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Recipient: University of Texas at El Paso

Principal Investigator: Diane I. Doser

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Program Element: I

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MERGING HISTORICAL AND RECENT RECORDS OF SEISMICITY TO BETTER DEFINE EARTHQUAKE SOURCE ZONES WITHIN THE ANCHORAGE REGION

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TECHNICAL ABSTRACT:

This research concentrated on merging results of studies of historic and recent crustal earthquakes to better define earthquake source zones in the Anchorage region (60.2° to 62.2°N and 148° to 152°W). The study involved: 1) relocation and merging of recent (post-1964 mainshock) seismicity recorded by the U.S. Geological Survey (1971-1988), the Alaska Earthquake Information Center (1988-present), and the International Seismological Centre (1964-1971), 2) relocation of older events (1928-1964) using recent earthquakes as master events, 3) collection of waveform data for moderate earthquakes ($5.4<M<6.5$) occurring up to 35 years prior to the 1964 mainshock, 4) collection of intensity information for historic and recent earthquakes, and 5) Coulomb failure stress modeling studies of crustal events. The results of the analysis show that there are four clusters of crustal seismicity near Anchorage and that these regions have been active throughout the entire study period (1928-present). Seismic moment rates estimated from historic (1933-1963) and recent (1964-2002) crustal earthquakes in the upper Cook Inlet region indicate that seismic moment rates have dropped by a factor of ~1000 since the 1964 mainshock. Geologic information for structures within the region was used to estimate geologic moment rates. The geologic moment rates are only 3 to 7 times lower than the pre-1964 seismic moment rates, suggesting that the 1964 mainshock has significantly slowed regional deformation. The moment rate deficit over the past 36 years is equivalent to a moment-magnitude 6.6 to 7.0 earthquake. Coulomb failure stress (δCFS) modeling indicated that aftershocks of the 1933 (M_w~6.9) northern Cook Inlet earthquake were likely triggered. The waveforms collected for aftershocks of the 1933 event show a remarkable similarity to the mainshock, suggesting rupture along similar fault planes. However, the 1933 mainshock does not appear to have raised δCFS in the region of the 1943 Susitna Lowlands (M_w~7.0) earthquake. δCFS modeling for aftershocks of the 1984 Sutton earthquake suggest the aftershocks are best explained by rupture downwards from the mainshock along an 8 km long, 7 km wide fault. Intensity data collected for Alaskan earthquakes suggests that separate intensity attenuation relationships will be required for events located in south-central and interior Alaska.

NON-TECHNICAL ABSTRACT

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NEHRP Element: I **Keywords:** geophysics**,** source characteristics, seismotectonics

This study focuses on the seismic hazards of crustal earthquakes in the Anchorage, Alaska region. Our results suggest that recent (post-1964) crustal earthquakes occur within the same regions along similar faults and structures that were active prior to the 1964 great Alaskan earthquake, but that the rate of crustal seismicity has decreased by a factor of 1000 since the 1964 mainshock. Geologic information suggests that the observed low rates of recent crustal seismicity do not represent the long-term geologic average. It appears that the 1964 mainshock has significantly slowed regional crustal deformation. This highlights the difficulty of using seismicity in the decades following a large, plate interface earthquake to adequately characterize long-term crustal deformation in the Anchorage region. These observations will aid in developing better seismic hazard models for the Anchorage metropolitan region.

Investigations undertaken:

Our research has focused on crustal earthquakes of the Anchorage, Alaska region (60.2° to 62.2°N and 148° to 152°W, roughly within 100 km of Anchorage). The study involved relocation and merging of recent (post-1964) seismicity of the Anchorage region using the HypoDD (Waldhauser and Ellsworth, 2000) technique, relocation of pre-1964 seismicity using the master event technique, collection of waveform data for moderate ($5.4<M<6.5$) earthquakes in the region, collection of intensity data for historic and recent earthquakes, and Coulomb failure stress modeling studies of crustal events.

Ms. Claudia Flores has worked as a graduate research assistant on the earthquake relocation portion of the project. She will defend her thesis (a relocation and stress analysis study of crustal seismicity between 1988 and 2001) in June 2003. Ms. Flores has presented results of her studies at the 2001 and 2002 meetings of the American Geophysical Union. We hope to write a paper on her results, combined with the studies of historic earthquakes during the fall 2003.

Dr. Diane Doser completed relocation of the pre-1964 earthquakes, collection of waveform and intensity data, and Coulomb stress failure analysis. She also initiated a study of seismic and geologic moment rates for the upper Cook Inlet region in collaboration with Dr. Natasha Ratchkovski (Alaska Earthquake Information Center) and Dr. Peter Haeussler (USGS, Anchorage). A paper on this study was submitted to the Bulletin of the Seismological Society of America in April 2003. She presented results of the moment rate studies at the 2002 meeting of the American Geophysical Union. Results of the relocation of pre-1964 seismicity and stress modeling were presented at the 2002 Seismological Society of America meeting. A paper on the seismicity of the Kodiak Island region following the 1964 mainshock was published in the Bulletin of the Seismological Society of America in December 2002. Dr. Doser also conducted relocation, first motion, and waveform modeling studies of historic earthquakes associated with the Denali fault system and was invited to present her results at a special session on the Denali earthquake at the 2002 meeting of the American Geophysical Union. She plans to submit a paper on her results for a special volume of the Bulletin of the Seismological Society of America on the Denali earthquake. Dr. Doser visited the USGS in Menlo Park in June 2002 and the USGS in Anchorage in July 2002 to discuss her results with interested researchers.

Results:

Relocations of Post-1964 Earthquakes

Figure 1 shows the relocated crustal (depth < 35 km) seismicity from 1988-2001. Faults are shown in black, and folds in red. Fault and fold data were obtained from Haeussler and Saltus (in review) and Haeussler et al. (2000). There are four regions of notable clustering of seismicity (Strandline Lake, Susitna Lowlands, Knik Arm and North Cook Inlet, Figure 1).

Earthquakes in the Strandline Lake region strike northeast-southwest, suggesting faulting along a structure perpendicular to mapped faults. All events are shallower than 20 km.

Earthquakes in the Susitna Lowlands may be related to mapped faults striking northeast-southwest. This region is the site of the 1943 Susitna Lowlands (Mw~7.0) earthquake (square, Figure 3) whose focal mechanism is consistent with right-lateral strike-slip faulting (Doser and Brown, 2001) along a fault striking N60°E, a direction similar to the observed trend of earthquakes. This suggests faults within the Susitna Lowlands are an important source of crustal earthquakes located north of the Castle Mountain fault system.

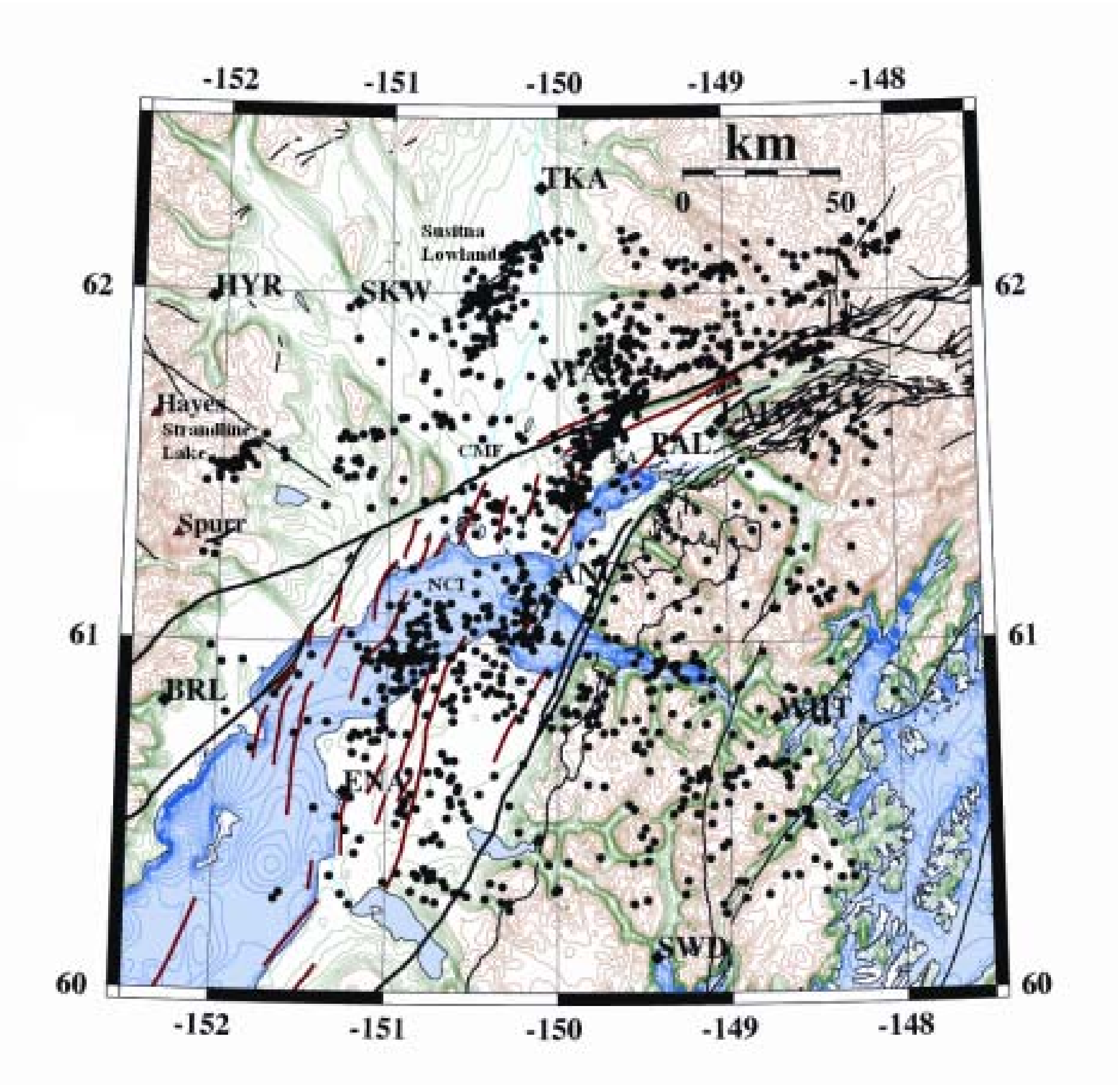

Figure 1 - Relocated crustal earthquakes (1988-2001) of the Anchorage region (black dots). Labeled diamonds are seismograph stations and volcanoes are triangles. KA indicates the Knik Arm region and NCI the northern Cook Inlet region. CMF is the Castle Mountain fault. Faults (black lines) and folds (red lines) of Pliocene or younger age are from Haeussler et al. (2000) and Haeussler and Saltus (in review).

Events in the Knik Arm region lie south of the Castle Mountain fault and trend similar to the strike of fold axes in the region. Most of these earthquakes, however, have depths > 25 km, and may be occurring within the subducting Pacific plate.

Earthquakes of the North Cook Inlet region are shown in detail in Figure 2. Note that the western cluster of earthquakes (at ~60.9°N, 150.8°W) strikes east-west although mapped faults and folds within the inlet strike north-northeast (Figures 1 and 2). Processed and filtered aeromagnetic data for the inlet (Saltus et al., 2002) indicates a long wavelength (>4.4 km and < 12 km) magnetic high whose northern edge is located near the western cluster of earthquakes and

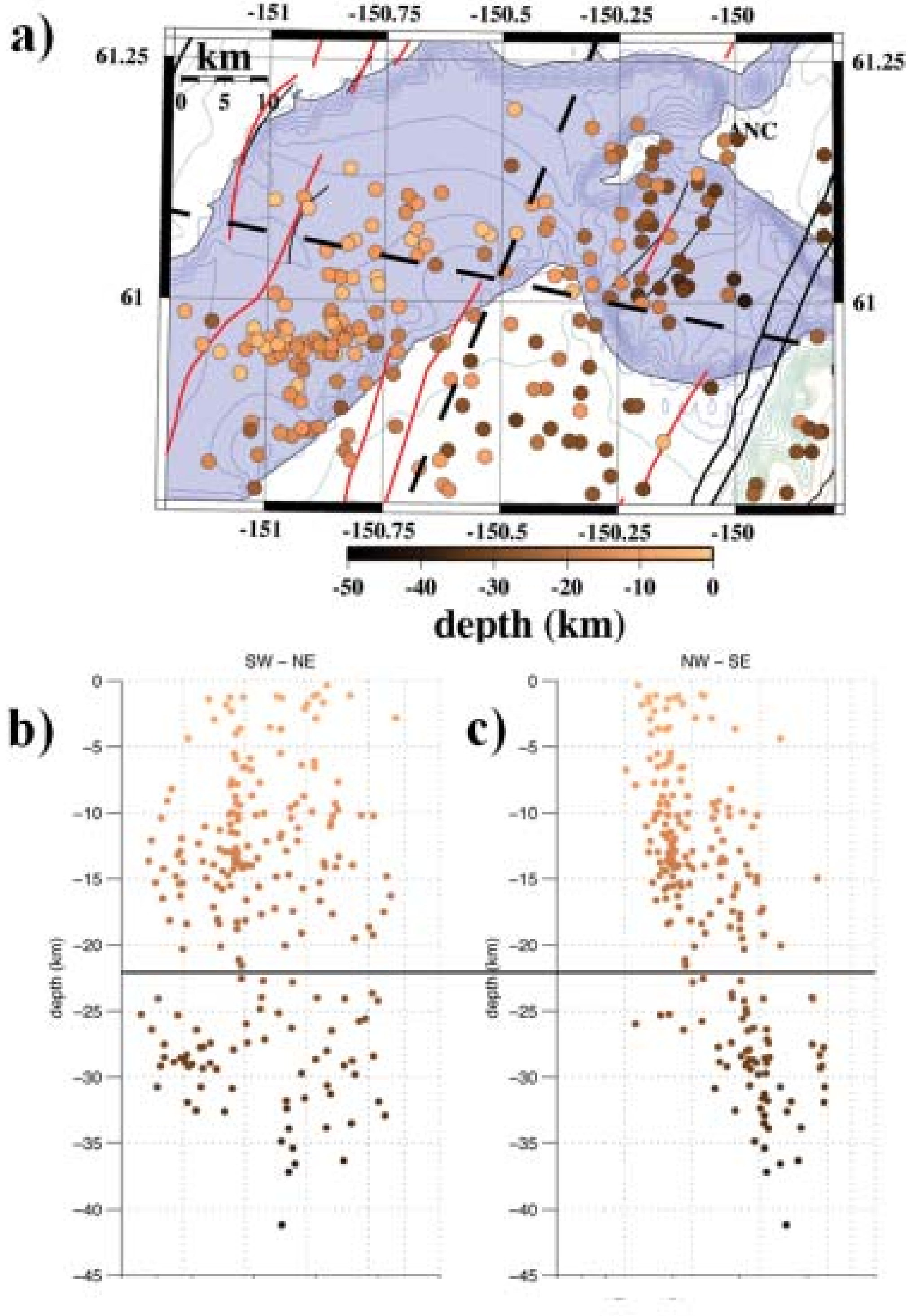

Figure 2 – Relocated crustal earthquakes of the northern Cook Inlet region. a) Map view of seismicity, color is related to focal depth as indicated. Faults and folds are as in Figure 1. b) southwest-northeast oriented cross section, c) northwest-southeast oriented cross section.

has a trend similar to that of the seismicity. This suggests the source of the seismicity may be a deeper seated feature. The western cluster of seismicity also lies at the southern edge of the 1933 North Cook Inlet mainshock (Mw~6.9) rupture zone (Figure 3). The mainshock appears to have involved reverse-oblique faulting along a fault striking N55°E (Doser and Brown, 2001) that may be related to the North Cook Inlet anticline. Cross sections of the seismicity (Figure 2) suggest that earthquakes are occurring throughout the crust and possibly the upper portion of the Pacific plate (depths > 30 km).

Ms. Flores has inverted first motion data for stress orientation in the western cluster of events using the inversion software of Robinson (e.g. Robinson and McGinty, 2000). Her results suggest faulting along northwest trending reverse faults with maximum compression oriented 50° clockwise of plate motion.

Relocations of Pre-1964 Crustal Earthquakes

Figure 3 shows the relocations of M>5.5 earthquakes (dots) within the Cook Inlet region. Relocations were accomplished using a master event technique. For earthquakes of the northern Cook Inlet region the April 27, 1933 mainshock was used as a master event. For earthquakes of the southwestern Kenai Peninsula the December 26, 1959 earthquake was used as a master event. Note that many of the earthquakes occur in regions associated with recent (post-1964) seismicity.

Collection of Waveform Data for Moderate Pre-1964 Events

We have collected seismograms for earthquakes of magnitude 5.5 to 6.5 within the Cook Inlet region. Black symbols in Figure 3 are Mw>6.5 events that have been modeled by Doser and Brown (2001). Gray symbols (Figure 3) indicate the events for which we were able to collect at least 3 seismograms. A preliminary comparison of the waveforms of the April 27, 1933 mainshock to its aftershocks (1933-1941) shows a remarkable similarity between the waveforms, suggesting the aftershocks occurred along faults with similar orientations to the mainshock.

Collection of Intensity Data

We have collected intensity data for earthquakes occurring in all of Alaska between 1900 and 1985 from the NOAA intensity web site. In addition, we have used zip code/internet response-based intensity information collected from the USGS's "Did You Feel It?" data archive (pasdena.wr.usgs.gov/shake/ak). Preliminary analysis of median distance values for each intensity interval show that we will need to group events into different subregions to develop intensity-distance attenuations relationships. We may also have to subdivide deep (> 100 km) and shallow (< 100 km) events within the Anchorage region.

Coulomb Failure Stress Modeling Studies

Results of Coulomb failure stress modeling for the 1933 North Cook Inlet earthquake sequence are shown in Figure 4. Three of the five larger (M>5.0) aftershocks of this sequence fall within regions where δCFS > 0.1 bars, the δCFS threshold level for triggering of aftershocks that has been suggested by King et al. (1992) and Reasenberg and Simpson (1992). The two aftershocks that do not correspond to regions of higher δCFS could either have occurred on faults with different orientations than the mainshock or could be mislocated (mislocations of no more than 10 km would place the events within the higher δCFS regions). However, considering the similarities of the waveforms of the mainshock and aftershocks we feel that event mislocation is the likely explanation. The modeling also suggested that the 1933 earthquake sequence did not raise δCFS in the vicinity of the Mw~7.0 1943 Susitna Lowlands earthquake (see Figure 3 for epicentral locations).

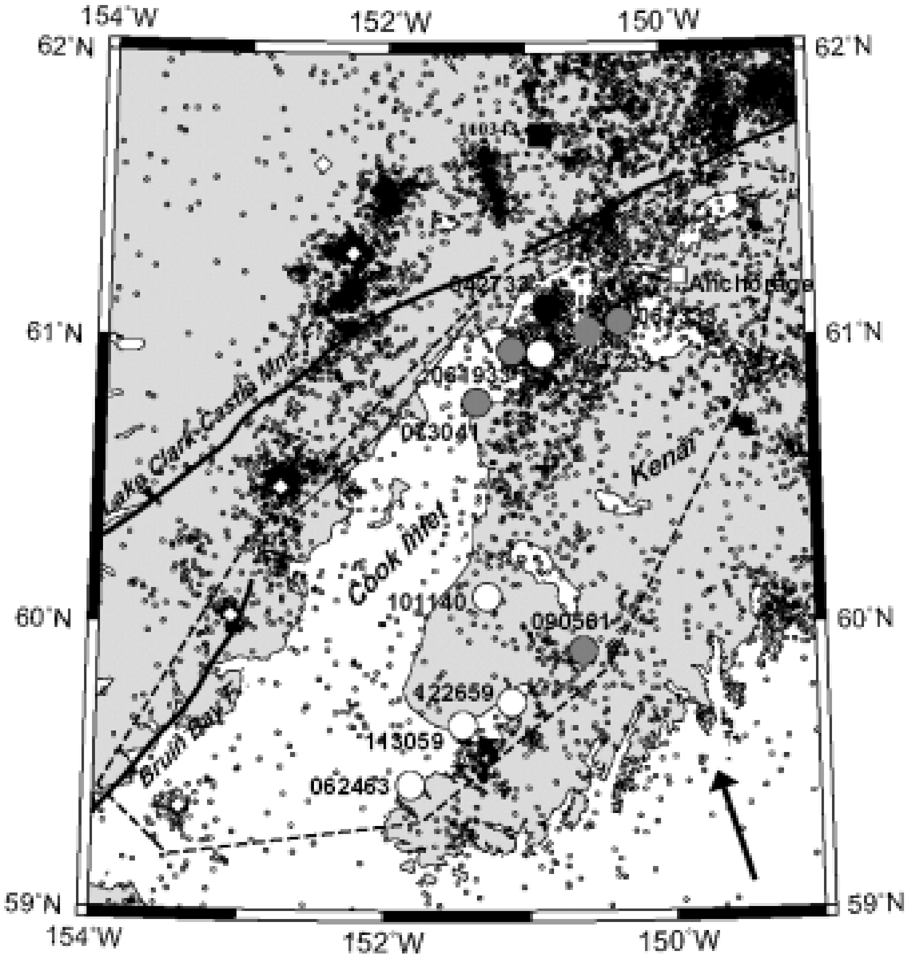

Figure 3 – Historic earthquakes (dots and square) and recent (1965-2001) earthquakes from the Alaska Earthquake Information Center catalog. Diamonds are volcanoes. Bold arrow indicates the direction of plate motion (DeMets et al., 1994). Dashed lines surround study area used in seismic and geologic moment rate studies.

δCFS modeling for aftershocks of the 1984 Sutton earthquake (Figure 5) suggests the aftershocks are best explained by rupture along a 8 km long and 7 km wide fault that ruptured downward from the mainshock hypocenter (at 19 km). With this rupture geometry 100% of the aftershocks occurring at depths of 17 km or less are located within a region of δCFS > 0.1 bars and 74% of all aftershocks are located within the same stress region.

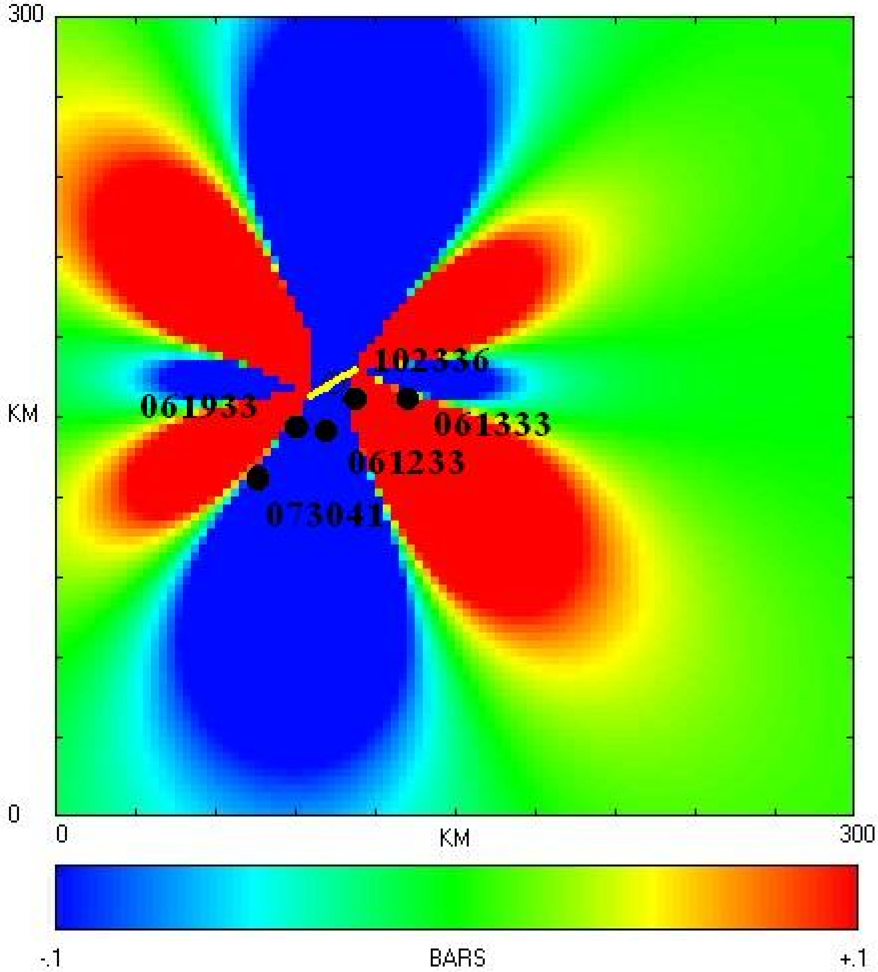

Figure 4 –δCFS at 9 km depth induced by the 1933 North Cook Inlet mainshock (fault rupture shown by yellow line) for faults with the same orientation as the mainshock. Aftershocks are shown as black dots. Red regions denote δCFS >0.1 bar.

Related Studies

Moment rate studies

In addition to research related to our 5 proposed tasks, we have conducted studies of seismic moment rates in the Cook Inlet region (area enclosed by dashed lines, Figure 3). Our seismic moment rate calculations show over a factor of 1000 decrease in moment rates following the 1964 mainshock. We then used geologic information on structures within Cook Inlet basin (e.g. Haeussler et al., 2000; Haeussler and Saltus, in review) to estimate a regional geologic moment rate. Since it is difficult to estimate the amount of horizontal offset that has occurred along these structures, our geologic moment rates could underestimate the true rates by up to 70%. Nevertheless, the geologic moment rate is only 3 to 7 times lower than the pre-1964 mainshock seismic moment rate. This suggests that the 1964 mainshock has significantly slowed regional crustal deformation. If we compare the geologic moment rate to the post-1964 mainshock rate, the moment rate deficit over the past 36 years is equivalent to a Mw 6.5 to 6.8

earthquake. These results have been submitted as a “short note” to the Bulletin of the Seismological Society of America.

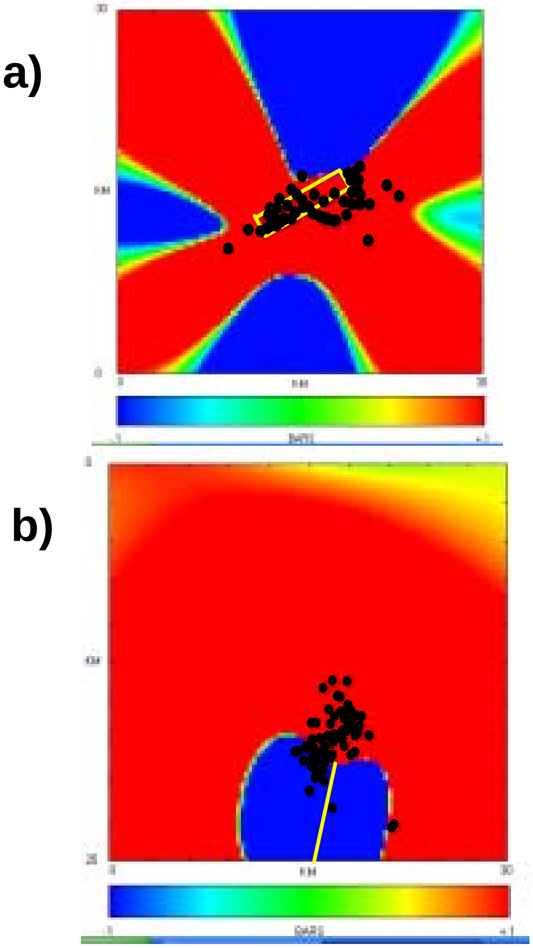

Figure 5 - δCFS models for the 1984 Sutton mainshock. The fault plane is indicated by the yellow line, aftershocks by black dots. Red indicates regions of δCFS > 0.1 bars. (a) Map view. (b) Cross section along fault dip. Aftershock locations are from Lahr et al. (1986).

Kodiak Island studies

A paper on Kodiak Island seismicity since the 1964 was recently published (Doser et al., 2002). The most intense seismicity and moment release in the Kodiak Island region occurred within the Pacific plate and along the plate interface of the southwestern edge of the Kodiak segment where slip during the 1964 mainshock was < 5 m. Few earthquakes have occurred within the North American plate. The intense seismicity in the southwestern portion of the region correlates well with the northern edge of a zone of high plate interface coupling detected by GPS/geodesy studies (Zweck et al., 2002) (Figure 6). Our studies suggest that during 1964-1974 faulting within the Pacific plate was characterized by normal and normal-oblique faulting. However, since 1974 reverse-oblique faulting has become more common in the Pacific plate. Seismic moment release in the Kodiak region is over 6 times greater than in the Prince William Sound-Cook Inlet region for the past 37 years, and we do not appear to see the decreases in seismic moment release as observed to the north. Unlike the Prince William Sound region, there is also a lack of down-dip migration of seismicity since 1964. Seismicity in the Prince William Sound-Cook Inlet region clusters around the edges of the zone of highest interface coupling. The few events with the region of highest coupling are immediate aftershocks of the 1964 sequence occurring within the North American crust. Events also appear to cluster around the zone of aseismic creep in Cook Inlet as defined by GPS/geodesy studies.

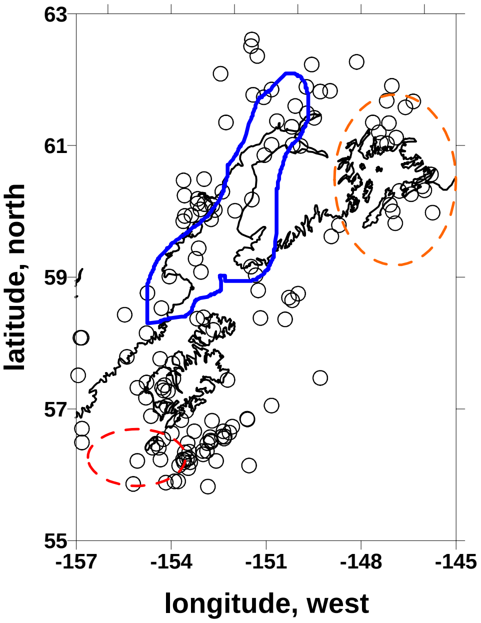

Figure 6 - Mw>5.5 earthquakes (1964-2002) in the epicentral region of the 1964 great Alaskan earthquake. Red and orange dashed lines indicate regions of high interface coupling (Zweck et al., 2002). Blue line denotes region of aseismic slip along the plate interface (Zweck et al., 2002).

Historic Earthquakes of the Denali Fault Region

During a previously funded NEHRP study we examined the source processes of several pre-1964 earthquakes associated with the Denali fault system (Doser and Brown, 2001). The recent Denali fault earthquakes rekindled our interest in examining these events a second time, as well as relocating and modeling the waveforms of other events along the fault system. Figure 7 shows relocations for events occurring prior to 1988. Figure 8 shows focal mechanisms obtained for events between 1933 and 1987. Our results to date suggest that many of the earthquakes of magnitude > 5.5 within this region do not represent motion along the Denali fault, but rather along compensating thrust and strike-slip faults. Preliminary results of this analysis were presented as an invited paper at the fall 2002 meeting of the American Geophysical Union.

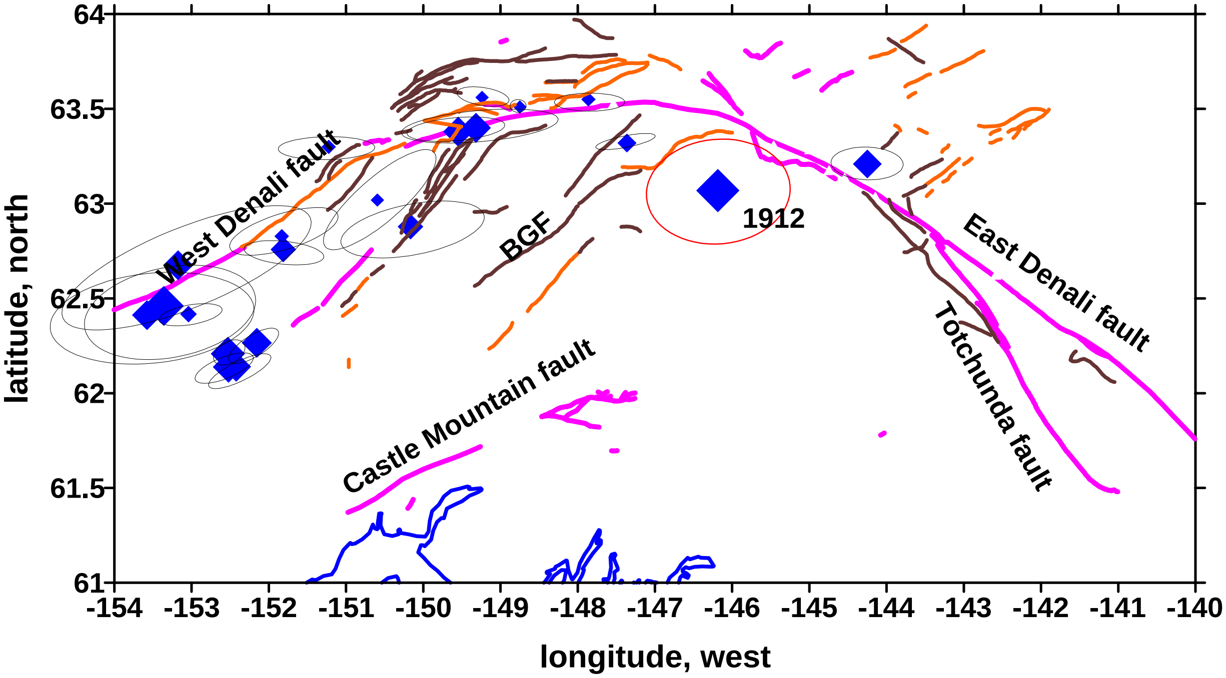

Figure 7 – Earthquakes (M>4.5) of the Denali fault region (1912-1987) relocated using the bootstrap technique of Petroy and Wiens (1989). Symbol size reflects magnitude. Error ellipses show 95% confidence interval, except for 1912 earthquake (red ellipse) which is the 75% confidence interval of Boyd and Lerner-Lam (1988). _Faults taken from Pflaker et al. (1994). Magenta faults show Holocene to late Pleistocene movement, orange faults show Neogene movement, and brown show pre-Neogene or suspicious movement. BGF is the Braxton Gulch fault.

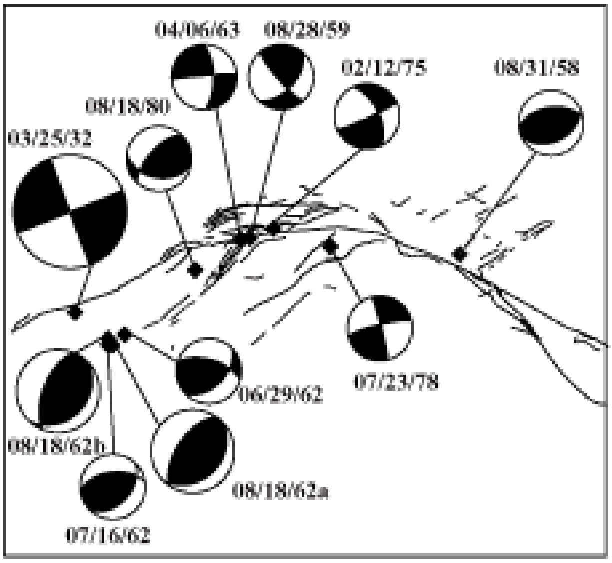

Figure 8 – Focal mechanisms for M>4.5 earthquakes (1932-1987). Larger mechanisms obtained from body waveform modeling, smaller mechanisms from grid searches of first motion data.

Note that over half the mechanisms indicate reverse faulting of left-lateral strike-slip faulting, styles of faulting that are not consistent with movement along the main trace of the Denali fault.

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