FINAL TECHNICAL REPORT

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A Study of Seismicity and Fault Interactions in the Upper-Southeast Alaska Region

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ABSTRACT

This research focused on historical and recent seismicity of the upper-southeast Alaska region where strike-slip (northwestern Fairweather, southeastern Totschunda, Duke River, eastern Denali) and thrust (Chugach-St. Elias, Boundary, Contact, Malaspina) faults, all interact in a complicated fashion to transfer plate motion between the Fairweather-Queen Charlotte transform boundary and the oblique plate convergence of the St. Elias region. We understand little about the complex interactions between faults within this region, how stress is transferred between fault systems, and the potential for future large earthquakes. The research included the following tasks:

1) Relocation of background seismicity and correlation of the seismicity to known faults and structures.
2) Analysis of changes in space-time seismicity patterns with particular emphasis on the 1979 St. Elias and 2002 Denali fault earthquakes and the events' influence on the background seismicity associated with other fault systems
3) Compilation of stress field information from previously published focal mechanisms and moment tensor analyses, as well as direct inversion of first motion data for stress field orientations in regions where moderate to large earthquakes have not occurred, to better understand stress transfer between major fault systems
4) Analysis of rupture processes for moderate to large earthquakes to determine if stress drop and rupture directivity variations exist along different fault systems.

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Introduction:

The upper-southeastern Alaska region lies in a zone of transition between the Fairweather-Queen Charlotte transform plate boundary and a complicated zone of oblique convergence between the Pacific Plate and Yakutat blocks with North America (box, Figure 1). A portion of strike-slip motion is transferred northward along the Denali, Totschunda, and Duke River faults. Thrust and reverse faulting predominates to the west within the St. Elias region, although some focal mechanisms (e.g. Doser and Lomas, 2000) indicate localized strike-slip and normal faulting is also occurring.

The northern Fairweather fault has one of the highest slip rates in North America (~46 mm/yr;) with Fletcher and Freymueller (2003) suggesting that enough slip has now accumulated along the fault since the 1958 M_S~7.9 Fairweather earthquake to generate a similar sized event. Although slip rates along the northern Fairweather fault are high, the fault does not accommodate all the 51 mm/yr of total relative plate motion (DeMets and Dixon, 1999) estimated at Yakutat. About 4 mm/yr of this motion must be accommodated by strike-slip faulting inboard of the Fairweather fault with the remainder possibly accommodated offshore (Fletcher and Freymueller, 2003).

Exactly how slip is transferred northward from the Fairweather fault to the Denali fault system and how the Fairweather fault links to thrust and reverse faults west of Yakutat Bay is poorly understood. Much of upper-southeast Alaska is covered by ice or steep terrain, making geologic mapping difficult. Rapid erosional processes also quickly erase any traces of Quaternary activity. Earthquakes of M_w>7.5 in 1958, and 2002 have ruptured to the edges of the region (Figure 2), but the 1979 St. Elias earthquake is the only M_w>7 event to have occurred within the region in the past 50 years. Previous seismological studies (e.g. Horner, 1983; Doser and Lomas, 2000; Estabrook et al. 1992; Doser, 2004) have either examined larger earthquakes (relocations of aftershocks, limited source parameter studies), smaller magnitude events within localized regions, or regional seismicity prior to the mid-1980's. None of these studies provide a comprehensive view of the seismotectonics of this complex region.

In the following sections we outline the progress we have made in understanding the seismicity and tectonics of the upper-southeast Alaska region. We focused on 4 tasks outlined in the following sections.

Earthquake Relocations:

We have relocated all earthquakes occurring between 1971 and 2005 using the HypoDD method (Waldhauser and Ellsworth, 2000). Figure 3a shows all the relocation results with colors indicating depth. Most seismicity is concentrated between depths of 0 and 20 km. Figures 3b and 3c compare earthquakes with focal depths of 0-10 km and 10-20 km with rupture zones for the 1899 (Plafker and Thatcher, 2008), 1958 (Doser, 2010), 1979 (Estabrook et al., 1992), and 2002 (Eberhart-Phillips et al., 2003) mainshocks. The relocations indicate that clustering of seismicity is common, with few features that can be directly linked to through going faults. The most intense zone of activity is located within the Icy Bay region. Much of this seismicity is related to the 1979 St. Elias sequence, but the area has been persistently active throughout the past 40 years. This region is at the intersection of the Pamplona fault zone, Chugach-St. Elias fault zone and the northern edge of the subducted Yakutat microplate. The deeper seismicity (Figure 3c) indicates an "L" shaped region of intense activity that occurs at the intersection between the Pamplona and Chugach-St. Elias fault zones.

Other clusters of activity are located in the Bering Glacier region, northern Yakutat Bay region (northwestern edge of 1958 rupture zone), and the end of the 2002 Denali mainshock rupture zone along the Totschunda fault. Seismicity along the Duke River fault zone is diffuse with the greatest concentration of events located near the junction between the Totschunda and Duke River fault zones. A band of seismicity between the Totschunda and Denali faults likely represents a cross fault between the two major fault systems. Several east-northeast striking lineations in seismicity occur between the Chugach-St. Elias and Duke River fault systems (Figure 3a) that may indicate the beginning of a system of fractures that is growing to link the fault systems.

Although Doser and Rodriguez (2010) have observed a correlation between zones of uplift > 20 mm/yr (due to rebound after glacial unloading; Freymueller et al., 2008) and increased seismicity in the Glacier Bay region (located just to the southeast of our study area), we do not observe a similar relationship here (Figure 4). This may be related to the fact there are few observations of uplift (black dots, Figure 4) for regions located > 50 km from the coast.

Comparisons to Bouguer anomaly gravity data (Saltus et al., 2008) (Figure 5a and 5b), however, do suggest a concentration of seismicity at the edges of gravity highs, similar to that observed in south-central Alaska (Doser et al., 2009). In particular, the strong Bouguer high that characterizes the subducting Yakutat microplate begins to break up in the region where the Pamplona fault zone comes onshore, with the "L" shaped pattern of deeper seismicity wrapping around a smaller gravity low. Note that the Bouguer anomaly again becomes higher and more continuous southeast of Yakutat Bay. Based on studies of the 1979 St. Elias mainshock rupture process Estabrook et al (1992) suggest that there is at least a 5 km vertical offset in the plate interface near the northern edge of the Yakutat microplate. Deeper seismicity and larger (M_w>4.5) earthquakes along the Duke River fault zone appear to be occurring near the northern edge of a Bouguer gravity anomaly low.

Aeromagnetic data (Saltus et al., 1999) for the study area are limited to the region north of 61ºN (Figure 6) with a significant gap in coverage along the Duke River fault system. The magnetic data clearly show a change in the magnetic character of basement rocks along the edge of the suspected cross structure located between the Totschunda and Denali faults. There also appears to be a significant magnetic high located at the southern end of the 2002 aftershock zone that might have served as a structural barrier to rupture.

We are still in the process of relocating earthquakes occurring in the region between 1963 and 1971. There were phase data available from the International Seismological Center for considerably more aftershocks of the 1964 great Alaska earthquake that occurred within the region (50+) than we had originally anticipated. This should allow us to compare how activity in 1964 abutted with the 1979 mainshock, as well as the 1970 offshore sequence along the Pamplona fault zone.

Space-Time Seismicity Patterns:

Examples of our analysis of space-time seismicity patterns are shown in Figures 7 through 12. Figure 7 shows seismicity occurring prior to the 1979 St. Elias mainshock. At this time there were few seismograph stations operating in the region, but some of the patterns observed for the complete data set (Figure 3) are observed in this more limited data, including the concentration of seismicity in the Icy Bay region within the rupture zone of the 1979 mainshock. There is also scattered seismicity in the Bering Glacier region

In the first year following the 1979 mainshock (Figure 8) there are prominent clusters of activity that likely represent rupture of faults within the upper Yakutat microplate. The colors and symbol shapes represent 3 month time intervals as indicated in the legend. Many of the clusters trend north-south across mapped faults of the Chugach-St. Elias fault zone suggesting possible linkages of the faults with depth, perhaps along a detachment structure. We have begun comparison of the clustering in time to predicted stress changes following the mainshock and larger (M_w>5) aftershocks (see next section).

In the second year following the 1979 mainshock (Figure 9) seismicity within the 1979 rupture zone is similar, although the activity has spread southward to the region just northeast of Icy Bay. In the third year following the 1979 mainshock (Figure 10) there is continued

seismicity within the 1979 rupture zone, although each year the seismicity appears to be more concentrated in a narrow zone northeast of Icy Bay. We are continuing analysis of the seismicity patterns for 10 years following the 1979 mainshock.

Seismicity occurring between 1989 (10 years after the St. Elias mainshock) and the 2002 Denali mainshock is shown in Figure 11. Seismicity in the Icy Bay region appears to have reached background levels (compare to Figure 7). There is continued activity within the Bering Glacier region, some of which may be related to glacial movement (e.g. Doser et al., 2007). Activity continues along the Duke River fault zone with 2 M_w>5.2 events (both showing strike-slip faulting)

In the year following the 2002 Denali mainshock (Figure 12) we observe a prolific aftershock sequence along the Totschunda fault, as well as activity along the cross structure between the Totschunda and Denali faults. The black star is M_w 5 event with focal mechanism consistent with reverse-oblique slip along an east-northeast (strike 66º) trending structure. Seismicity along the Duke River fault system remains diffuse, although there appear to be more events located to the northeast of the fault zone than in 13 years prior to 2002 (Figure 11).

Stress Field Variations:

We have compiled stress orientation information for the region (Figure 13) based on the inversion of focal mechanisms by Ruppert (2008) and Ristau et al. (2007). Maximum principal stress orientations are shown in Figure 13. The thick gray lines are from Ruppert (2008) for regions indicated by dashed black lines and the thick blue lines denoting results for west of Yakutat Bay (YW) and east of Yakutat Bay (YE) are from Ristau et al. (2007). P-axes orientations for events with moment tensors determined either from historic studies, the global CMT catalog, the Geological Survey of Canada (GSC) or the Alaska Earthquake Information Center (AEIC) are shown by thinner lines. In general, regions to the north of the Chugach-St. Elias fault zones show north-northeast directed compression. To the east along the eastern Denali fault and between the Denali and Fairweather faults maximum compressive stress appears to rotate slightly toward the northeast. There is a great mixture of P-axes orientations along the northern Denali fault, within the Icy Bay region, and offshore within the Pamplona fault zone. These orientations likely reflect the fracturing of the Yakutat microplate, effects of glacial loading/unloading and stress reorientation following the 1970 Pamplona and 1979 St. Elias mainshocks. We plan to directly invert first motion data for stress field orientations using smaller events occurring at the edges of the Icy Bay and Yakutat Bay regions

Analysis of Earthquake Rupture Processes:

This task has focused on determining stress drops and rupture directivity using an empirical Greens function approach and examining the possibility of static stress triggering in mainshock/aftershock sequences. Figure 14 shows the change of Coulomb failure stress (ΔCFS) following the 1979 mainshock for optimally oriented faults at a depth of 12 km (the average aftershock depth) using the mainshock rupture model of Estabrook et al. (1992) that consists of two rupture planes with varying amounts of dip-slip versus strike-slip motion. The gray stars are aftershocks with M_w>5 and the smaller symbols are earthquakes occurring within 1 year of the mainshock. Note that one of the greatest clusters of aftershocks (including 2 of the M_w>5 events) occurs at the southern end of the mainshock rupture in the region between the two rupture planes. In this region ΔCFS exceeded 6 MPa. Figure 15 shows ΔCFS following a M_w=5.4 aftershock on May 2, 1982 for faults having a similar orientation and depth as the

aftershock. The small symbols are earthquakes occurring within 90 days of the aftershock. Note the cluster of earthquakes in the region south of the aftershock where ΔCFS exceeded 1.5 MPa.

Figure 16 shows stress drops for earthquakes of the study area and surrounding regions that we have obtained using empirical Greens function techniques. The purple symbols are estimates for aftershocks of the Denali fault sequence, the green symbols are estimates for an event on the Duke River fault zone, the blue symbols are estimates for an event just north of Yakutat Bay, the gray symbols are for an event along the Fairweather fault and the orange symbols are for an event in the Glacier Bay region. Dots denote stress drops estimates from time domain average of relative source-time functions (RSTFs). Triangles are estimates from stacked RSTFs in the time domain. Diamonds are estimates from frequency domain average of RSTFs and triangles are from stacked RSTFs in the frequency domain. Stars represent averages of all 4 stress drop estimates. The Denali fault events appear to have slightly lower stress drops for their moment-magnitudes than those in other regions. We are also using the information on the variation of the width of the RSTFs with azimuth to determine the likely direction of rupture propagation during these earthquakes.

Related Studies:

We (Doser and Rodriguez, 2010) submitted a paper on studies of southeastern Alaskan seismicity to Tectonophysics in June 2010. A paper on the source processes of the 1958 Fairweather fault earthquake and a comparison to the 2002 Denali fault earthquake was recently published in the Bulletin of the Seismological Society of America (Doser, 2010). Doctoral student Christian Escudero is also studying the stress drops of earthquakes along the Fairweather, Queen Charlotte, and Cross Sound fault systems as part of his dissertation research.

Reports Published:

We presented posters on our research at the 2009 fall meeting of the American Geophysical Union (Escudero and Doser, 2009) and the 2010 meeting of the Seismological Society of America (Doser et al., 2010).

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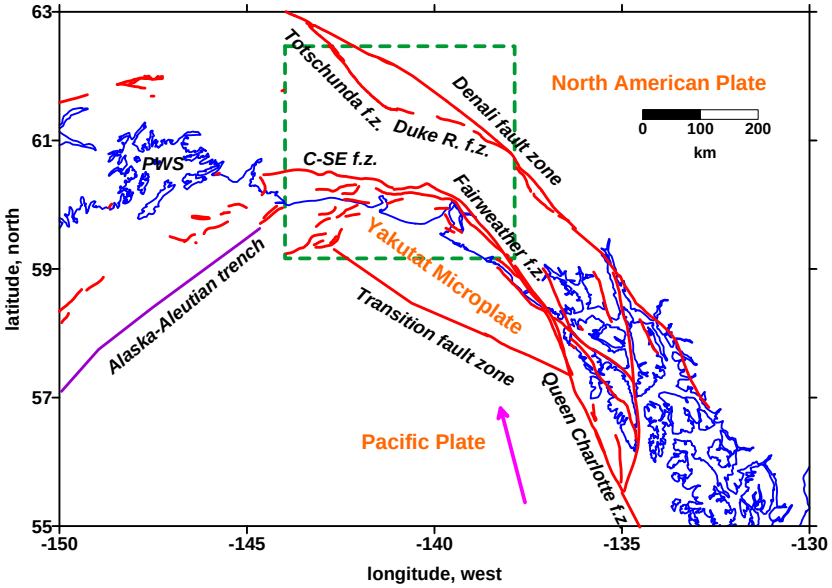


Figure 1 – Map of study area (dashed box) and surrounding regions. Red lines are major faults from Plafker at al. (1994). Arrow shows direction of Pacific plate motion (DeMets and Dixon, 1999). Dashed lines indicate study area. C-SE f.z. is Chugach-St. Elias fault zone, PWS is Prince William Sound.

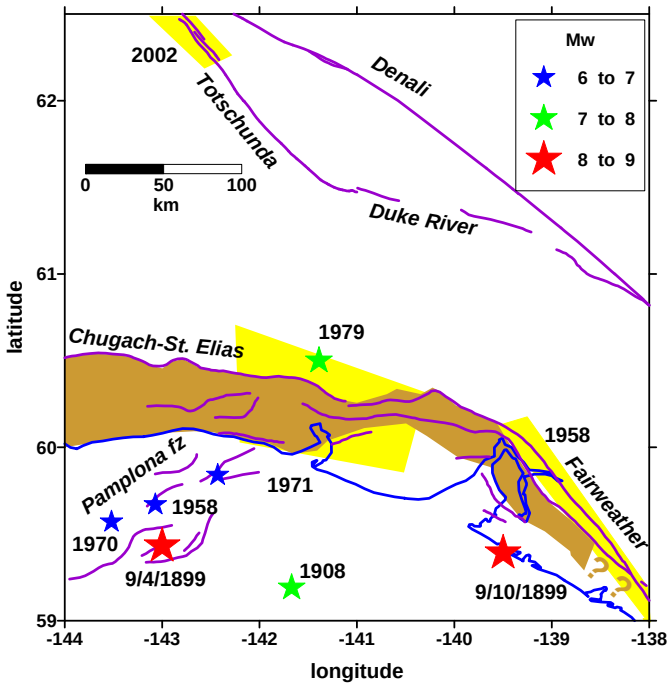
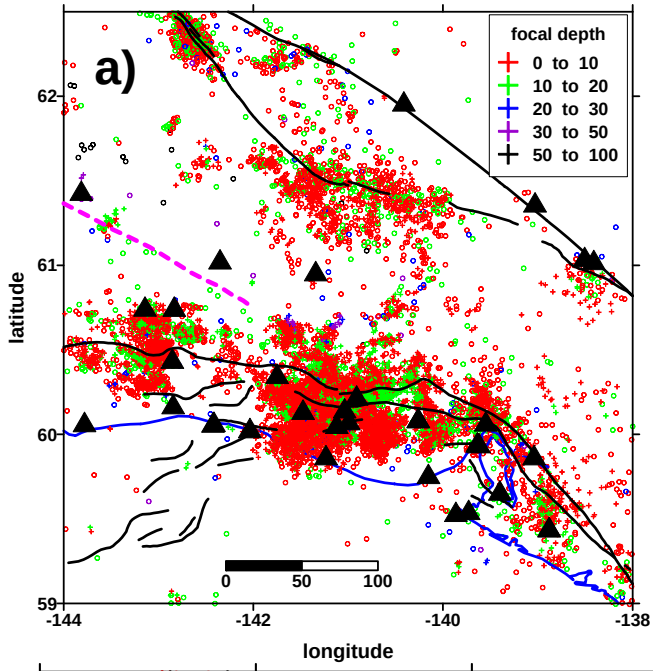
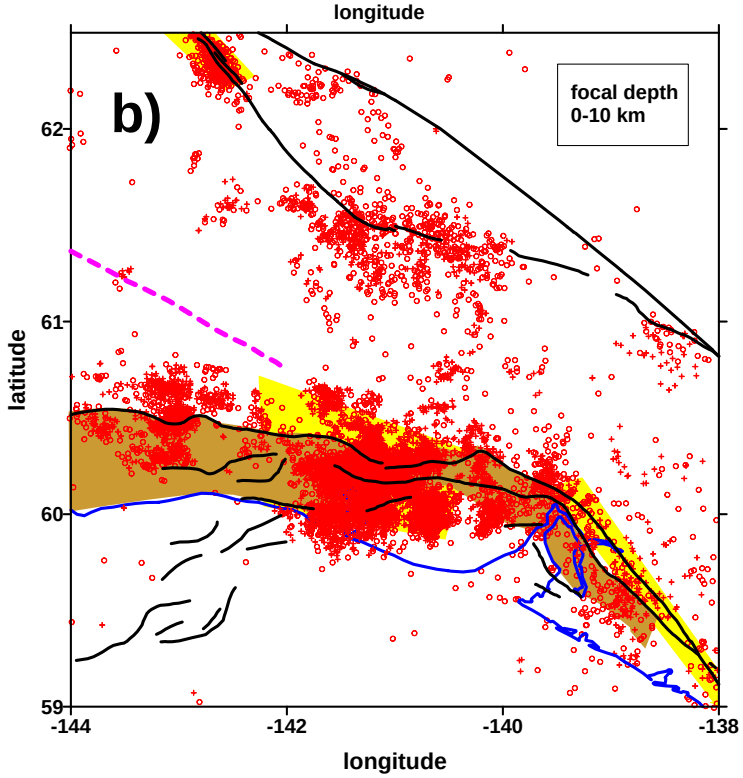


Figure 2 – Earthquakes (stars) with moment-magnitude > 6 in the study area. Yellow shows rupture zones of earthquakes as inferred from waveform modeling studies and/or surface faulting (1979 from Estabrook et al., 1992; 1958 from Doser, 2010; 2002 from Eberhart-Phillips et al. 2003). Light brown is the inferred rupture zone of the 1899 sequence from Plafker and

Thatcher (2008) based on seismic, geologic and geodetic information. Southeastern limit of 1899 rupture is poorly known, as indicated by question marks.





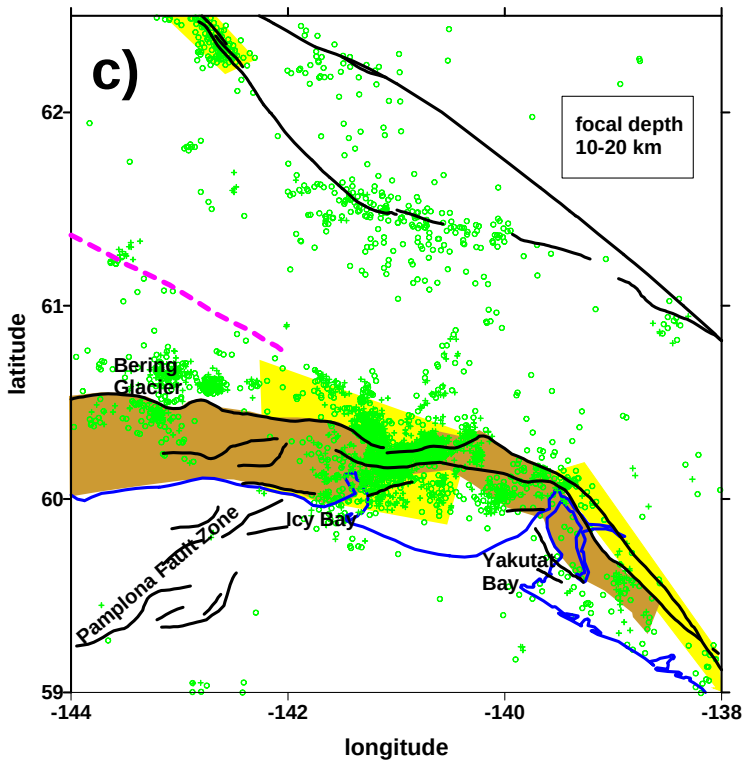


Figure 3 – (a) Relocated seismicity (plusses, 1971-2005) and catalog (circles, 2005-2009) for the study area. Depths are indicated by colors. Dashed line is the eastern edge of the subducted Yakutat microplate from Eberhart-Phillips et al. (2006). Triangles are seismograph stations. (b) Shallow (depth < 10 km) compared to earthquake rupture zones (see Figure 2). (c) Earthquakes with depths of 10-20 km.

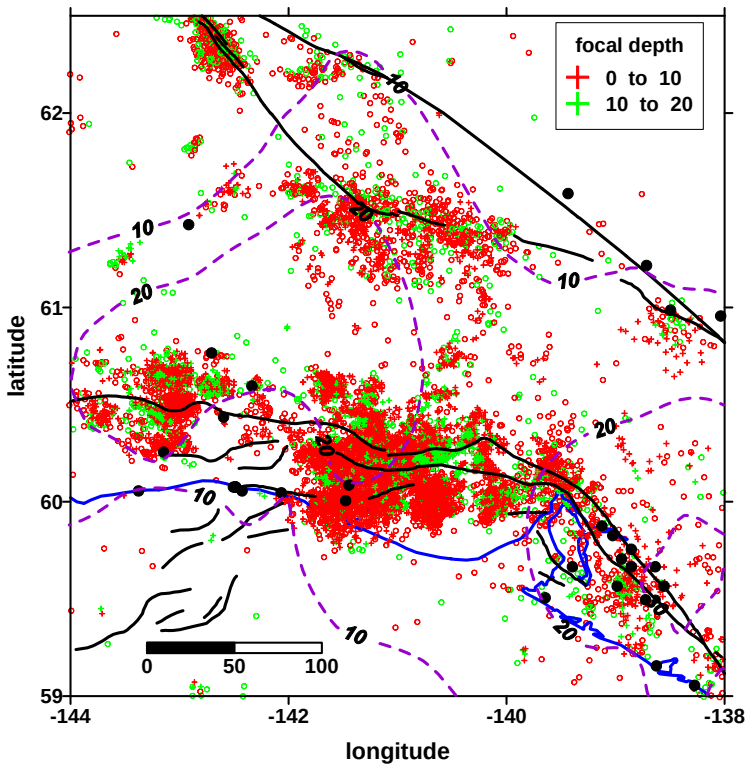


Figure 4 – Uplift rates from Freymueller et al. (2008) (10 mm/yr contour intervals, purple dashed lines) compared to earthquakes < 20 km deep. Dots represent locations of GPS stations where uplift rates were measured.

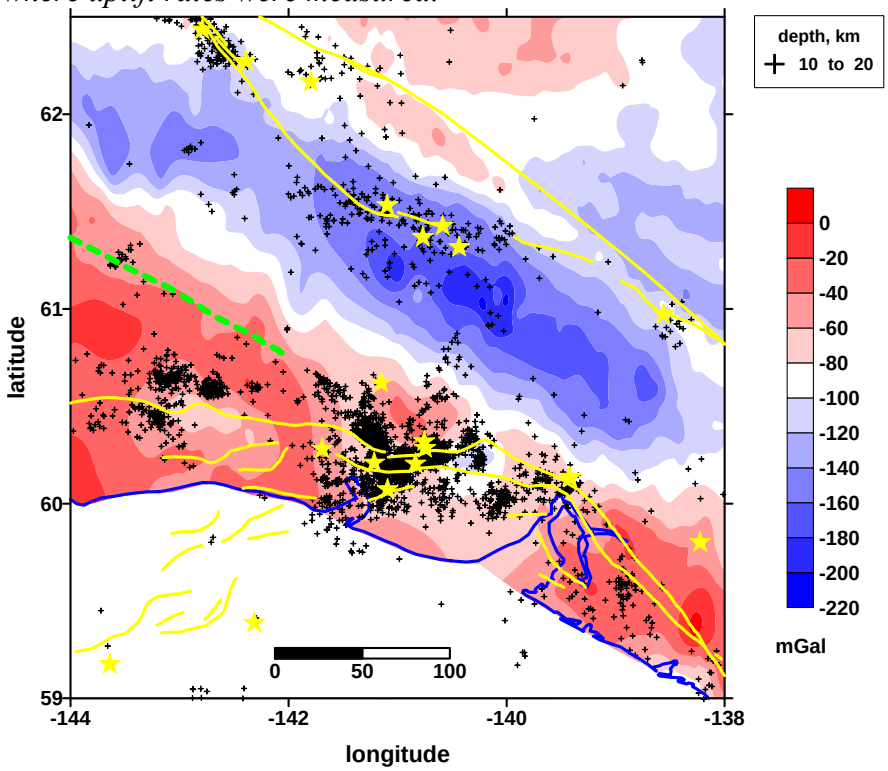


Figure 5 –Bouguer gravity anomaly data for study area from Saltus et al. (2008) and Natural Resources Canada (20 mGal contour interval). Note that coverage in the south-central portion

of the study area and offshore is poor. Green dashed line is edge of subducted Yakutat microplate. Seismicity shown has focal depths of 10 to 20 km. Yellow stars are earthquakes with Mw>4.5.

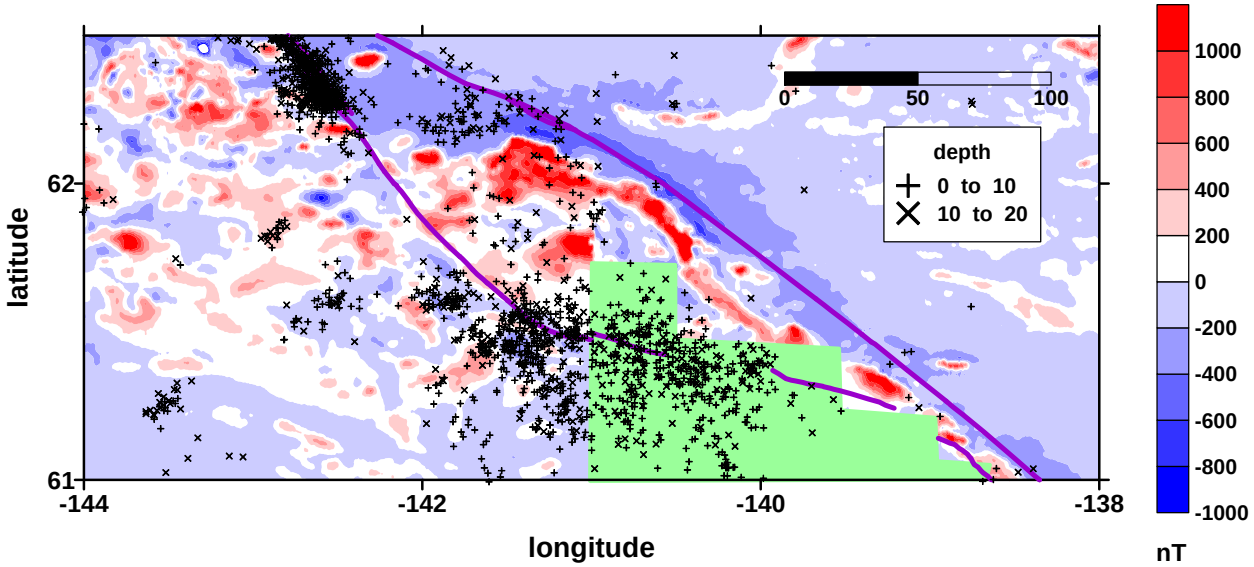


Figure 6 – Aeromagnetic data for northern portion of the study area from Saltus et al. (1999) (200 nT contour interval) compared to shallow (depth < 20 km) earthquakes. Data coverage in the southern portion of the study area and within the green area is too poor for detailed analysis.

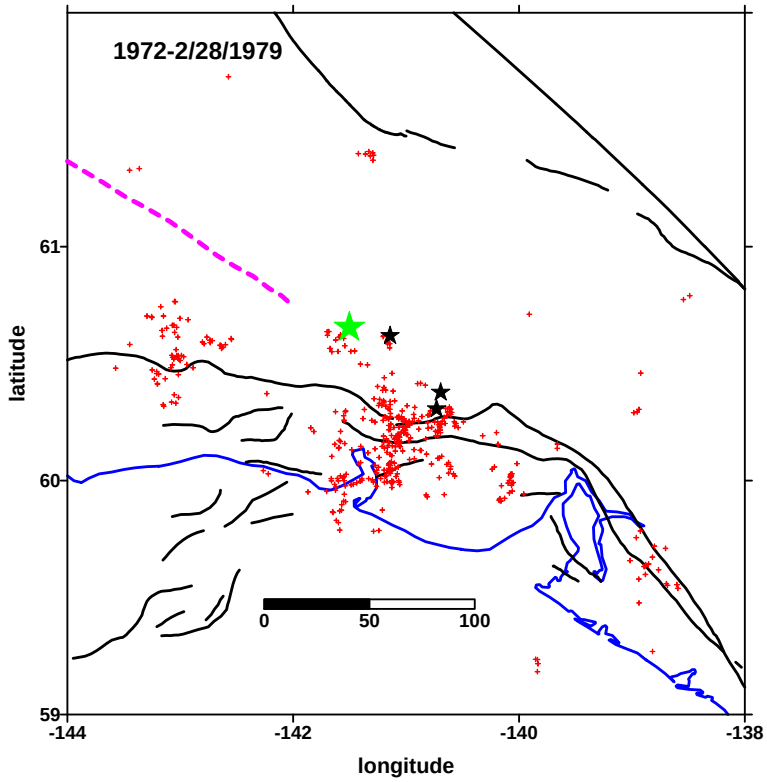


Figure 7 – Relocated seismicity for ~7 years preceding the 1979 St. Elias sequence. Green star is mainshock. Black stars are Mw>5 aftershocks occurring within first 3 months of the sequence.

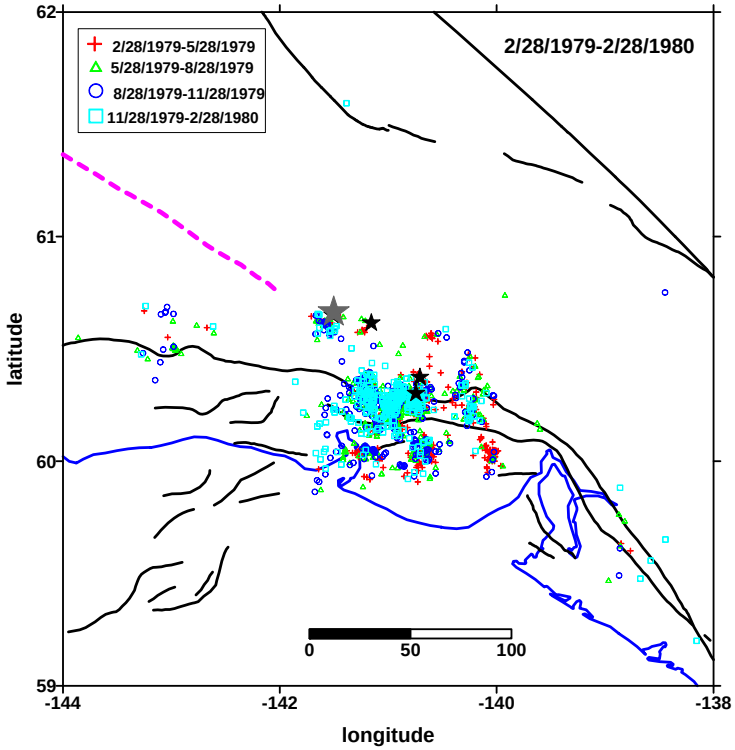


Figure 8 – Relocated seismicity for 1 year following 1979 St. Elias mainshock. The mainshock is the gray star. M_w>5 aftershocks are black stars. Colors and symbol types denote 3 month intervals as indicated in legend.

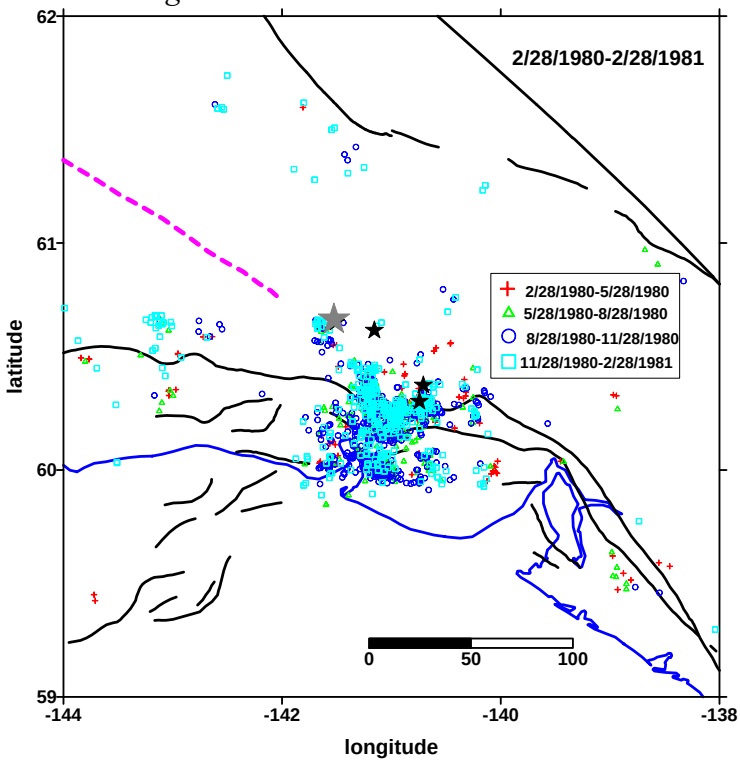


Figure 9 – Relocated seismicity from 1980-1981. Stars are as in Figure 8. Legend denotes three month time intervals.

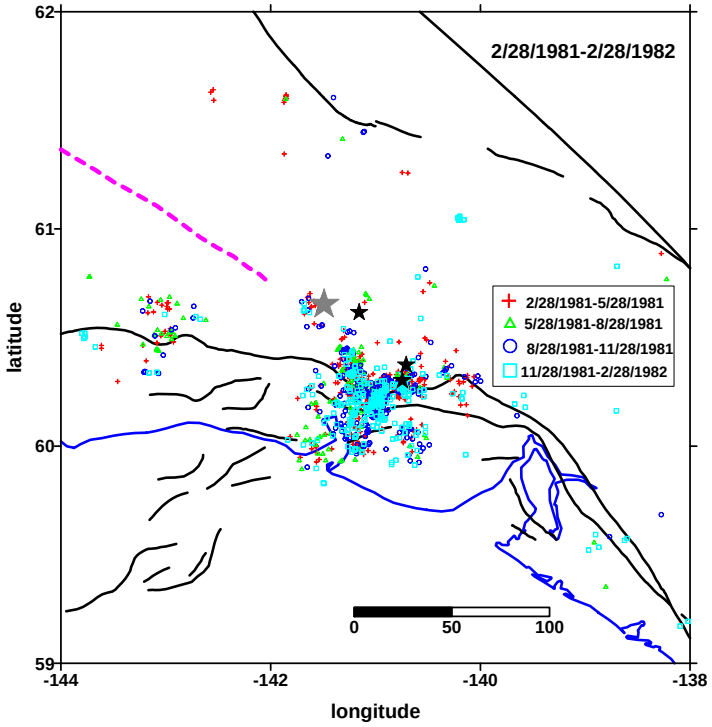


Figure 10 – Relocated seismicity from 1981-1982. Stars are as in Figure 8. Legend denotes three month time intervals.

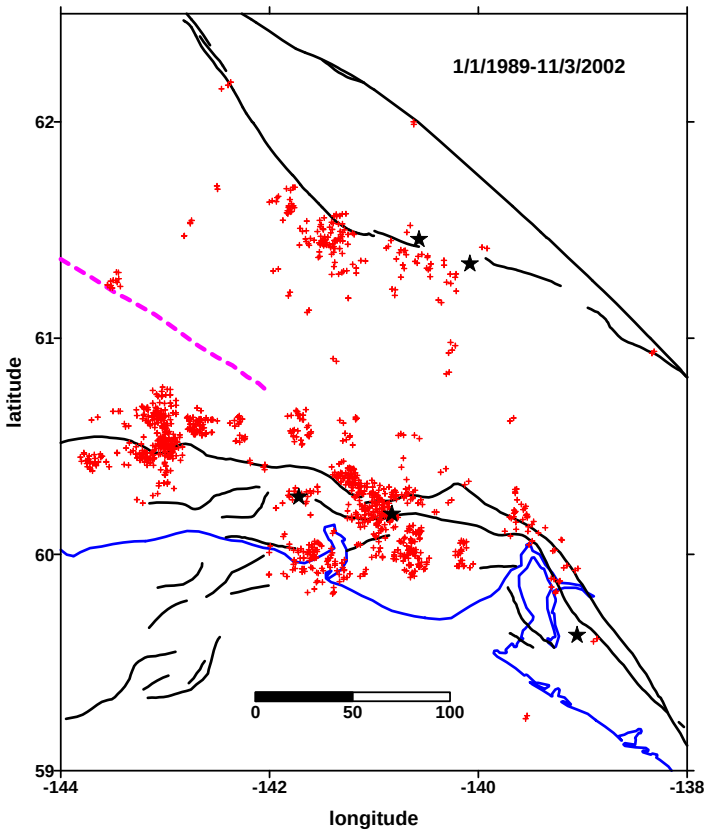


Figure 11 – Relocated seismicity occurring from 1989-November 3, 2002 (day of the Denali fault mainshock). Stars are M_w>5 earthquakes occurring during this time period.

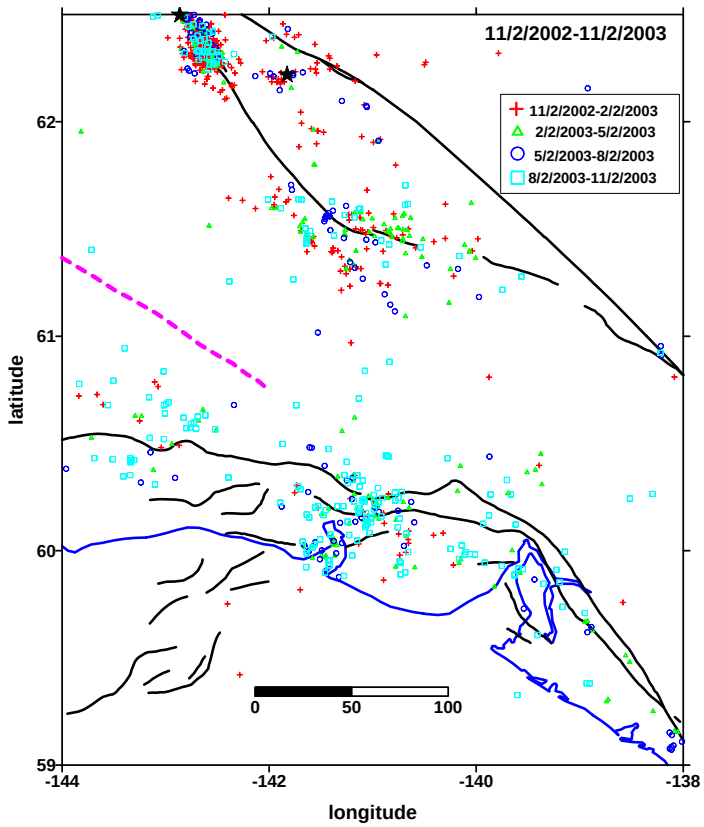


Figure 12 – Relocated seismicity occurring within 1 year of the Denali fault mainshock. M_w>5 aftershocks are indicated by black stars. Symbols represent 3 month time intervals as indicated in legend.

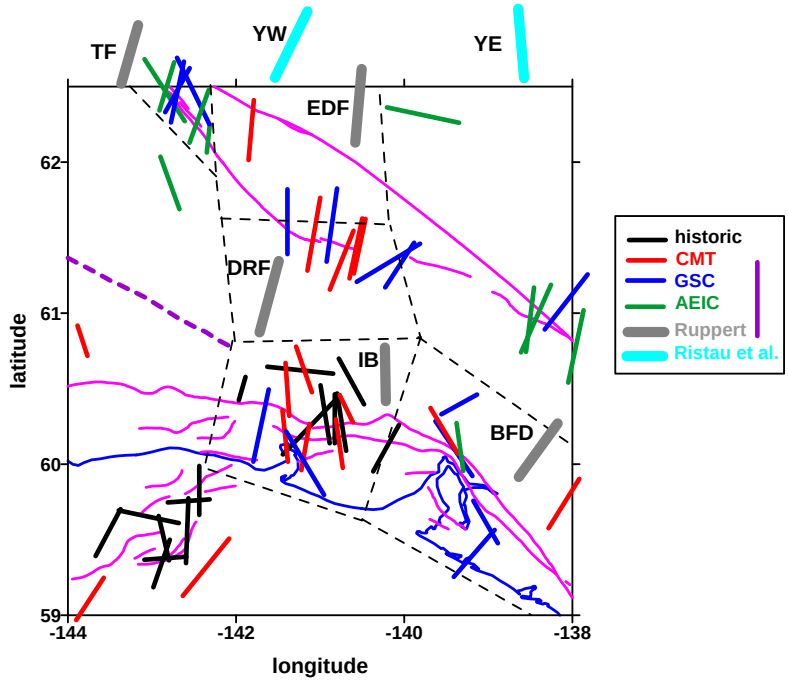


Figure 13 - Orientation of P axes (thin lines) from moment tensors (Global Centroid Moment Tensor Catalog (CMT), Alaska Earthquake Information Center (AEIC), (Geological Survey of Canada (GSC), historic (Doser and Lomas, 2000)) for study area. Lengths of lines are

proportional to plunge, with the vertical line within the box at right indicating a plunge of 0°. Thin dashed lines indicate subregions identified by Ruppert (2008) for stress analysis (orientations shown by thick gray lines). BFD is Between Denali and Fairweather fault region, DRF is Duke River fault region, EDF is Eastern Denali fault region, IB is Icy Bay region, and TF is Totschunda fault region. Thick blue lines are stress orientations from Ristau et al. (2007) YE is Yakutat East (roughly corresponds to the BFD region) and YW is Yakutat West (includes the DRF and IB regions).

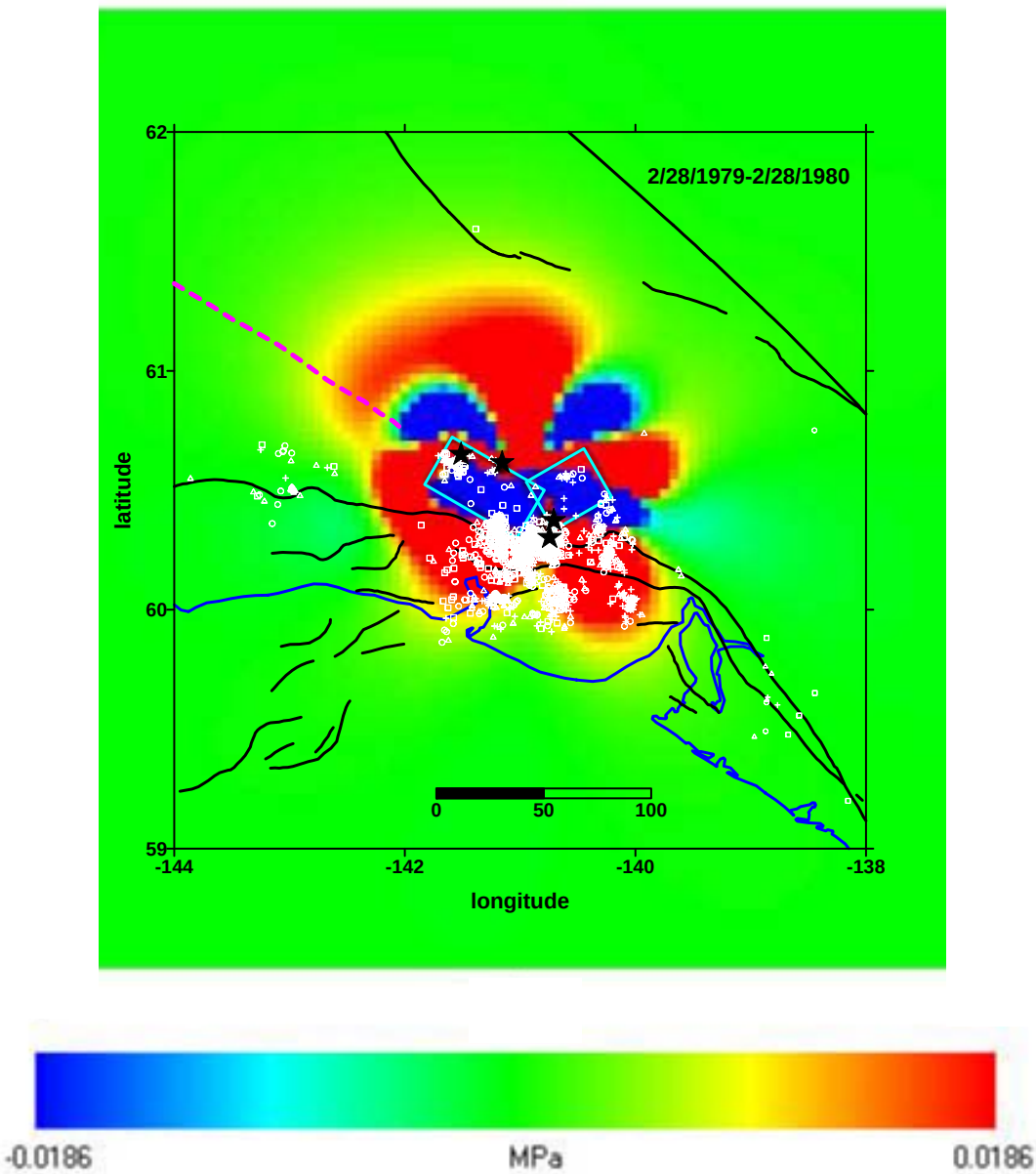


Figure 14 - ΔCFS for optimally oriented faults at 12 km depth following the 1979 St. Elias mainshock. Fault rupture model (blue rectangles) was taken from Estabrook et al. (1992). White symbols are aftershocks occurring within 1 year of the mainshock. Symbol shapes indicate the same time intervals as shown in Figure 8.

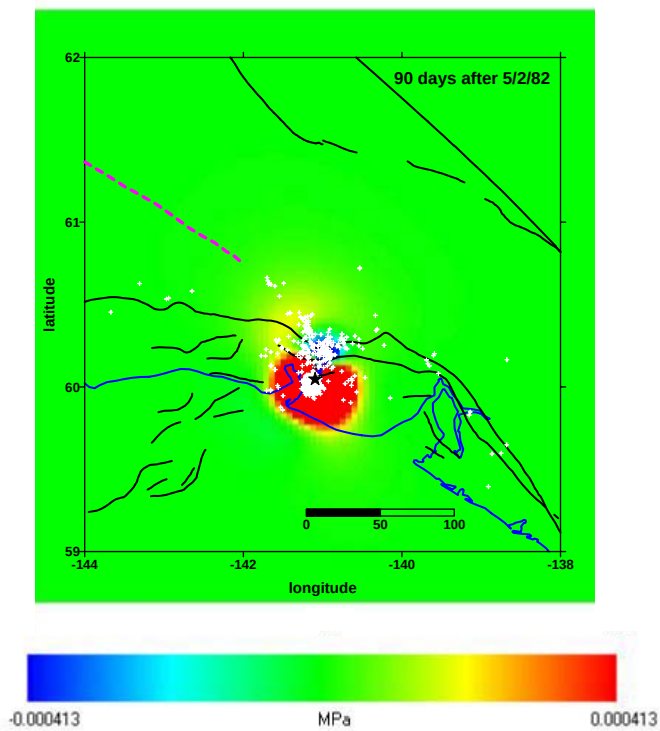


Figure 15 - ΔCFS for faults at 8 km depth having the same orientation as the May 2, 1982 M_w=5.4 aftershock. White symbols are events occurring within 90 days of May 2. Maximum ΔCFS was 1.5 MPa.

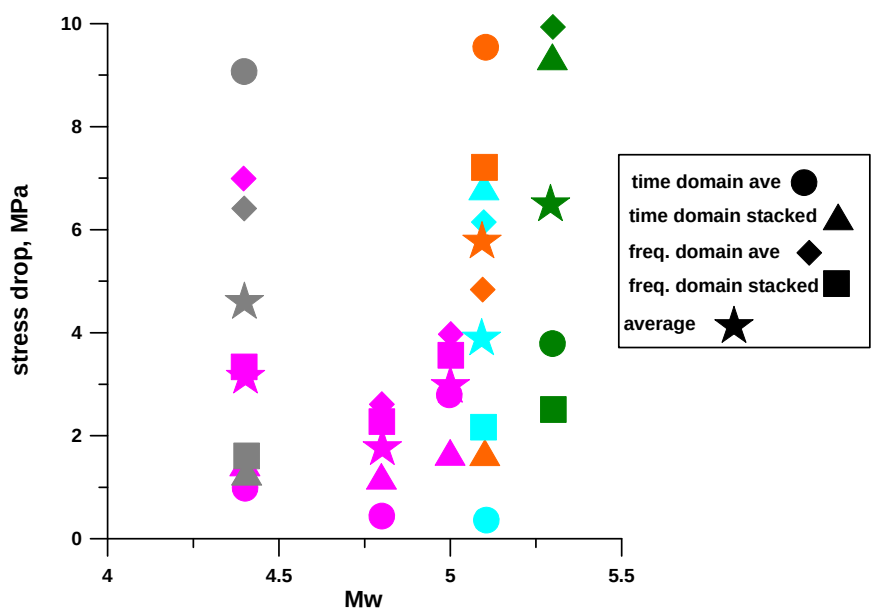


Figure 16- Stress drop estimates for events obtained from empirical Greens function analysis. Dots denote stress drops estimates from time domain average of relative source-time functions (RSTFs). Triangles are estimates from stacked RSTFs in the time domain. Diamonds are

estimates from frequency domain average of RSTFs and triangles are from stacked RSTFs in the frequency domain. Stars represent averages of all 4 stress drop estimates. Purple symbols are earthquakes aftershocks of the 2002 Denali fault sequence occurring within the study area, green symbols are for an event on the Duke River fault, blue symbols are for an event north of Yakutat Bay, orange symbols are for an event in the Glacier Bay region, and gray symbols are for an event along the Fairweather fault system.