Measurement of Active Crustal Motions in Upper Cook Inlet and the Anchorage Urban Area: Collaborative Research with the US Geological Survey

99HQGR0055
Final Report

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NEHRP Element(s): II
Key Words: GPS-Campaign

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 99HQGR0055*. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.*

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MEASUREMENT OF ACTIVE CRUSTAL MOTIONS IN UPPER COOK INLET AND THE ANCHORAGE URBAN AREA: COLLABORATIVE RESEARCH WITH THE US GEOLOGICAL SURVEY

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TECHNICAL ABSTRACT

The goal of this project is to constrain rates of motion on potentially seismogenic features in upper Cook Inlet basin, such as the Castle Mountain fault or faults within the basin itself. We made geodetic measurements using the Global Positioning System that show significant shortening across part of the basin; if this was due to motion on faults within the basin it would indicate a significant seismic hazard to Anchorage. However, we have demonstrated that these spatial variations do not result from active faults in the overriding plate, but instead from the interaction of two sources of deformation related to the subduction interface: along-strike variations in plate coupling and continuing postseismic deformation following the 1964 earthquake. Slip rates on structures within and bounding Upper Cook Inlet appear to be low, no more than 2-3 mm/yr; although we cannot make a quantitative estimation of the hazard posed by these structures without knowing their earthquake histories, it is likely that large and damaging earthquakes on these structures are rare. On the other hand, our results for the plate interface suggest that hazards from subduction earthquakes may be underestimated.

NON-TECHNICAL ABSTRACT

We used Global Positioning System (GPS) measurements to try to detect crustal movements associated with active faults in the Anchorage urban area that might generate significant earthquakes. The most important of these faults are the Castle Mountain fault and faults within the Upper Cook Inlet Basin that core folds that deform young sediments. Although the GPS measurements show significant shortening across the basin, we find that these data and other data from the surrounding area are best explained by a cause related to the subduction of the Pacific plate beneath North America. We find that the rates of slip along the crustal faults immediately north of Anchorage total no more than 2-3 mm/yr.

Investigations Undertaken

Goals and History

The goal of this project is to constrain rates of motion on potentially seismogenic features in upper Cook Inlet basin (Figure 1), such as the Castle Mountain fault or faults within the basin itself, by measuring contemporary rates of deformation using the Global Positioning System (GPS). This project has now been funded two years by the USGS NEHRP program. In 1995 and 1996, prior to receiving any USGS funds for this project, I carried out limited GPS measurements in cooperation with Peter Haeussler (USGS Anchorage) using institutional funding and limited vehicle support (for Peter) from the Anchorage office. USGS funding was provided under grant G03088 during FY1997 and FY1998. Using those funds we surveyed a more complete network, including sites accessible only by helicopter, resurveyed many sites and established a permanent GPS site in Palmer. This report covers the continuation of this work in FY1999.

Somewhat to our surprise, deformation related to the Castle Mountain fault and faults in Cook Inlet Basin proved to be subtle and difficult to detect. However, we observed large variations in site velocities that result from a combination of variations in coupling along the subduction plate interface and continuing postseismic deformation following the 1964 earthquake. The magnitude and spatial variability of these deformation sources was sufficient to drown out any signal from the local sources we sought to study in this grant. Therefore, the results presented here are based in part on the larger-scale processes rather than the more local features that we originally intended to examine.

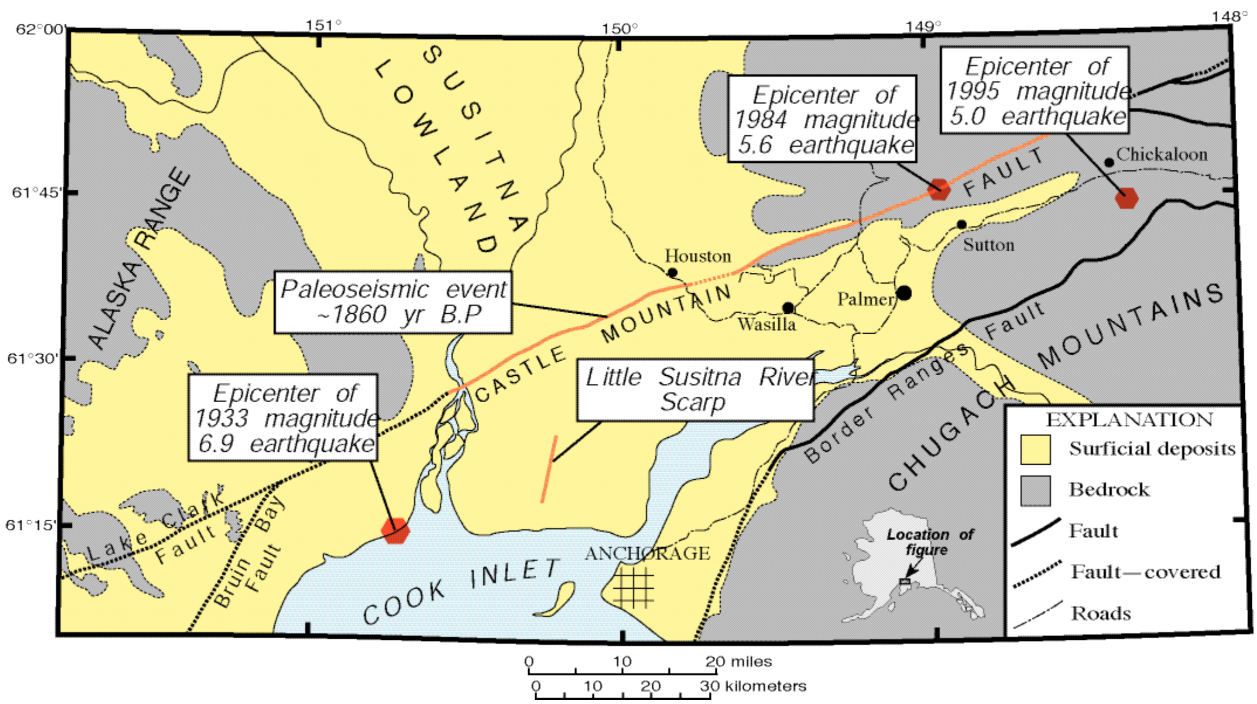

Figure 1. Mapped faults in upper Cook Inlet. Red fault segments show evidence for Holocene activity. Epicenters of three significant shallow historical earthquakes are shown. Roads are shown as dash-dot lines (note the lack of roads on the northern and western shores of Cook Inlet, and the general absence of roads in areas that have outcropping bedrock. For reasons of site stability we locate as many sites as possible in bedrock.

Field GPS Observations

In the summer of 1999, we re-occupied selected sites of the Cook Inlet network we initially surveyed from 1995-1998 and extended the network in a few cases. A total of 22 sites were observed, for a total of 63 station-days of data. A map of the sites supported by this grant is shown in Figure 2. All data are archived at the UNAVCO archive, although data are mixed together with other sites from the Kenai Peninsula that were supported by an NSF grant. All data have been analyzed, and results for the 1995-1999 data will be discussed in a later section.

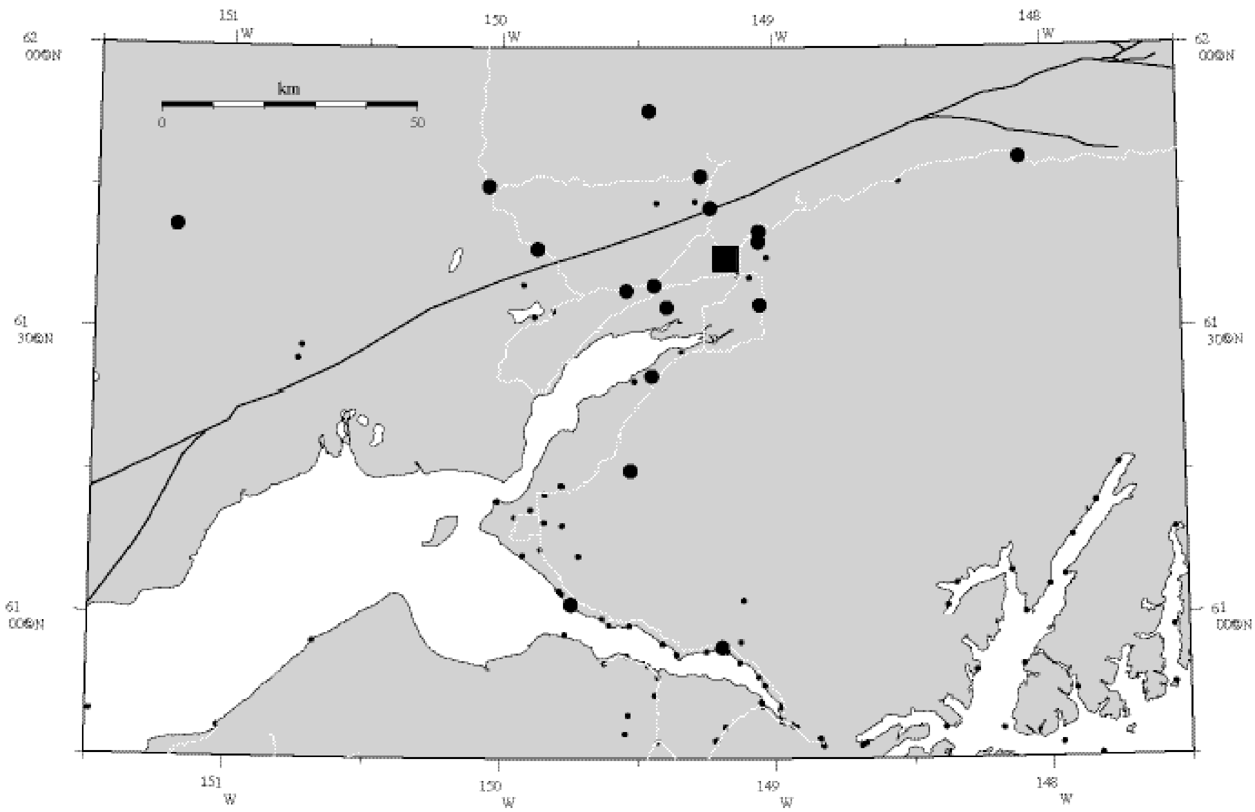

Figure 2. Map of sites surveyed under this grant. Large circles are sites surveyed under this support in FY1999, and dots are other sites that have been surveyed at least one time (some of these are from other support, others from local surveyors or other data sources). The large square indicates the permanent GPS site ATWC. Major roads are indicated by light lines.

Permanent GPS Site

This grant supported continued operation of the continuous GPS site ATWC in Palmer, Alaska. Palmer is located in the uppermost part of the Cook Inlet Basin, and the site is located south of the Castle Mountain fault. The time series for ATW2 is shown in Figure 3. The site is located at the West Coast and Alaska Tsunami Warning Center operated by NOAA. The staff at the Tsunami warning center have been extremely cooperative and supportive. We built a monument patterned after the “Wyatt-type” drilled-braced monument that has been adopted as a standard by SCIGN in southern California. A drilled monument with inclined pipes would be a poor choice for Alaska, because the shallow ground freezes seasonally, and the frozen ground will couple very well with an inclined pipe or rod. Instead, we excavated a large hole, into which we placed a braced structure anchored with concrete. A two foot thick slab of concrete was poured at a depth of 10 feet below the surface, well below the level of seasonal freezing. The hole was refilled with non-frost-susceptible fill. This type of fill contains no fine-grained materials and is the least-susceptible to frost-heaving.

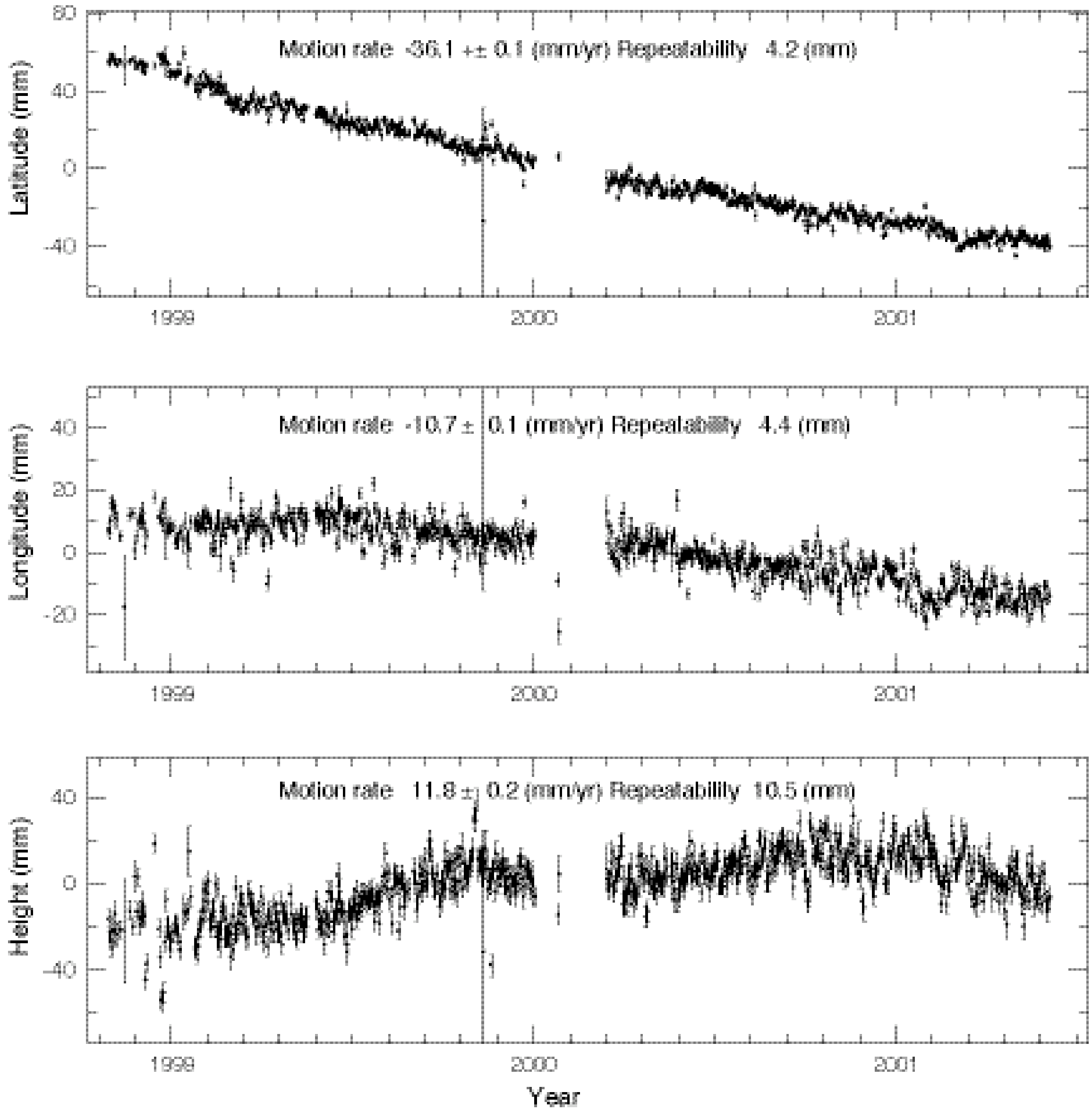

Figure 3. Position time series for the Palmer (ATWC) GPS site. Positions are given in ITRF97. The (concave upward) curvature visible in the latitude component results from the impact of a slip event that began in mid-1998 in the area, although that event was not recognized until after the end of this grant period. The data gap at the beginning of 2000 was related to a combination of a Y2K-related program bug and a receiver firmware bug.

We chose an innovative approach to data transfer. Instead of making a long-distance phone call to the receiver every day for downloading, we have a PC at the site that downloads the data and then makes a call to the local Internet Service Provider and transfers the data to us. This option offers a considerable cost-savings given the University's high phone rates (20-50 cents per minute for in-state long distance calls). Our 'smart-site' model also serves as a prototype for possible future sites in parts of Alaska much more remote. When first set up, we used a Windows-based PC, which caused a variety of problems due to things like Windows waiting for someone to click "OK" after terminating a session. Although we did find solutions to all of these problems, in the spring of 2000 we replaced the PC with a machine running Linux. This has worked flawlessly and required no rebootiong.

Results

On a large scale, GPS velocities relative to North America (Figure 4) are dominantly to the NNW, and generally decrease in magnitude, and rotate counterclockwise at sites further to the NW. These NNW vectors are subparallel to the inferred PCFC-NOAM plate vector (DeMets and Dixon, 1997). The largest measured velocities are in Prince William Sound and nearly equal to the magnitude to the PCFC-NOAM velocity, indicating nearly complete coupling between the overriding crust and the subducting plate. However, a number of sites move trenchward, a result of continuing postseismic deformation following the 1964 earthquake. Zweck et al. (2002) constructed a plate coupling model based on these data, and that model will be discussed here as this grant contributed to that work. However, first I discuss the results from the immediate Cook Inlet region.

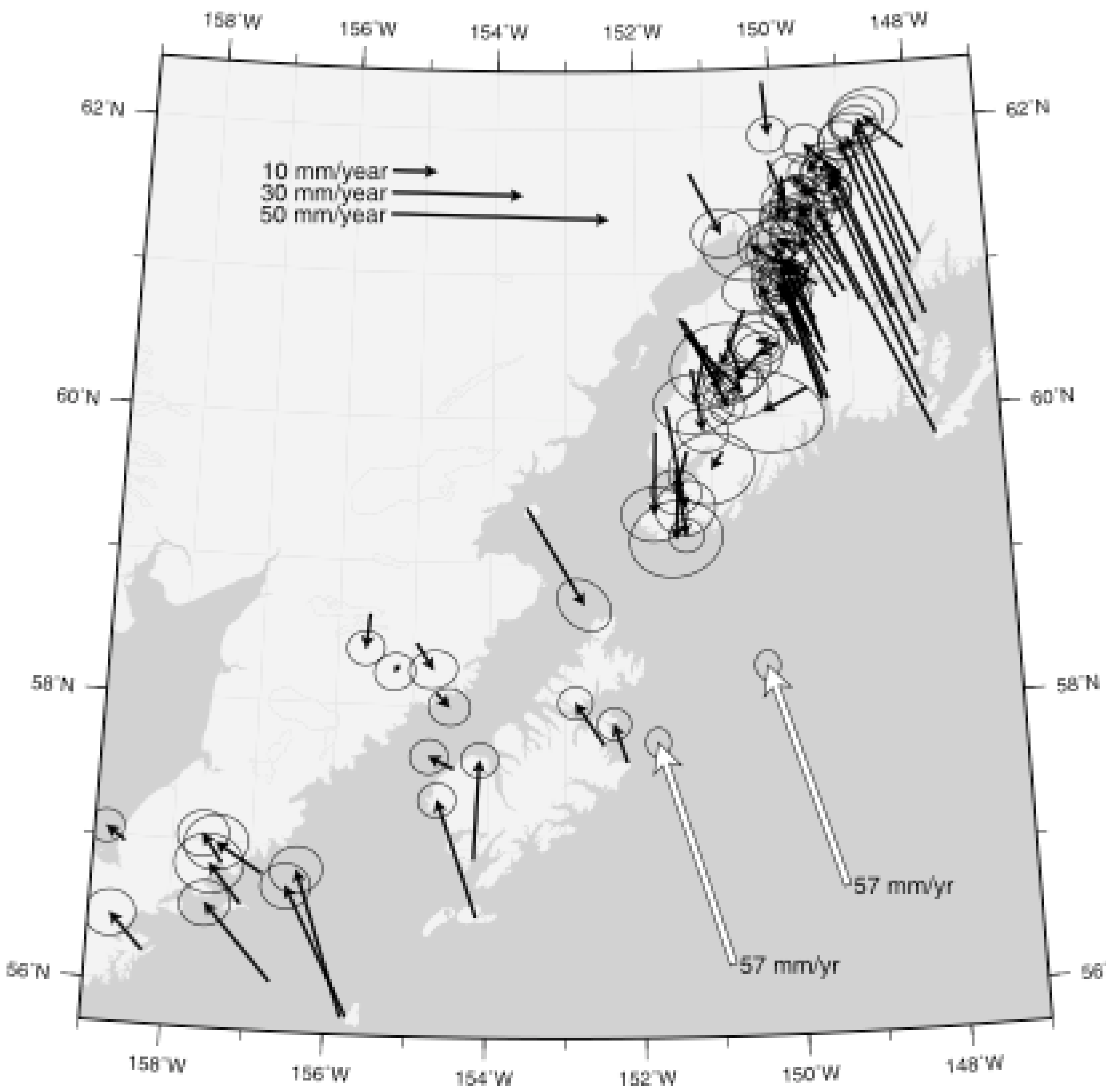

Figure 4. Site velocities relative to North America for the region of the 1964 earthquake, including the study area. Figure from Zweck et al. (2002). Note the rapid trenchward motion of sites in the western Kenai Peninsula, but also on theAlaska Peninsula near Kodiak island and also north of the Cook Inlet Basin.

Upper Cook Inlet Region

Upper Cook Inlet basin shows spatial variations in deformation on a surprisingly small scale (Figure 5). Horizontal velocities are shown relative to EAGLE, the site with the best-determined site in the area. Most sites move either to the northwest or southeast relative to EAGLE, which is not unexpected given the large contraction signal seen in the data from sites to the south of EAGLE. However, sites to the north of EAGLE can be divided into two groups: western sites that move southeast (toward EAGLE), and eastern sites that move to the north or northwest. The contrast in velocity between these two groups, which form two rough profiles, is about 10 mm/yr. As viewed from the vicinity of Palmer, the western sites show what appears to be 10 mm/yr of contraction across Upper Cook Inlet basin. The difference between the two profiles is quite striking, because they are only about 50 km apart.

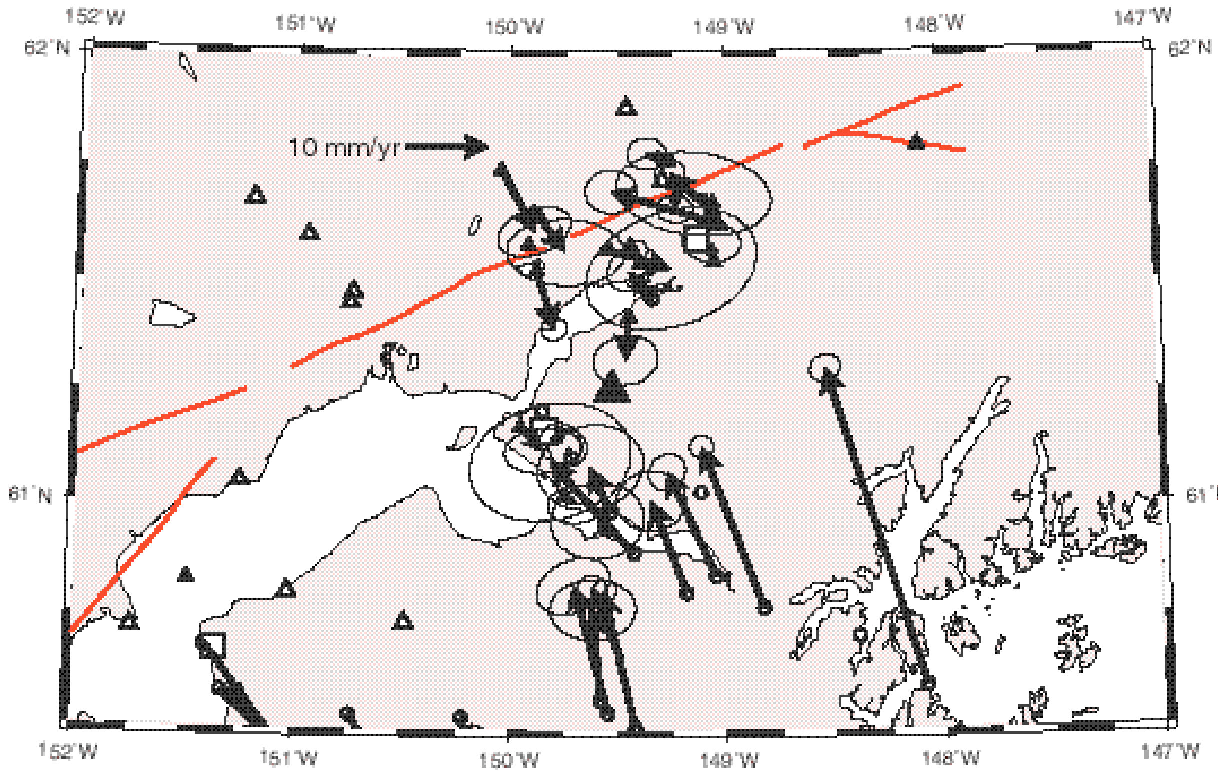

Figure 5. Horizontal velocities of Cook Inlet basin sites relative to site EAGL (large triangle).

If the convergence in the western profile was indicative of contraction within the basin, such rapid motion would suggest the Anchorage urban area faces a significant seismic hazard from contractional structures within the basin. However, most of this signal is due to spatial variations in the deformation caused by the megathrust (Zweck et al., 2002). This region lies near the edge of the large Prince William Sound asperity. Sites in the eastern part of Figure 5 lie above or downdip of the fully-locked asperity, and their velocities include a large component of NNW-directed motion that results from the locked plate interface. However sites in the western part of the figure have little NNW-directed motion due to the locked asperity, as the plate interface trenchward from them is essentially unlocked. In addition, a component of trenchward motion results from continuing postseismic deformation following the 1964 earthquake. The region impacted by 1964 postseismic deformation overlaps the western boundary of the asperity.

As can be seen in Figure 5, there is little discernable signal from the Castle Mountain fault. Sites on either side of the fault have very similar velocities. When we consider both profiles, we find that an upper limit for the possible fault slip rate is 2-3 mm/yr; if there were a higher slip rate, it would be detectable given our GPS velocity precision.

Larger-scale patterns

Horizontal site velocities, relative to North America, for all sites around the study area are shown in Figure 2, including data from a USGS Prince William Sound and Kodiak GPS profiles (Savage et al., 1998; Savage et al., 1999). These velocities are very large just south of Cook Inlet, due to elastic strain accumulation on the Pacific-North America plate interface (Freymueller et al., 2000). The shallow, seismogenic, part of the interface is fully locked, causing sites on the overriding plate to move in the direction of relative plate motion at rates of up to 50 mm/yr in western Prince William Sound (Savage et al., 1998). However, this simple interpretation holds true only for the eastern part of the Kenai peninsula and western Prince William Sound. On the western Kenai Peninsula, sites are moving trenchward at rates of up to 40% of the relative plate motion. Trenchward motion is well explained by trenchward creep of the hanging wall down dip of the 1964 rupture area (Freymueller et al., 2000; Zweck et al., 2002).

The biggest surprise in these results is the extreme spatial variability in the pattern of deformation. A model for the eastern Kenai Peninsula data would misfit velocities in the western Kenai by as much as 25-30mm/yr. The pattern of deformation on the Kenai peninsula is replicated on a smaller scale (and magnitude) in the Cook Inlet area. At a given distance from the trench, sites to the east have a larger component of motion in the direction of relative plate motion than do sites in the west, and the westernmost sites show trenchward motion relative to North America. The USGS' Prince William Sound profile passes through the upper Cook Inlet area, and our expectation was that data from this profile would be sufficient to describe the regional deformation, allowing the detailed network from Cook Inlet to be used purely to study local structures. Clearly, that assumption was incorrect.

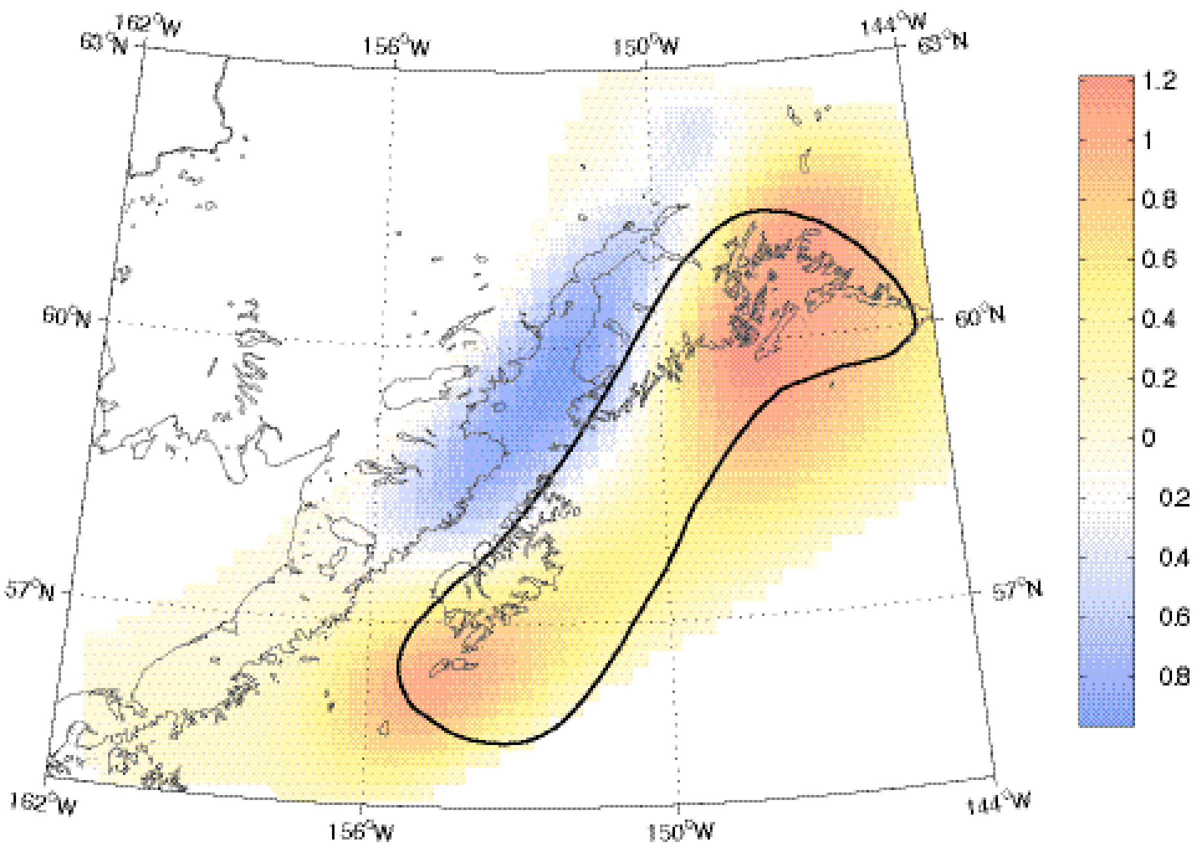

Figure 6. Plate coupling distribution, based on the data in Figure 4. Red colors show locked patches (slip deficit), and blue colors show regions of inferred postseismic creep (slip excess). The locked patches determined from the GPS data correspond to the inferred asperities of the 1964 rupture, and postseismic deformation is found downdip of almost the entire 1964 rupture.

To test the alternate hypothesis we have constructed a model of the position of the plate interface (Figure 6), and used this model as a geometric constraint on 3D elastic dislocation models for the subduction zone. We digitized and interpolated seismic transect and secondary data onto a plan-view model of the megathrust. The data sources are Doser et al (1999), Page et al (1991), Wolf et al (1991) and Moore et al (1991). We employed ETOPO5 data to estimate the trench bathymetry. A two-dimensional cubic spline interpolation was used to generate the profile of the megathrust. We then discretized the resulting surface and estimated the plate coupling distribution on the plate interface (Figure 6). The plate coupling distribution shows areas within the 1964 rupture zone and adjacent areas of the shallow seismogenic interface that are locked (having a slip deficit). Within the 1964 rupture zone, we find two large locked patches with a gap of low coupling (low slip deficit) between them. Zweck et al. (2002) showed that this intervening segment is creeping aseismically at essentially the full plate convergence rate. We also find a large area downdip of the 1964 rupture zone with an excess of slip, interpreted to be continuing postseismic creep following the 1964 earthquake. This is in accord with previous results (e.g., Cohen et al., 1995; Cohen and Freymueller, 1997), but this study was the first to constrain the spatial distribution of the postseismic creep.

The locked patch inferred from the 1993-1998 GPS measurements corresponds almost exactly in space with the Prince William Sound and Kodiak asperities that ruptured in 1964 [*Christensen and Beck*, 1994; *Johnson et al.*, 1996]. The same holds true for the region SW of the 1964 rupture zone. In other words, the spatial distribution of coupling observed through geodesy over roughly five years agrees is the same as the distribution of moment release in the last major earthquakes over more than 1000 km of the Alaska subduction system. We conclude that, at least in Alaska, the asperities are long-term features of the plate boundary system and not ephemeral features. If this is true in general, then the present distribution of coupling at subduction zones observed by geodesy over a few years corresponds directly with the seismic coupling observed over decades and perhaps even centuries.

Implications for Earthquake Hazards in the Anchorage urban area

One clear conclusion of our work is that the slip rates on crustal faults near Anchorage are small. In particular, slip on the Castle Mountain fault is not yet visible in the results of either profile that crosses the fault (Figure 5). The large difference in velocity between the two profiles is due primarily to the 3D geometry of the plate interface. The contrast between the profiles can be explained to first order if the downdip end of the shallow locked part of the interface is terminated at ~26-27 km. A small slip rate does not mean that these features do not pose significant earthquake hazards, because it appears that it has been a long time since the last event – the next event may be "due" soon. However, the likelihood of an event occurring in any particular time window is reduced as the slip rate is reduced.

We believe that the hazards posed by great earthquakes on the megathrust may be underestimated. We find that a very large area of the plate interface is completely locked, suggesting a 100% coupling between the plates. The downdip width of the locked region increases from about 270 km at Seward (*Freymueller et al.*, 2000; Zweck et al., 2002) to more than 300 km under Prince William Sound if we assume that the interface there is locked to the same depth as at Seward. A completely locked interface will accumulate a slip deficit of 20 meters (the approximate maximum slip in 1964) in less than 400 years. This is in contrast to geologic estimates of recurrence time, which suggest a recurrence interval of >600 years. It is possible that not all moment accumulated is released in 1964-type earthquakes. If 10% of the accumulated moment is released in magnitude 8 earthquakes, such events could happen once or twice per century on average. Although the 1964 event is not likely to recur for a few centuries, more investigation is needed into the history of magnitude 8 earthquakes in the Kenai Peninsula – Prince William Sound region.

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Two papers have been published based on data and modeling carried out under this grant. This grant supported the data collection described above, as well as a portion of Dr. C. Zweck's salary as a postdoctoral researcher.

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Data Availability

All GPS data collected under this project can be obtained either from the PI or (preferably) from the UNAVCO archive. Data are available in both Trimble raw binary and ascii RINEX form. Users of the GIPSY software can get clean (free of cycle-slips and outliers) QM files from the PI. Data from the ATWC permanent site are available from the UNAVCO Seamless archive at both Boulder and Scripps.

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