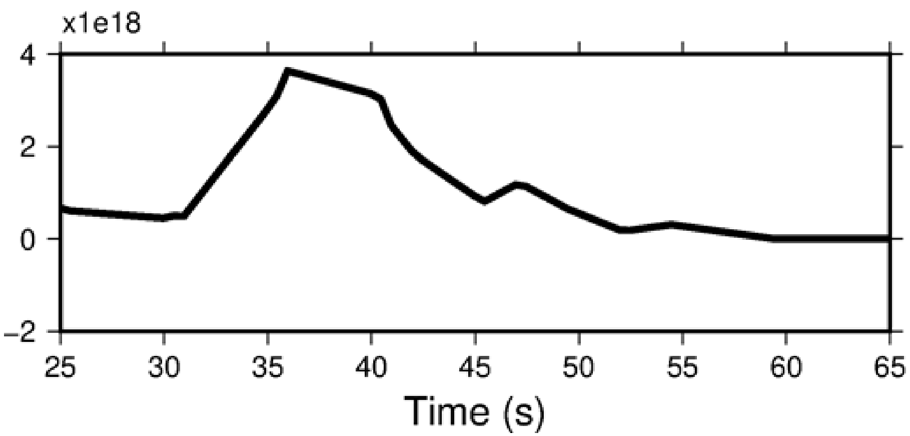
- **Another smaller subevents (sub2, 3, etc.) ? Exist or not?**
  - Many attempts were made to detect some smaller subevents.
  - All tests provided either additional subevents that were too small in terms of moments, sub2 << sub1, or sometimes comparable, e.g. sub2 ~ sub1/3
  - both having focal mechanisms of similar type as sub1

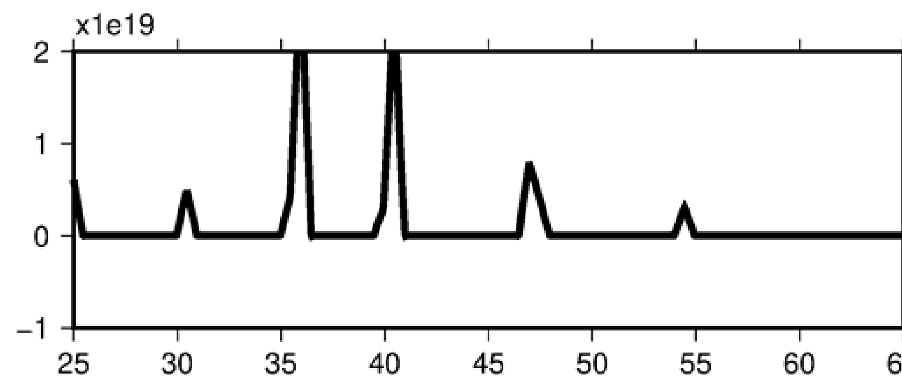
Time function

- non-negative-least-square (NNLS) method [Zahradník and Sokos, 2014], implemented in ISOLA
- SM stations as above, and frequencies 0.02-0.10 Hz

- effectively superimpose ~10-s triangles

- stable moment-rate function, basically composed of two dominant terms, mutually shifted in time by ~4-5s, providing the source duration of ~15s

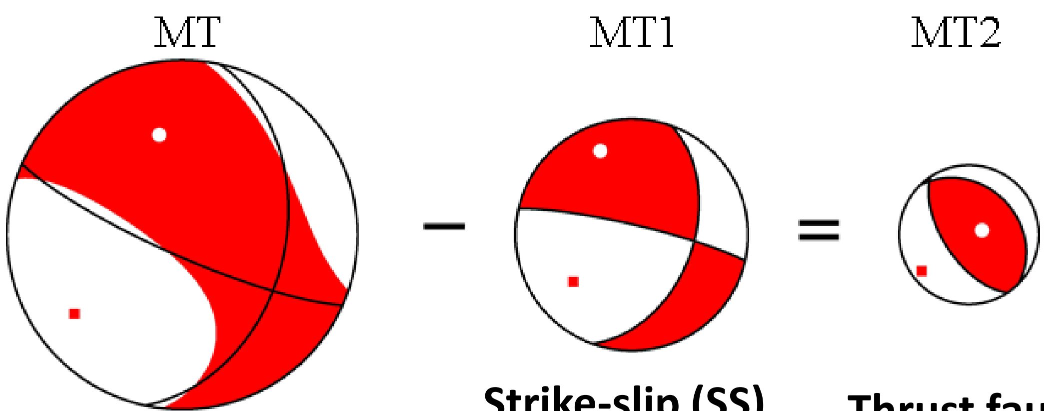




weighting coefficient of the significant contributions

Possible thrust-fault (TF) source component

- Iterative deconvolution cannot resolve position, time and mechanism of smaller subevents
- Assumption
  - **non-DC centroid moment tensor (MT) is composed from just two components**
  - **MT1** - 100%DC major subevent and **MT2**
  - **MT2 = MT – MT1**
  - we interpret **MT2** as a hypothetical subevent 2 whose position and time remains unresolved

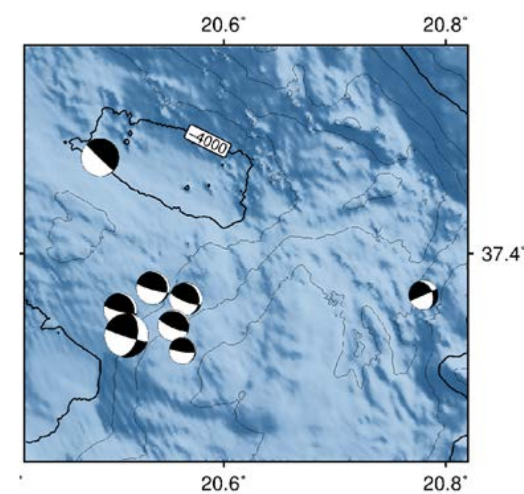


Strike-slip (SS) **Thrust fault (TF)**

Nearly 100% DC tensor MT2
strike = 315, dip = 30, rake = 81

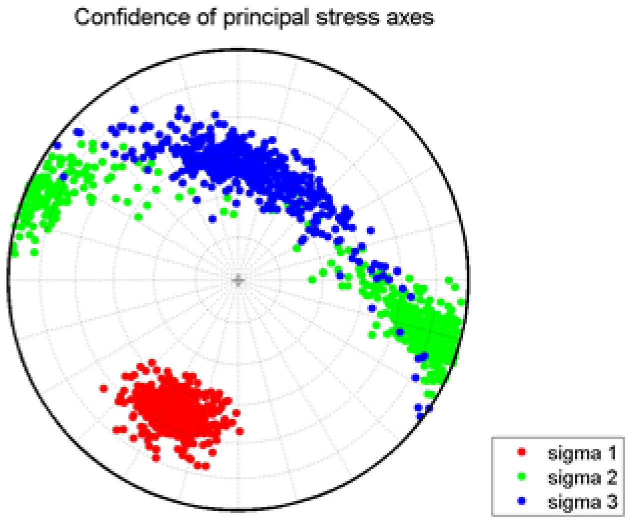
identical direction of the P axis, T and B tradeoff with each other.

Such result is not surprising when considering focal mechanisms of the largest events of the sequence reported to EMSC by NOA.
In fact, there were 6 low-dip (< 20°) thrust faults, all striking at ~300°.



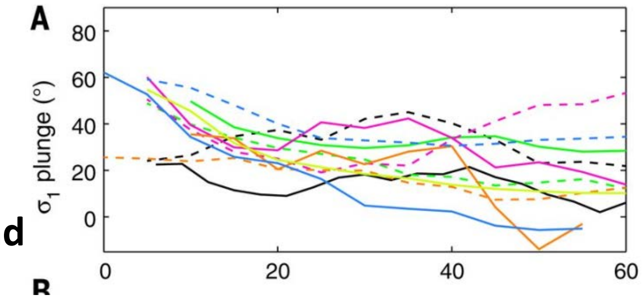
Rough estimate of stress field

- The first guess of the stress field from focal mechanisms
- StressInverse code [Vavryčuk, 2014]



- The principal stress axis Sigma 1, close to P-axes of the analyzed events, is the only well resolved axis.
- Axes sigma2 and 3 tradeoff with each other in the plane perpendicular to Sigma 1
- Sigma 1: azimuth 208° (range 200°-230°), plunge 37° (range 30°-50°)
- The indeterminacy of Sigma2 and 3 explains 'flipping' of the T and B axes of the observed events

Comparission of our stress field estimate to global empirical relations



- natural explanation for thrust eventsseems to be related to **subduction process**

- **Hardebeck, 2015, Stress orientations in subduction zones and megathrust faults**

- He found that for depth ~30 km, Sigma 1 plunge is ~20-50°
- ***Our solution: plunge 37° (range 30°-50°)***

- He predicts the plate boundary to be at angle 40-60° relative to Sigma 1, thus we could expect the slab dip of ~ 10-20° degrees (agreement with [Sachpazi et al., 2016])

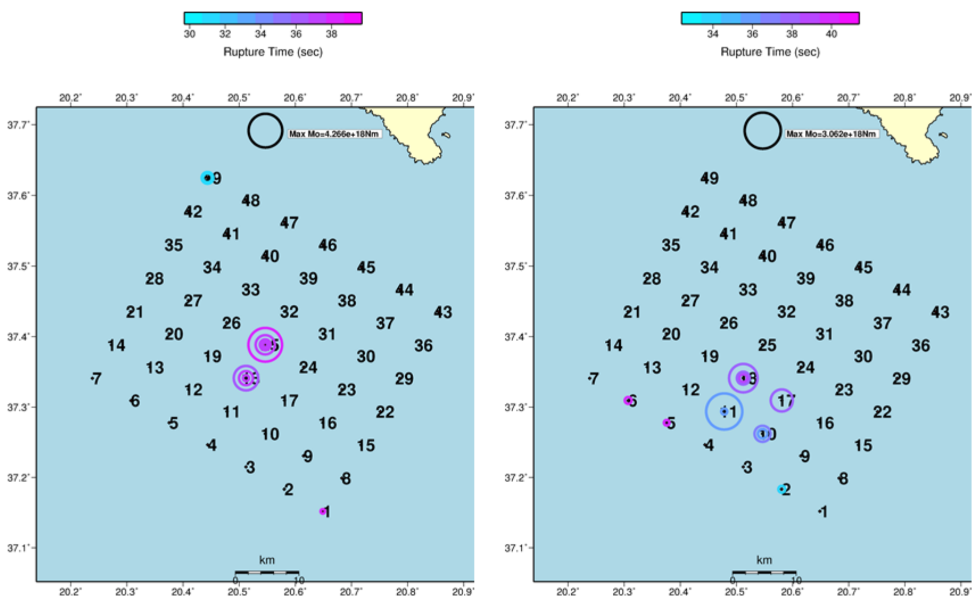
- Although the slab dip is not necessarily the same as the dip of focal mechanisms we remind that several thrust-faulting NOA aftershocks indeed have such a dip.

- The local strike of the slab in the studied region is ~300°. Indeed, the two mutually trading Sigma 2 and 3 axes indicate this strike.

Additional waveform evidence

- we grid-search a plane of trial sources, striking at 300°, and dipping at 30°, passing through a point below NOA epicenter at depth of 25 km.

- **Two tests:**
  1. inversion with fixed SS mechanism (100%DC , strike = 15, dip = 50, rake = -175)
  2. Inversion with fixed TF mechanisms (strike = 315, dip = 30, rake = 80)
- we search independently for possible position, size and time of a SS and TF event, respectively.



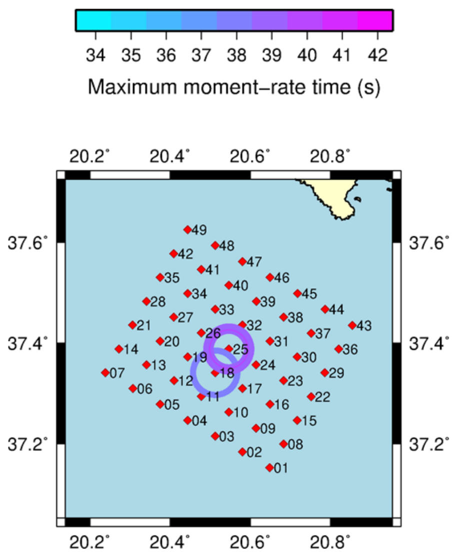
1) a SS major subevent at points 25 or 18, time 37s, VR~0.6 or,
2) a TF event at point 11 or 18, time 37s, VR~0.4.

These preferred positions and times in models 1) and 2) are almost the same. This is a proof why iterative deconvolution method cannot separate them into two subevents.

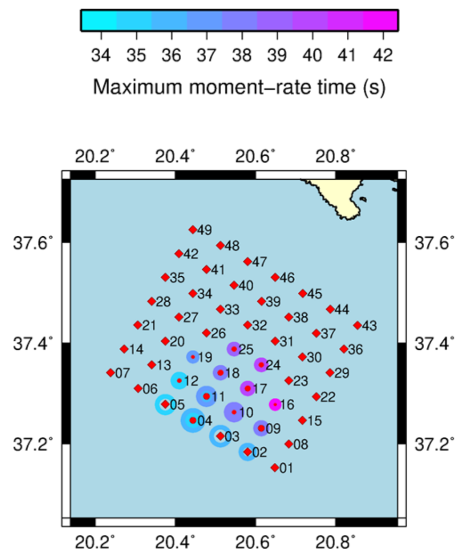
Joint NNLS inversion of source pairs

- TF subevent cannot be retrieved by iterative deconvolution => joint search for source pairs, where the two members of each pair have a prescribed mechanism:
  - SS with s/d/r = 15 /50/ -175, and TF with s/d/r = 315 /30 /80.
  - Mo constrained to 2e19 Nm, but relative moment ratio of the two members is free.
  - Each source member has its arbitrary (possibly complex) moment-rate time function.
  - The pairs are searched in the same trial plane as in previous case.

SS members



TF members



SS subevents are most likely below the NOA epicenter.

TF subevent are less clearly determined, they occur at the shallower tested depths.

TF subevents are weaker than SS.

Only ‘acceptable’ source pairs are shown, i.e. the pairs whose VR > 0.9 VRopt

Summary

- We investigated possible source complexity (two events delayed to each other by ~4 s), indicated by the time function of centroid
- Stress regime in the study region allows co-existence of strike slip (SS) and thrust-fault (TF) events due to tradeoff between two principal stresses of similar size, as also supported by aftershocks.
- We conclude that mainshock might have consisted of two events.
  - First, a weak and early TF subevent with s/d/r = 315 /30 /80 appeared close to epicenter, at a relatively shallow depth (18km). Due to uncertainty, we can consider this event situated on the plate boundary
  - Then, the weak TF event was followed by a major SS subevent, with s/d/r = 15 /50/ -175, situated ~10 km deeper, and delayed by ~4 s.

- **Further work plan:**
  1. Aftershocks will better delineate fault geometry and improve stress-field estimate
  2. Finite-fault models should consider possible segmentation of the fault (variable dip and focal mechanism).
  3. Seismic evidence should be combined with geological data about the subducting slab and other faults.
  4. Strong uncertainty due to azimuthal gap should be taken into account. In any case, this event represents a rare possibility to illuminate shallow subduction west of Peloponnese.

Thank you