Coupling, Slip Partitioning and Arc Deformation Along the Aleutian Subduction zone

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Equipment Needed: 30 GPS receivers, 30 broad-band and strong motion seismographs.

More than 99% of the historic seismic moment release in the Pacific-North America plate boundary zone has occurred along the Alaska-Aleutian trench. This region, one of the world's great subduction zones, must be a focus of the PBO. Instrumentation of this region will create a facility capable of addressing three fundamental interrelated subduction plate boundary problems: the nature of coupling along the plate boundary, the extent to which slip partitioning occurs where subduction is oblique, and the near-field study of M~8 or larger earthquakes. Provided the far-field velocity of the overriding plate (Bering Sea plate or North American plate) is known, even deformation of an approximately one-dimensional array of sites can provide a first order mapping of the strength of seismic coupling, and when densified by survey mode measurements and complemented by geologic structural analysis, can be a powerful tool to study slip partitioning and the arc stretching that accompanies it. Finally, during the ten year period of the PBO facility it is very likely that an M8+ great earthquake will occur along this boundary. We expect several sites within the relatively sparse GPS network we propose to show significant displacements given the typical rupture length and slip of such events.

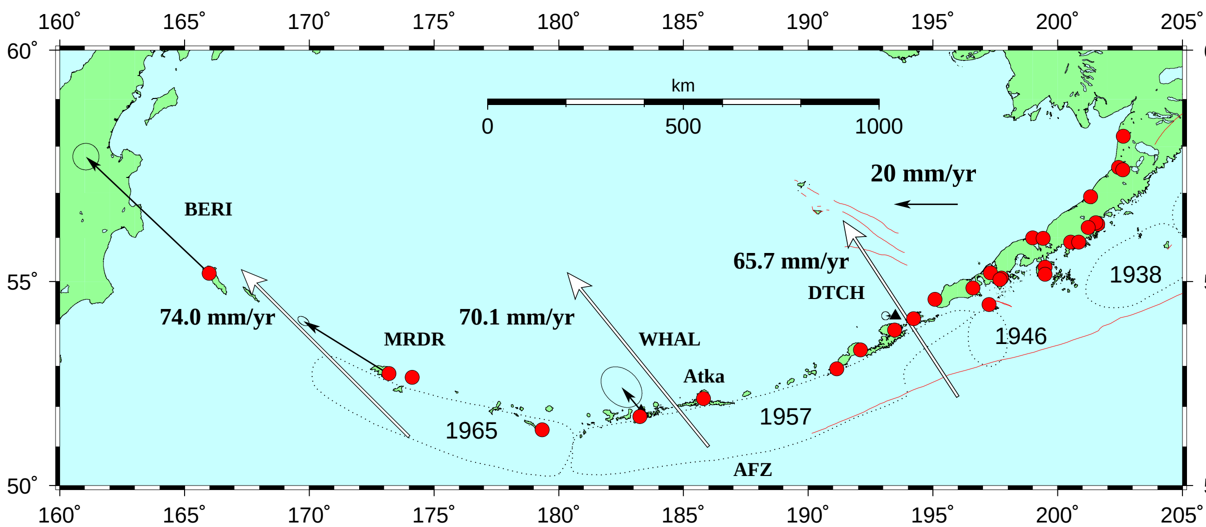

Figure 1: Aftershock areas of large and great earthquakes along the Aleutian-Alaskan subduction zone. White arrows indicate relative plate motions, and black arrows GPS velocities from survey-mode sites. Major earthquake ruptures are outlined. AFZ: Amlia Fracture Zone.

The GPS deployment should be complemented by collocated broadband and strong motion seismometers; together these instruments will constrain slip models and provide a wealth of new scientific and engineering data about great earthquakes. Both from the point of view of science and hazards, a joint geodetic and seismic observatory is desirable. Currently, there is only one (US Coast Guard) permanent GPS site in the study area, only three broadband seismometers, and eight short-period, single component, low dynamic range seismic networks on active volcanoes. This level of instrumentation falls far short of what is required to seriously study one of the world's most significant and active plate boundaries.

Background

The Alaskan-Aleutian plate boundary is 4000 km long. Subduction along it has caused some of the largest earthquake ruptures on this planet. The great earthquakes of 1964, 1957 and 1965 are all M9 class events and rank globally among the six largest historic earthquakes (Figure 1). Their rupture lengths range from 600 to 1000 km, and their average slip ranged from 3 to 20 m. At a 6 to 7.5 cm/year convergence rate, the potential slip accumulated in plate boundary segments that have not ruptured since 1938 (or about 1960 in much of the arc) ranges from 2.5 to 3.5 m and will increase by another 0.8 m by the end of the PBO project (unless released in earthquakes). Even in the 1964 rupture zone, the slip deficit is probably sufficient to cause an M8-class earthquake if the entire Prince William Sound asperity re-ruptured today.

Ten great earthquakes have occurred along this plate boundary since 1900. Some of this activity was concentrated in the three periods 1890-1906, 1929-1938 and 1957-1965. If we randomly select ten-year intervals from the 100-year record, only 25% of these intervals do *not* contain a magnitude 8 class earthquake. An almost equal fraction of the randomly selected intervals have two or more events. We conclude that it is likely that one or more great earthquakes (M8 class) will occur along this plate boundary during the PBO project. The high level of activity affords PBO a unique opportunity to gather data critical for making progress in understanding great earthquakes and the seismic hazard they pose by installing geodetic and seismographic sensors that will record coseismic slip and interseismic deformation over a wider frequency band.

Although the overall rate of moment release along the Aleutian arc is enormous, seismic coupling may not be uniform along the arc. There are gaps where no great earthquakes have occurred for many decades, and slip in some of the great events was surprisingly low: for example, the 1957 earthquake appears to have had only 2 m of slip near both Adak and Dutch Harbor, despite its more than 1000 km long rupture. Aftershock distributions show considerable spatial complexity. Recent geodetic work on plate coupling in Alaska demonstrates that to first order, the coupling is mostly either 0 or 100% where it has been studied over the eastern 1200 km of the arc. Furthermore, the geodetic coupling distribution is strongly correlated with the moment release distribution of the last great earthquakes. This allows us to use GPS measurements, either of strains or absolute motions relative to the far-field overriding plate, to map the locations of locked patches that may represent seismic asperities.

The angle of subduction in the Aleutians varies from trench-normal to nearly trench-parallel. In the western Aleutians the plates move obliquely, giving rise to complex tectonics. Where relative convergence between two lithospheric plates is oblique to the plate boundary, deformation is often partitioned into boundary-normal and boundary-parallel components. The result is displacement of the frontal portion of the overriding plate with respect to the backarc region along arc-parallel strike-slip faults. Boundary-parallel translation of the upper-plate assemblage typically is accompanied by internal shortening along an axis oriented at a high-angle to the trench. The Aleutian arc is one of the best convergent plate boundaries in which to characterize this tectonic process, because of the variation in convergence direction and several other factors.

Understanding this process requires GPS velocities, accurate earthquake locations and moment tensor solutions, and geologic investigations. Structural analysis of deformed rocks on several Aleutian Islands, published bathymetric and seismic reflection data, GPS velocities and earthquake focal mechanisms suggest that displacement partitioning has occurred along the Aleutian arc in the past and is still active today. At Unalaska, the velocity is 3.1 ± 1.2 mm/year toward N90°W ± 17.5°. Farther west, Adak shows an increased velocity of 9.6 ± 8.0 mm/year toward N39°W ± 25°. At the western end of the Aleutian chain, Attu records a velocity of 31.4 ± 3.0 mm/year toward N57°W ± 2.5°, about 49% of the Pacific–North America relative plate motion.

Bering Island, on the Russian side of the border, moves at almost full Pacific plate velocity. All of these are consistent with active slip partitioning except for Adak, where partitioning may be disturbed by subduction of the Amlia Fracture Zone.

Unresolved Problems

• *Plate coupling.* How does plate coupling vary along the length of the arc? Do the parts of the plate interface that are presently locked and unlocked correlate with areas of high and low seismic moment release over the entire length of the arc, or is the agreement over the eastern 1200 km coincidental?

• *The eastern parts of the 1957 great rupture*. This earthquake had unusually small slip for such a large magnitude event, and two M8 class earthquakes have already re-ruptured the western part of the aftershock area in 1986 and 1996. What is the distribution of locked and unlocked segments of the 1957 rupture zone? Can this help to explain how the 1957 event was able to rupture such a long distance despite only 3 m average slip?

• *Oblique Convergence.* What parameters control the partitioning process in oblique convergence? How sensitive are these processes to convergence obliquity? Is the subduction of the Amlia fracture zone responsible for the anomalous velocities of Adak Island? How much do the Aleutian Islands rotate? How much of the displacements represent permanent deformation?

• *Development of arc systems.* What is the current rate of stretching of the Aleutian arc and how does it compare to rates inferred from structural analysis, and what is the role of longitudinal extension in the development and deformation of arc systems?

• *Near-field geodetic and seismic recording of M8-class earthquakes.* Several segments of the Aleutian trench are likely candidates for M8-class earthquakes within the next decade, including the eastern half of the 1957 rupture. In particular, if the plate boundary segment that ruptured in the 1938 M8+ segment (Figure 1) has been locked since the occurrence of that earthquake, as it appears to be now, that segment has the potential for an earthquake with almost 4 m slip.

• *The Shumagin segment.* Although the Shumagin segment is largely unlocked today, it has participated in an M8-class earthquake at least once. Are there variations in time in the behavior of this segment? The existing geodetic data allow the possibility of a locked patch offshore, close to the trench; does such a region exist? Seafloor geodetic observations in this area are required.

Measurement Objectives: (1) Record the steady-state crustal deformation using GPS. (2) Define locked and freely slipping segments by modeling geodetic and seismological data (variation of deformation vectors, differences in directions of principal stresses and local recurrence time anomalies), and study partitioning and arc deformation. (3) Record the time history of surface displacement before, during, and after great thrust earthquakes (scale of minutes to years) using continuous GPS measurements. (4) Make on-scale recording of time series of weak and strong ground motions in large to great earthquakes by seismographs. (5) Record background microseismicity along the megathrust and in the deep seismic zone (6) Model details of earthquake ruptures (moment release along strike) and correlate them with asperities modeled using geodetic and seismological background data. (7) Model the relationship of seismicity in deep seismic zones with arc volcanism. These instruments would also allow valuable hazard-related studies: (8) Estimate the potential for tsunami generation in real time when a large rupture occurs. (9) Provide time series of strong ground motion for M8+ earthquakes for use by the engineering community to model expected shaking for critical structures in the case of the megathrust events that have to be expected not only in Alaska, but also in the Cascadia subduction zone.

Deployment of Instruments

Because the Aleutian plate boundary can only be accessed on relatively remote islands, there are not too many potential locations for deploying permanent instruments. For this reason we propose sparse coverage of the 4000 km long plate boundary (Figure 1). Table 1 is a list of all readily accessible locations known to us that have the facilities necessary to run seismographs and GPS receivers without undue difficulty. Of these sites, some already have short period seismographs. We propose that we install one seismograph in each of the locations that do not have a broad-band station, together with a GPS station and that two additional stations be established on islands large enough for additional stations. This sums up to a total of 30 GPS receivers and seismographs, a truly minimal effort given the scientific payoffs. In addition, a permanent site on Bering Island in the Komandorskiye Islands (Russian part of the arc) has operated for a few years but is now without long-term support or reliable communications. We propose that this site be upgraded or replaced with a new site installed by PBO; the tectonics do not stop at the border.

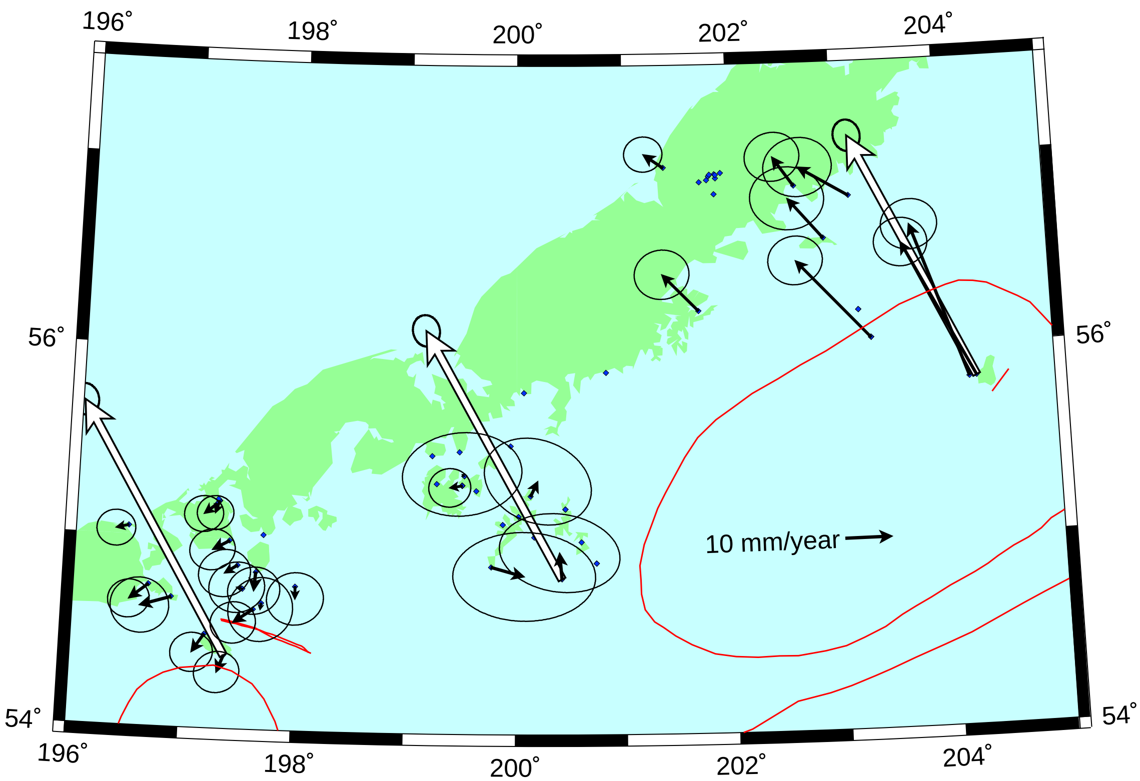

Figure 2. Velocities relative to North America of sites along the Alaska Peninsula.

Everywhere in the PBO region, except for the Aleutians, there is a seismic network already in place with a site density in reasonable proportion with the rate of seismicity. In the Aleutians the network is exceptionally poor, and thus earthquake catalogs have a magnitude of completeness M_C~4 instead of M_C<2 typical for other seismically active areas. To fully integrate geodetic and seismological data, it is necessary for PBO to install modern seismographic equipment along with the GPS receivers. PBO will be deploying quite a few seismometers in boreholes; the only difference in our request is that we do not require borehole installations. Neither ANSS nor USArray have shown any inclination to instrument the Aleutians (and in any case USArray is too short a deployment). ANSS appears to be mandated by the USGS to focus on urban hazards; a significant ANSS deployment anywhere in Alaska is not guaranteed.

A largely linear array of instruments would result from instrumentation of all the locations in Table 1, which might seem inadequate to resolve variations in plate coupling. However, if we know the velocities of Aleutian sites relative to the far–field on the overriding plate, we can still make a first-order inference about plate coupling. In the case of the Aleutians the overriding plate is either the North American plate or Bering Sea plate. The arc-parallel motion seen in Figure 2 (especially for the western sites) may be a result of Bering Sea plate motion, but could also reflect the translation of a sliver of the forearc and arc, or of a section of the Bering Sea crust as well. The PBO backbone network must include sites in western Alaska and the inhabited Bering Sea islands, and the proposed Western Alaska cluster would add more sites. Figure 2 shows the strong contrast in velocities between the 1938 rupture segment and the Shumagin seismic gap, where little strain is observed. It is straightforward to see the difference between a strongly coupled segment and a weakly coupled segment, even from a single site. The first-order inferences about coupling and partitioning from the permanent sites can be strengthened through additional survey-mode measurements.

To fully answer the questions we have posed will require more than just permanent GPS and seismographs. Local survey-mode networks should be observed to measure the strain rate around each permanent site. If this strain results from coupling at the subduction zone, the orientation of the maximum compressive strain will indicate the direction of convergence between the Pacific plate and the forearc/arc. Small survey-mode networks could be observed at very low cost whenever the PBO instruments are serviced (the cost of getting to the site is much more than the cost of staying there for a few days). Even as little as a day or two of survey-mode data every year or two for a decade will produce excellent measures of local strain.

Structural analysis of the deformed rocks are a key component because they allow comparison of the instantaneous deformation measured by GPS with the cumulative deformation over recent geologic time. This effort plays a role similar to the paleoseismological investigations that will be undertaken in other areas. Paleoseismological measurements are important in the Aleutians as well. Unlike the case where faults are exposed subaerially, when studying earthquake recurrence histories at subduction zones the record of great earthquakes usually comes from marshes or estuaries where evidence for sudden subsidence can be preserved. These studies can provide a geological context for instantaneous deformation measurements, and can be used to infer whether the coupling measured today is typical of the long term.

Table 1: Possible Seismic Station Locations on the Aleutians and the Alaska Peninsula.

Location	Lat	Long	Tel	AC	Seis	Location	Lat	Long	Tel	AC	Seis
Adak	51º45'	-176º45'	√	√	BB	Ivanof Bay	55º54'	-159º29'	√	√	
Akutan	54º08'	-165º46'	√	√	SP	King Cove	55º03'	-162º19'	√	√	SP
Amchitka	51º 25'	179º20'				Nelson Lagoon	56º00'	-161º00'	√	√	
Atka	52º12'	-174º12'	√	√		Nikolski	52º56'	-168º51'	√	√	
Attu	52º49'	173º11'		√	SP	Pauloff Harbor	54º28'	-162º45'			
Belkofski	55º05'	-162º15'				Perryville	55º54'	-159º09'	√	√	
Cape Sarichef	54º35'	-164º55'				Pilot Point	57º33'	-157º34'	√	√	
Cold Bay	55º12'	-162º42'	√	√	SP	Port Heiden	56º55'	-158º41'	√	√	SP
Chignik	56º18'	-158º24'	√	√		Port Moller	55º59'	-160º35'	√	√	
Chignik Lagoon	56º20'	-158º29'	√	√		Sand Point	55º20'	-160º30'	√	√	SP
Chignik Lake	56º14'	-158º47'	√	√		Shemya	52º43'	174º07'	√	√	BB
Egegik	58º13'	-157º22'	√	√		Ugashik	57º30'	-157º23'	?	?	
False Pass	54º51'	-163º24'	√	√		Unalaska	53º52'	-166º32'	√	√	BB
Fort Glenn	53º23'	-167º54'		√		Unga	55º10'	-160º30'			