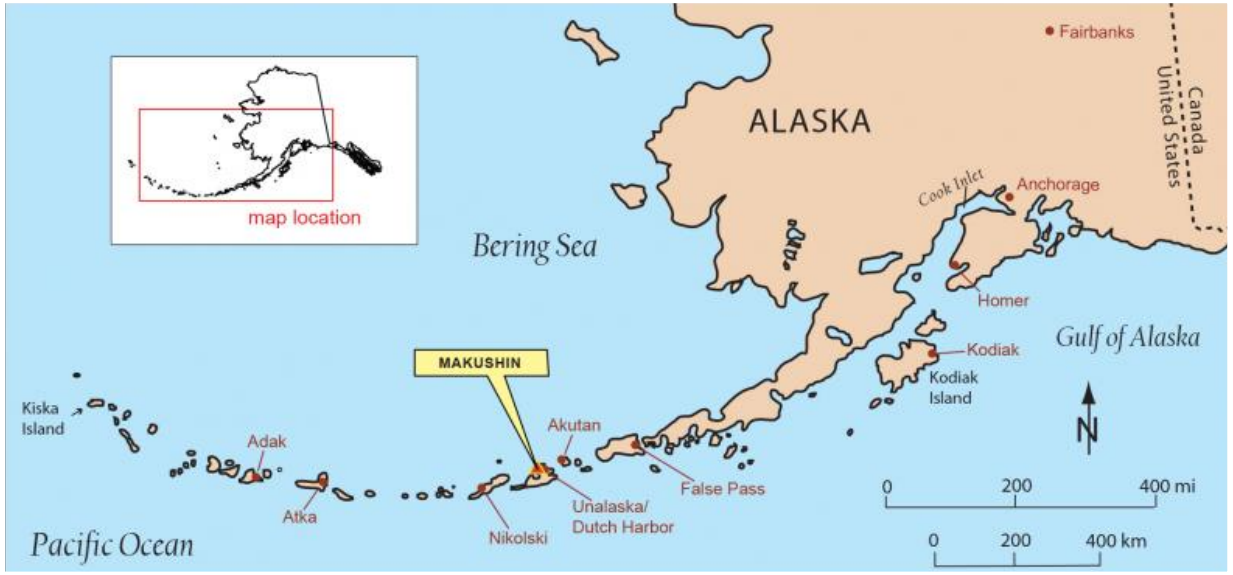
Complex magmatic-tectonic interactions during the 2020 Makushin Volcano, Alaska, earthquake swarm

Diana Roman, **Federica Lanza** (federica.lanza@sed.ethz.ch), John Power, Clifford Thurber & Thomas Hudson

Makushin Volcano, Alaska

Makushin Volcano is located in the eastern portion of the Alaska-Aleutian subduction zone. It is among the most active volcanoes in the United States and has been classified as **high threat** based on eruptive history and proximity to the City of Unalaska and international air routes.



Dutch Harbor, 2018; Photo by: Alex iezzi

Photo by: Samuel Zmolek

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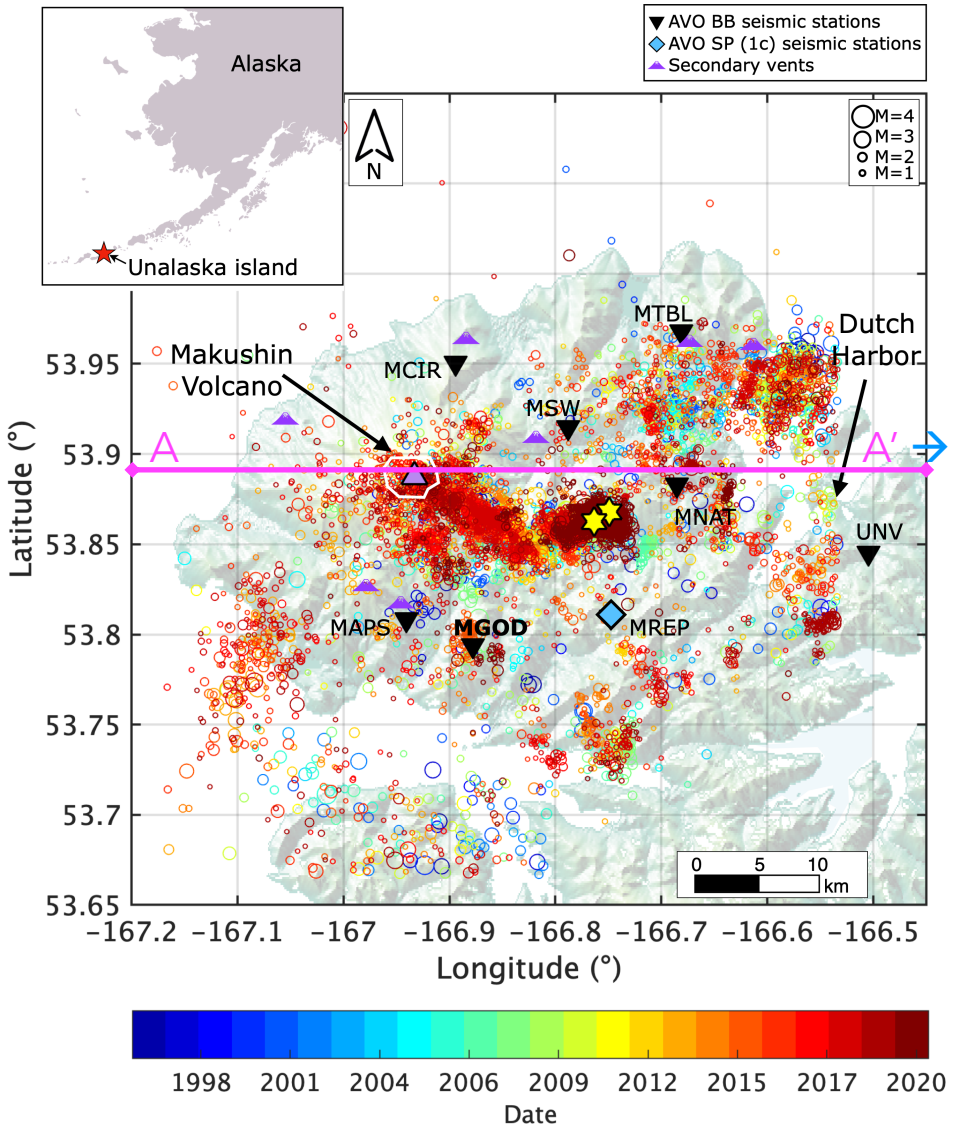
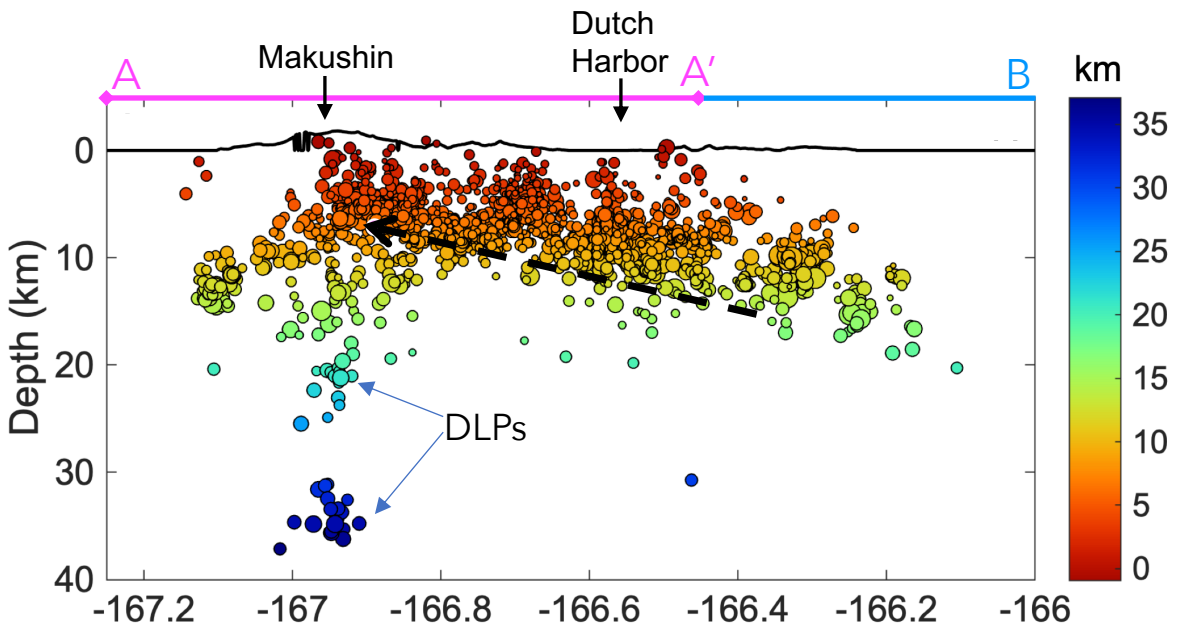
Background Seismicity

AVO catalog 1996-2020

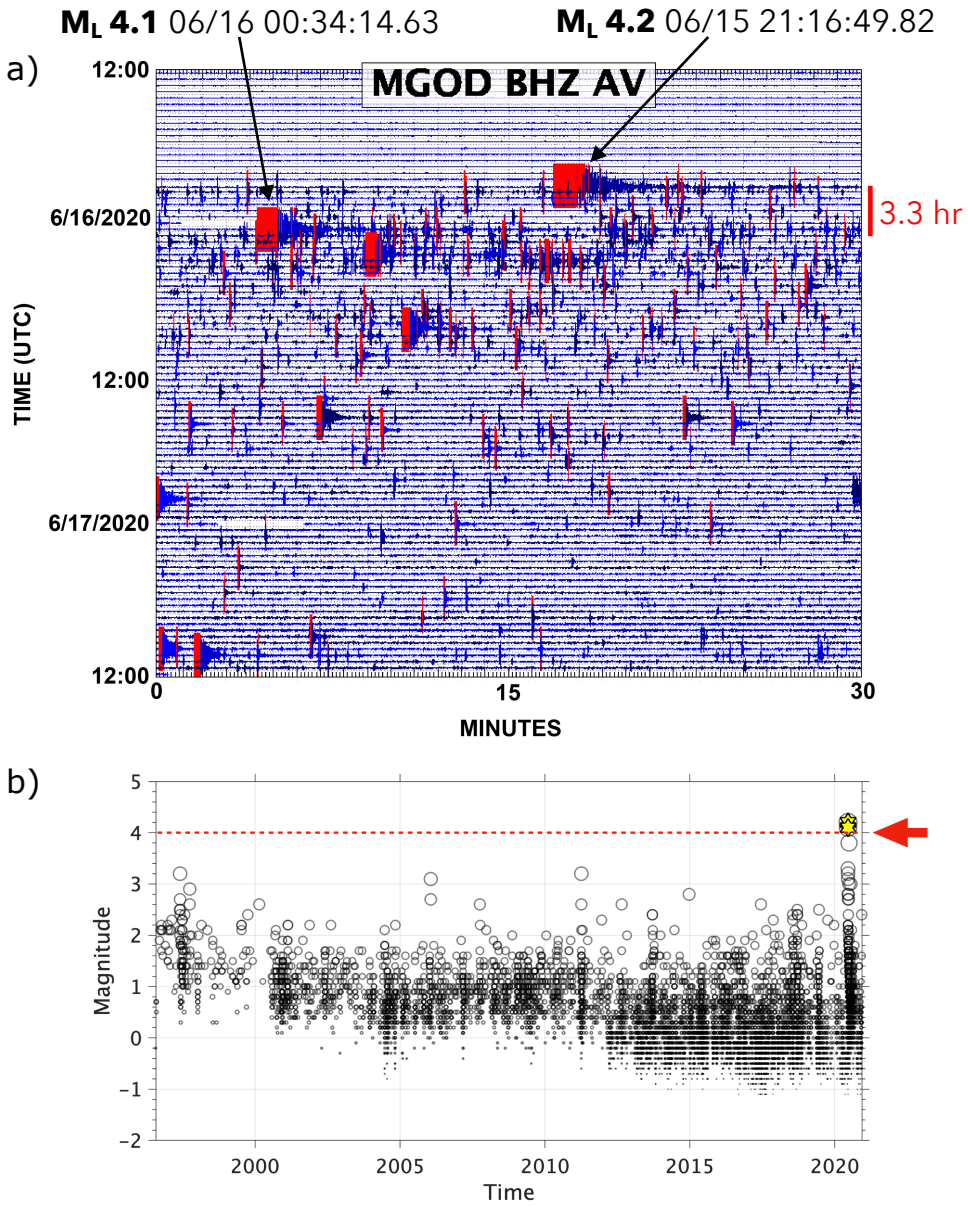


Since 1996, recorded seismicity has documented regular earthquake swarms elongated in a NW-SE pattern extending 15 km E of the caldera and focused between 5 – 10 km depth, shallowing to 0 – 7 km depth as it approaches the volcano's summit. Occasional deep (~15-37 km) long period events (DLPs) have also been observed below the summit area.



Relocations of 1996–2009 and 2015–2016 seismicity from *Lanza et al. (2020)*

The June-December 2020 seismic swarm



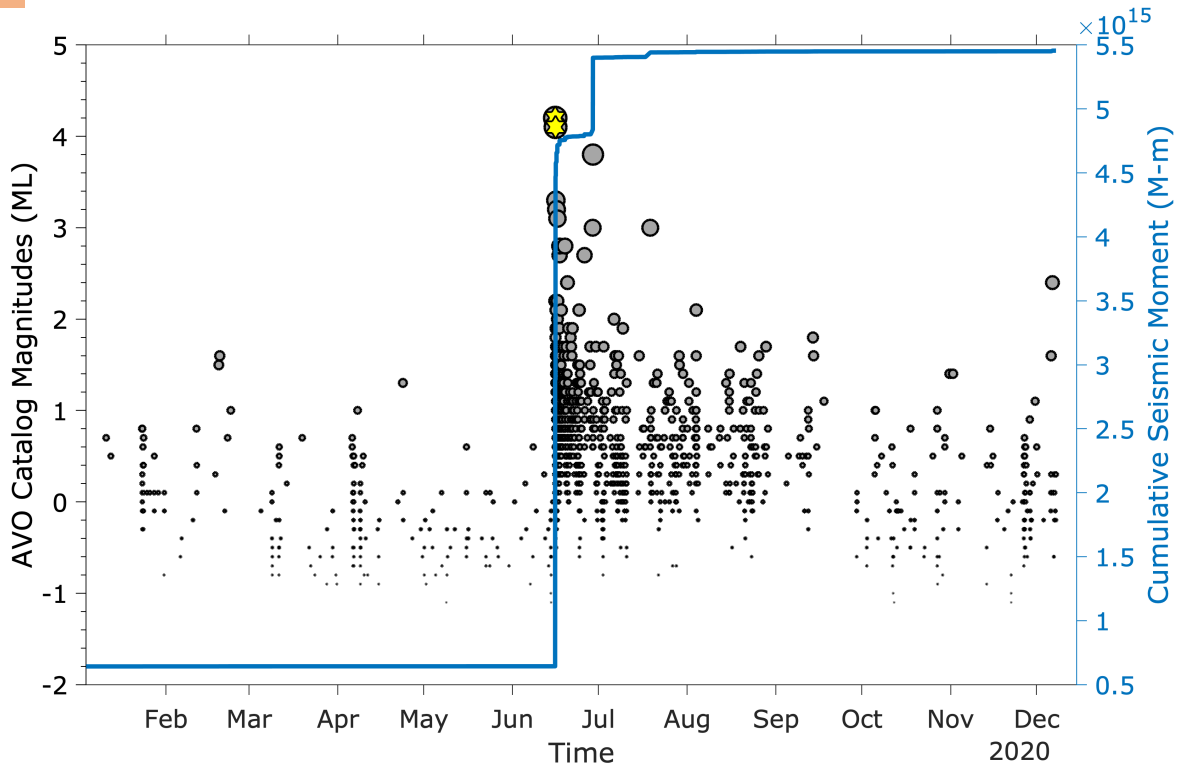
On June 15th, 2020, at 21:16 UTC, a locally-felt earthquake of magnitude 4.2 struck Unalaska Island, ~15 km west of Dutch Harbor. The event was followed by a M4.1 earthquake and several M3+ aftershocks, initiating a prolific swarm, with thousands of earthquakes recorded into mid December. To date, no eruptive activity or other surface changes have been observed at the volcano in satellite views, GPS, or webcam images. This swarm is the strongest seismic activity recorded at Makushin since its last minor eruption in 1995 and since instrumental monitoring began in 1996.

Questions we want to address in this study:

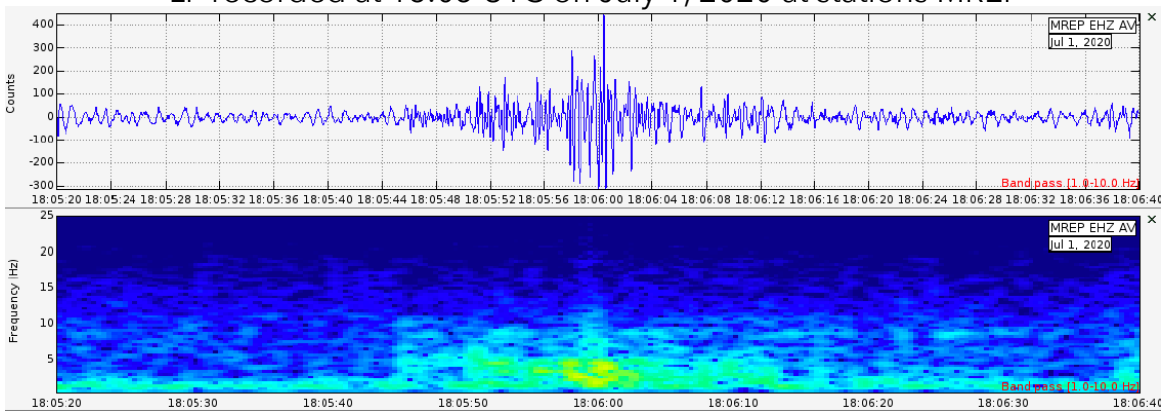
1. What are the main triggering mechanisms at the origin of the current seismicity?
2. Is there an indication of a magmatic intrusion that could explain the ongoing seismicity?
3. What does this reinvigorated seismic activity tell us about the plumbing system geometry and state of stress of the volcano?

The June-December 2020 seismic swarm

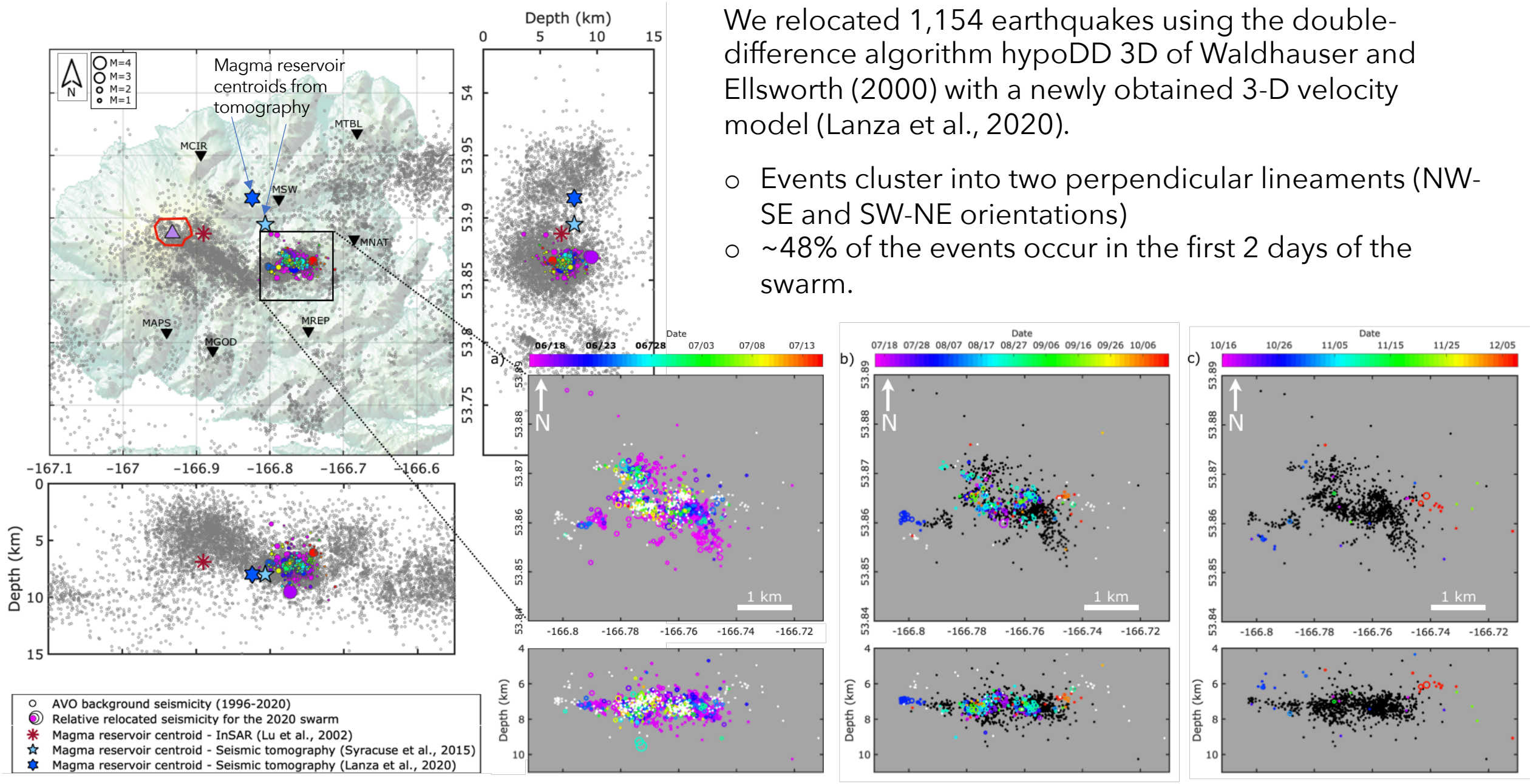
- ~1,414 earthquakes between June 15 – December 7, 2020. Only AVO manually-picked events are included in the analysis.
- Eight M_L 3 or greater events.
- Weak low-frequency (LF) and tremor activity.
- Located ~12 km SE of Makushin's summit, just south of the seismic tomography magma reservoir centroids (next slide) and at the termination of a corridor of background seismicity that extends towards the SE from the summit.
- AVO catalog depths between 7 and 10 km BSL.



LF recorded at 18:05 UTC on July 1, 2020 at stations MREP



Swarm relocations



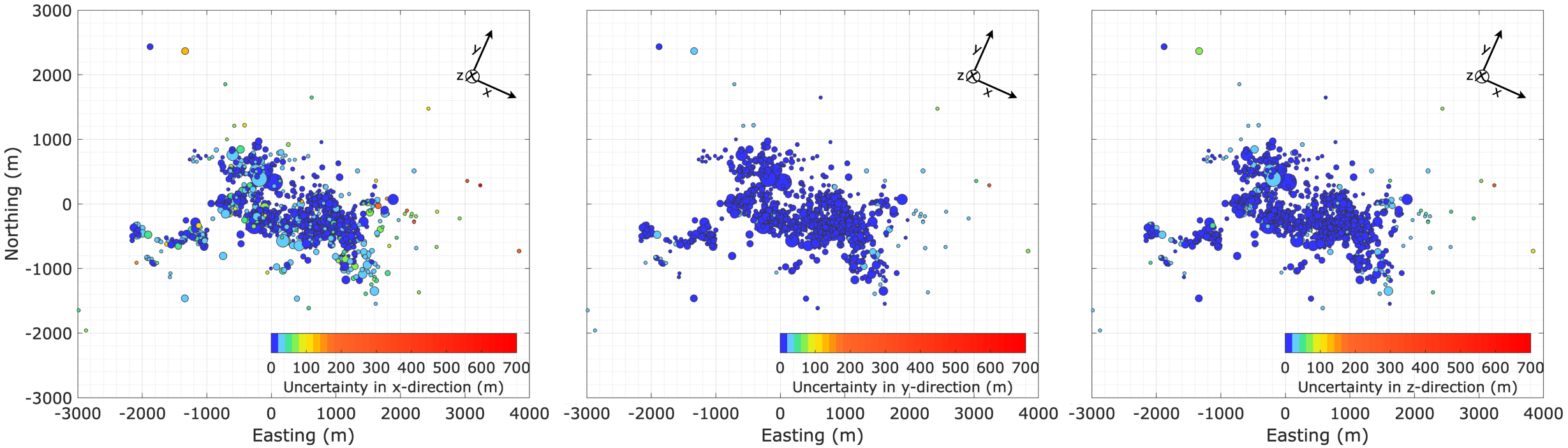
We relocated 1,154 earthquakes using the double-difference algorithm hypoDD 3D of Waldhauser and Ellsworth (2000) with a newly obtained 3-D velocity model (Lanza et al., 2020).

- Events cluster into two perpendicular lineaments (NW-SE and SW-NE orientations)
- ~48% of the events occur in the first 2 days of the swarm.

Swarm relocations II (uncertainties)

- 5,541,317 phase-derived differential times and 354,002 cross-correlation-derived differential times (with a normalized cross-correlation coefficient > 0.8)

- The median 95% confidence error ellipse semi-major axis lengths for all the events are ~23.8 m, 11.4 m, and 14.1 m in the x, y, and z directions, respectively.



Spatial and Temporal migration?

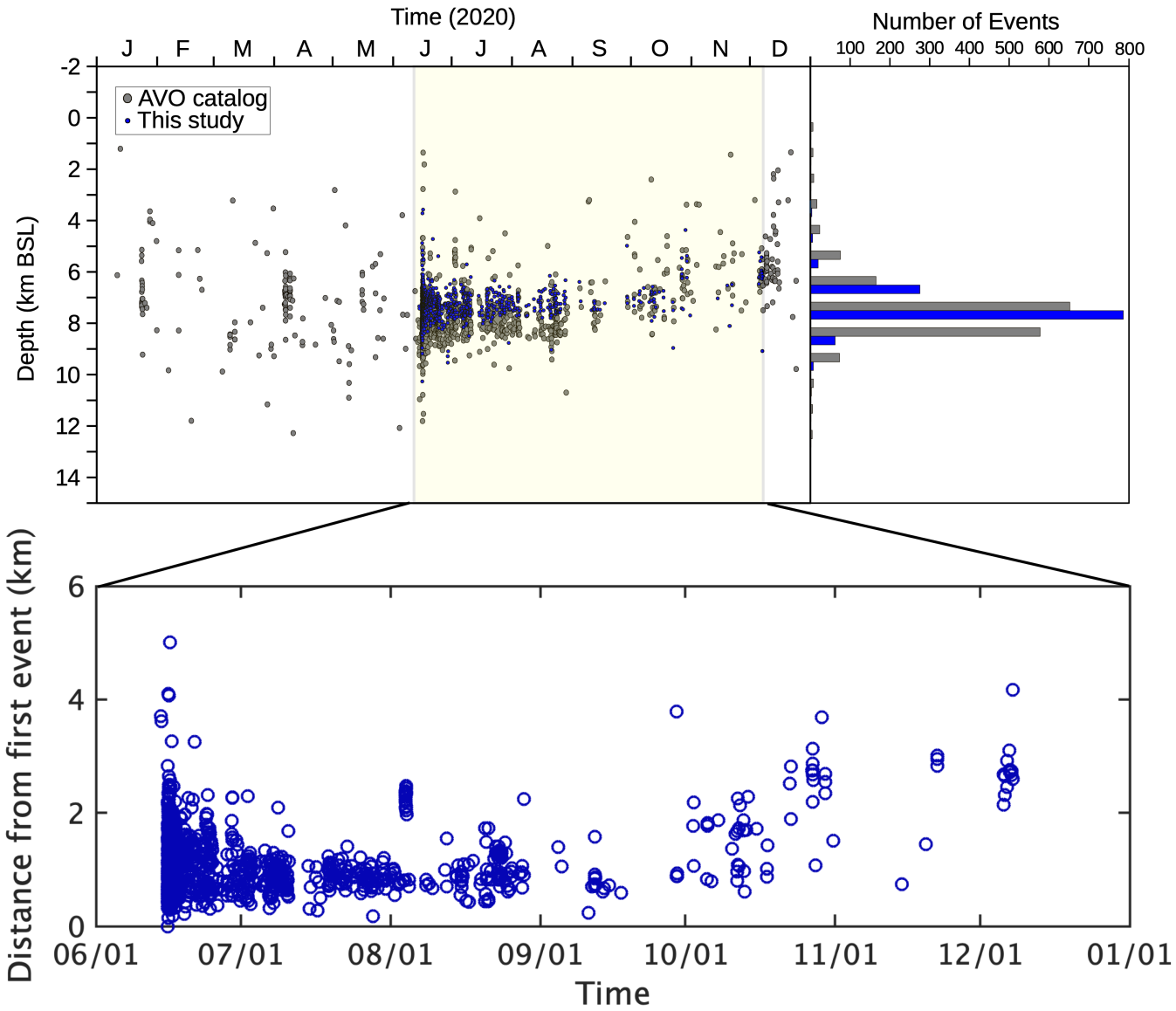
Spatial migration:

- We observe a consistent shift in depths with relocated events ~1-2 km shallower than the initial catalog locations.

- A **weak shallowing in depths** is then observed for the December events, which locates 1-2 km shallower and west with respect to the main cluster.

Temporal migration:

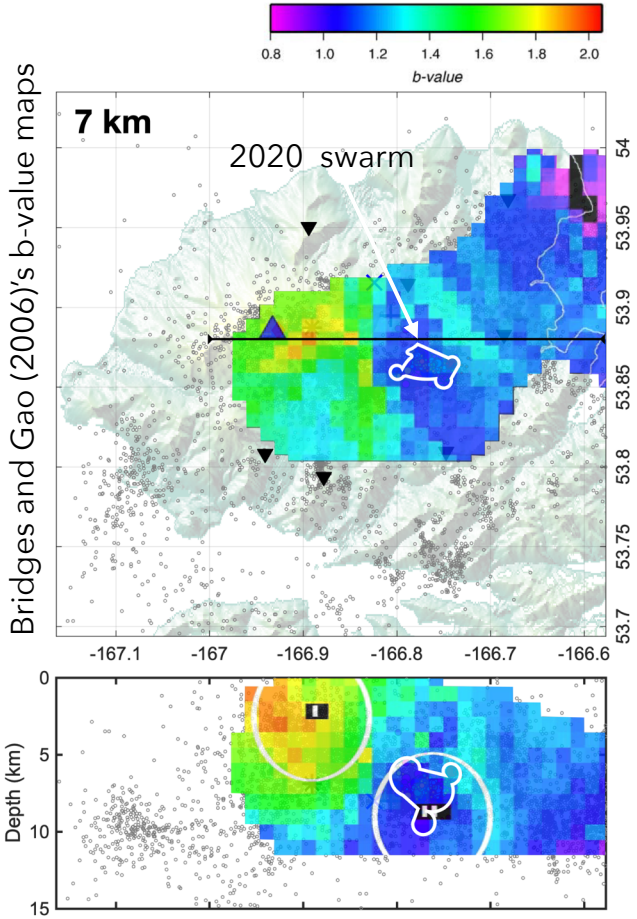
- with ~48% of the events occurring in the first 2 days of the swarm, indicates **no obvious earthquake migration** or tendency to cluster over time.

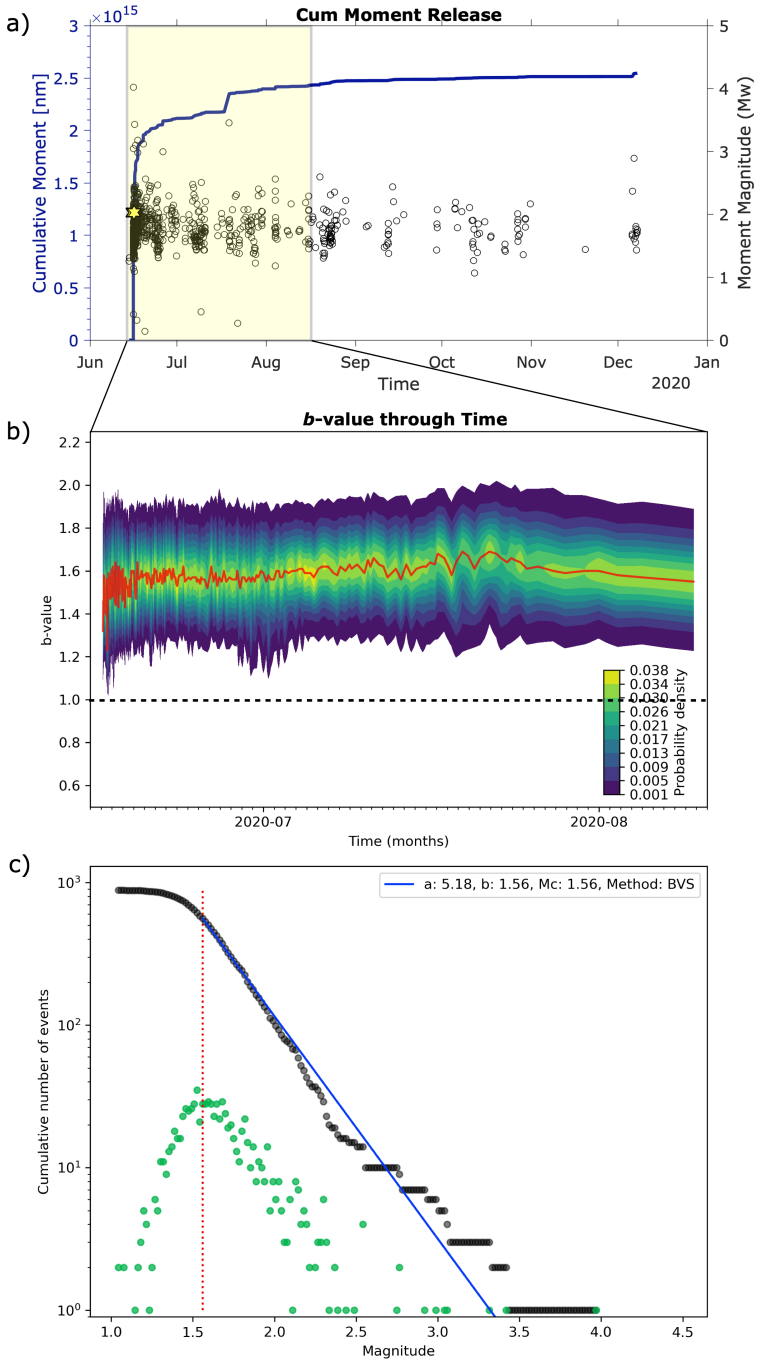


Frequency-Magnitude Distribution and *b*-value variation

We measured Mw using the spectral method described in Stork et al. (2014) and the open-source code *SeisSrcMoment* by Hudson et al. (2020b; https://doi.org/10.5281/zenodo.4010325). *b*-values are then calcuated using Mw and the *b*-value Stability Criterion (BVS) method of Roberts et al. (2015).

- The magnitude of completeness (Mc) is equal to 1.56.
- The **Mw *b*-value is 1.56**, which is significantly greater than 1, and remains fairly constant through time.
- The estimated *b*-values using Mw are higher than the *b*-values mapped by Bridges and Gao (2006) in the same area, where they found an overall average of 1.2.

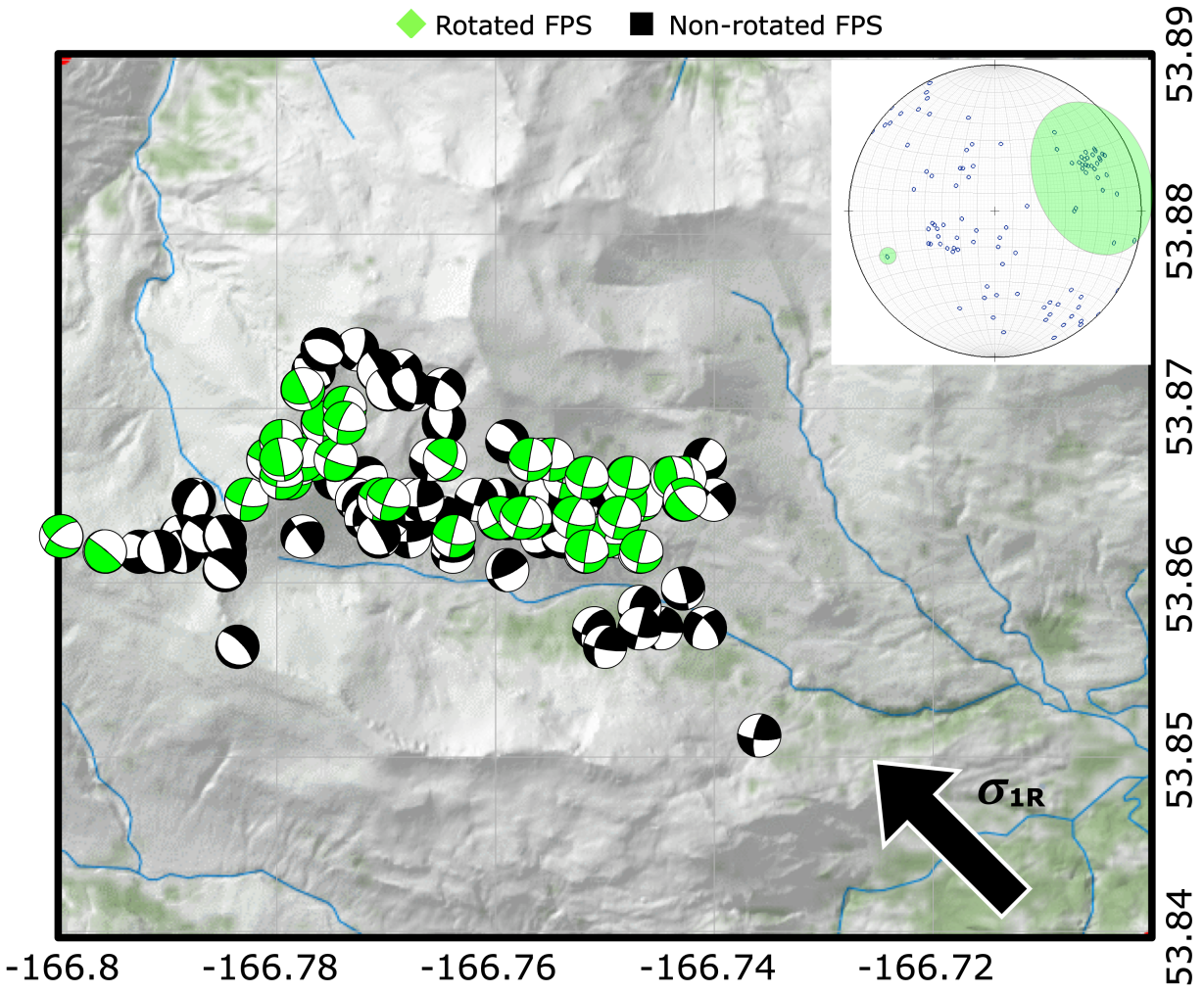




Fault-Plane Solutions (FPS) Analysis

We calculated 108 double-couple FPS for swarm earthquakes by combining our polarity picks with relocated hypocenters.

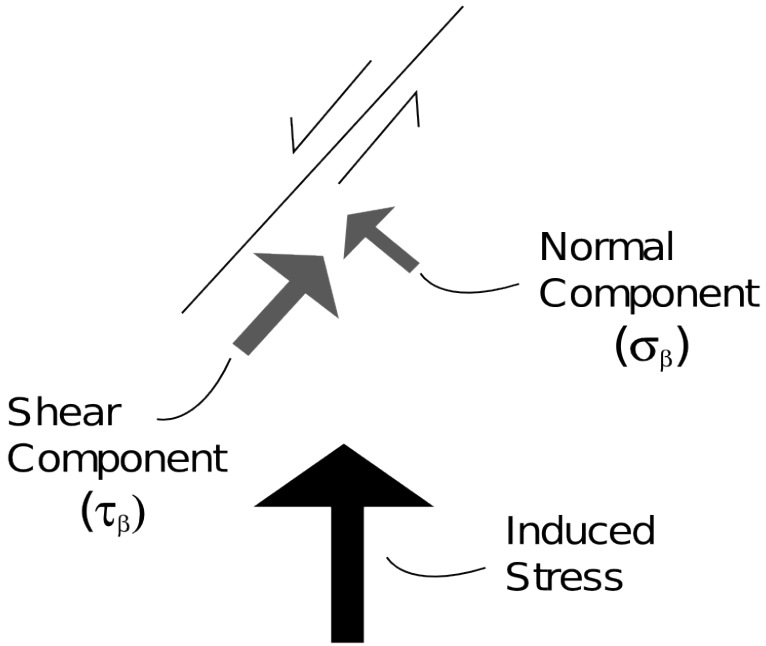
- Nearly 50% (51 FPS) have P-axes rotated by ~90° with respect to regional maximum compression.
- The remaining 57 FPS indicate a mix of predominantly strike-slip and normal faulting mechanisms.
- Rotated FPS are not distinct in space or time from non-rotated FPS, but form two distinct clusters (west and east clusters).
- All but one M_L 3 or greater earthquakes has an FPS consistent with the regional stress field.

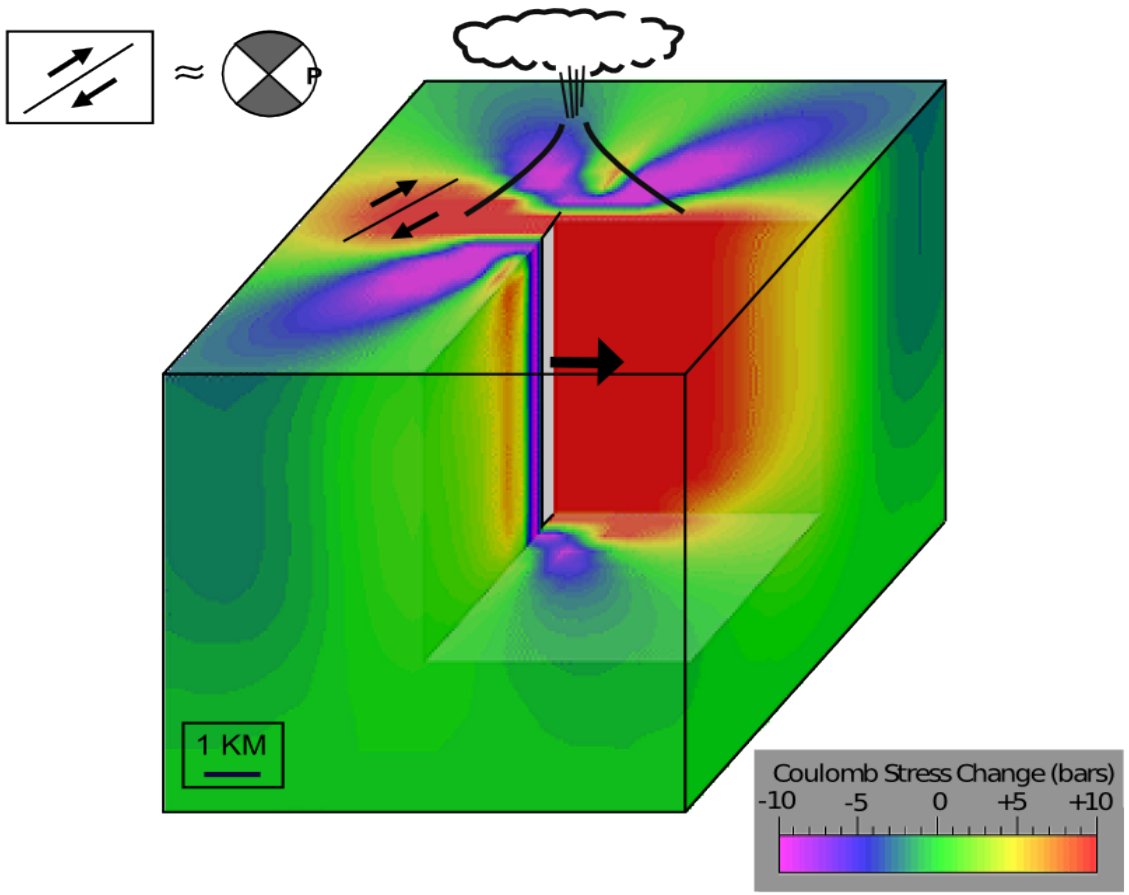


Coulomb stress change

Coulomb stress change:

$$\Delta\sigma_f = \tau_\beta - \mu\,(\Delta\sigma_\beta - \Delta p)$$



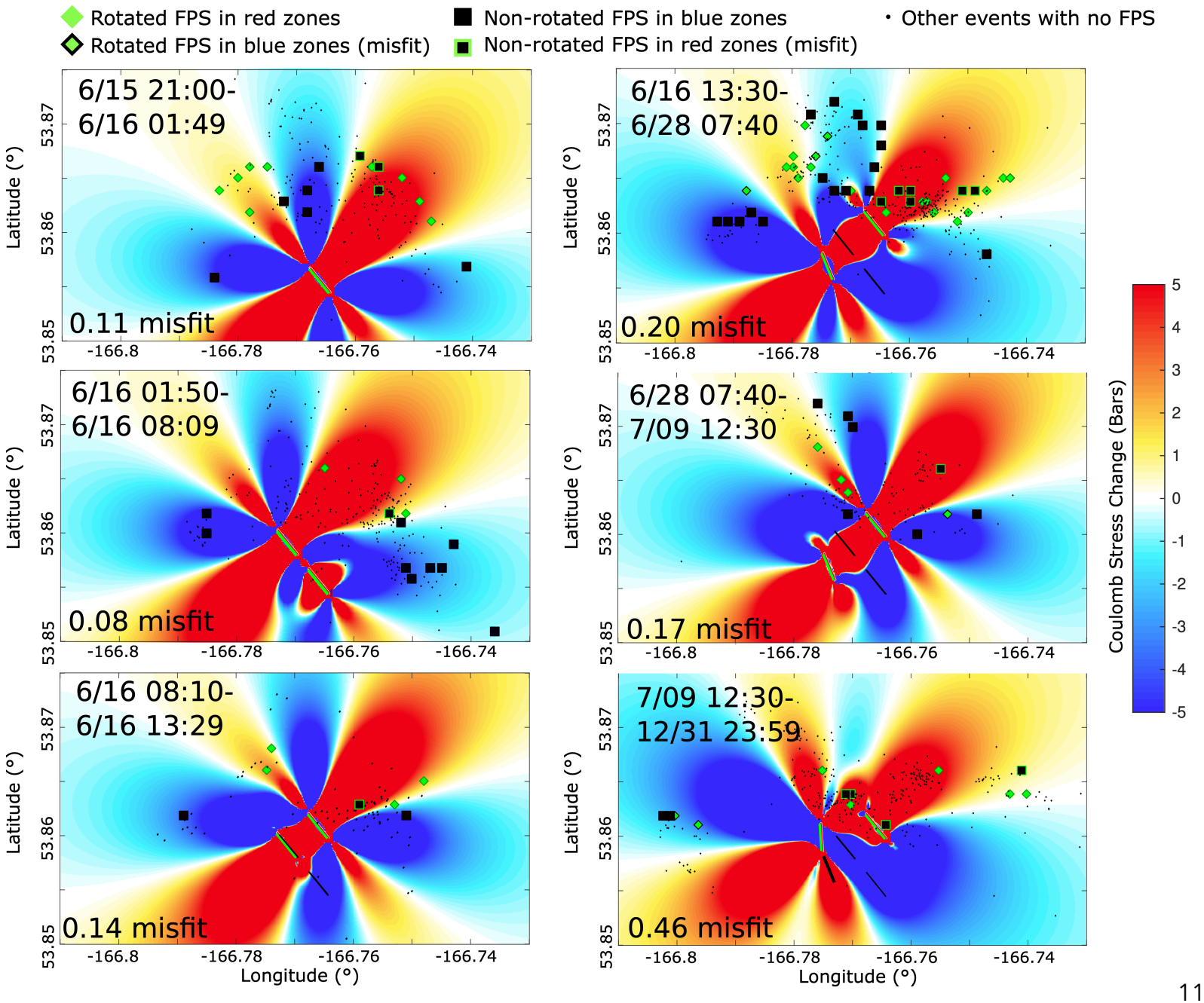


See Toda et al., 2002; Segall et al. 2013;
Coulomb 3.3: https://earthquake.usgs.gov/research/software/coulomb/

Coulomb stress change

For Coulomb modelling the FPS dataset is broken into six periods starting at each M_L 3+ earthquake.

- The active dike in each period has 0.5 m inflation, the immediately-previously-active dike in each period has 0.1 m inflation.
- The misfit is below 20% until the final period when it's impossible to fit a two-dike model anymore, suggesting that either the period needs to be broken into multiple periods, or the stress field is too complex.

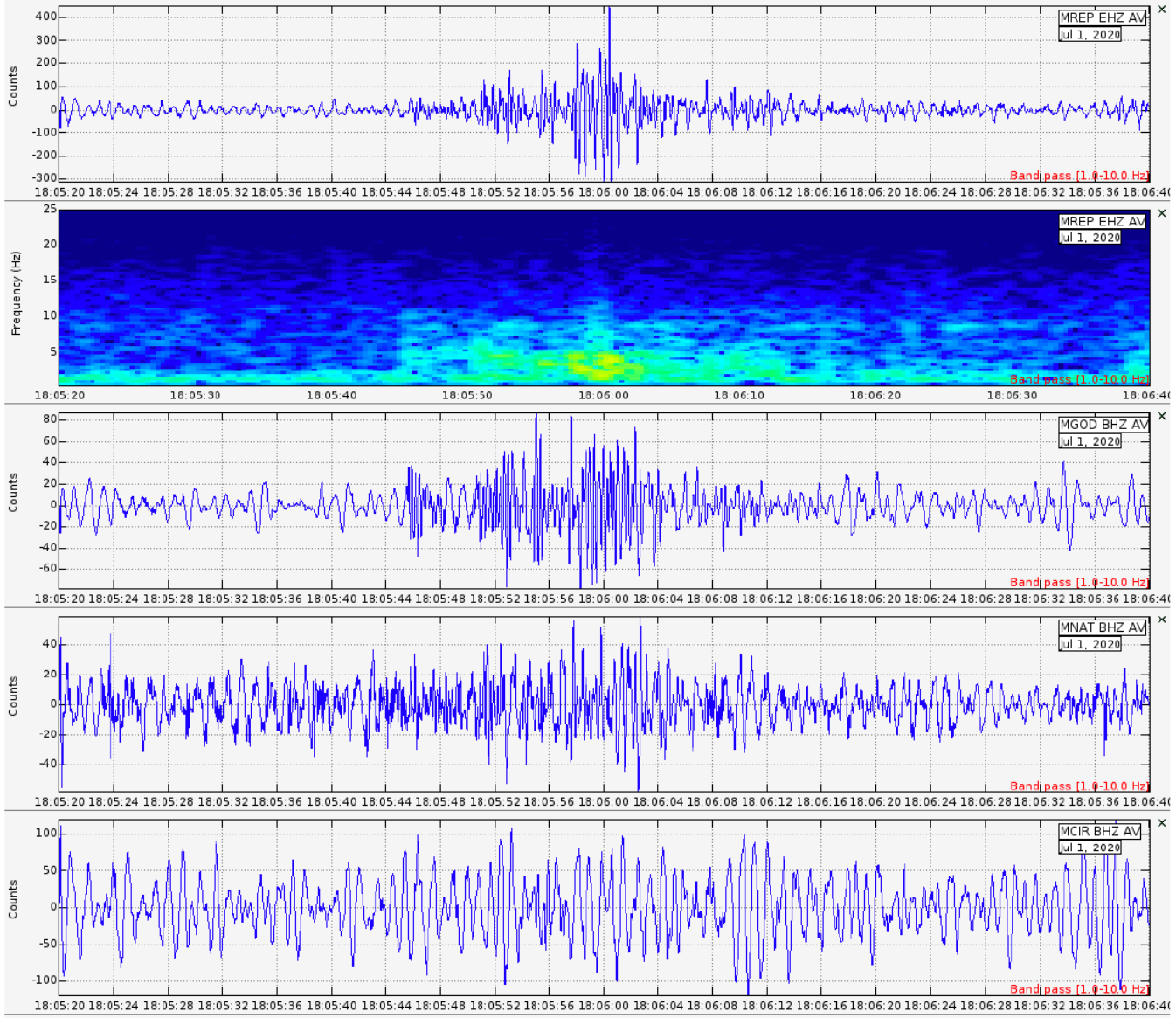


LF Seismicity

During the 2020 swarm, AVO analysts noted occasional low-frequency (LF) seismic events and light harmonic tremor between July 1 and September 8.

- LFs were emergent and characterized by energy concentrated at around 2 Hz.
- LFs were highest in amplitude on station MREP (~6 km south of the swarm volume), followed by station MGOD (~10km SE of the swarm volume).
- Additional analyses are needed to assess the rate and location of LF seismicity during background and swarm periods at Makushin.

LF recorded at 18:05 UTC on July 1, 2020 at stations MREP

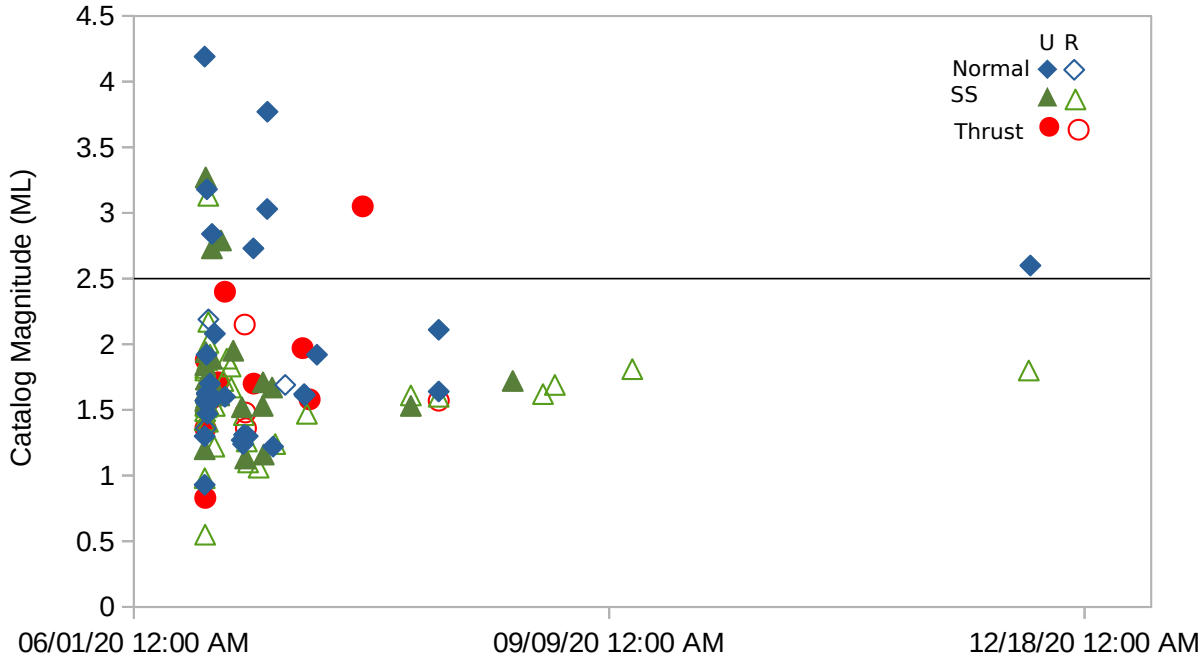


Discussion I

1. Swarm or tectonic earthquake sequence? And what do earthquake relocations tell us?

Most likely both. Although the first event had the largest magnitude in the sequence, the presence of rotated FPS (R, open symbols) are inconsistent with a purely tectonic process and rather point to a magmatic intrusion. All but one of the M2.5+ earthquakes has non-rotated FPS (U, solid symbols); which would be expected as a result of constructive interference between the tectonic stress field and the dike-induced stress field.

The earthquakes seem to align on two conjugate faults. The absence of a migration pattern of the hypocenters both in time and space indicates that both faults slipped concurrently, also pointing to a complex interaction of regional and magmatic stresses.



Discussion II

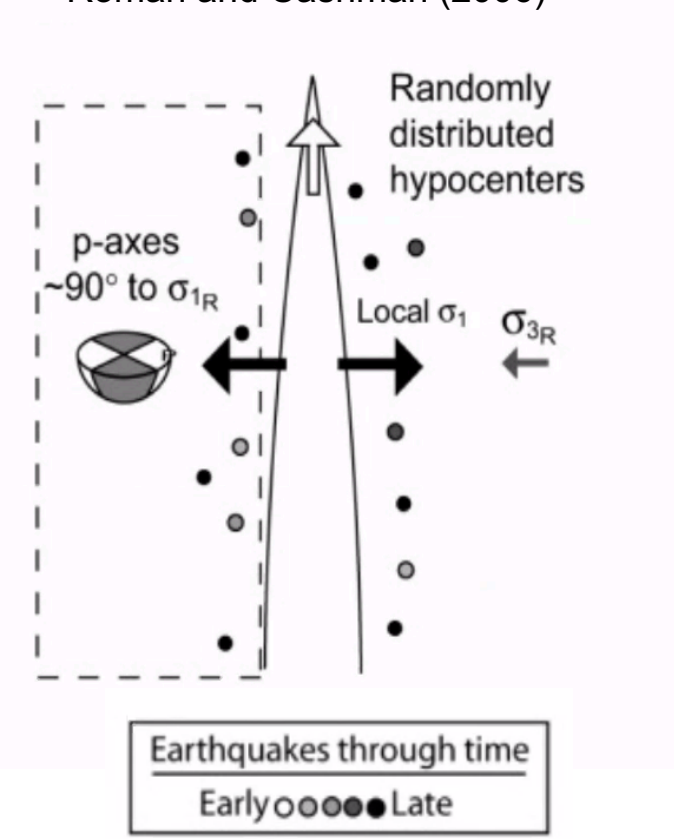
2. Is there evidence for magma intrusion?

Rotated FPS (relative to regional faulting) provide strong evidence for the presence of a local stress field induced by dike inflation/magma intrusion (e.g., Roman and Cashman, 2006; Lehto et al., 2010; Roman and Gardine, 2013, Roman et al., 2021).

Further indication of a possible magmatic signature lies in the **high b-values** which could be an indication of (1) high thermal gradients; (2) high pore pressure found in the vicinity of a magma reservoir; (3) vesiculation and fragmentation of ascending magma that can create stress-induced cracks.

Moreover, **LF seismicity** is often linked to fluid movements and could support the hypothesis that magmatic processes are at play in the triggering of the 2020 swarm. However, it is unclear whether LF activity also occurs as a background process and additional analyses are needed.

Roman and Cashman (2006)

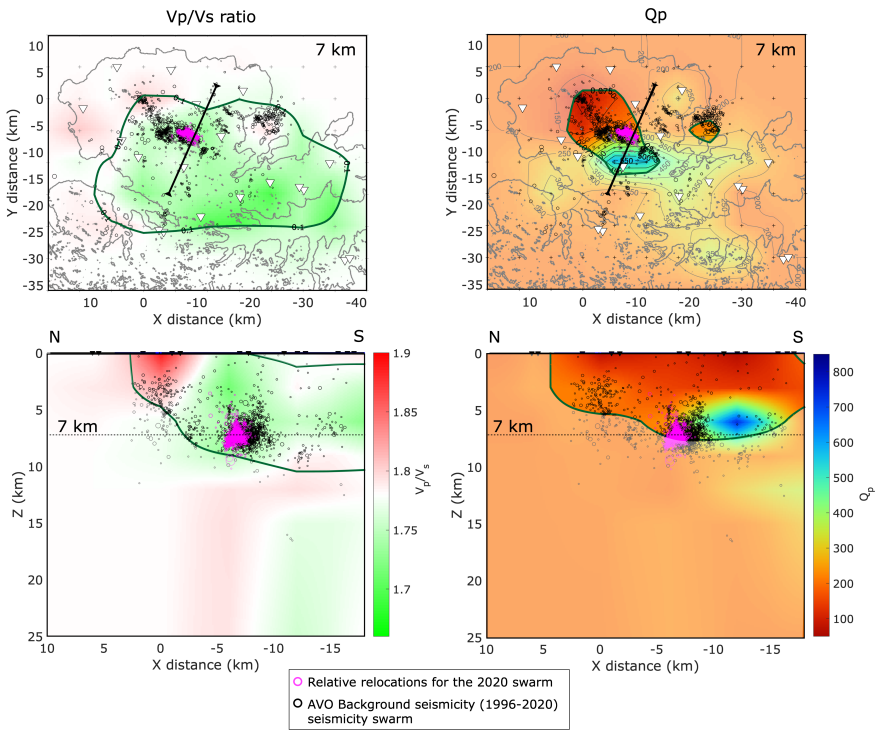


Discussion III

3. Then, where is the magma?

Coulomb models seem to point to multiple dike intrusions in quick succession, with some dikes being reoccupied within the same episode. Evidence for “snuggling dikes” model, in contrast to radial patterns of dikes observed at caldera systems, has also been observed for an eroded volcano in Summer Coon, in south-central Colorado (Poland et al., 2004).

An ensemble of seismically active fractures/fluid-filled pathways is also reflected in the complexity of the earthquake relocation patterns and it is in agreement with the swarm being located in an area close to the inferred magma reservoir at Makushin in a region of low Qp (150-250) and low Vp/Vs ratios (Lanza et al., 2020).



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