

Complex faulting and triggered rupture during the 2018 M_w 7.9 Offshore Kodiak, Alaska Earthquake

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Key Points:

- Seismic and GPS data suggests complex rupture along conjugate strike-slip fault planes
- Static and dynamic stress change modeling suggests dynamic triggering during the rupture
- Left-lateral faulting on SW-trending fault planes released most of the energy dominating the radiated wavefield and the crustal deformation

Abstract

We combine aftershock relocations, source mechanisms, teleseismic P-wave back-projection and GPS data inversion to constrain complex faulting geometry of the 2018 M_W 7.9 Offshore Kodiak earthquake. Relocated aftershocks delineate several N-S trends including a prominent 110-km-long segment, as well as broad NE-SW trends. GPS modeling and back-projection indicate that the NE-SW trending left-lateral strike-slip segments released most energy dominating far field crustal deformation and radiated wavefield. Back-projection infers fast E-to-W rupture propagations superimposed on a slower S-to-N migration. We propose a five-segment model of the rupture that was partially driven by dynamic triggering.

1. Introduction

In the early morning hours of January 23, 2018, a magnitude 7.9 earthquake struck ~300 km offshore Kodiak Island, Alaska in the outer rise region of the Alaska-Aleutian subduction zone. While the moment tensor for the earthquake suggests predominantly strike-slip faulting, the true complexity of the source has only become evident through analysis of multiple datasets.

The Alaska-Aleutian subduction zone extends for ~3,800 km from the Gulf of Alaska westward to the Komandorsky Islands and accommodates relative motion between the Pacific and North American plates. The characteristics of this tectonic boundary, such as convergence direction and rate, trench separation and degree of coupling, vary widely along its extent (Freymueller et al., 2008). The nature of outer rise seismicity also changes along the arc: typical normal faulting outer rise events are more common in the central and western Aleutians (west of 160°W) and nearly absent in the eastern Aleutians and southern Alaska (Christensen & Ruff, 1988). Very few earthquake source mechanisms are catalogued for the outer rise region offshore Kodiak. Those that do exist do not indicate a uniform pattern of faulting. An m_b 5.4 event occurred a few months after the great 1964 M_W 9.2 Alaska earthquake and featured typical outer rise normal faulting (Stauder & Bollinger, 1966). An M_W 6.0 earthquake in 1999 east of the current sequence was a reverse faulting event and an M_W 4.9 earthquake in 2017 was a strike-slip event with a similar focal mechanism to the 2018 M_W 7.9 earthquake (Figure 1).

A series M_W 7.2-7.8 strike-slip events occurred in the northeast Gulf of Alaska in 1987-1988 on a system of conjugate and parallel faults in an area with very little historic seismicity (Lahr et al., 1988; Hwang & Kanamori, 1992) (Figure 1, inset). However, seismic reflection data provide clear evidence that these faults were active long before the earthquake sequence began (Reece et al., 2013). These events were followed by more examples of complex faulting in oceanic lithosphere. The 1998 M_W 8.1 Balleny Islands (Antarctic Plate) earthquake ruptured faults that did not correlate with any known features on the ocean floor and may have involved sub-events on different fault planes (Henry et al., 2000). The 2000 M_W 7.8 Wharton Basin earthquake (off Sumatra) involved ruptures of both NS- and EW-trending fault planes during the mainshock (Robinson et al., 2001; Abercrombie et al., 2003). The 2004 M_W 8.1 Tasman Sea earthquake reactivated old structures with a new mechanism, rupturing an old spreading ridge in a strike-slip event (Robinson, 2011). More recently, the 2012 Wharton Basin sequence involved multiple $M > 8$ sub-events within a complex set of faults intersecting at highly oblique angles (Meng et al., 2012).

These examples are a reminder that the far-field observations are often an aggregate over a series of sub-faults. The studies above suggest this may be particularly common in oceanic crust, where the preexisting fabric may not necessarily align with the dominant stress directions.

In these cases, stress release might be most easily accommodated through a complex set of sub-fault ruptures instead of occurring along a single canonical fault line.

Several fracture zones have been identified in the vicinity of the 2018 Offshore Kodiak Island earthquake such as the Aja Fracture Zone to the south (Pitman & Hayes, 1968; Matthews et al., 2011). In addition, seismic reflection and high-resolution bathymetry have revealed numerous ~N-S trending faults (Reece et al., 2013), which were interpreted as preexisting fractures in the Pacific Plate spreading fabric that have been reactivated as predominately normal plate bending faults by Pacific Plate subduction. This sea floor fabric bears striking resemblance to that imaged in the Wharton Basin region (Singh et al., 2017).

We combine analysis of the aftershock locations, seismic moment tensors, teleseismic P-wave back-projection and GPS displacements to constrain complex faulting during the 23 January 2018 M_w 7.9 earthquake.

2. Methods and Results

2.1. Aftershock Relocations and Source Mechanisms

The Alaska Earthquake Center analyzed over 2,800 aftershocks through the end of March, 2018. Due to the offshore location, the magnitude of completeness is higher than the on-land catalog's on-land, at $M=3.0$. The aftershocks illuminate a complex network of ruptured sub-faults (Figure 2).

To better resolve aftershock locations, we employ the earthquake relocation technique GrowClust (Trugman & Shearer, 2017). First, we subset the catalog to include earthquakes with $M>3.3$, resulting in 515 events. Eliminating the smallest magnitude events improves computational efficiency and removes the most poorly constrained events. Using *hypoddy* (Krischer, 2015), for each aftershock we link up to 20 neighboring events that have at least four phase arrivals in common at nearby seismic stations. This produces 6,239 event pairs with an average offset of ~8 km between linked events (on the order of the location uncertainty for these offshore events). In total, >90,000 P-phase and >28,000 S-phase pairs are selected, bandpass filtered from 1-5 Hz, and 5 seconds of data are extracted around each phase (-1 to +4 seconds) prior to cross correlation. The resulting cross correlations are used as input to the GrowClust program. Within GrowClust, we use a maximum station distance of 600 km, a max rms residual of 1 second to join clusters, and a minimum of 5 events required to perform a cluster shift test. We allow earthquakes within 20 km catalog distance and 15 km relocated distance to join clusters, and allow up to 10 km of shift. These parameters result in 420 earthquakes being relocated, with rms differential time residuals of ~1 second for both P- and S-phases.

We used 14 moment tensor solutions from National Earthquake Information Center ComCat catalog that range in magnitudes between M_w 4.1-5.1 and centroid moment tensor solutions from Global CMT catalog for the mainshock and the largest aftershock (M_w 5.5, 24 January 00:04 UTC).

The overall aftershock distribution illuminates several sharp N-S and broad NE-SW trends (Figure 2). We identified 4 distinct aftershock groups associated with possible fault planes labeled as S1-4 in Figure 2b. The most prominent is the 110-km-long N-S trend S1 with the mainshock epicenter located near its southern end. Neither catalog nor relocated aftershocks indicate a single, well-defined ~EW-striking trend. Instead, epicenters in the region west of S1 are distributed over a broad NE-SW trending zone (S2) and form several clear N-S streaks ~10 km long (Figure 2a). Focal mechanisms for aftershocks along these streaks show right-lateral

strike slip faulting. There is also a broad 70-km-long NS-aligned cluster northeast of the main S1 segment (S4). However, no connecting structure between the main segment and this northeast segment is clear in the aftershock locations (S3).

The focal mechanisms for aftershocks within S1 and S4 segments predominantly indicate right-lateral strike-slip motion. A cluster of reverse-faulting aftershocks is concentrated near the southern end of the main S1 lineation. These are located just north of the identified fracture zone and may indicate rupture interaction with this structural barrier. One of the only two normal faulting aftershocks is associated with the S4 aftershock cluster and indicates NS-fault planes (it was the largest aftershock). The second normal-faulting aftershock is located in the middle of the S2 segment and indicates a W- or SW-trending fault plane. Its location is close to the m_b 5.5 normal faulting event in 1964.

2.2. Teleseismic P-wave Back-Projection

We back-projected teleseismic P waves recorded at 298 broadband stations in continental Europe to image the kinematic rupture process of the M_w 7.9 mainshock (Figure 3a). The back-projection technique utilizes very few prior assumptions on fault parametrization, Green's functions, or rupture velocity, and thus can robustly constrain the spatio-temporal evolution, rupture extent and rupture speed of large complex earthquakes (Ishii et al., 2005; Meng et al., 2012; Zhang et al., 2012; Fan & Shearer, 2016; Wang et al., 2016). In this study, we adopted the Multitaper-MUSIC array processing technique that provides superior resolution to separate closely spaced sources (Meng et al., 2011). We collected coherent waveform data from the ORFEUS data center (<http://orfeus-eu.org/webdc3/>). The seismograms are filtered in the band of 0.5 to 2 Hz, and empirically aligned with the first 5 seconds of the P-wave arrivals. This correction procedure assumes that the first arrivals originated from the hypocenter (Ishii et al., 2005) and provides a static correction of travel time due to 3D path effects. The aligned data are then back-projected using a 1D reference velocity model to pinpoint when and where difference source regions were radiating energy.

The results suggest complex conjugate ruptures and segmentation along several faults trending $\sim$ NS and $\sim$ EW – observations that are remarkably consistent with the aftershock locations (Figure 3). The earthquake initiated as a relatively low-energy bilateral rupture along a NS-trending fault (S1) near its southern end with the first notable energy burst at around 10 seconds (Figure 3d-e). Between 20 and 30 seconds, the rupture leaps $\sim$ 60 km NW from the earthquake epicenter (S1.5 segment, Figure 3c). From 30 to 50 seconds, the dominant release occurs along a continuous E-to-W trending path with a rupture speed of 3 km/s (S2 segment, Figure 3c). Beyond 50 seconds, radiators are less energetic. This late energy appears well constrained to a region north and east of the rest of the rupture. It likely represents another fault segment near the northern end of S1 with the strike in the westerly direction and predominant propagation path from east to west (S3). The rupture speed on S3 is around 3 km/s, similar to that on S2 (Figure 3c). The aftershock locations clearly image a 70-km-long NS-oriented fault segment (S4), which corresponds to high-frequency radiators at around and after 65 seconds. Beyond 75 seconds, back-projection is no longer viable because the teleseismic P waves lack coherency. The overall rupture extent is $\sim$ 100 km in the NS direction, which is consistent with the aftershock zone extent. The average NS rupture speed is ($\sim$ 1.4 km/s), is lower than the two EW ruptures. The rupture pattern is overall highly complex, as inferred for the previous oceanic-plate events.

2.3. GPS Modeling

Following the Offshore Kodiak earthquake, UNAVCO made available a dataset of processed coseismic displacements at Plate Boundary Observatory (PBO) GPS stations in Alaska (Figure 4). We first explore whether the GPS displacement field could have been produced by slip on the N-striking faults. We build a slip model consisting of segments S1, S1.5, and S4 and estimate the final static coseismic slip on these segments from the horizontal and vertical GPS displacements using a Monte Carlo method assuming a homogeneous halfspace Earth model, all slip planes vertical, slip pure right-lateral and strike 0° (Supplementary Material S1). The horizontal displacements predicted by the resulting slip model show a systematic azimuthal misfit to the horizontal GPS displacements (Figure S1). The inferred slip model and misfit do not improve by assuming that the segments have a westward dip (Figure S2), or allowing for a normal component of slip (Figure S3). We next add segments S2 and S3 to the model; to reduce the number of free parameters, we assume again that all segments are vertical and restrict slip to be pure right-lateral on S1, S1.5 and S4 and pure left-lateral on S2 and S3. We test different values for the strike of S2 and S3 (Figures S4-S7). The resulting models fit the GPS significantly better than those with only the N-striking segments, but all have unconvincing attributes. Some models feature the highest slip at the far northeast of the aftershock distribution (Figure S4 and S5), where back-projection indicates minimal high-frequency radiation, while the other features a less one-sided slip distribution, but under-predicts the displacements at stations to the northeast (Figure S7). Allowing for non-vertical dips again does not change the inferred slip or the misfit (Figure S6). This suggests that the displacements may have been proportionally amplified by an aspect of the earthquake or setting that the homogeneous halfspace model does not account for.

To assess whether this effect may have been related to heterogeneous elastic properties, we construct a 3D earth model of the southern Alaska margin that includes the Prince William Complex, an accretionary wedge that likely extends from the trench to the southeast coast of Kodiak (Plafker et al., 1994) (Figure 4, Supplementary Material S2, Figures S8-S9). Elastostatic modeling suggests that this sedimentary wedge may have acted like a cushion: compared to a homogeneous Earth model, it would damp the displacements on Kodiak relative to those northeast of the earthquake (Figure S10), producing the apparent proportional amplification of the latter in the GPS displacements. Incorporating this heterogeneous model into the inversion where S2 and S3 strike 253° yields a slip distribution that is more consistent with the distribution of high-frequency radiators (Figure 4b) and brings the predicted displacements on the northeast into a better agreement. We thus choose this as our preferred GPS-based model (Figure 4b). Most of the slip is inferred on the segments S2 and S3, and indeed an inversion using only those segments fits the GPS nearly as well as the five-segment model (Figure S11). The total coseismic moment release in the GPS-based model (computed as the sum of $S \cdot A \cdot \mu$, where S is the slip, A is the area of each patch and μ is the shear modulus along each patch, here 45 GPa as per the heterogeneous Earth model) is equivalent to a $M_w=7.81$ earthquake. We calculate (Supplementary Material S3) that this slip distribution would have imparted a Coulomb stress increase of ~ 0.5 bars to the Alaska subduction zone along the nearby trench (Figure 4).

3. Discussion

The 2018 M_w 7.9 Offshore Kodiak earthquake is another example of a complex rupture of the oceanic lithosphere. The source complexity is evidenced by the aftershock distribution, which extends over a $>100 \times 100$ -km region and includes several well-defined N-S lineations but no clear E-W trends. At the same time, GPS modeling of crustal deformation and finite source

modeling with teleseismic recordings (<https://earthquake.usgs.gov/earthquakes/eventpage/us2000cmy3#finite-fault>) favor left-lateral faulting on faults striking south of west. The back-projection results presented in this study also support complex rupture model featuring rupture in both N-S and E-W directions.

P-wave first-motion analysis, location of the epicenter and back-projection results all point to the rupture initiation as a right-lateral strike-slip earthquake on a N-S oriented fault plane, with predominant propagation to the north, but also some propagation to the south. However, instead of simply continuing along this faulting plane, the rupture bifurcated into a left-lateral strike-slip conjugate fault plane westward. The most energetic back-projection radiators coincide with the location of the GCMT centroid moment tensor near the point where the two proposed planes would intersect (Figure 3). The GPS modeling also required significant motions on this westerly-trending fault plane (Figure 4, Supplementary Material). At the same time, a number of smaller right-lateral strike-slip ruptures were triggered along NS oriented plate bending faults (Figure 2a).

Additional complication of the rupture process occurred between 20–30 seconds when the high-frequency radiators suddenly shifted 60 km NW of the epicenter to a region that is seemingly disconnected from the main rupture propagation (Figure 3).

To test triggering mechanisms during the mainshock rupture we compute the progression of static Coulomb and dynamic stress. We use the elastic component of RELAX (Barbot & Fialko, 2010a,b) to compute Coulomb stress changes between sub-faults using the fault segments and slip distribution in the preferred GPS model (Figure 4) assuming a shear modulus of 45 GPa, a Poisson's ratio of 0.25, and an effective friction coefficient of 0.4 (King et al., 1994). We again assume that slip is pure right-lateral and pure left-lateral on the N-striking and SW-trending fault segments, respectively. We find that progressive Coulomb stress changes throughout the rupture are predominantly negative and would have inhibited failure (Figure 5a–c), reminiscent of the 2012 Wharton Basin earthquake, which twice ruptured into compressional quadrants (Meng et al., 2012). The only positive stress changes are those on segment S4 following the ruptures of segments S1 and S2 (Figure 5d), which could have conceivably promoted failure on that segment at that point in the rupture. The results otherwise do not suggest static triggering as a plausible mechanism for the propagation and diffusion of the rupture, and so we turn to dynamic triggering.

To address the effect of dynamic triggering from S1 to S1.5 and S2, we compute the synthetic three-component velocity seismograms using the frequency–wavenumber integral method (Zhu & Rivera, 2002). Moment tensor of S1 and the fault orientation of S2 are taken from the GCMT inversion (Figure 3). Figure 5e is an example of the seismogram at (55.95°N, 149.82°W), where we see the cluster of high frequency (HF) radiators on S1.5 and S2. The amplitudes of the radial component are more pronounced than the transverse component, suggesting that Rayleigh waves play a dominant role of triggering the rupture. Moreover, the timing of the radiators on HF matches with the pulses of the seismogram. According to Jaeger & Cook (1979), peak dynamic stress can be inferred from the velocity:

$$\sigma_d = Gu/v_s \quad (1)$$

where G is the shear modulus, u is the peak velocity and v_s is the phase velocity. In this study, we use a shear modulus of 30 GPa and a constant Rayleigh waves velocity of 3.5 km/s (Miyazawa & Brodsky 2008). The peak ground velocity is about 0.78 cm/s, and the corresponding peak stress change is around 0.67 bar, above the threshold of triggering of around

0.1 bar (Brodsky & Prejean, 2005; Hill & Prejean, 2015). Therefore the HF radiators observed on S1.5 and S2 can be dynamically triggered by the Rayleigh wave radiated from S1.

In summary, we hypothesize that the dynamic stress change played a significant role in triggering N-S sub-fault rupture S1.5 ahead of the main rupture front reaching that area and promoted westerly bifurcation of the rupture onto a conjugate fault plane S2. The static stress changes were significant enough to possibly promote the rupture of S4.

4. Conclusions

Complex faulting of the 2018 M_w 7.9 Offshore Kodiak earthquake involves simultaneous rupture on a system of N-S and NE-SW-oriented conjugate faults. The N-S faults correlate with plate bending faults imaged by seismic imaging and high-definition bathymetry (Reece et al., 2013). The NE-SW faulting trends do not coincide with locations of oceanic plate fractures, but correlate with orientations of fault planes of previously recorded earthquakes in the area. Rupture propagation during the earthquake did not follow a continuous path and was partially driven by dynamic and static stress triggering. We propose a model with 5 ruptured sub-faults. The teleseismic P-wave back-projection and GPS modeling results indicate that NE-SW-trending left-lateral strike-slip segments released most energy thus dominating the radiated wavefield and the resulting crustal deformation.

Acknowledgments and Data

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Figure captions

Figure 1. Regional map showing background seismicity ($M \geq 3$, 1990-2017, yellow circles), 2018 aftershocks ($M \geq 3$ and 4, black and red circles, respectively), moment tensors and locations of previously recorded events in the outer rise region (white squares) and the 23 January 2018 M_w 7.9 earthquake (circle indicates location of the centroid). Inferred fracture zones are shown by white lines and the megathrust is marked by red line. Inset figure shows location of the study area within the regional frame and locations of the 1987-1988 Gulf of Alaska earthquakes (NAP – North American Plate, PP – Pacific Plate, YT – Yakutat Terrane).

Figure 2. Map of the aftershocks and moment tensors: black – $M \geq 3$ aftershocks from Alaska Earthquake Center catalog, yellow – relocated aftershocks. Grey beach balls are from National Earthquake Information Center ComCat catalog (M_w 4.1-5.1) and red beach balls are the centroid moment tensors from Global CMT catalog for the mainshock and the largest aftershock (M_w 5.5, 24 January 00:04 UTC). Inset map (a) shows a subset of relocated aftershocks that demonstrates right-lateral faulting along NS trending faults. Inset (b) shows a proposed fault segment model.

Figure 3. Kinematic rupture process revealed by teleseismic P-wave back-projection (BP). The circles are color-coded by time and sized by power (see panel (e)) to represent the location of high frequency radiators at different time frame. Red star is the M_w 7.9 epicenter and black circles are $M \geq 3$ aftershocks. Inset map (a) shows distribution of stations used for BP. Inset (b) shows a proposed fault segment model. Right top panel (c) shows rupture distance along the EW direction (positive distance indicates rupture to the east of the hypocenter); dashed lines are reference rupture speed of 3 km/s. Right middle panel (d) shows rupture distance along the NS

direction (positive distance indicates rupture to the north of the hypocenter); the dashed line indicates reference rupture speed of 1.4 km/s. Right bottom panel (e) shows beam power of the radiators as a function of time.

Figure 4. Observed and modeled static GPS displacements (a) and estimated slip on fault segments (b). Black arrows and small colored circles are observed horizontal and vertical displacements. White arrows and large colored circles are model-predicted horizontal and vertical displacements. Warm colors indicate uplift at GPS stations in (a) and left-lateral slip on segments in (b); cool colors indicate subsidence and right-lateral slip. Gray points are aftershocks. Background beige color represents accretionary prism in the model; green represents lithosphere. Red lines are faults (Koehler et al., 2012). Also shown are Coulomb stress changes imparted to the megathrust. **b)** 3D view of inferred slip distribution. Gray points are aftershocks; colored circles are high-frequency radiators from back-projection (Figure 3).

Figure 5. Results of the static and dynamic stress triggering tests. Progressive Coulomb stress changes throughout the rupture. Stress changes imparted by slip on (a) the southern half of S1 to S1.5; (b) the southern half of S1 to S2; (c) the full length of S1 to S3 and S4; (d) S1 and S2 to S3 and S4. (e) Synthetic three-component velocity seismograms recorded at 55.95N, 149.82W. The blue dashed line marks the timing of the high frequency radiators of back projection on sub-fault S2.

Figure 1.

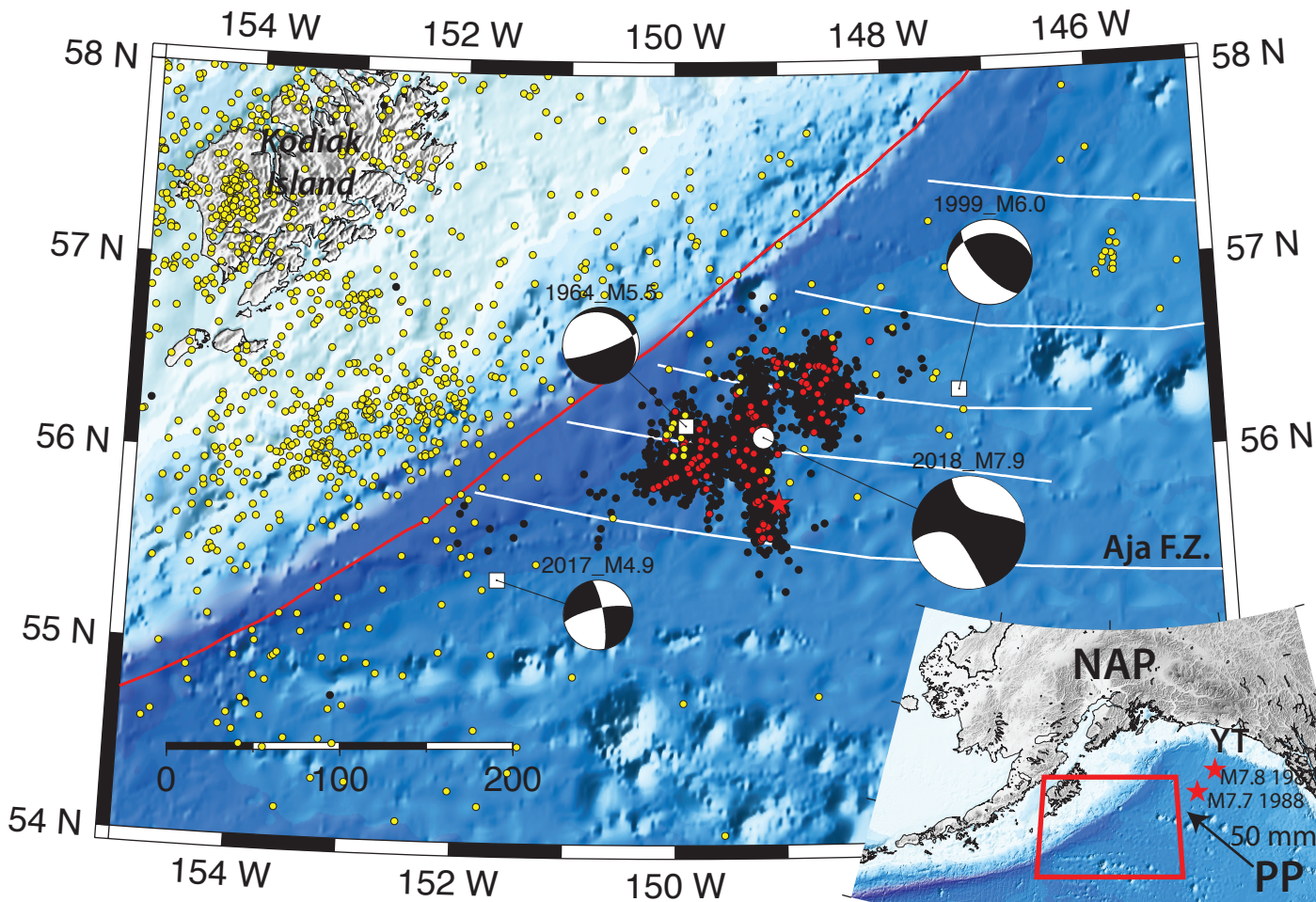


Figure 2.

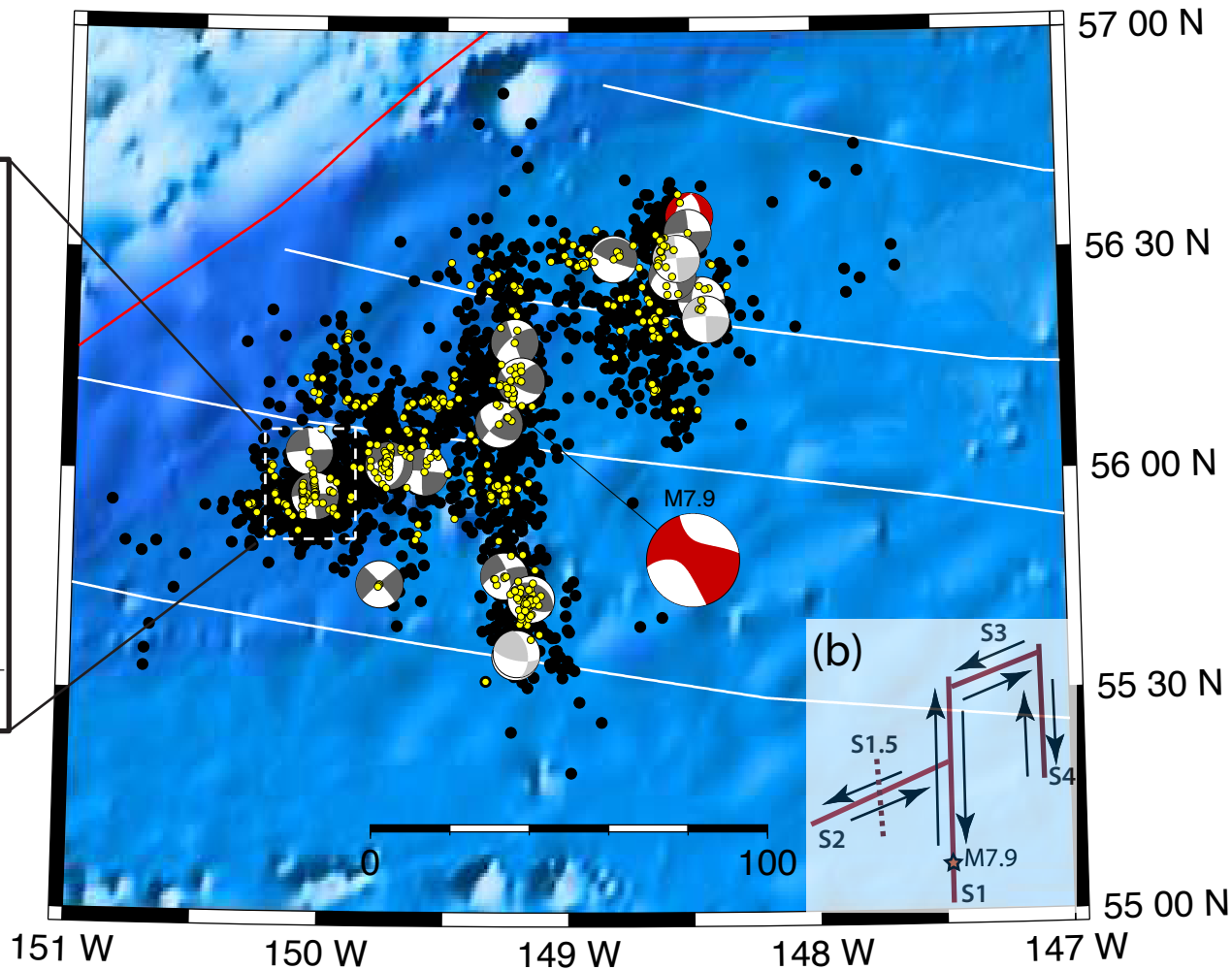
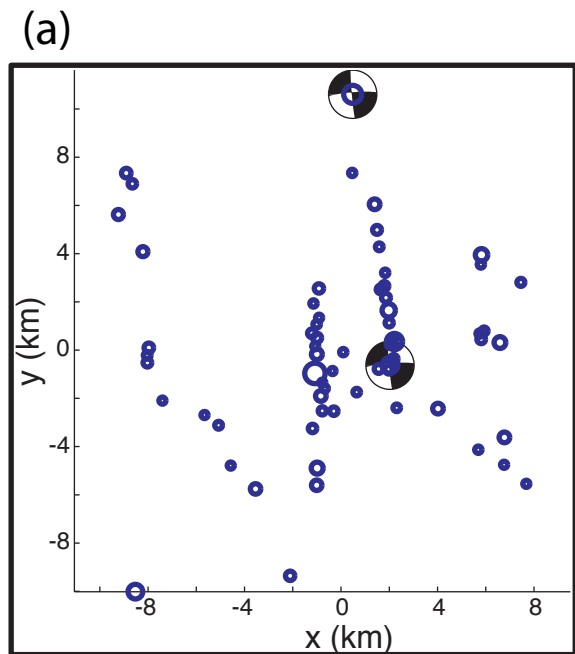


Figure 3.

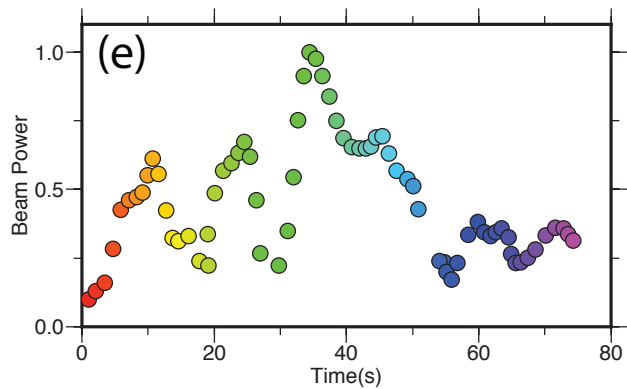
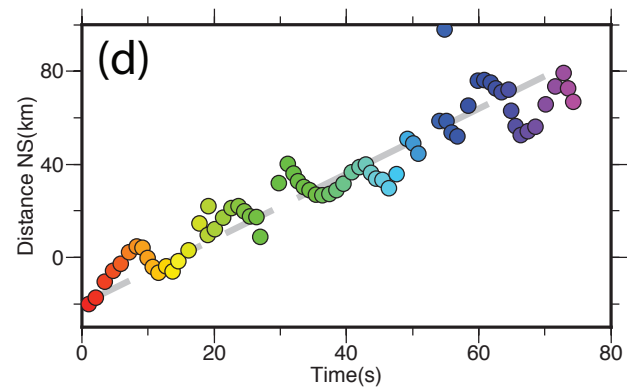
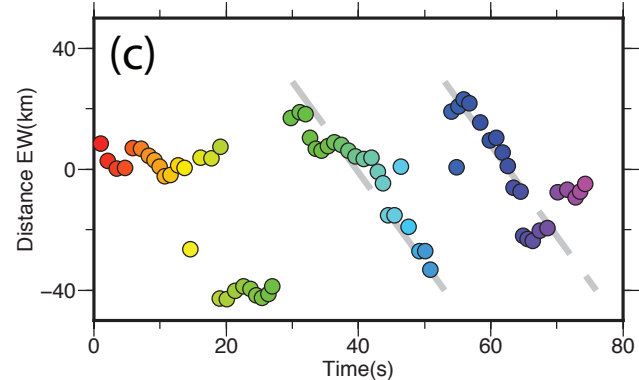
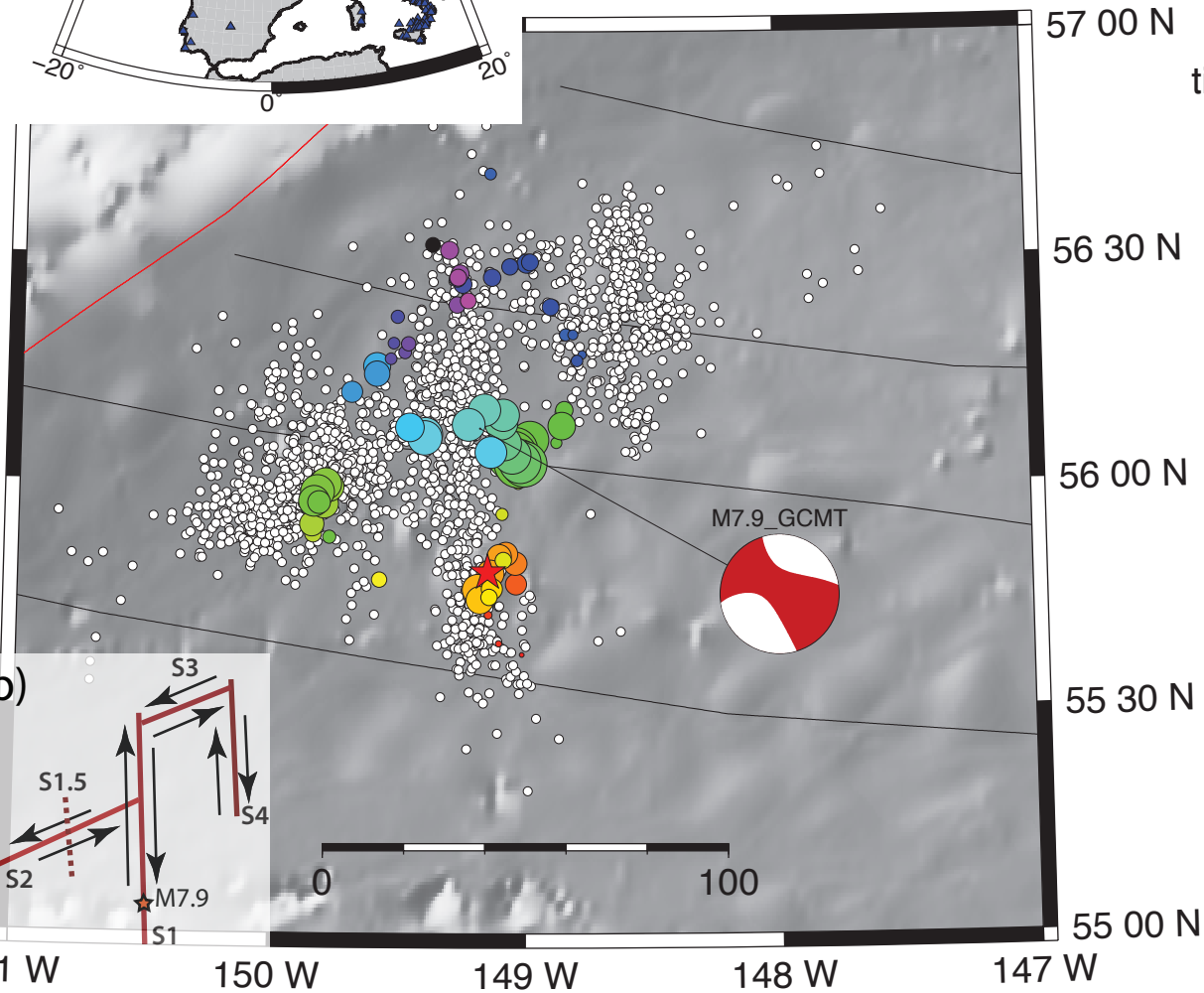
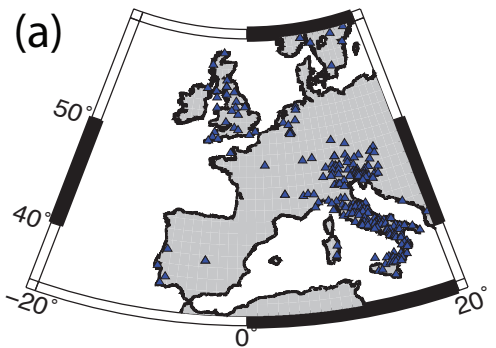


Figure 4.

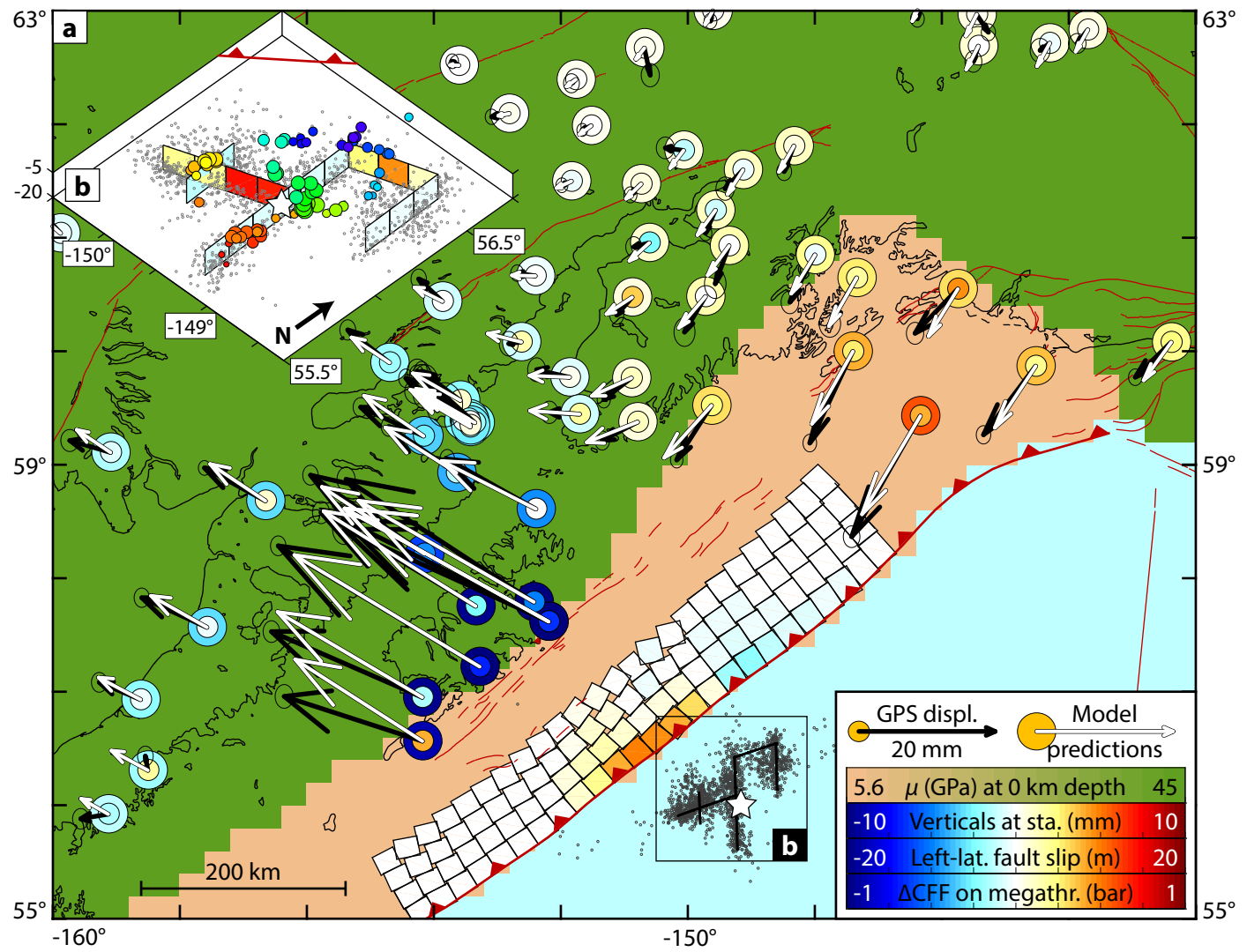


Figure 5.

