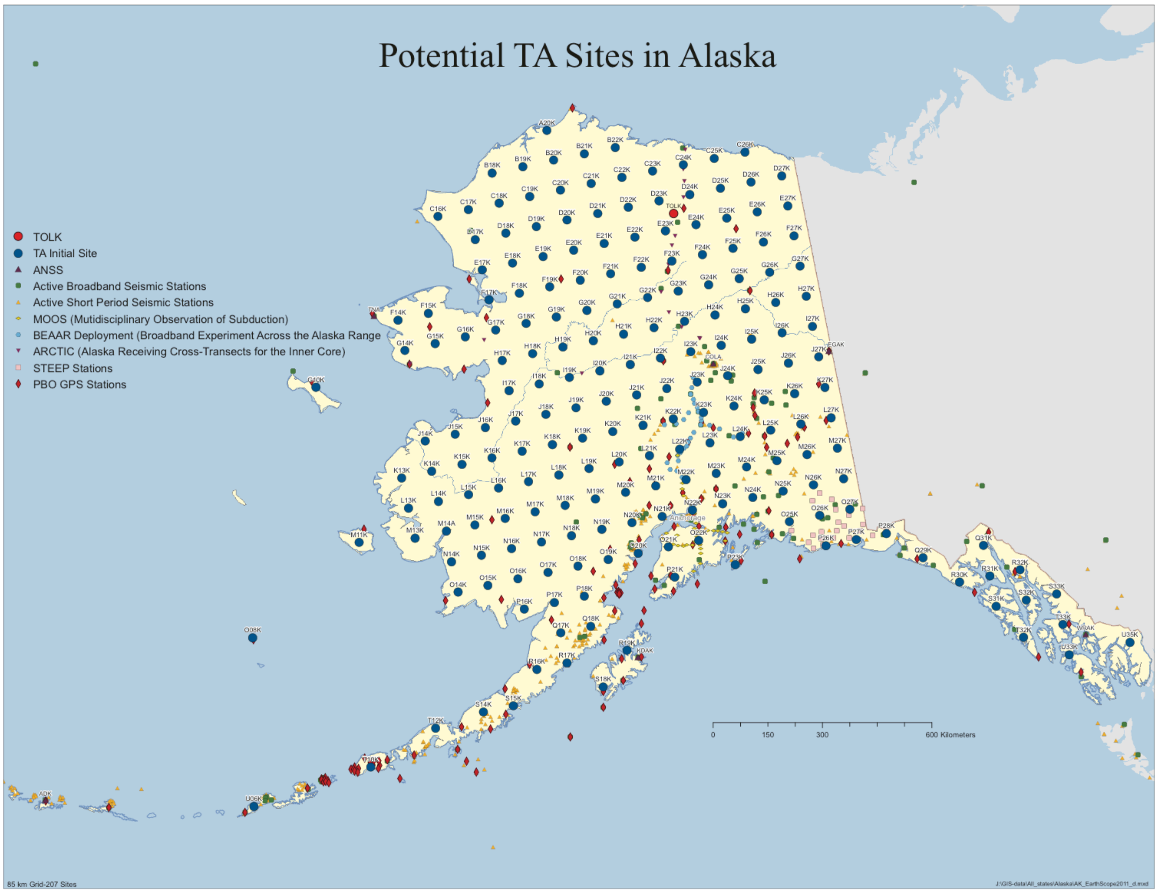
Opportunities for EarthScope Science in Alaska in Anticipation of USArray

Workshop held May 16-17, 2011 in Austin, Texas

FINAL REPORT 10/5/11

"The scale of EarthScope is ideal for Alaska"



Workshop Conveners and Organizing Committee: Jeff Freymueller, Sean Gulick, Doug Christensen, Peter Haeussler, Roger Hansen, Stephane Mazzotti, Steve McNutt, Gary Pavlis, Terry Pavlis, Sarah Roeske, Jeanne M. Sauber-Rosenberg, Donna Shillington, Carl Tape, and Michael West.

Executive Summary

The workshop on EarthScope science opportunities in Alaska was held in Austin, Texas in May 2011 and covered the day and half preceding the EarthScope national meeting. It Involved 76 attendees, some of whom came to Austin solely for the workshop. The workshop was organized into three plenary sessions, a series of 5-minute mini-talks drawn from the 32 submitted white papers, and five breakout groups examining critical science questions, suggesting EarthScope Transportable Array deployment strategies and priorities, and discussing ancillary measurements and key strategic partners for EarthScope in Alaska. In this workshop report we include a description of the meeting, an overview of crustal history and tectonics, a summary of neotectonics and geohazards, a description of earthquake rates and resultant imaging potential, the science discussions from the workshop, logistical suggestions that grew out of these breakouts, and a list of synergies and partnerships such as those with Canada, GeoPRISMS, AVO, AEIC, and others.

Alaska is an excellent target for EarthScope due to its diverse crustal structure and geologic history. The Alaska crust was built by successive subduction-to-arc systems and accreting terranes combined with 1000s of kilometers of strike-slip motion on continental-scale fault systems. In terms of active tectonics, all parts of Alaska are currently moving relative to stable North America and active seismicity spans most of the state and surrounding areas. There are ~5x the number of earthquakes within Alaska each year as in all of the lower 48 states combined, and there is significant potential for hazardous high-magnitude subduction earthquakes and tsunamis as well as strike-slip earthquakes and volcanic eruptions.

In many ways Alaska is a geoscience frontier with enormous area never having been studied beyond reconnaissance level; large areas devoid of instrumentation of any kind, either campaign or permanent deployments, such that the crustal structure remains to be determined and areas of certain or possible active tectonics lack any precise earthquake locations. The tens of thousands of earthquakes in a single year in Alaska also provide a remarkable set of sources for study of the crustal structure, volcanic centers, and major faults systems throughout the region. There is also a high likelihood of recording a magnitude 7 or larger event within the TA deployment.

Key globally relevant science topics that can be addressed in Alaska include: *the presence and role of relic slabs and arcs, strike-slip boundaries as lithospheric scale structures, mantle flow around slab edges, differences between oceanic and continental arcs, causes of earthquake rupture segments and the boundaries between them, what processes control deformation spatially and temporally, imaging magma ascent from the slab to the surface, magma storage within the shallow crust and its ascent to eruption, examining the lithospheric process of flat-slab subduction, terrane accretion, and far-field deformation, determining any relationship between seismicity and rock uplift, effects of glacial unloading, and using seismometers to investigate ice quakes, land slides, and sea ice changes.*

Logistical recommendations reached by consensus of the attendees were that EarthScope should *maintain comprehensive coverage (70 km spacing where practical) but allow flexibility where an individual site is too costly, include a backbone array spanning the Alaska Peninsula and Aleutians, consider some deviations from a grid in the form of small* *arrays centered on a standard TA station, prioritize the number of stations over real-time/rapid access to data due to the frontier environment, and to examine the possibility of including meteorological packages and strong motion sensors on some of the TA stations.*

Workshop Organization

A workshop focused on EarthScope science opportunities in Alaska was held in May 2011 in Austin, Texas, in conjunction with the EarthScope National Meeting. The workshop lasted 1.5 days in total, with a combination of talks, plenary discussion periods, and breakout sessions. Invited speakers were paired up, so that each talk was prepared and presented by two authors from different disciplines. This approach was successful in integrating viewpoints across disciplines, and the pairs of authors chose a variety of strategies for the presentations. Presenters selected from the white papers solicited from all attendees gave a series of 5-minute mini-talks. The workshop also featured several breakout sessions to highlight exceptional scientific opportunities and integration with other projects, especially GeoPRISMS. The complete meeting agenda is given at the end of the report.

The first morning featured two sessions of plenary talks followed by discussion. The afternoon featured several mini-talks, followed by two hours of breakout group discussions. It concluded with another session of plenary talks (and discussion). After dinner we held an informal poster session. The second morning featured an additional two hours of breakout group discussions, with a different set of breakout groups. This was followed by breakout reports, and some general discussion that focused on recommendations for the USArrray and on potential scientific partnerships that could be explored.

The workshop featured three plenary sessions:

- "Tectonics, History and Structure" covered the geologic history and active tectonics of Alaska, setting the stage for further discussions of seismic imaging possibilities and for studies of active processes.
- "Testing Hypotheses Developed in the Lower 48" focused on three of the scientific problems or discoveries that have been a focus of EarthScope research to date, mantle flow at slab edges, history and effects of slabs under North America, and tremor and slow slip. We asked speakers, some of whom had not previously focused on Alaska, to address how data from Alaska could be used to test hypotheses developed in comparable regions in the lower 48.
- "Active Processes Modifying the Continent" focused on volcanism and earthquakes/tectonics. Alaska is by far the most geologically active part of North America by essentially any standard.

Participants

A total of 76 participants attended the workshop, with most of those attending for both days. This number represented nearly 25% of the attendance at the EarthScope National Meeting, which followed immediately after, although several workshop participants came only for the Alaska workshop.

A complete list of the participants is given in an appendix.

Overview of Crustal History and Tectonics

The northern Cordillera, in particular the western Yukon, across Alaska and into Siberia, can broadly be considered a plate boundary zone and active tectonics impact the region as far as 1200 km in from the trench. This region is a textbook place to study the wide range of variables that control continental deformation, in particular the role of plate boundary interactions, mantle flow, and crustal rheology.

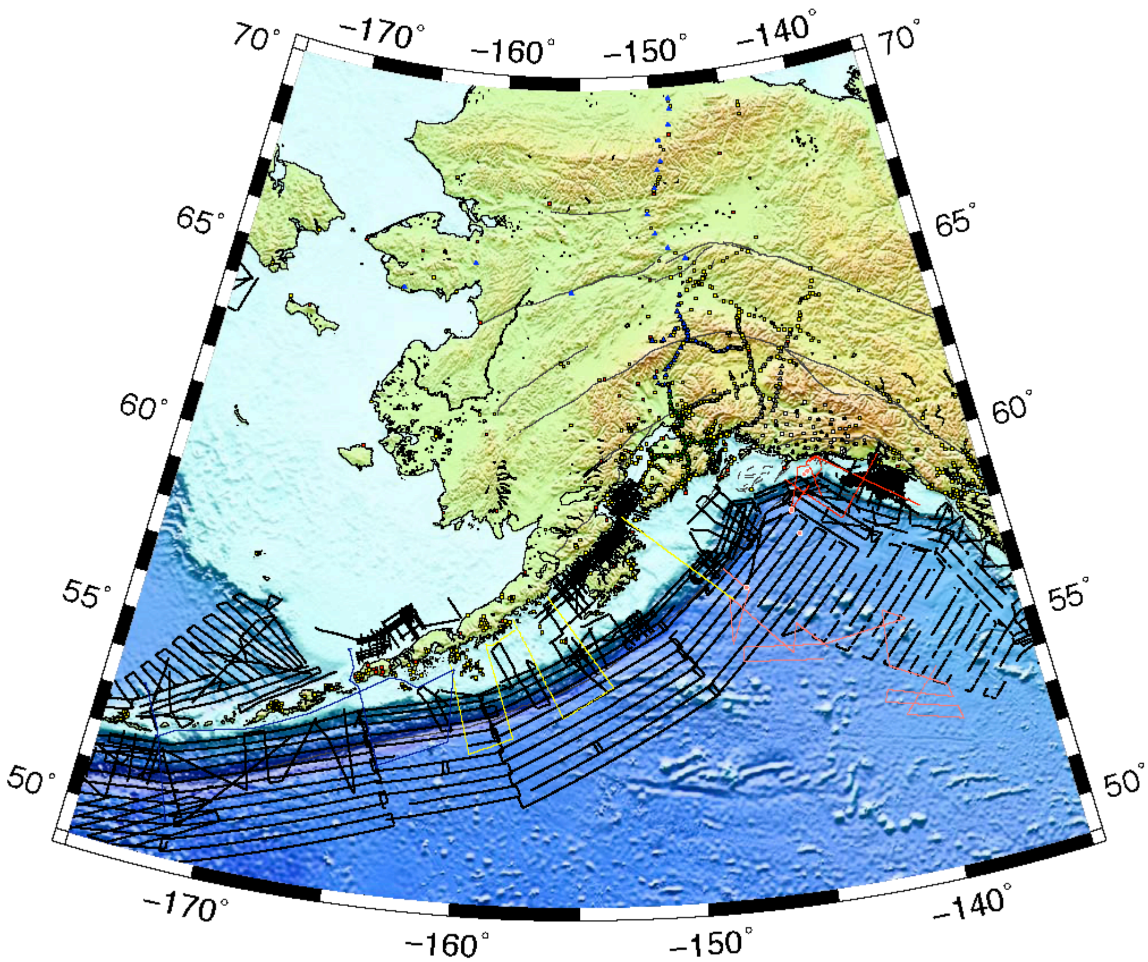


Figure 1. Summary of geophysical experiments in Alaska acquired or planned as of the workshop (Courtesy of Lindsay Worthington). Small symbols on land include both permanent and temporary seismic and GPS stations, and effectively map out the extent of the road system. The TACT transect extended from the Pacific coast to the Arctic coast.

The diverse nature of the Alaskan crust, both in composition and thickness, and the presence of long-lived rheological boundaries expressed as large-scale strike-slip faults, may have profound influence on the focusing of crustal strain. Our current knowledge of the crustal character of Alaska is based on a blend of potential field and regional mapping (scales of 1:250,000 and locally smaller). Large swaths of interior and western Alaska are heavily vegetated, so the sparse geophysical transects (TACT, BEAAR, and MOOS, shown along the roads in Figure 1) have been key in helping us interpret the potential field results.

EarthScope holds the promise of resolving specific debates about tectonic boundaries and current lithosphere and mantle conditions in the better-studied areas of southern and central Alaska and the pipeline corridor. Data from much of the western and northern part of the state is sparse (Figure 1), thus it is a true frontier for science, and EarthScope will provide much needed constraints on existing tectonic hypotheses on the nature of the lithosphere in this region. This section outlines a basic geologic framework of the region that is the authors' interpretation of the above data sets combined with the geologic history, in order to provide a simplified overview of the crustal composition of the northern Cordillera margin.

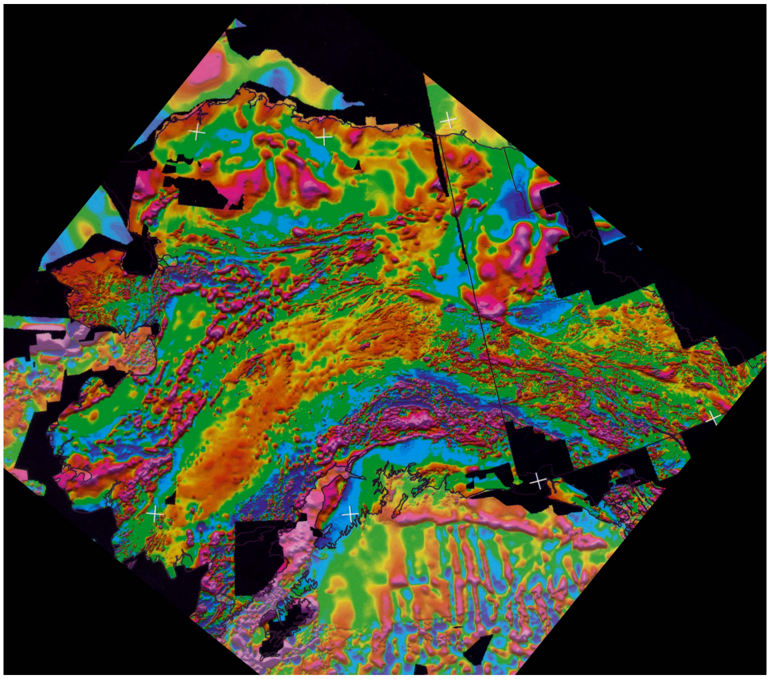


Figure 2. Magnetic field map of northern Cordillera, extracted from the Magnetic Anomaly map of North America (North American Magnetic Anomaly Group, 2002). The map spans about 2500 km by 2500 km, from the Pacific plate in the south to the southern Arctic Ocean in the north.

The magnetic anomaly map of the region (Figure 2), combined with a simplified, interpreted version of the terrane map (Figure 3), highlights the composite character of Alaska crust and gives geologists more confidence in extending the bedrock geology under vast regions of tundra and muskeg. These two maps, combined with the knowledge of the regional geologic history, allow us to subdivide the state broadly into three regions, each of which contains a history of convergence and collision (Figure 4). The boundaries between the regions are currently faults of great regional extent, which have a long-lived history dominated by Late Cretaceous through Cenozoic dextral strike-slip displacement. Total amounts of displacement are poorly known because the faults run parallel to the strike of the major units and few lithologic units are unique enough to provide piercing points. Most of these faults have received limited study; there are opportunities for significant discoveries in future EarthScope research.

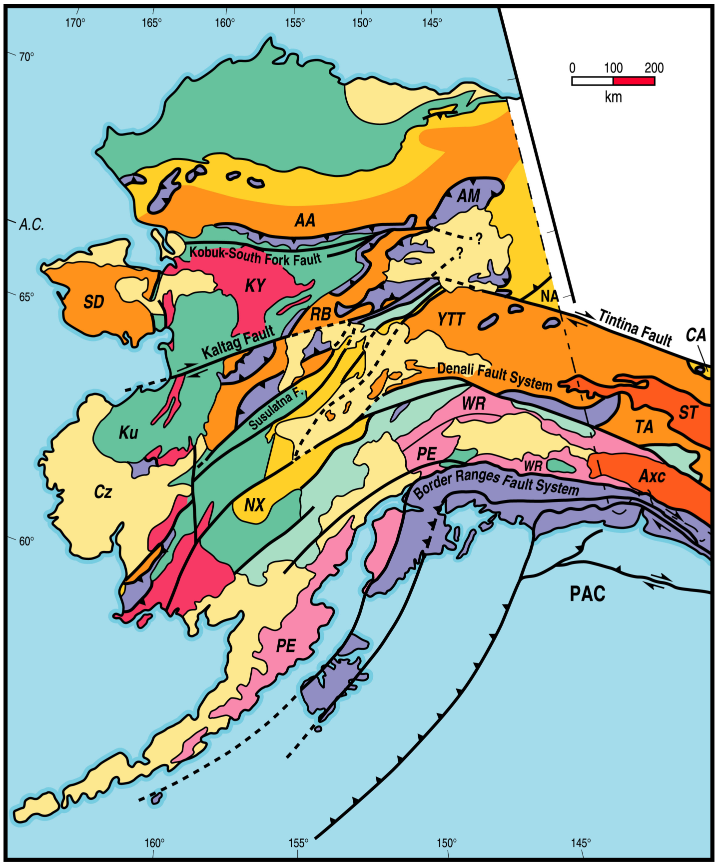


Figure 3 Simplified and interpretive terrane map of Alaska, compiled by S. Roeske, drawn by Janice C. Fong/UC Davis Geology. Terrane color codes and names: Dark to light orange – continental crust or crustal fragment, AA=Arctic Alaska; NX= Nixon Fork-Farewell; RB = Ruby; SD=Seward; TA=Taku; YTT= Yukon-Tanana composite; Red-Orange – composite arc-continental block fragment, Axc=Alexander; ST=Stikine. Red-Pink – Mafic to intermediate composition igneous rock, arc and rift related, KY=Koyukuk. PE=Peninsular (part of Wrangellia composite terrane); WR=Wrangellia. Purple – Accretionary prism and other off-scraped or obducted oceanic material, locally including extensive mafic-ultramafic complexes, AM= Angayucham, also modern system. Pale green – Marine sedimentary basins formed prior to and during terrane accretion. Green – Sedimentary basins, dominantly marine, formed during and after terrane accretion, Ku=Kuskokwim. Pale yellow – Quaternary deposits. Blue – Offshore tectonic elements, PAC=Pacific Plate.

The southern Alaska margin preserves a 200 million year history of episodic subduction and accretion processes along the outer side (south in today's coordinates) (Plafker et al., 1994). The Border Ranges fault system (Pavlis and Roeske, 2007) separates the accretionary margin from mafic crust of the Wrangellia composite terrane. The Wrangellia composite terrane in southern Alaska has a late Paleozoic arc basement overlain by Triassic basalt and Jurassic and Cretaceous volcanic arc rocks. The thickness and composition of Wrangellia crust is documented along a few discrete transect lines (TACT, BEAAR, MOOS, Figure 1) (Fuis et al., 1991; Veenstra et al., 2006) and regional extrapolation (Eberhart-Phillips et al, 2006) indicates varying thickness but overall between ~ 30-50 km, with locally deeper roots to 55-60 km. The strong magnetic anomaly along the boundary between the arc and the forearc, the Border Ranges fault system, indicates the continuity of the fault system from southwest of the Kodiak Islands to southeast Alaska. The fault originated at the forearc-accretionary prism boundary and subsequently reactivated as a strike-slip fault in the Late Cretaceous-Paleogene. Geologic offsets indicate a minimum of ~600 km of dextral offset but could be much greater (Roeske et al., 2003).

The Chugach accretionary complex has been modified by Early Cenozoic ridge subduction (see Sisson et al., 2003 GSA volume) and strike-slip, but no significant collision is thought to have occurred along this margin until the Neogene arrival of the Yakutat terrane along the southeastern margin. This buoyant block has a distinct high magnetic anomaly (Fig. 1) associated with a thick section of Eocene mafic rock. This magnetic signature, combined with results from the BEAAR and MOOS passive arrays, show the trace of the Yakutat subducting slab extending well into central Alaska, to near the vicinity of the Denali fault (Schwab et al., 1980; Bruns, 1983; Ferris et al., 2003). The crust of the Yakutat terrane appears to be a remnant of an oceanic plateau, with thick mafic crust covered with sediments derived from the North American continental margin (Christeson et al., 2010).

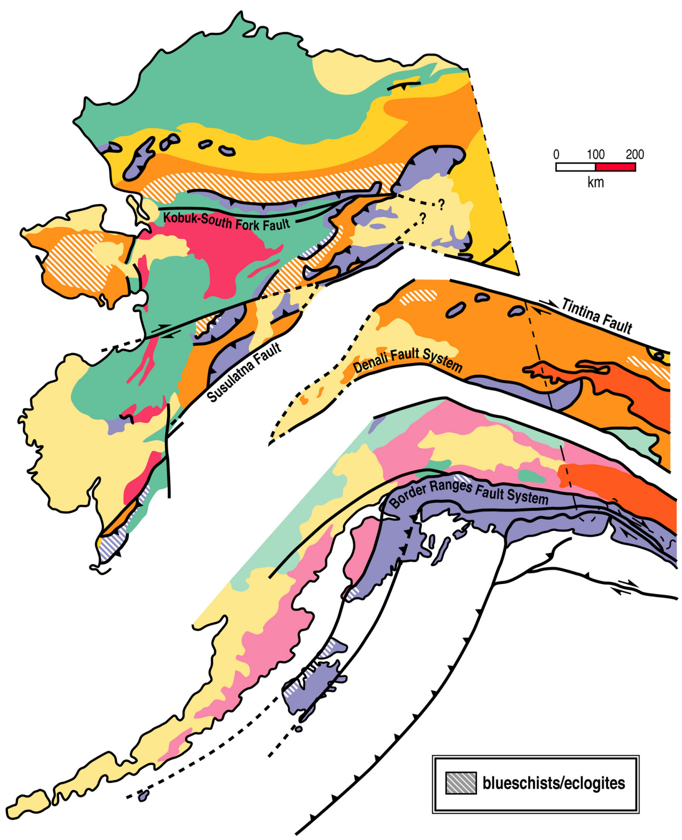


Figure 4. Terrane map of Alaska split into 3 provinces of convergence/collision. Compiled by S. Roeske, drawn by Janice C. Fong/UC Davis Geology

Our knowledge of the central Alaska tectonic history is more limited due to poor exposure and limited geophysical data. The warm colors that occur as a swath across the center of the state on the Figure 3 coincide well with the neutral region of magnetic anomalies (~0 nT) on the Figure 2 and indicate the whole region is underlain by crust of sialic composition. The boundaries of this region are the Tintina and Susulatna faults in the north and the Denali fault system in the south. The western portion of this area, the Yukon-Tanana composite terrane, has a late Paleozoic through mid-Mesozoic history of collision between continental blocks with most crustal exposure today being mid-continental crust. This collisional history involved more-inboard material (Tempelman-Kluit, 1979; Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002) and the record of the collision was modified by a combination of extensional and strike-slip faulting. The relatively thin (~25-30 km) (Beaudoin et al., 1994; Veenstra et al., 2006) crust in this region may be inherited from post-collision extension in the mid-Cretaceous (Pavlis et al., 1993). The Tintina fault system along the northern boundary of this collisional system has a minimum of 450 km of dextral displacement in the Late Cretaceous through the Eocene (Tempelman-Kluit, 1979; Hansen, 1990). The Tintina can be traced through most of the northern Cordillera, into extensional complexes in southern British Columbia and is one of the most continuous and best-defined magnetic lineaments in the Cordillera (Gabrielse, 1985; Pavlis, 1989; NAMAG, 2002). The western extent of the Yukon Tanana composite terrane is not well-known, and further west and south the Proterozoic, Paleozoic and lower Mesozoic rocks of the Farewell terrane preserve shallow to deep marine rocks with continental affinity locally overlying a Proterozoic basement (Decker et al., 1994; Bradley et al., 2003). The thickness of the crust is unknown throughout this western and southwest region, and the boundaries between the mafic rocks of island arc affinity (red on Figure 3) are also unknown. The southern boundary of central Alaska's continental crust region is the Denali fault system, which is a series of active and inactive faults that mark Late Mesozoic closure of an ocean basin between the juvenile southern Alaska material and the more evolved crust of interior Alaska. Extensive sedimentary deposits within the suture zone (pale green on Figure 3) record pre-, syn-, and post-collisional evolution of this region (van der Heyden, 1992; Ridgway et al., 2002; Hampton et al. 2010). The moderate magnetic low associated with the basin (Figure 2) may mark transitional crust between Wrangellia and interior Alaska, in sharp contrast to the magnetic high associated with the mafic crust to the south (Figure 2).

Cretaceous through Cenozoic strike-slip displacement has extensively modified the suture zone, with perhaps sinistral slip in the early Cretaceous (Monger et al., 1994; Gehrels et al., 2009) and (better documented) dextral slip in the Cenozoic (St. Amand, 1957; Grantz, 1966, Miller et al., 2002, and others). Total displacement on the Denali fault system since the Late Cretaceous is proposed to be in the range of 300-400 km (see Lowey, 1998 for a summary) but these offsets are not well constrained because the geologic ties are not unique enough to qualify as true piercing points or the units being matched have had significant periods of vertical displacement and/or possibly sinistral displacement as well. The current slip rate along the eastern extent of the Denali fault is estimated to be 6-8 mm/yr from GPS data (Fletcher, 2002; Freymueller et al., 2008), or ~10-12 mm/year from paleoseismic data (Matmon et al., 2006); this is in the region that ruptured in the mostly dextral strike-slip 2002 M 7.9 Denali Fault earthquake. It is not clear how long the fault has been slipping at a similar rate, but the present phase of activity may be recent. Oligocene to present-day total strike-slip has been proposed to be no more than 38 km in the past 38 million years (Lanphere, 1978), which would suggest the current slip rate began less than 4 million years ago. However, the reliability of this estimate is in question because it depends on the correlation of two specific plutons out of a set of several similar plutons within the Alaska Range. Clear evidence for active Holocene offset is known along the eastern Denali fault through Canada; however, it is not known how far to the west the Denali fault remains an active system (see neotectonics section).

Northern Alaska contains one of the best-preserved and regionally most-extensive arc-continental collisional systems in the world that formed during the Mesozoic, known as the Brookean orogeny. The collisional record is documented in extensive blueschist facies and local eclogite in rocks of continental affinity in the Seward Peninsula, Brooks Range, and much of the uplands of west-central Alaska (Seward, Arctic Alaska, and Ruby terranes on Figure 3; hachure pattern on Figure 4), indicating a vast region potentially more than 1000 km long was subducted (Mayfield et al, 1988; Till, 1992; Moore et al., 1994). The remnants of that margin are not well-documented but probably included what is now the Yukon-Koyukuk basin of west-central Alaska, which has a Jurassic-Early Cretaceous arc built on crust of mafic to intermediate composition (Box and Patton, 1989). The present-day curvilinear arrangement of continental and mafic blocks in this region likely developed as the region evolved from subduction to collision, and eventually to rotation and/or strike-slip as the Arctic ocean opened in the Late Cretaceous. The magnetic anomaly map clearly outlines the boundaries of the collision along the Kobuk-South Fork fault but also highlights that some of the mafic features at the surface in the western Brooks Range, which are mapped as thin klippe of mafic crust (Figure 3), cannot be responsible for the deep-seated magnetic high (Figure 2) (Saltus and Hudson, 2007). The latter may record Paleozoic rift magmatism, or other inherited igneous features. The magnetic anomaly map of northern Alaska points out how extensively the continental crust has been modified by large-scale thrust sheets and strike-slip displacement and thicknesses of various geologic units are generally poorly understood. Like the Yukon-Tanana composite terrane to the south, this region was profoundly overprinted by extensional tectonics in the middle Cretaceous (e.g. Gottschalk and Oldow, 1988; Pavlis, 1989; Miller and Hudson, 1991 and numerous more recent papers) but the extent of these structures, the scale of associated basins, and its effect of crustal structure remains poorly understood. The TACT transect showed that the thickest crust in Alaska north of the Denali fault is within the Brooks Range, where the high part of the Brooks Range is underlain by ~ 48 km of crust (Fuis et al., 1997).

The Aleutian arc began to form in its present location beginning at ~50-45 Ma (Vallier et al., 1994; Jicha et al., 2006). The arc has remained in roughly the same location since that time, with no significant back arc extension splitting the arc massif, as has occurred at a number of other oceanic arcs. Thus the entire magmatic history of the arc is preserved in one place, and in the adjacent basins where eroded materials have accumulated. Prior to the formation of the Aleutian arc, there was an active volcanic arc along the Bering shelf margin (Plafker and Berg, 1994), which reflected subduction beneath that margin.

Assembly of the Alaska crust in something close to its current state probably was complete by ~45-40 Ma, with the exception of modifications in southern Alaska by the Yakutat collision. By that time, Cretaceous and Paleogene extension and very large scale (>1000 km) dextral slip that occurred in northern and central Alaska was complete. The location of the Benioff zones beneath the central and eastern mainland from ~45 Ma to recent are less well known than in the Aleutians due to a lack of extensive arc volcanism. A Benioff zone distinct from the Pacific plate- Aleutian trend exists beneath eastern Alaska (Stephens et al., 1984) and is sub parallel to the Wrangell volcanic chain. This belt of volcanoes initiated by ~25 Ma and is particularly well documented since ~12 Ma (Richter et al., 1990; Skulski et al., 1992). The seismic zone beneath this arc is very poorly expressed and debate continues on the extent of a slab currently beneath it. We lack a clear 3-dimensional image of the current plate geometry east of the well-expressed Benioff zone associated with the Yakutat-Pacific plate subduction and anticipate EarthScope will play a major role in resolving how the transition from subduction to strike-slip along the Fairweather-Queen Charlotte transform margin occurs.

Debate continues on the total displacement of the major faults in the northern Cordillera but even minimum estimates from offset geologic features across the Tintina, Denali, and Border Ranges faults would require northward translation of the Late Cretaceous part of the accretionary prism by 1000 km relative to the North American craton. Paleomagnetic estimates of displacement between the outermost margin and North America are closer to 3000 km total since Latest Cretaceous –Early Paleocene (Plumley et al., 1983 and others). A significant amount of Late Cretaceous – Paleocene displacement (>2000 km) is indicated by paleomagnetic studies from rock units between the Denali and Tintina faults (see Enkin, 2006 for summary), which would require either much greater slip on the Tintina fault than is currently recognized or that a cryptic fault exists beneath the fold and thrust belt to the northeast. Thus linking pre-Oligocene coeval events across strike, using the current spatial relations, will continue to be a challenge until the location, amount, and timing of strike-slip on the major faults is better documented.

Neotectonics

The collision of the Yakutat terrane, which is ongoing today, dominates the recent and active tectonics of southern Alaska. The collision of this remnant of an oceanic plateau (Pavlis et al., 2004; Christeson et al., 2010) has substantially modified a portion of the southern Alaska margin for at least the last 6 million years, drives uplift of the Chugach-St. Elias range and possibly of the Alaska Range (Koons et al., 2010). Stratigraphic, provenance, geochronologic, and thermochronologic data from the region indicate that flat-slab subduction was shaping southern Alaska by late Eocene–early Oligocene time (Finzel et al., 2011). The flat slab subduction is presumably related to the subducted part of the Yakutat terrane, with the prodigious volcanism of the Wrangell volcanoes since that time potentially related to slab-edge phenomena. However, the evolution of this collision/subduction system over the last 25 million years needs to be determined in more detail. Collision of the Yakutat terrane may drive tectonic escape and active faulting across a broad swath of southern Alaska (Redfield et al., 2007) and the Northern Cordillera of Canada (Leonard et al., 2008; Mazzotti et al., 2008; Elliott et al., 2010). Whether due to the collision of the Yakutat terrane or not, seismicity extends across all of Alaska and the Yukon, from the Pacific Ocean to the Arctic Ocean (Figure 5), and all of Alaska appears to be moving relative to North America at the present time (Freymueller et al., 2008).

In the process of collision, essentially the entire sedimentary cover of the Yakutat terrane is being stripped off and incorporated (and recycled) in a rapidly uplifting fold and thrust belt, while the crystalline basement underthrusts the entire package (Berger et al., 2008a,b; Enkelmann et al., 2009; Worthington et al., 2010; Enkelmann et al., 2010; Berger et al., 2009). This drives exceptional uplift and exhumation rates in the coastal ranges, and the flat slab geometry that results from the subduction of the relatively buoyant Yakutat crust has had a profound impact on upper plate faulting, arc volcanism, and on patterns of mantle flow and anisotropy.

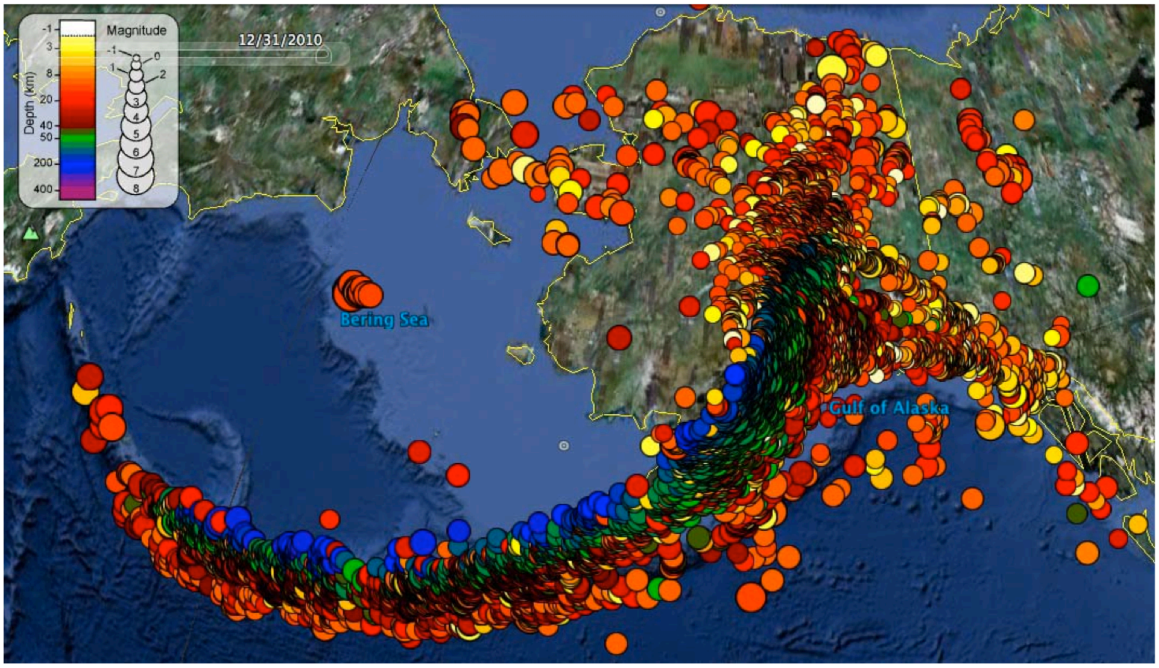


Figure 5. Earthquakes in Alaska in 2010, color-coded by depth (hot colors are shallow). The size of the circles is scaled by magnitude.

The geometry of the already-subducted part of the Yakutat terrane remains subject to speculation. It appears to underlie the entire flat slab region beneath southcentral Alaska (Ferris et al., 2003l; Eberhart-Phillips et al., 2006). There is some evidence that the thickness of the basement increases to the south and east, which could make it something like a doorstop in shape (Worthington et al., 2010). In this conception, the 6 million year intensification of uplift in the southern coastal ranges represents the arrival of a sufficiently thick part of the doorstop. However, there is evidence for possible flat slab subduction over the last 20-25 million years, and uplift of parts of the Alaska Range began around that time (Benowitz et al., 2010; Benowitz, 2011). Whether these observations fit with a simple model of subduction of the Yakutat terrane or not is unclear.

Active or potentially active faulting in the upper plate extends across most of Alaska. Parts of the Denali fault system are certainly active, including the central segment that ruptured in 2002 and the eastern segment in the Yukon Territory (Fletcher, 2002; Hreinsdóttir et al, 2006; Matmon et al., 2006). Additional slip may feed into the Denali fault system via a "Connector fault" that connects the Fairweather transform fault of southeastern Alaska with the Totschunda fault, part of the Denali system, and part of which ruptured in 2002 (Richter and Matson, 1971; Kalbas et al., 2008). The Denali fault extends across Western Alaska to the Bering Sea coast, but it is not known whether the fault remains active over that entire segment. If not, then the significant change in slip rate implied for the fault requires the existence of other, rapidly slipping (a few to several mm/yr) faults that connect with the Denali fault. In essence, a shutoff or large reduction of slip on the Denali fault system requires either a particular combination of block rotations or a triple junction (to use the terminology of large plates). North of the Denali fault, one small segment of the Tintina fault has evidence for Holocene rupture, but most of the fault remains unstudied. The diffuse seismicity of northwest and northeast Alaska implies the existence of additional active faults, possibly including the northern boundary of the Bering plate (Mackey et al.,1997; Cross and Freymueller, 2008). South of the Denali fault system and outside of the immediate collision of the Yakutat terrane in the St. Elias range, known Holocene active faults include the Castle Mountain fault on the north side of Cook Inlet (Willis et al., 2003), and faults that underlie actively growing folds within Cook Inlet. GPS velocities suggest that the Castle Mountain fault connects with additional active faults extending along the Alaska Peninsula, making that part of a fundamental active block boundary (Cross and Freymueller, 2008; Freymueller at el., 2008; Freymueller, 2010; Freymueller, 2011).

In terms of overall geologic history and crustal structure of Alaska some key questions are:

- *Are there relic slabs/subduction structures in western AK including but not limited to a relic Aleutian Arc? In general crustal structure of all of western AK is relatively unknown and thus this is a frontier area.*
- *Why did subduction move southwest at 45 Ma to the present Aleutian arc?*
- *Are strike-slip boundaries lithospheric in scale? If so, how are these linked to mantle processes?*
- *What is the tectonic setting of the Arctic? This is another frontier area; investigation would likely require cooperation with our Canadian colleagues.*
- *How deep do the slabs go in this region? Where have the subducted slabs gone and can this be determined with body wave tomography and combined body wave and surface wave tomography.*
- *Is the western Denali fault active today and if so, at what slip rate? What other upper plate faults have significant slip rates, such that they presently may define the boundaries of moving blocks?*
- *To what extent is southern Alaska "escaping" to the southwest, away from the Yakutat terrane collision? Are large regions moving as coherent blocks, or is the portion of the crust that is escaping restricted to small slivers along the southern Alaska margin?*
- *Is there a Bering Plate and what is its extent in 3D?*

Earthquake Rates and Imaging Potential

Substantially more earthquakes occur in Alaska than in the rest of the United States combined. More than 30,000 earthquakes were located in Alaska in 2010, a fairly typical count for years without major earthquakes. Shallow seismicity extends across a large fraction of the region, up to the Arctic coast and across to Russia (Figure 5). Only the western Arctic coast and the southwestern Alaska mainland appear to be seismically quiet; keep in mind, however, that southwestern Alaska has never been instrumented and the number of earthquakes smaller than M~4 is completely unknown. The westward extension of the Denali fault system passes through this region, although its present level of activity is uncertain.

A comparison of earthquake rates in Alaska and rest of the United States over the last 50 years (1960-2010) is illustrative. For most magnitude bins, Alaska has ~5 times as many earthquakes as the rest of the continental US combined (Figure 6). The slight falloff below magnitude 5 is due to lack of completeness of parts of the Alaska catalog at those magnitudes. Above magnitude 7, the pattern becomes more intriguing. In the range from magnitude 7 to 7.4, more earthquakes occurred in the lower 48 states than in Alaska, but all 12 US earthquakes larger than magnitude 7.4 during that period occurred in Alaska (Alaska averages one M7+ earthquake per year). The apparent shortage of M7-7.4 earthquakes could be a result of sampling too short a seismic catalogue, reflecting only a small sample size. However, if reflects a real difference then it might indicate that the continental fault network in Alaska is simpler than that of the lower 48, where there are many fault segments that, even rupturing together, can only produce earthquakes in the M~7 range; in contrast, Alaska has large sections of the megathrust that tend to rupture more rarely in much larger events.

The potential for seismic imaging is dominated not by the very large events, but rather by those of intermediate magnitude that are large enough to be recorded well over a large area, but small enough to have very simple sources. The historical record shows that Alaska experiences on average ~150 earthquakes per year with magnitude ≥ 4.5. The slab beneath Cook Inlet and southern Alaska is a particularly rich seismic source, generating hundreds of earthquakes per year that would be broadly recorded in the overlying region. These very high levels of seismicity will make for a rich data set for seismic imaging of all kinds.

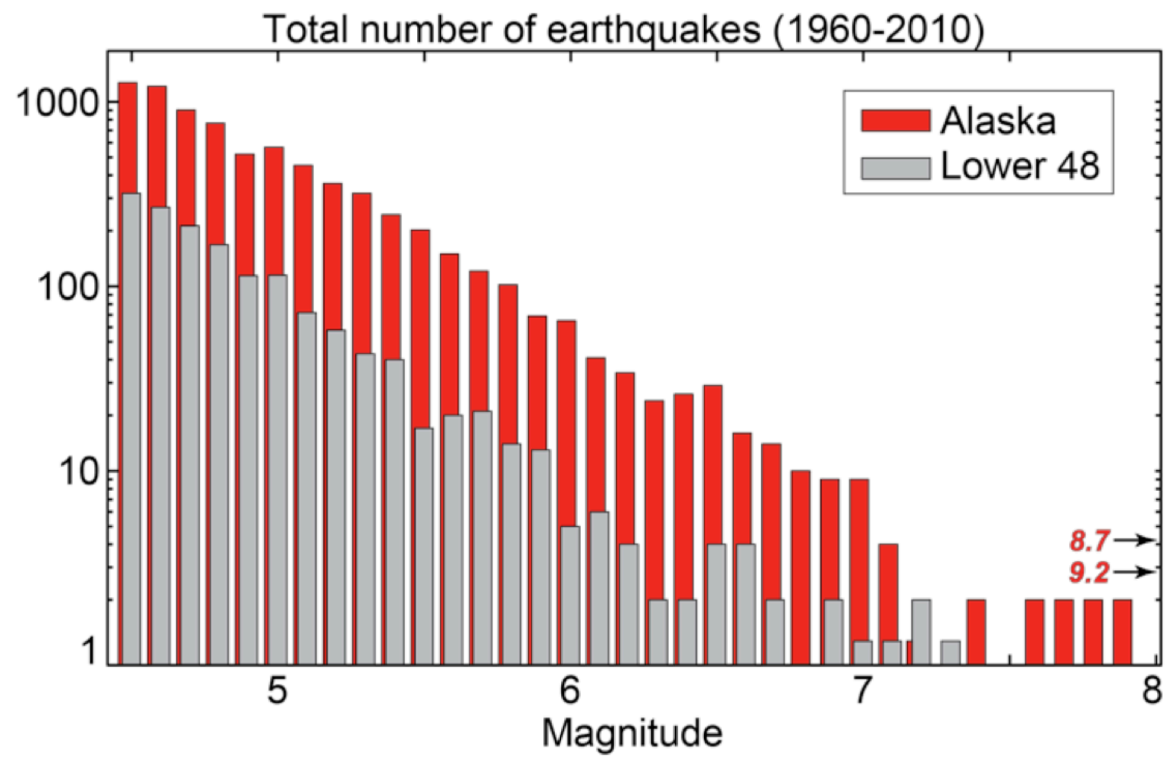


Figure 6. Comparison of earthquake statistics by magnitude, 1960-2010. Red bars are for Alaska (including the Aleutian arc), and gray bars are for the lower 48 contiguous states and offshore regions. Note that the Alaska catalog is not complete at the smallest magnitudes shown on this plot. Note that the y-axis is on a logarithmic scale.

Science Discussions from Workshop

Slab and mantle structure and dynamics

Shear wave splitting observations are commonly interpreted as indicators of mantle flow lines, and the pattern of splitting observed across central Alaska is intriguing (Figure 7). Observed splitting orientations in southern Alaska are dominated by either trench-parallel or trench-normal orientations, with abrupt along-strike and down-dip transitions between them (Bellesiles, 2011). Splitting observations in southern Alaska probably reflects a complex interplay between anitropy in the mantle wedge, beneath the downgoing slab, and possibly in the subducted crust (Christensen and Abers, 2010; Bellesiles, 2011.) Farther to the north, splitting orientations are roughly parallel to the absolute motion of the North American plate, at least for certain absolute plate motion models (Bellesiles, 2011).

The pattern of mantle flow around the slab edge at the east end of the Aleutian arc remains an important problem. Figure 7 shows two examples model of mantle flow, but importantly this version did not include the effects of the change in crustal thickness associated with the Yakutat terrane. Observations made at and near this edge may be used to test whether models developed for the Cascadia slab edge make testable predictions for similar regions. Determining the extent and geometry of subducting Pacific Plate is a pre-requisite for these studies, and also would have an impact on other problems like postseismic deformation and glacial unloading studies. Key questions regarding this geometry include position of the eastern edge, shape of the corner where the convergent margin meets the Queen Charlotte-Fairweather transform system, and the detailed geometry of the central flat-slab region.

Currently, the exact eastern limit of slab edge is unclear, and it is unclear whether a separate slab subducts under the Wrangells or not. The best constraints come from tomography (Eberhart-Phillips et al., 2006), but the resolution of the tomography was seriously limited by the station distribution. These data are consistent with the dipping "Wrangell slab" representing a downward curving edge of the Yakutat slab that moves to the NW, rather than a textbook slab moving downdip to the NE. Other alternatives, including slab tears, may also be possible. Different mantle flow fields and thus different patterns of anisotropy are expected depending on the slab geometry (Figure 7). The USArray TA will provide a tremendous new opportunity for enhanced imaging of the slab and upper mantle.

Potentially related to this question is the nature of the active but enigmatic Wrangell volcanic complex, which may be some sort of slab edge phenomenon. What are flow processes around the corner (Figure 7) and how do they compare to other well-imaged corners? By investigating this problem we could improve understanding of slab dynamics. Some other tectonic regions with potentially similar tectonic complexities arising from slab edges are the Mendocino Triple Junction region of northern California and the northern Vancouver Island region at the northern limit of the Juan de Fuca Plate. Comparing and contrasting Alaskan EarthScope results with these regions and others globally could be productive.

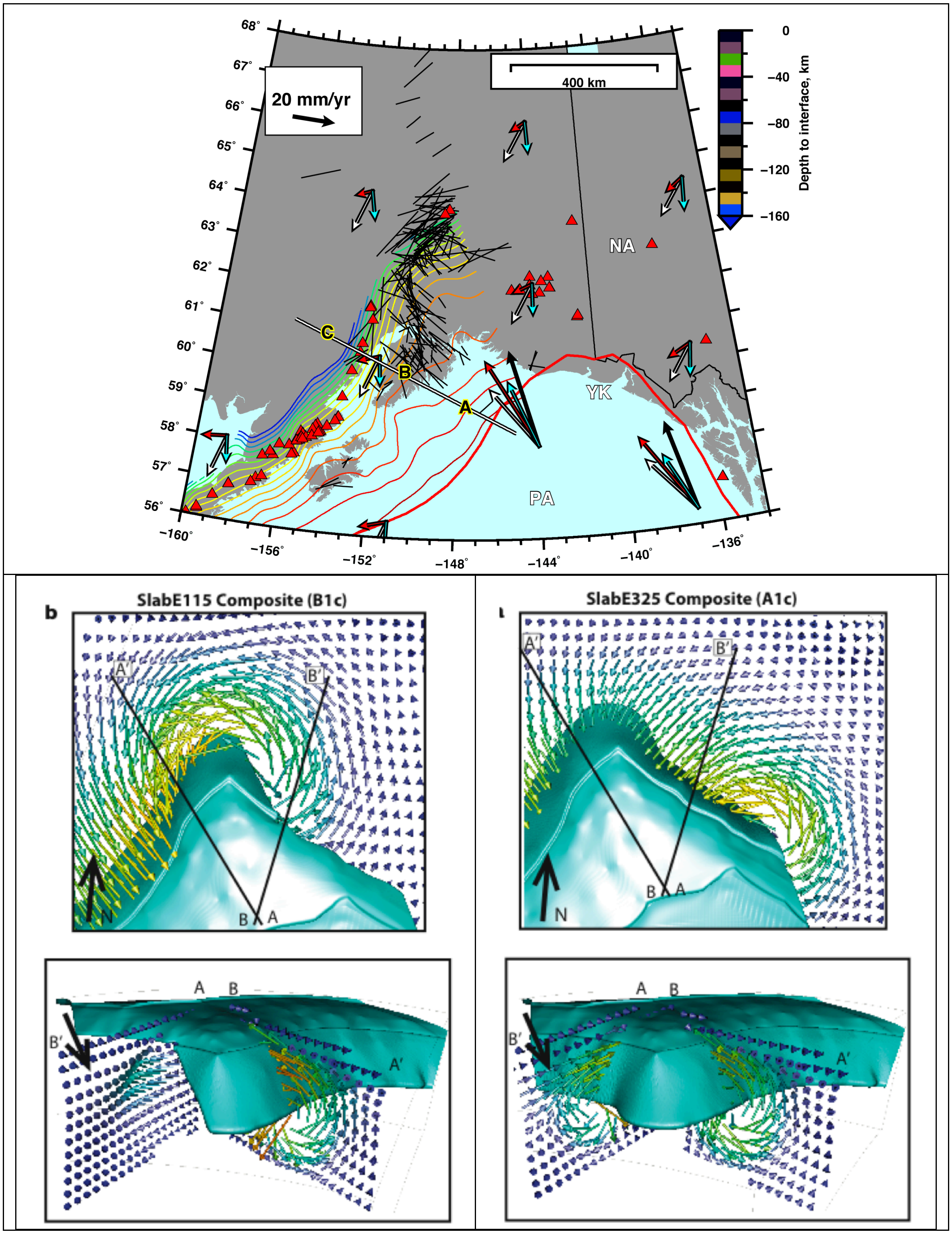


Figure 7. Shear wave splitting and mantle flow models. (Top) Shear wave splitting observations (solid lines), from Bellesiles (2011), compared to absolute plate motion vectors. (Bottom) Model mantle flow fields for two different slab geometries, from Jadamec and Billen (2010). In the case at left, there is no distinct Wrangell slab, while in the case at right, there is a continuous slab connecting the slab beneath the Alaska Range and the Wrangell slab.

There is a clear flat-slab region along the Alaska Peninsula. Some fundamental questions include why is it there and is it linked to Yakutat Block subduction. Is the model of anomalous lithosphere connected to the Yakutat slab correct? What is the spatial extent of the subducted Yakutat crust and how is it coupled to the Pacific Plate? EarthScope could allow the determination of the crustal structure and location of the transition from flat slab to more "normal" subduction. Also importantly what is the northern limit of the area influenced by flat-slab subduction and what are the far-field effects of this process. What is the role of the mantle in controlling deformation in the interior compared to crustal processes? Examining active flat-slab subduction in Alaska today could be key in unraveling past potential flat-slab subduction events in the lower 48 such as the Laramide Orogeny. Many of these problems will require an integration of modeling and tomography.

Science opportunities for investigating upper mantle structure include:

- *What is the nature of the transition zone in AK? Alaska provides the unique capability of using large Aleutian earthquakes to illuminate the transition zone through upper mantle triplications. Detailed tomography and mapping of the 410 and 660 km discontinuities can address thermal variations.*
- *What is the overall flow field we can infer from seismic anisotropy?*
- *What is the geometry of the Lithosphere-Asthenosphere boundary in AK? This question requires recording P to S or S to P conversion data. A better context for this problem will be determined after the Transportable Array covers the craton. Additionally this investigation may address questions as to what parts of the lithosphere are "cratonic".*

The Aleutian Arc, and especially its oceanic parts offer clear science opportunities, but also may require some variation from the standard operating procedure of EarthScope. For example, workshop attendees supported the idea of using small arrays rather than single stations in this section, where the TA is constrained to follow a linear array. In this region, there is the opportunity for tremendous synergy between EarthScope and the GeoPRISMS program; amphibious investigations supported by GeoPRISMS may be needed to answer the most important questions. Key questions include: What is the geometry of the arc and what is the nature of the lower crust along the arc? What is the nature of the mantle wedge and how does it change along strike of the arc? What are the effect of along strike variations in subduction parameters such as obliquity, depth of slab beneath volcanoes, sediment thickness, plate age, volume and rate of magma generation, overriding plate structure (transition from continental to pure oceanic). The Alaska-Aleutian Arc may be the place to directly link volcanic processes to crust and mantle structure.

Seismogenesis and Earth's response

Alaska is an ideal place to study the genesis of great earthquakes and the Earth's response to these events. Nearly the entire length of the subduction zone has ruptured in great earthquakes within the historic record despite its short length (no more than 250 years) (Figure 8). Major active crustal faults, including the Denali fault, have generated magnitude 7-8 earthquakes within the instrumental record, and zones of significant earthquakes (earthquakes larger than M~6) or active microseismicity extend north to the Arctic Ocean and northwest to the Bering Strait and Chukchi Sea (Figure 5). The seismic activity is accompanied by broad-scale active crustal deformation, measured by GPS (Freymueller et al., 2008; Elliott et al., 2010; Elliott, 2011). Large and great earthquakes trigger postseismic deformation transients, which provide an opportunity to study the dynamic processes associated with the earthquake cycle.

Great megathrust earthquakes are a particularly compelling target of investigation. The Alaska-Aleutian subduction zone features a rapid convergence rate and a generally wide seismogenic zone, leading to a relatively large number of large to great earthquakes compared to many other subduction zones. Of particular interest in Alaska are the significant along-strike variation of both subduction parameters and the behavior of the seismogenic zone. The Alaska subduction zone displays relatively abrupt boundaries between segments that appear to be dominated by creep and segments that remain locked over a large downdip width (Figure 8) [Fournier and Freymueller, 2007; Cross and Freymueller, 2008; Freymueller et al., 2008]. *What causes these abrupt changes, how long do they persist over time, and how do they relate with the general controls on rupture dimensions?* Studying regions with significant along-strike changes in behavior offers a critical opportunity to identify what properties most affect the extent of seismic rupture.

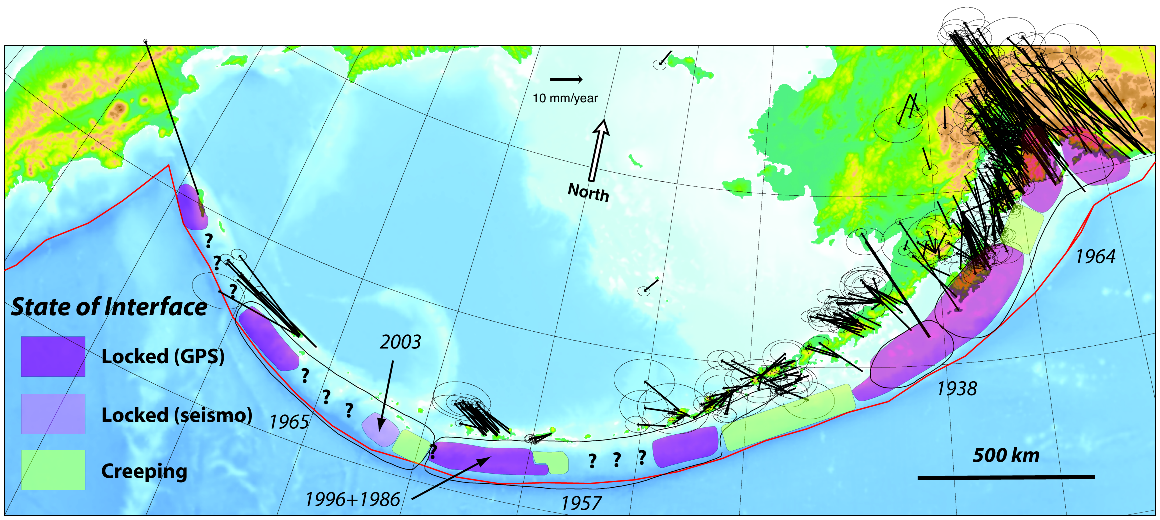


Figure 8. Summary of locked and creeping patches on the plate interface, based mostly on GPS data, from Freymueller et al. (2008). Dark patches are locked, and accumulating stress to be released in future large and great earthquakes. Yellow patches are dominantly or entirely creeping. Boundaries appear to be abrupt in the along-strike direction, with changes from locked to creeping occurring over distances that are short relative to the width of the locked zone. Resolution of the on-land GPS data is poor near the trench, and that region may be either locked or creeping (seafloor geodetic measurements would be needed to resolve this).

What limits the extent of great earthquake ruptures in general? Possibilities include geometric changes such as plate curvature, structural features like seamounts, ridges, frictional property variations due to different incoming sediment or crustal properties, underplating or subduction erosion processes, and temperature.

Additional questions raised at the workshop include:

- *How 'characteristic' are megathrust earthquakes?*
- *How long-lived are first-order segmentation characteristics?*

- *How stationary is the distribution of slip deficit (extent of locked regions, sometimes referred to as coupling) inferred geodetically? New evidence suggests that the downdip extent of locked patches may change abruptly on scales of weeks to months, although the changes that have been documented reflect only a small fraction of the overall width of the locked region.*
- *What physical properties control and/or are diagnostic of the slip behavior of the interface? Workshop participants noted that the seismic record is insufficient but geodesy is useful to learn about the current state of coupling and short-term variability. 'Slow' slip phenomena (geodetic transients, tremor, etc.) could be useful for examining these coupling questions.*

Discussion also occurred on how the megathrust rupture processes may interrelate with other margin processes such as fluid transport, volcanic activity, and crustal faulting. Additional questions asked include:

- *How does the deformation field evolve spatially and temporally following great earthquakes?*
- *What processes control the deformation (aftershocks, viscoelastic processes, afterslip, etc.)?*
- *How will this vary from the arc across the zone into the backarc? (The best place to study this is would be along the Alaska Peninsula and Eastern Aleutians due to the opportunity to make marine observations in the back-arc).*
- *Why do some areas have more intraslab earthquakes than others?*
- *How significant is glacial unloading to driving deformation and as a tool to constrain effective viscosity?*

EarthScope could be critical to investigate or answer many of these questions.

Some key features that need better characterization include:

- *The geometry and extent of the slab east of the 1964 rupture.*
- *The connectivity between the Yakutat and Pacific megathrusts.*
- *The existence or lack of a slab subducting beneath the Queen Charlotte fault.*
- *More accurate boundaries of rupture in past/future earthquakes.*
- *Linkages between megathrust and the Fairweather and other major crustal fault systems.*

In general, it was noted that all of Alaska is in motion relative to "stable" North America and all of Alaska is seismically active. Thus a key conclusion is all of Alaska is worthy of instrumentation and new data from areas never instrumented may lead to fundamental new discoveries. US Array deployment will likely catch at least one M~7 event and potentially an M~8 within the network (see Figure 5 for an example of seismicity during one year).

Postseismic Studies

The stress changes caused by large and great earthquakes trigger a significant response within the fault zone and in the surrounding medium, which in turn causes measurable surface deformation. Precise measurement of this deformation allows, in theory, the determination of its source mechanism(s), and thus the stress distribution and rheology of fault zones and the lithosphere and asthenosphere. In practice, tradeoffs between potential postseismic deformation mechanisms pose a significant challenge and careful assessment of all bounds on rheology, from geodesy and other disciplines, is needed.

The main postseismic deformation mechanisms are afterslip within fault zones (potentially including focused shear within deep, ductile fault zones), and viscoelastic relaxation of the surrounding material. It is clear that very large earthquakes such as the 2002 Denali fault earthquake (Freed et al., 2006; Johnson et al., 2009) or the 1964 Prince William Sound earthquake (Sauber et al., 2006; Suito and Freymueller, 2009) cause significant viscoelastic flow in the asthenosphere. What is less clear is whether (depth) layers within the lithosphere also undergo significant viscoelastic relaxation. These shallower postseismic processes can be difficult to separate from afterslip, given that they occur at similar depths. This is a major unresolved problem that can only be addressed by continued observation of earthquakes and their postseismic response, and continued modeling studies. In addition, other processes can be important, such as fluid flow driven by postseismic pressure changes, which results in poroelastic deformation. This mechanism is probably more important at shallow depths and close to regions of fault complexity.

Continued study of the postseismic effects of the 1964 and 2002 postseismic transients is needed, along with continued modeling studies. Data are probably too sparse for the other large and great earthquakes of the 20th century in Alaska, but study of the effects of future large and great earthquakes will be very important. Given the high level of seismicity, the likelihood of a major event that would justify a postseismic response by EarthScope is high. In addition, the rheological models developed for postseismic studies need to be integrated with results from independent models, such as slab dynamics and corner flow models and glacial unloading models. All of these models are trying to describe the response of the same earth, and ultimately all need to be made mutually consistent if we are to find the correct rheological description and stress models.

Some key questions are:

- *How does the deformation field evolve spatially and temporally following great earthquakes?*
- *What processes control postseismic deformation, and how can we better predict in advance how important afterslip and viscoelastic relaxation will be for a given earthquake?*
- *Can better models for the postseismic responses of the 1964 Prince William Sound and 2002 Denali Fault Earthquakes be developed?*

Science opportunities for investigating seismogenesis and response include:

- *Recording large to great earthquakes and their postseismic response.*
- *Correlation of physical property changes with changes in slip behavior, along-strike or down-dip.*

Structure and dynamics of active volcanoes

Alaska offers great opportunities to study the structure and dynamics of active volcanoes, examine magmatic processes at depth, and illuminate eruptive processes. Several volcanoes in Alaska were selected for instrumentation by the Plate Boundary Observatory (PBO), based in large part for the potential for observing future eruptions. In addition to geophysical observations, volcanoes that erupt allow assessment of physical properties of the magma and enable petrologic studies of the magma storage and ascent conditions. These data can be highly complementary to geodetic and seismic observations of the volcano, and provide rich opportunities for multi-disciplinary studies. Volcanoes currently instrumented geodetically by EarthScope/PBO include Augustine (erupted 2006), Westdahl, Fisher, to a lesser extent Shishaldin (Unimak island), and Akutan. Okmok volcano, which was removed from the PBO plan by an NSF de-scoping decision, experienced a large eruption in 2008, and is instrumented by Alaska Volcano Observatory (AVO) with 4 stations. Other volcanoes with AVO geodetic instrumentation include Akutan, Redoubt and Spurr, each with 4 sites.

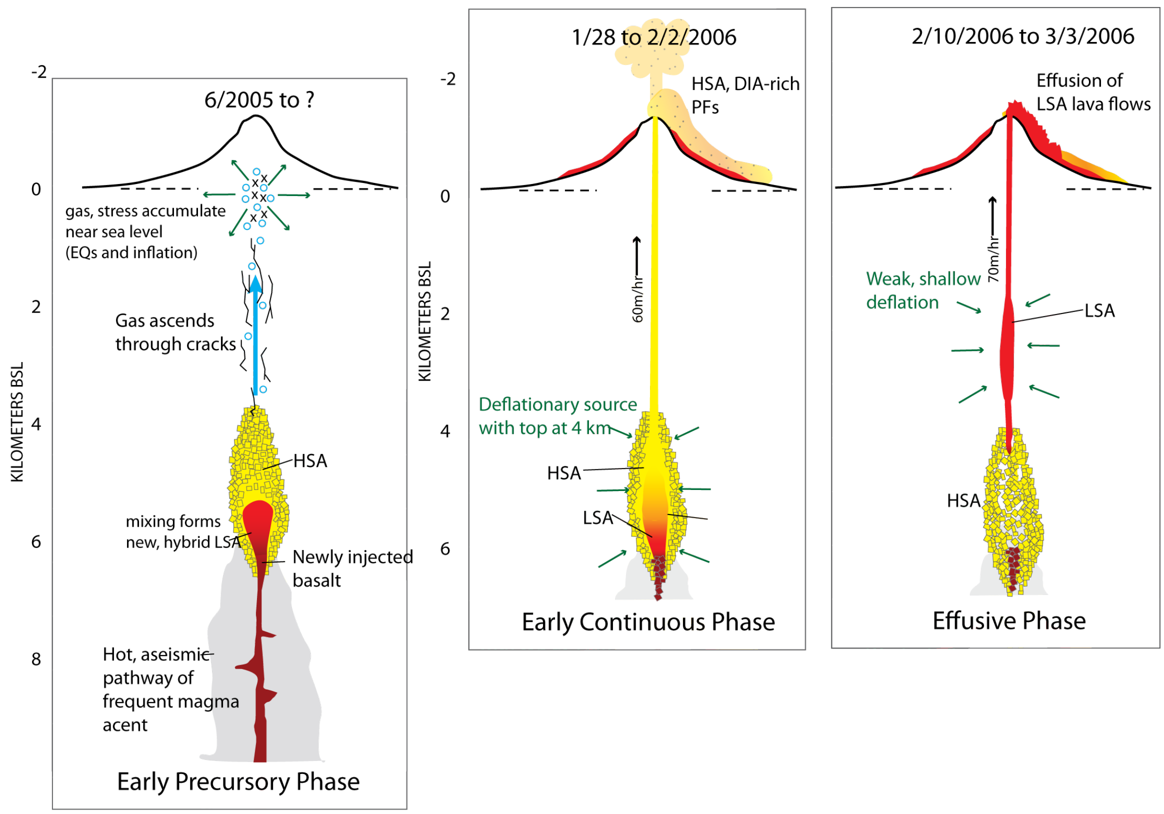


Figure 9. Summary of processes active prior to and during parts of the 2006 eruption of Augustine volcano, modified from Larsen et al. (2011). Precursory seismicity and inflation reflected pressurization of a volume near sea level, probably by accumulation of volatiles. Deformation during eruption was associated with injection of basalt, magma mixing, and evacuation of high-silica (HSA) and low silica (LSA) andesites. Seismicity during the entire period mainly reflected shallow processes, including breaking of rock throughout the edifice.

Workshop attendees strongly supported the concept of expanded and spatially dense instrumentation on key volcanoes, although debate continued about which volcanoes would be the best targets, and to what extent such deployments should be part of the base

EarthScope facility rather than individual proposals. Additional geophysical observations from active source seismology, magnetotellurics, InSAR and gravity (especially gravity change) could provide critical new data to complement EarthScope network data. The most compelling scientific problems are likely to require additional studies beyond those enabled by EarthScope networks, including efforts in petrology, geochemistry and geochronology. Baseline geochemistry data on Aleutian lavas is in hand, but further analysis of time series data is needed to track chemical changes over time.

Volcanic eruptions and the processes that build up to eruption are of great interest both from purely scientific inquiry and to address the need for mitigation of eruptive hazards. The buildup to eruption can be detected through patterns of crustal deformation and seismicity, with deformation seemingly providing evidence of the long-term buildup of magma within the shallow to middle crust, and seismicity marking the breaking of rock as pressure reaches a critical point and magma ascends (Figure 9). Catching the precursory or early stages of unrest and eruption generally requires pre-existing networks, although deformation can often be detected using InSAR as well. Existing data provide evidence for both quasi-continuous and pulsed accumulation of magma, even at the same volcano. *Over what timescales does magma accumulate in the upper crust, what triggers and stops magma rise, and what conditions determine whether magma erupts or remains within the crust as an intrusion? How do upper plate structures and stresses modulate magma rise?*

Volcanic arcs are built over geologic time by a combination of intrusive and extrusive volcanic processes. Studying intrusive processes poses particular challenges, as it requires remote imaging of processes at depth. Even the critical question of *what fraction of the magma that ascends into the crust is eventually erupted* remains unknown. Growth of arcs through intrusion of plutons is an important factor, and there are several places along the Aleutian arc where exhumed plutonic rocks offer the chance to study these processes, for example in the Fox Islands (eastern Aleutians) and in the central Aleutians. For example, in the Andreanof Islands in the central Aleutians, the active arc is perched at the northern edge of the arc massif, with older plutonic and extrusive volcanic rocks exposed on the southern parts of the islands. Developing a more complete and quantitative description of the magma generated in the mantle wedge, its ascent and intrusion into the crust, and its differentiation within the crust and eventual fate (eruption, cooling, delamination) remains an essential EarthScope science goal.

Critical scientific opportunities and questions in Alaska for studying volcanic/magmatic processes include:

- *How do upper plate structures modulate magma ascent?*
- *Quantifying the growth of arcs through plutons.*
- *What is the role of magma mixing in triggering of eruptions. Volcanoes in Cook Inlet provide an especially diverse set for studying magma mixing.*
- *What is the role of magma water content in controlling magma ascent and dynamics. Augustine is wettest volcano around, and other Aleutian volcanoes span a wide range of initial dissolved water contents.*
- *Improving geochronology: there are large-scale trends in timing of magmatism (e.g.,*

large temporal gaps - 38-5 Ma on the Alaska peninsula). Are these a result of changes in plutonism versus volcanism, and is arc growth is steady state versus pulsed?

- *Tracking magmas from slab to surface: linking deep sources of magma genesis to mid-crustal chambers; imaging of deep roots of volcanoes: slab and above (20-100 km); connecting slab to upper 5 km*
- *Why is the depth to slab beneath Aleutian volcanoes unusually shallow, among the shallowest in the world?*
- *The origin and magma supply of the Wrangell volcanoes is not well understood. They overlie a slab edge but are not the result of direct slab melting.*

Illuminating past tectonics with present seismicity

Alaska and the Aleutians provide exceptional opportunities for basic geoscience research. The basic crustal and upper mantle structure of Alaska is largely unknown (see Figure 1 for coverage of existing geophysical experiments). Geophysical characterization of the crust and upper mantle is required to differentiate between competing models of the tectonic history of the northern Pacific and accretion of the Alaskan terranes. EarthScope can identify the basic crustal boundaries (faults and sutures: geometry, depth extent) using seismicity and tomography and will image subducting slabs and slab edges as well as potentially relict slabs. The widespread crustal seismicity and slab seismicity provide ample data for EarthScope investigations of crustal structure and tectonic processes.

A broad spectrum of plate boundary processes (subduction, collision, strike-slip) can be imaged at unprecedented level in Alaska. These include collision and syntaxial processes associated with the collision of the Yakutat Terrane and formation of the St. Elias Mountains that can provide an important comparison for studies in Tibet and the Himalaya. Another question of global importance is the longevity and lateral continuity of major strike-slip systems such as the Fairweather and Denali Faults that can in turn be compared to the North Anatolian and San Andreas Fault systems. Flat-slab subduction can affect geologic evolution of a continent over large areas such as potentially occurred in the Laramide Orogeny in the past and currently in South America; in Alaska active flat-slab subduction is occurring beneath central and southern Alaska and provides a unique opportunity to examine the effect on crustal structure and basin development. Continental Alaska was potentially built by both terrane accretion and arc magmatism and imaging the integrated product will prove a nice contrast to regions within the lower 48 previously examined by EarthScope. Tomographic imaging in Alaska can be attained for different times intervals (weeks, months, etc) providing information about transient deformation and volcanism. EarthScope in Alaska can also seek to image the subduction of anomalous topography (seamount chains, transforms, plateaus), the subducting plate interface itself including the geometry fine structure, active volcanoes on the arc and on the continent, and the cryosphere including glaciers, permafrost, ice fields, and sea ice and using icequakes.

The workshop attendees identified some key crustal targets, opportunities and hypotheses:

- *Linking surface geology with structure at depth from outcrop scale to mantle and* *examining whole crustal-scale structural blocks or "flakes" of accretion.*

- *Determining whether the hypothesized Fairweather-Totschunda connector fault exists, and if there is a northern extension of Fairweather Fault linking to the Denali Fault and this boundary related to the eastern edge of the Yakutat Terrane.*
- *What is the Pacific-Yakutat interaction/relationship at depth?*
- *Characterizing the Bering plate as a transition between the North American and Eurasian Plates.*
- *Understanding magmatic evolution and tracing the arc through time.*
- *Examining far-field deformation and the influence of flat slab subduction and Yakutat Terrane collision.*
- *Constraining tectonic evolution with basin stratigraphy and ages.*

Some key questions:

- *What is the transition between deformation in western and eastern Brooks Range (northern edge of Bering plate)? One is seismogenic and one is not.*
- *What is the crustal thickness (Moho) across Alaska?*
- *What is the structure of the major sedimentary basins?*
- *What is the relationship between seismicity and uplift or subsidence?*
- *Where was the southern boundary of Alaska crust prior to the Yakutat collision?*

Hydrosphere, cryosphere, and atmosphere

Moving EarthScope to Alaska provides an unparalleled opportunity to advance understanding of ice mass fluctuations, glacial earthquakes, and tectonic earthquakes (seasonal seismic rate changes are documented for small tectonic and glacial events but we need uniform detection). Uplift rates in parts of southeast Alaska from glacial isostatic adjustment are the highest in the world, and amplitude of seasonal hydrologic load variations is exceeded only by tropical river basins. The TA will enable discovery of regions where later denser deployments are needed. Continuous recording in Alaska will provide ample data to seek to differentiate glacial icequakes and landslides from earthquakes. Some clear science goals provided for by EarthScope include:

- *Examining ice quakes frequency and locations relative to glacial termini, topographic changes, and tectonic features.*
- *Using seismic noise characteristics to study sea ice changes after quantifying signal to wind, pressure.*
- *Examining the frequency and magnitude of the signal from landslides, and the temporal relations between seasonal changes and frequencies of ice quakes and landslides.*
- *Testing whether hydrologic and glaciological models can explain the seasonal and interannual variations in GPS time series.*
- *Developing a comprehensive load model to appropriate scale that can be used to predict glacial isostatic adjustment, and secular and shorter-term variations in stress caused by changing loads.*

Any meteorological information in Alaska could allow significant increases in the accuracy for regional climate models. Much discussion occurred amongst in the breakouts at possibilities of including meteorological add-ons to the TA stations (met packs). Additional ideas were to explore snowfall estimate options and permafrost options that could be externally funded. Finally the need to install seismometers at several meter depths in permafrost regions allow for the potential to add thermistors and examine freeze-thaw cycles.

Logistical Suggestions from Workshop

Because the Plate Boundary Observatory construction phase is already completed and the PBO network is essentially fixed, most of the recommendations here relate to the upcoming USArray TA deployment. However, we strongly encourage IRIS and UNAVCO to cooperate closely in their work in Alaska. IRIS may be able to leverage existing UNAVCO infrastructure (for example in communications), and UNAVCO might be able to take advantage of new IRIS infrastructure to make targeted enhancements to PBO at low cost.

Overall the Alaska EarthScope workshop attendees endorsed a uniformly spaced and comprehensive deployment for the Transportable Array as a core goal. Station spacing will be dictated by cost and logistics, but all efforts should be made to minimize the station cost so that the maximum number of stations can be deployed, to make the Alaska deployment as close as possible to the 70 km spacing of the rest of the TA. There is a strong trade off between coverage (number of stations) and real time data access in Alaska due to the number of remote locations. There was a strong consensus that coverage is more important, and that we need to prioritize maintaining data quality (e.g., knowing state of health data) over ensuring immediate access to the data.

Two points emphasize the importance of maintaining the same 70 km spacing of TA wherever it is practical: Alaska has vast areas with (1) intense local seismicity (crustal or slab) and (2) limited or no seismic station coverage, either permanent or campaign (Figure 10). Thus there are great opportunities for discoveries. With the same station spacing and therefore comparable resolving capabilities, the scientific discoveries in Alaska will allow for one-to-one comparisons with those in the Lower 48: for example, the Farallon slab vs the Kula/Pacific slab or variations in crustal structure.

Likely Alaskan deployment challenges mean that we will need to consider a revision of standard flexible array deployment procedures and expand logistical support. We should consider focusing FA deployments in the active arc for volcanic processes, earthquake processes, and active tectonic processes. Instrumentation could be targeted:

- *In places where significant changes in seismogenic character are known or likely.*
- *To complement (improve) capabilities of existing networks (this may involve sacrificing some coverage uniformity).*
- *On as many Aleutian islands as practical.*
- *Where reoccupations are useful (e.g. previous sites along the Denali fault).*

It was noted by several breakout groups however that OBS are likely a necessary component for many Aleutian questions. EarthScope and GeoPRISMS might carry out OBS deployments jointly.

Some specific instrumentation recommendations include adding strong motion sensors to TA stations. The infrasound sensors now part of the TA package are likely to be very useful for volcanic studies. Other recommendations include insuring the ability to record and retain high-rate GPS measurements, considering transects (possibly for the FA) across interesting transitions such as the Shumagins, keeping spare 'RAMP' instruments for post-earthquake studies, and considering the deployment of arrays in some places as appropriate.

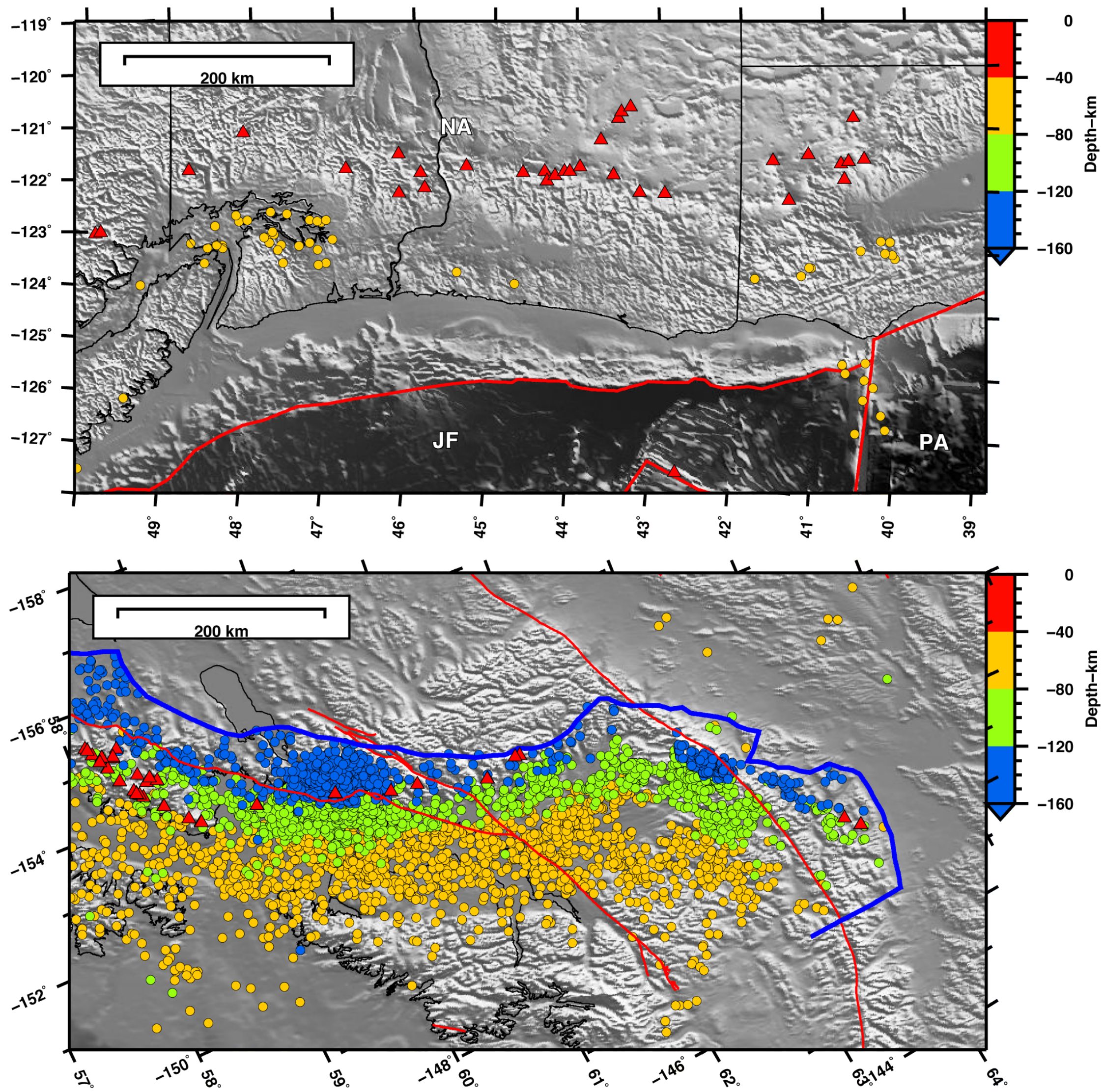


Figure 10. Comparison of seismicity in the Alaska and Cascadia subduction zones at the same map scale, over the same time period (1990-2010, earthquakes with depth>40km, M>3.0). Rd triangles are active volcanoes. (Top) Cascadia. (Bottom) A portion of the Alaska subduction zone at the same scale. Other segments would look similar, except where the Alaska catalog is not complete to M~3.

In general, low data latency was viewed as less important than comprehensive coverage. A high-return rate and high data quality were viewed as important; thus perhaps we should compromise with a low data rate in real time but higher rate recorded on site. It is likely logistics will drive what stations get real time telemetry and existing infrastructure such as internet capable schools should be explored as partners to deliver the data in real time or near real time where possible. The frontier nature of Alaska makes the recording of the maximum possible new data absolutely critical, as this may be the only way to detect unexpected new signals in this highly active, yet largely untouched region.

In terms of TA spacing there was strong interest in 70 km spacing where that is practical. Integration with AEIC stations needs to be considered along with issues of maintenance funding and priority. Some targets such a volcanic targets and ETS will need small aperture arrays and perhaps some of these instruments could be less expensive broadbands, so that an array with a central TA station and less expensive satellite equipment could be deployed for not much more than a TA station, especially in areas where access is expensive. Where logistics dictate a sparser network, we need to maintain a rationality check on the cost for any station. It makes sense to densify the array to 70 from Denali Fault south (the subduction zone and volcanic arc) and have it sparser in the more remote areas north and west. Making use of airstrips and deployment out of small aircraft will increase the number of stations that can be deployed in remote areas. EarthScope should make use of logistical and other experience in Alaska, and partner with AEIC and AVO. In addition to aircraft, large parts of western and central Alaska might best be accessed through winter logistics employing snow machines for "heavy lifting" of materials to sites. This technique would minimize the need for aircraft usage and provide significant cost savings for installations in these remote areas. Finally, everything hauled in for the TA will need to be hauled out, unless the stations are adopted, which further puts a premium on lightweight and compact installations.

Strong motion sensors could be really important for larger magnitude earthquakes given their prevalence in Alaska and thus the suggestion arose to put them everywhere in southern and central Alaska as even the larger 4s can cause nonlinearities in instrument response. The M7.9 2002 Denali Fault earthquake clipped most of the broadband sensors across Alaska and a significant swath of NW North America. An earthquake of M~7.5 or larger in mainland Alaska would not produce usable seismograms across most of the Alaska TA deployment unless strong motion instruments were deployed with the TA. There is a substantial probability (~50%) of such an event occurring within a 3-year TA deployment period.

Slow slip and ETS targets are exciting in AK and investigating these processes require coincidence of PBO and TA. More GPS stations in the areas of slow slip and tremor would be desirable. Specific locations include the Cook Inlet region, and the subduction zone near Unalaska/Dutch Harbor. That area is the most active known area in the oceanic arc as far as tremor is concerned, but the PBO stations are not deployed to allow comparison of slow slip and tremor. More stations on the Pacific side of the islands are required.

A large amount of discussion occurred about including parts of Canada in the TA deployment. Doing so would provide data coverage needed to study the whole Denali system and its potential connection to the Fairweather-Queen Charlotte system, would improve the ability to locate and study seismicity in the Arctic, and the allow the study of far field effects of the Yakutat collision in the Mackenzie Mountains. After some discussion, an hourglass shape Canadian deployment was envisioned extending the Alaskan EarthScope array into southern and northern proximal parts of Canada with the highest priority being the southwest Yukon. The northern part of this might resemble a densified version of the broadband deployment recently proposed by Pascal Audet of the University of Ottawa (Figure 11). The remainder of the deployment would target the tectonically active coast of Canada between Alaska and the lower 48 (Figure 12). Opportunities for collaborating on the Canadian side include the Polaris array, Canadian academic partners, and the Yukon territorial government; note examples of success from lower 48-Canada partnerships.

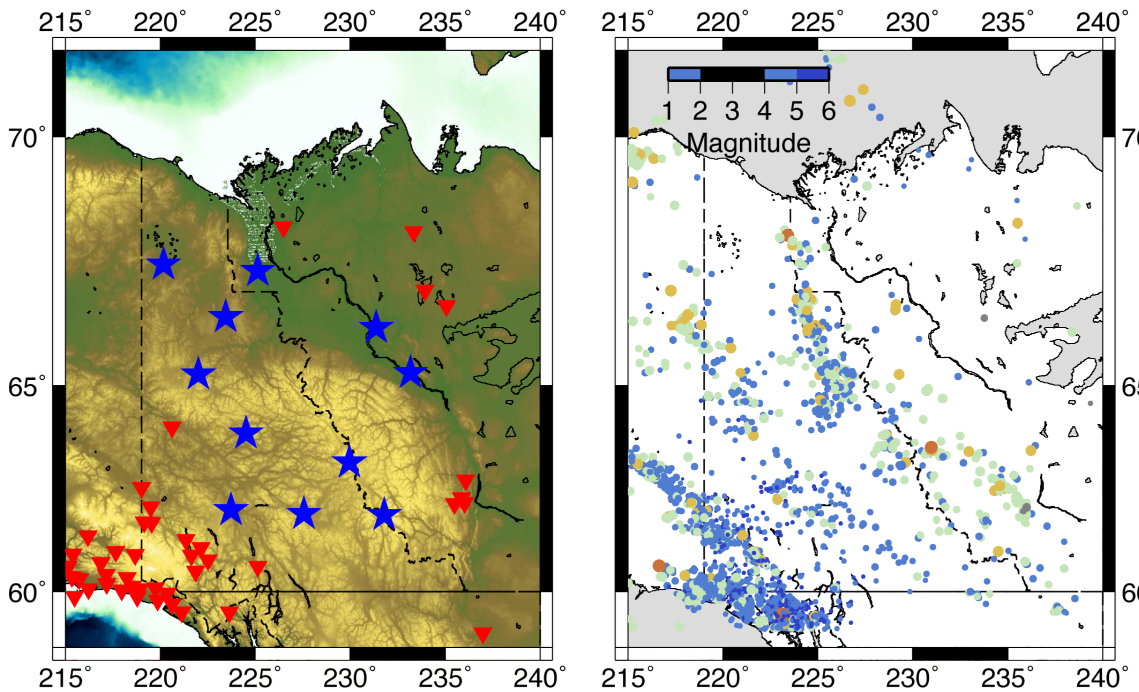


Figure 11.Broadband deployment proposed in the Yukon Territory by Pascal Audet, University of Ottawa. (Left) Blue stars are proposed new broadband deployment, red triangles are existing seismic stations (including short period stations). (Right) seismicity.

Air cell batteries, lithium batteries, or other high capacity, lightweight batteries should be considered in place of lead-acid batteries because transport is expensive in Alaska. Solar powered sites will require a lot of batteries, so careful thought should be given to whether a temporary (2-3 year) deployment really needs that much lead hauled out and back. Investigate experiences of NSF-OPP on battery issues, based on their deployments of sites in Greenland and Antarctica. Some potential logistical aids include be fish and wildlife vessels, snowcat-based winter deployments, and dog sleds.

Some other instrumentation ideas that arose include tide gauges for sea level and slow slip and tsunami observation, but it was noted these are a long-term commitment. Variable wind & barometric pressure will influence seismic noise characteristics. It costs $2300/station for met system plug in which would be useful input for regional climate models. There was support for using met data to estimate snowfall throughout the year for “ground truth” to satellite measurements and for loading models. There is also potential to use seismic noise characteristics to study sea ice changes after quantifying signals due to wind. The TA grid would be helpful for this kind of study, but might need a denser array near the Bering Sea coast. For examination of effects of seasons and climate change continuous operation of the TA sites is vital. A potential add-on for permafrost sites is that the 5 m seismometer emplacement depth could be monitored for temperature throughout the deployment to document freeze/thaw cycles.

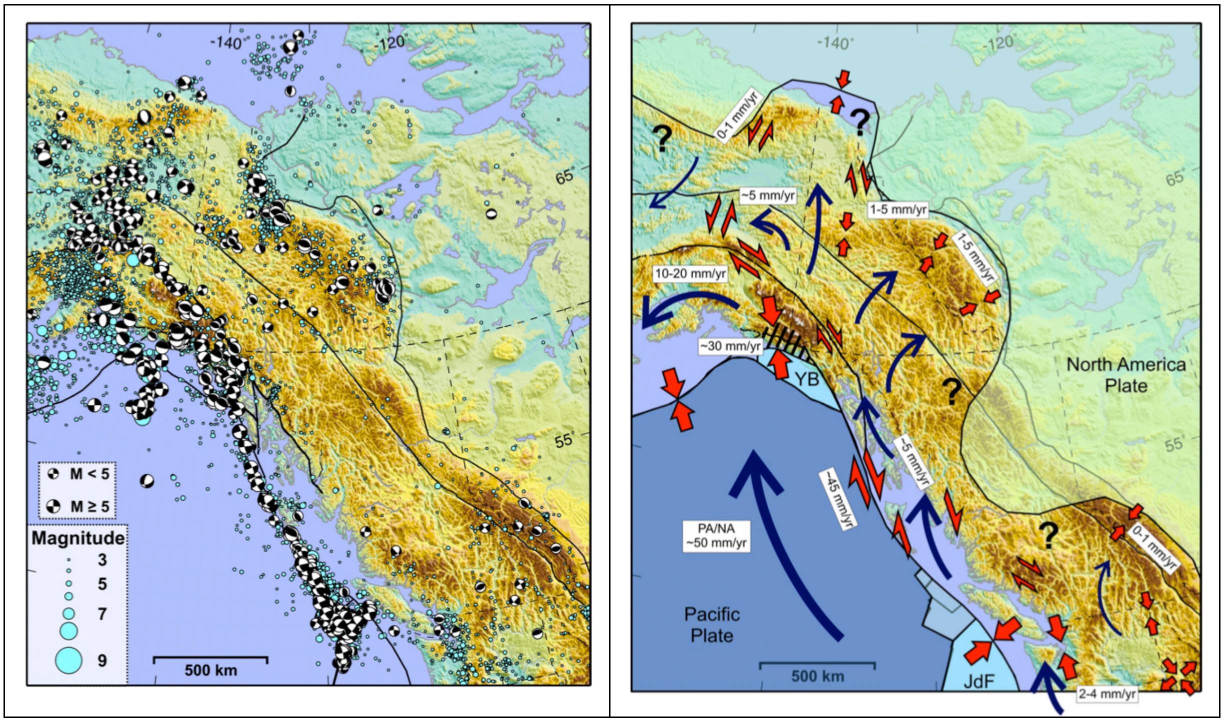


Figure 12.Seismicity and tectonics of the Northern Cordillera, from Mazzotti et al. (2008). (Left) Seismic focal mechanisms. (Right) Patterns of tectonic motions and regions of contraction and strike-slip faulting.

Suggestions for Synergy and Cooperation

There is a clear and compelling opportunity for synergy and collaboration between EarthScope and the NSF GeoPRISMS program. GeoPRISMS has chosen Alaska as its first choice of Primary Site for its Subduction Cycles and Deformation (SCD) component. The GeoPRISMS SCD program scientific goals have considerable overlap with EarthScope goals. Over the next decade, GeoPRISMS expects to support a variety of multi-disciplinary land and marine based studies of subduction zone seismogenesis, fluid cycling and volcanism/arc development in Alaska. Some of these studies will depend on EarthScope instrumentation and/or deploy additional complementary instrumentation. There will also be considerable opportunity to exploit the combination of marine-based data with EarthScope networks on land.

Some GeoPRISMS projects will overlap in time with the deployment of the USArray TA. Extension of the TA down the Alaska Peninsula and into the Aleutians is critical because the TA can form the backbone not only for EarthScope FlexArray deployments but also for GeoPRISMS efforts.

There is also potential for a future deployment of the Cascadia initiative OBS instruments to Alaska. While the future of these instruments is not settled, and will not be settled here, if these instruments went to Alaska immediately after the deployment in

Cascadia finished, their operational period would coincide with that of the TA. Such a simultaneous deployment would provide the greatest opportunity to study selected regions of the arc with dense onshore and offshore networks. This would provide greatly increased capabilities to precisely locate and model waveforms from shallow earthquakes on the megathrust and in the forearc of the overriding plate through OBS and land station recordings of natural seismicity. An OBS deployment would most likely also coincide with active source marine seismic profiling, which would be enhanced by having additional land station recordings of offshore airgun sources. These data will better delineate active seismogenic structures and provide a wealth of sources for imaging studies.

Alaska is also prime territory for the expansion of seafloor geodetic networks. The deformation signals in Alaska are 50-100% larger than comparable signals in Cascadia. The dramatic along-strike variations in the interseismic slip deficit in Alaska provide attractive research targets, in which potential end member models can be easily distinguished. This characteristic potentially allows important questions about the nature of the seismogenic zone to be answered.

EarthScope-supported geophysical networks and instrumental deployments should be complemented by geologic studies of past megathrust ruptures. These would consist mainly of the identification and dating of tsunami deposits and abrupt relative sea level changes, and measurements of short-term or long-term uplift or subsidence through coastal geomorphology. Collection of LIDAR data and efforts like the GeoEarthScope investigations in the Lower 48 could provide critical quantitative data on geomorphic features. Particular targets of interest include the remainder of the Denali fault, and coastal terraces and other features that relate to tectonic and other vertical motions.

Several NASA missions produce complementary data for EarthScope science investigations, and NASA programs support complementary studies. The GRACE mission provides estimates of surface mass loads globally with a resolution of 10-30 days (depending on wavelength). These mass variations cause corresponding deformation of the Earth, measured by PBO, and stress changes within the earth that may cause variations in seismicity. These data also constrain longer-term loading models, for glacial isostatic adjustment studies of deformation and stress changes. NASA is supporting wide-swath LIDAR measurements as part of its Project Icebridge, although mainly of glaciated areas, and other satellite data related to topography and topographic change. NASA remote sensing data may be combined with point sampling at USArray sites to better characterize surface properties, surface geology, and related characteristics on a synoptic scale. SAR data and a potential future InSAR satellite mission is another significant NASA contribution to EarthScope studies in Alaska. NASA currently supports imaging of a number of volcanoes in the eastern Aleutians using its UAVSAR airborne SAR sensor, and supports extensive data acquisition efforts for SAR imagery from foreign SAR satellite missions.

The National Geodetic Survey (NGS) GRAV-D program is in the process of flying airborne gravity surveys across Alaska and its immediate offshore areas. The primary goal of GRAV-D is to enable NGS to develop improved geoid models for Alaska and all of the coastal US, by filling in complete gravity coverage and eliminating data gaps in the immediate offshore regions. However, land gravity data in many parts of Alaska are extremely sparse, and mostly derived from data from decades old surveys that had poor positional control. The new data will greatly aid EarthScope studies that depend on using gravity data to infer compensation mechanisms or deep properties of the lithosphere.

Data from several past active and passive source seismic experiments are available for integration with EarthScope data into a coherent 3D model. These data come from projects of a variety of scales including TACT, SNORCLE, ACCRETE, BATHOLITHS, STEEP, EDGE, BEAAR, MOOS, and more recent active source projects acquired in the last few years for research or for definition of the outer continental shelf for Law of the Sea characterization. Considerable industry seismic and drilling data exists in certain areas as well.

The EarthScope focus on Alaska also offers opportunities to extend studies across both the Canadian and Russian borders. Active structures and correlatable geologic or geophysical features related to past episodes of continental growth and modification extend across both borders. When geophysical data, geologic maps or other data stop at national boundaries, it encourages scientists to think of those as "free boundaries", over which anything is permissible.

The long border with Canada provides a particular opportunity. The Alaska-Canada border cuts across active tectonic structures associated with the collision of the Yakutat terrane and the active Northern Cordillera. The Alaska panhandle extends ~800 km down the coast, a narrow strip of land that might support perhaps two rows of TA stations. Extending the TA grid into Canada would dramatically increase imaging capabilities. In addition, this entire section of the coast, inboard of the offshore Queen Charlotte transform fault, is tectonically active and is moving and deforming at rates comparable to many areas of the Lower 48 that have received intensive study, such as the Cascadia forearc (Mazzotti et al., 2003; Mazzotti et al., 2008; Freymueller, 2010). Cooperative expansion of the TA into Canada can build on the successful expansion of the TA into Canada in the Great Lakes region, and existing Canadian investments in projects in the northern Cascadia and Northern Cordillera regions.

Active tectonic structures cross over the Alaska-Russia border. Some or all of the Bering Sea crust makes up part of the Bering plate, which rotates clockwise relative to North America (Mackey et al., 1997; Cross and Freymueller, 2008). Bering plate motion and related movement of the Alaska Peninsula and Aleutian arc may accommodate the westward escape of crust from southern Alaska, driven by the collision of the Yakutat Terrane. The detailed configuration of active faults and moving tectonic blocks remains uncertain in this region. Active seismic belts cross the US-Russia border at the Bering Strait and on the north side of the Aleutian arc, in addition to the continuation of the Aleutian megathrust south of the arc. Additional tectonic connections may exist in this poorly studied and instrumented region.

EarthScope investigations may also benefit from collaboration and interaction with a variety of other efforts in the area:

- *Alaska Volcano Observatory.*
- *Alaska Earthquake Information Center (the Alaska Seismograph Network).*
- *NOAA tsunami program and the West Coast/Alaska Tsunami Warning Center.*
- *US Geological Survey proposed Natural Hazards Program.*
- *The upcoming IODP Expedition 341- Tectonics and sedimentation in the Gulf of Alaska,*

scheduled for 2013.

There may be additional benefits and collaborative opportunities with communities outside of earth sciences, including those studying climate change and weather and their effects on northern latitude fauna and flora. Their studies require some of the same things we need, including remote instrumentation and access to remote areas.

Conclusions

The ~75 person workshop participants exhibited a high degree of interest and excitement about the prospect of future research opportunities that will be enabled by EarthScope in Alaska. Alaska is extraordinarily active, which promises a tremendous number of potential signals to measure, and remains a frontier for earth science research. First order problems remain to be investigated, and the high level of activity and limited amount of past work means there are great opportunities for making new and unexpected discoveries. Opportunities for discovery and for answering many of EarthScope's fundamental science questions abound in Alaska.

Consensus was reached among the participants regarding the deployment of the Transportable Array in Alaska. EarthScope should maintain comprehensive coverage at the standard 70 km coverage where practical, but include some flexibility of widening spacing where an individual site is too costly. In such areas, a station spacing of 85 km or potentially even larger should be considered. Achieving a 70 km spacing in part of Alaska will probably require IRIS to find ways to deploy stations at lower cost than their initial estimates. If the average cost per station can be kept down, more stations could be installed within the fixed budget, and this is a high priority. EarthScope should include a backbone array spanning Alaska Peninsula and Aleutians as far as practical in addition to the comprehensive coverage of mainland Alaska. The participants also suggested EarthScope should consider some deviations from grid including small arrays where TA would be linear. Lastly, the participants suggested EarthScope prioritize the number of stations over real-time/rapid access to data given that Alaska is a frontier deployment. Logistical realities dictate that Alaska TA stations will be constructed differently than lower 48 standard and given the likelihood of high magnitude earthquakes and the limited climate data in Alaska the participants suggested examining the possibility of including meteorological packages and strong motion sensors on some of the TA stations.

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Appendix 1: Agenda

2011 EarthScope Workshop:
Opportunities for EarthScope Science in Alaska in Anticipation of USArray

Sunday, May 15

Icebreaker at Dog and Duck Pub
Hosted by the University of Texas Institute for Geophysics (UTIG)
6-8 pm Sunday May 15th
406 West 17th Street
Austin, TX 78701

Directions: Walk west from AT&T Conference Center to Guadalupe Street, turn left and walk 1.5 blocks, Dog and Duck Pub is on the right and the icebreaker is on the back patio. Hors d'oeuvres provided with selection of local and imported beers, ciders, and wines for purchase at the bar.

Monday, May 16

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*The workshop will feature several **breakout sessions** to highlight exceptional scientific opportunities and integration with other projects. We have two one-hour breakout periods and people are expected to switch halfway through. Charge to Breakout groups:*

- *Discuss scientific opportunities addressable through Alaska/Canada deployments*
- *Based on the scientific opportunities, what recommendations should be made for facility design or operation?*
- *In each area, what opportunities exist for synergy or cooperation with other programs, especially GeoPRISMS?*

7:00 Registration, breakfast
8:00 opening remarks, workshop overview/goals, EarthScope 2010-2020 plan

Session 1: Tectonics, history and structure
Presiding: Sean Gulick
8:15 Tectonic History and current knowledge of the crust (*Sarah Roeske* and *Rick Saltus*)
8:55 Discussion
9:10 Active Tectonics (*Peter Haeussler*, *Jeff Freymueller*, *Stephane Mazzotti*)
9:45 Discussion

10:00 Break

Session 2: Testing Hypotheses Developed in the Lower 48
Presiding: Sarah Roeske
10:30 Mantle flow at slab edges (*Margarete Jadamec* and *Doug Christensen*)
10:50 Discussion

11:00 History and effects of slabs under North America (*Lijun Liu* and *Geoff Abers*)
11:20 Discussion
11:30 Tremor and slow slip (*Justin Brown* and *Tim Melbourne*)
11:50 Discussion

12:00 lunch

Session 2.5: Mini-Talks
Presiding: Jeff Freymueller
13:00 Mini-talks (5 minutes each)
13:30 Discussion (30 minutes)

14:00 Charge to Breakouts (Sean Gulick)

Breakout Session 3A: Slab and mantle structure and dynamics
--conveners Gary Pavlis and Pascal Audet
14:00 Discussion (1 hour)
15:00 Discussion (1 hour)

Breakout Session 3B: Exploring the genesis zones and Earth's response from great (M > 8) earthquakes
--conveners Peter Haeussler and Joan Gomberg
14:00 Discussion (1 hour)
15:00 Discussion (1 hour)

Breakout Session 3C: Accessory measurements and enhancements of the facility instrumentation
--conveners Adam Schultz and Steve McNutt
14:00 Discussion (1 hour)
15:00 Discussion (1 hour)

Session 4: Active processes modifying the continent
Presiding: Mike West
16:30 Volcanism and magmatic processes (*Brad Singer* and *Mike Lisowski*)
17:00 Discussion
17:15 Earthquake processes (*Chen Ji* and *Rowena Lohman*)
17:45 Discussion
18:00 Mini-talks (5 minutes each)
18:30 Discussion (45 minutes)

19:30 dinner

Evening informal poster session and discussion

Workshop Agenda: Tuesday, May 17

7:30 breakfast

08:00 Charge to Breakouts (Sean Gulick)

Breakout Session 5A: Structure and dynamics of active volcanoes, and magmatic processes at depth.
--conveners Donna Shillington and Cliff Thurber
8:00 Discussion (1 hour)

9:00 Discussion (1 hour)

Breakout Session 5B: Illuminating past tectonics with present seismicity: Crustal structure and seismic imaging with slab seismicity, widespread crustal seismicity, teleseisms, ambient noise, and active sources.
--conveners Carl Tape and Lindsay Worthington
8:00 Discussion (1 hour)
9:00 Discussion (1 hour)

Breakout Session 5C: Hydrosphere, Cryosphere and Atmosphere
--conveners Jeanne Sauber and Dan Lawson
--coupling of solid Earth to changes in the hydro-, cryo- and atmosphere (models and observations)
--additional met measurements (P, T, precipitation) at PBO and TA sites for improvement of regional climate models
--monitoring of wave energy and sea ice changes from near coastal TA sites
8:00 Discussion (1 hour)
9:00 Discussion (1 hour)

10:00 Break

Session 6: Wrap-up
Presiding: Jeff Freymueller
10:15 Breakout reports and discussion (45 minutes)
11:00 Recommendations for USArray

12:00 lunch
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Appendix 2: Participants

First Name	Last Name	Institution
Geoffrey	Abers	Lamont-Doherty Earth Observatory of Columbia University
Kent	Anderson	IRIS
Eiana	Arias	IRIS/PASSCAL
Pascal	Audet	University of California Berkeley
Bruce	Beaudoin	IRIS PASSCAL
Paul	Bedrosian	US Geological Survey
Sean	Bemis	U.S. Geological Survey
Patrick	Brennan	Purdue University
Richard	Briggs	US Geological Survey
Justin	Brown	Stanford University
Robert	Busby	IRIS
Douglas	Christensen	Geophysical Institute, University of Alaska Fairbanks
Gail	Christeson	UTIG
Harmony	Colella	UC Riverside
Vincent	Cronin	Baylor University
Diane	Doser	University of Texas at El Paso
Julie	Elliott	Geophysical Institute, Univ. Alaska Fairbanks
Max	Enders	UNAVCO
Emily	Finzel	ExxonMobil Exploration Co.
Lucy	Flesch	Purdue University
Tom	Fournier	Rice University
Jeff	Freymueller	University of Alaska Fairbanks
James	Gaherty	LDEO, Columbia University
Joan	Gomberg	US Geological Survey
Ronni	Grapenthin	UAF-GI
Marie	Green	University of Utah
Sean	Gulick	University of Texas at Austin
Peter	Haeussler	USGS
Brian	Hampton	Michigan State University
Matthew	Haney	U. S. Geological Survey/Alaska Volcano Observatory
Roger	Hansen	University of Alaska Fairbanks
Erik	Hauri	Carnegie Institution of Washington
Margarete	Jadamec	Monash University and Brown University
Helen	Janiszewski	Rutgers University
Chen	Ji	UC Santa Barbara
Alan	Levander	Rice University Earth Science
Michael	Lisowski	USGS Cascades Volcano Observatory

Lijun	Liu	IGPP, SIO, UCSD
Rowena	Lohman	Cornell
Stephen	McNutt	UAF Geophysical Institute
Julia	Morgan	Rice University
Elisabeth	Nadin	University of Alaska Fairbanks
Alex	Nikulin	Rutgers University
Gary	Pavlis	Indiana University
Terry	Plank	Lamont-Doherty Earth Obs, Columbia Univ
John	Power	USGS - AVO
Ken	Ridgway	Purdue University
Sarah	Roeske	University of California, Davis
Emily	Roland	Woods Hole Oceanographic Inst (as of 2012 - USGS)
Diana	Roman	University of South Florida/DTM-CIW
Natalia	Ruppert	University of Alaska Fairbanks
Jeanne	Sauber	NASA Goddard Space Flight Center
David	Scholl	University of Alaska Fairbanks
Adam	Schultz	Oregon State University
Donna	Shillington	Lamont-Doherty Earth Obs, Columbia Univ
Brad	Singer	University of Wisconsin-Madison
Brian	Stump	Southern Methodist University
Carl	Tape	University of Alaska Fairbanks
Clifford	Thurber	UW-Madison
Anne	Trehu	Oregon State University
Jennifer	Wade	National Science Foundation
Spahr	Webb	LDEO/ Columbia U
Michael	West	GI/UAF
Douglas	Wiens	Washington University in Saint Louis
Bob	Woodward	IRIS
Lindsay	Worthington	Texas A&M University
Jacob	Walter	UC Santa Cruz
Robert	Dietrich	NSF
Doug	Neuhauser	UC Berkeley
Göran	Ekstöm	LDEO/Columbia University
David	Simpson	IRIS
James	Gridley	IRIS/PASSCAL
Rob	Porritt	UC Berkeley
Mike	Brudzinski	Miami University
Harm	van Avendonk	University of Texas at Austin
Greg	Anderson	NSF

Appendix 3: White Papers

All submitted white papers are reproduced on the following pages, in the form submitted by the individual authors.