Time-Dependent Deformation Following the 1964 Alaska Earthquake

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Requested Equipment: 76 GPS

We propose a dense PBO instrument cluster in and around the rupture area of the 1964 Great Alaska earthquake (M_w 9.2). The goals of this instrument cluster are to: (1) investigate the mechanisms of postseismic deformation, (2) refine estimates of the spatial distribution of locked and slipping patches on the plate interface and investigate how presently locked patches correlate with asperities observed through earthquake observations, and (3) to study the transition from subduction of the Pacific plate beneath North America to collision of the Yakutat terrane, and its implications for segmentation of seismic rupture and mechanisms of deformation of the continental crust. Significant survey-mode measurements have already been made here and the spatial and temporal complexity of the deformation field make the 1964 rupture zone the most promising location in North America to study mechanisms of postseismic deformation and variations in plate coupling. The signal to noise ratio in the deformation field is second to none in the PBO region, due to the rapid convergence rate of 56 mm/year and the extremely shallow dip angle of the subducting slab. Time-varying postseismic deformation (~20 mm/year or greater surface velocities) is seen over a large area, providing an extremely large signal to noise ratio.

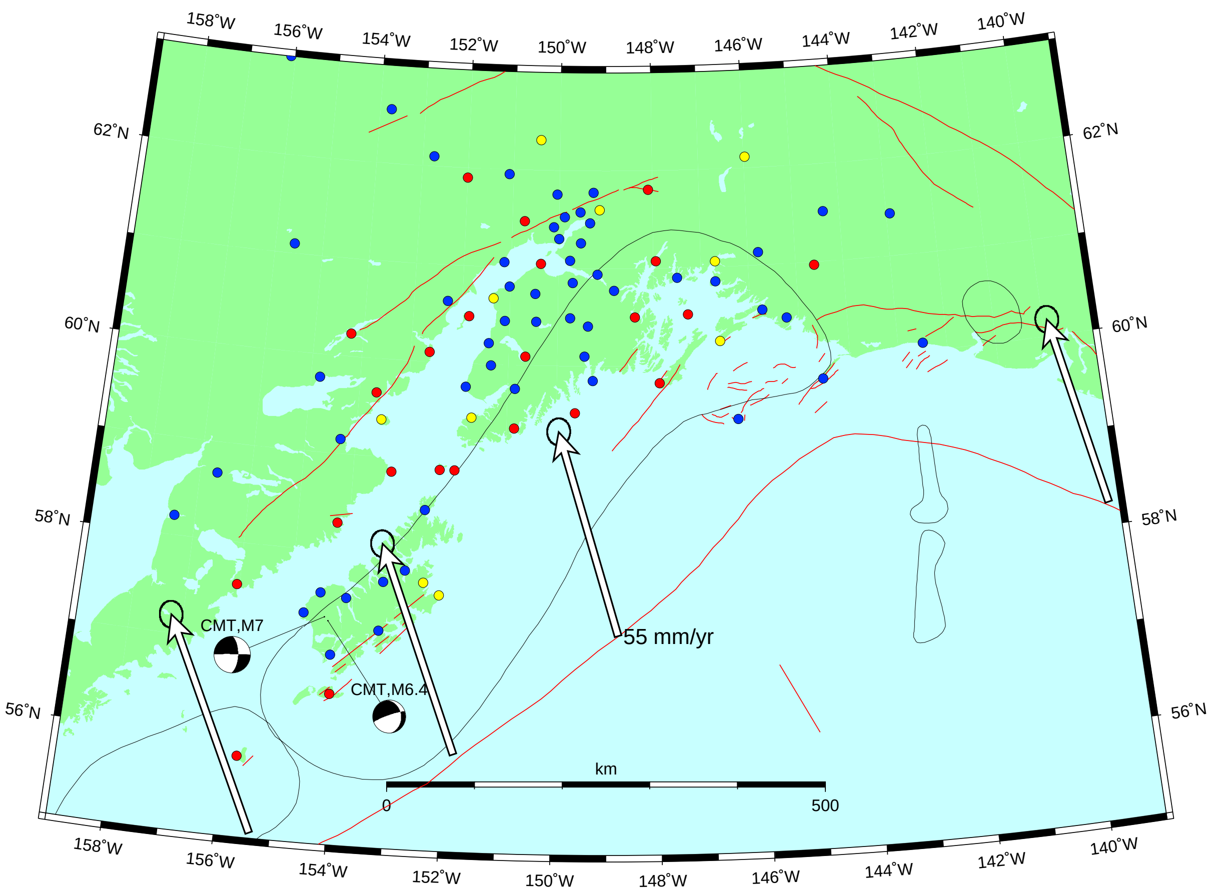

Figure 1: Location map with rupture zones and proposed network. Yellow dots: existing permanent sites, most of which are US Coast Guard sites; Blue dots: proposed new sites where power and communications easily available; Red dots: proposed new sites, remote power and communications. Focal mechanisms for December 1999 slab earthquake and largest aftershock are shown.

The deformation field has shown substantial temporal variations over the last five years. In particular, the existing data demonstrate that in early 1998 there was a significant change in the deformation field, when sites within an area at least 100 by 100 km^2 changed velocity by up to 30 mm/year. The change from one steady velocity to the other occurred over a period of several months or less, and was not associated with any significant earthquakes. The inferred source area for this change in velocity lies on the plate interface well downdip of the 1964 coseismic rupture. Measurement of the timescales for initiation and decay of transients like this will place powerful constraints on postseismic deformation mechanisms, one of the key phenomena PBO aims to measure. Measurement of the further temporal development of the postseismic transient will allow better understanding of the mechanisms of postseismic deformation following great subduction earthquakes, the data required to construct more realistic models of the earthquake cycle, and a better understanding of how viscoelastic and creep postseismic deformation may be related.

At the eastern end of the 1964 rupture zone the North American plate is underthrust by a sandwich of the Yakutat block and Pacific plate. The Yakutat block is colliding with and thrusting beneath North America, and undergoes significant internal deformation. It is possible that there is significant slip occurring on two separate thrust interfaces, and PBO instruments densified with survey-mode measurements should allow us to understand in three dimensions the transition from normal subduction (Pacific plate beneath North American plate) to terrane collision (Yakutat block colliding with and underthrusting North American plate).

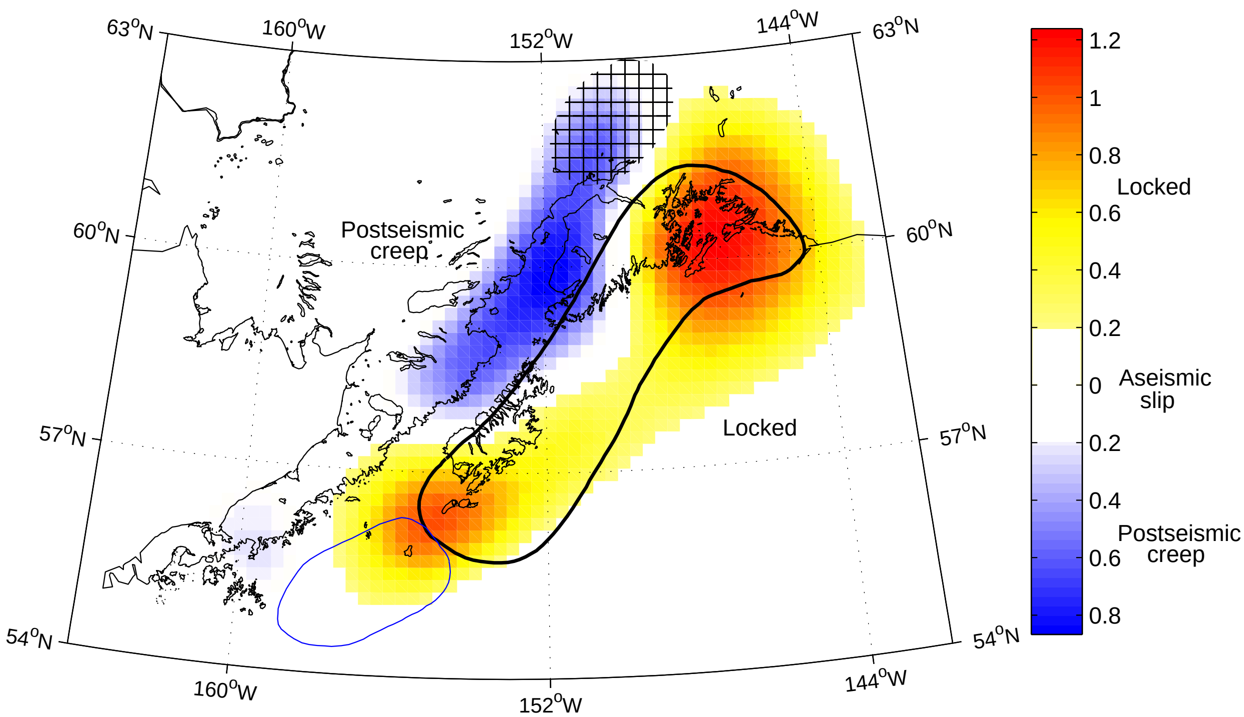

Figure 2: Distribution of plate coupling and postseismic creep inferred from inversion of GPS velocities. Hot colors represent locked patches while cool colors represent postseismic creep. The 1964 rupture zone is shown by a black line and the 1938 rupture zone by a thin blue line. The hachured area shows the region where coupling changed significantly around early 1998.

Background

The 1964 Alaska earthquake (M_w 9.2) was the second-largest ever recorded instrumentally, and the largest within the Pacific-North America plate boundary zone (Figure 1). The rupture zone was about 800 km long and about 200 km wide, with an average slip of 15-20 meters. The width of the rupture zone is exceptional because the average dip of the subducting slab is extremely shallow, 3-6°. Moment release was concentrated in two major asperities, the Prince William Sound asperity (roughly 300 by 250 km^2) and the smaller Kodiak asperity (roughly 100 by 100 km^2) to the west, with a gap of low moment release between them. Repeated leveling along Turnagain Arm of Cook Inlet, south of Anchorage, following the earthquake documented postseismic uplift at rates of up to 200 mm/year, that appeared to decay exponentially with a time constant of a few years. The timescale for the decay of postseismic deformation appears to vary with space, and at some locations there is evidence for multiple timescales, implying multiple postseismic processes. The present deformation field in and around the 1964 rupture zone is spatially heterogeneous, resulting from variations in coupling at the plate interface and the spatially-variable postseismic deformation, based on survey-mode GPS measurements made over 1993-2000.

The problem of understanding postseismic deformation cannot be separated from the problem of understanding the interseismic deformation; we always measure the sum of the two. We inverted velocities from survey mode GPS sites to determine which parts of the plate interface were locked or slipping during 1995-1999. Positive coupling in this model corresponds to locked areas, and negative coupling to areas where creep is faster than the average plate motion rate. The latter are inferred to be postseismic creep or afterslip. Two separate locked patches in the shallow seismogenic zone are clearly visible, and the postseismic creep is found downdip of the entire 1964 rupture zone (Figure 2). The two locked patches correspond to the Prince William Sound and Kodiak asperities identified from coseismic slip models, and are separated by a region of nearly zero coupling. The present pattern of shallow coupling strongly resembles the pattern of moment release as determined from the coseismic rupture models.

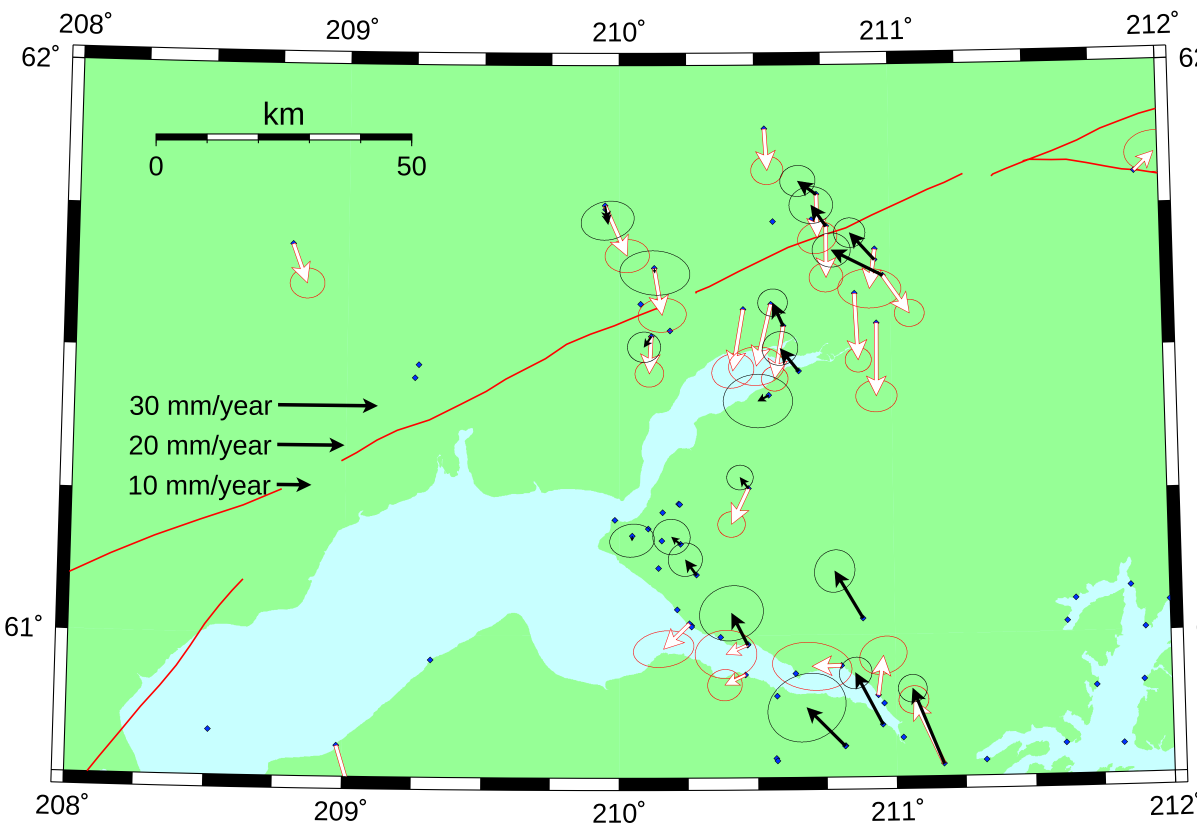

Figure 3: Velocities for the time periods 1992-1997 (solid black arrows) and 1997-2000 (hollow red arrows). All sites with horizontal velocity uncertainties less than 5 mm/year are shown.

The model finds significant creep in excess of the rate of plate motion occurring downdip of the entire 1964 rupture zone but not outside of it. The excess creep reaches up to 100% of the plate motion rate, suggesting that parts of the plate interface slip at approximately twice the rate of plate motion. It is interesting that the interface here is at a depth of 30-45 km; at many subduction zones worldwide this would be part of the shallow seismogenic zone. The area inferred to be creeping is approximately 800 km long by 150-200 km wide, and aseismically releases moment equivalent to several Hector Mine earthquakes per year. A lack of long-term uplift rules out the possibility that this pattern can be typical of the entire interseismic time period.

Fifteen survey-mode sites show a *change* in velocities of about 20-30 mm/year starting in early or mid-1998 (Figure 3). Sites that were moving northward prior to 1998 began to move rapidly southward. Elsewhere in southern Alaska the velocities of all sites are constant in time. The area where temporal changes in velocity is seen lies above an edge of the postseismic transient, and we hypothesize that the temporal variations in observed surface velocities are related to spatial migration of the postseismic transient. Comparing coupling models for 1992-1997 and 1997-2000, the major change is that there is postseismic creep on an area roughly 100 by 100 km^2 north of Anchorage in the 1997-2000 model that is absent in the pre-1997 model (hachured area in Figure 2). That is, a significant area of the plate interface that had been creeping at the average rate of plate motion suddenly accelerated to creep at approximately twice the rate of plate motion. We do not know whether this change occurred over a period of seconds, hours, days, or months, although it must have occurred over a time period less than several months. Eleven earthquakes of M_L 5.0-5.7 have occurred within 100 km of 61.5°N,149.4°W since 1995, but only three of those earthquakes was larger than M_L 5.3. Seven of the eleven occurred during 1995-1997. None of these earthquakes was large enough or close enough to a GPS site to cause significant deformation. A sudden change in velocity without a large earthquake suggests a creep mechanism for the 1998 change in velocities, but we do not know what triggered it – creep on the adjacent section? stresses resulting from viscoelastic relaxation at greater depth?

In December 1999, an M_S 7.0 earthquake (shown on Figure 1) occurred within the slab beneath Kodiak Island near the southwestern end of the 1964 rupture zone. This event is interesting because it appeared to rupture most or all of the slab with a vertical strike-slip fault, and it located directly between the updip locked patch and downdip postseismic creep. The stress pattern inferred from this rupture (downdip tension) is consistent with the stress induced by the combination of a shallow locked zone and postseismic creep, so this event may have been triggered or its time of occurrence may have been advanced by the postseismic deformation.

Outstanding Questions

• Are the temporal changes in the rate of postseismic deformation more consistent with a creep-type mechanism or a viscoelastic mechanism? If creep is the mechanism, how deeply does it extend? Does a complex interaction of viscoelastic relaxation and creep on an interface produce the dynamic changes we have already observed and hope to observe much more fully with PBO?

• What is the timescale for decay of the remaining deformation and what constraints does this place on the mechanism responsible for it? In particular, what is the timescale for the decay of creep on the patch that began creeping in 1998?

• How common are sudden spatial changes in the pattern of deformation such as the change that occurred around early 1998? How long does it take such a change occur: seconds, hours, days, or months? What is the mechanism for it? What stresses drive such changes?

• What is the three-dimensional structure of the plate boundary beneath eastern Prince William Sound and in the Yakutat block to the east? The Yakutat block at its eastern end moves 45 ± 1 mm/year relative to North America, and much of that relative motion must be taken up in faults within the Chugach-St. Elias Range. How is the transition between this collision and the standard subduction to the west accomplished?

• Can we track spatial migration of the postseismic creep?

Proposed Deployment

The number of instruments required to answer these questions depends on exactly which problem we consider to be highest priority. We used a model like that shown in Figure 2 as a basis for resolution tests to determine what station spacing for permanent sites would be required to resolve *changes* in locking or creep rate of patches of various sizes on the plate interface. The smallest resolvable patch size is related to the typical station spacing and depth of the source. Our proposed network gives good resolution for a patch size of 40 km by 40 km over the downdip edge of the locked zone and the updip edge of the postseismic creep, where the network has a station spacing of 50 km or less. For a patch size of 20 km by 20 km, resolution is good only for the densest part of the network. This analysis only shows what sort of signal the network is capable of detecting; whether or not a particular signal would out visible above the noise requires a separate analysis. We also tested the resolution assuming that the number of stations was cut in half but the same area covered; in this case the resolving power of the network is seriously degraded.

We propose a three-tiered GPS deployment that takes advantage of what we already know from the extensive survey-mode GPS work. In the accessible land areas we start with a typical permanent station spacing of about 50 km, and reduce this spacing to 15-30 km above the updip edge of the postseismic creep, in the areas where infrastructure makes this feasible. In the area where velocities changed around early 1998, we propose the highest density of sites so that we can study the temporal decay of this deformation. The third tier of sites are densification sites using survey-mode measurements. These will be required to improve resolution of steady-state processes. The proposed permanent network features a modest number of GPS sites that lie over or adjacent to the asperities in Prince William Sound and Kodiak Island, which probably will record steady motion with time. Existing data do not delimit the Kodiak asperity well, and this deployment will give us significantly better resolution in that area. Additional densification through survey mode measurements will be required to better. Over the Kenai Peninsula those denser measurements mostly exist. New dense survey-mode measurements are required in Prince William Sound and the area of the Yakutat block collision, and also in the Kodiak Island region. Due to the inaccessible terrain and heavy snowfall only a few locations in these areas are suitable for cost-effective permanent sites. Other terrain restrictions (rugged mountains, large swamps, etc.) limit the density of the proposed network in other areas.

We propose to extend the network far enough away from the rupture zone that we will be able to see deformation that may result from viscoelastic relaxation, although by necessity the sites are very sparse in the largely uninhabited Alaska Range. We propose to locate sites near all permanent tide gauges so that long-term uplift rates can be compared with relative sea level records, some of which are continuous since the time of the earthquake. We incorporated realistic assessments of the local infrastructure and terrain in design of the network, so all dots represent real places where sites are possible rather than idealized equally-spaced sites. The complete network of permanent sites is shown in Figure 1.

This network is not designed to saturate the entire area with sites – it is less dense than our present survey-mode network except on Kodiak Island – but is targeted at places where *changes* in velocities are most likely to be observed: near the edges of the observed postseismic creep and especially where we have already observed changes in velocities. That is, we assume that the areas presently locked are unlikely to become unlocked except in case of an earthquake, but that areas near those present experiencing postseismic creep are likely to display more dynamic behavior – at a minimum the postseismic deformation rate will decay with time. We use this conservative approach because the ideal network would require such a high percentage of the non-SAF PBO resources – more than 200 sites would be needed just to maintain a uniform 30 km spacing over the area where significant deformation is expected – that PBO would be unlikely to support it.

Our resolution tests suggest that our proposed network is the *minimum* network required to address the questions we have posed. If the number of sites in the network were reduced, we would not be able to maintain acceptable resolution over the entire area where time-dependent deformation will occur. In fact, resolution tests show that if the number of sites is changed, the network should have more sites rather than fewer sites. However, if sites were added beyond those proposed, most would have to be more expensive, remote power and communications sites off the road network. These sites are more expensive but certainly feasible. Access by helicopter or boat makes site visits expensive, but is not a limiting cost if installation and maintenance is well-planned. For many “remote” sites (red dots on Figure 1) there is no land-line telephone service, but digital cellular coverage allows us to download by cell phone for reasonable cost, no more than long-distance phone charges. Cellular communications is especially useful for remote sites near major waterways like Cook Inlet and Prince William Sound. Remotely powered sites will require solar panels augmented by wind generators or fuel cells.