THE BENEFITS OF ENHANCED EARTHQUAKE MONITORING AND POTENTIAL EARTHQUAKE EARLY WARNING IN ALASKA

A Stakeholder Survey

Developed by the Alaska Seismic
Hazards Safety Commission

ASHSC Alaska Seismic Hazards Safety Commission

seismic.alaska.edu

Prepared for the Office of
Governor Bill Walker

June 27, 2016

Front: Anchorage, Alaska. Photo from pixabay.com
Back Top: Alaska Railroad train traveling through the Indian River Valley. Photo from Alaskarailroad.com
Back Bottom: Seward, Alaska. Photo from pixabay.com

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The Alaska Seismic Hazards Safety Commission

The Alaska Seismic Hazards Safety Commission (ASHSC) was established in 2002 (Alaska Statute 44.37.067) and is charged on behalf of the governor, legislature, local governments, industry, and the public to:

- Recommend goals and priorities for mitigating seismic hazards (e.g. strong ground shaking, landslide, avalanche, liquefaction, tsunami inundation, fault displacement, and subsidence);
- Recommend policies including needed research, mapping, and monitoring programs;
- Review the practices for recovery and reconstruction after a major earthquake and recommend improvements to mitigate losses from similar future events; and,
- Gather, analyze, and disseminate information of general interest on seismic hazard mitigation to reduce the state's vulnerability to earthquakes.

The Commission is comprised of eleven members, appointed by the governor to three-year terms, and represents a broad range of entities and expertise. The present members include:

John L. Aho, Ph.D., Sc.D.	Engineering Consultant; Anchorage	(Past Chair)
Charity Carmody	State Farm Insurance; Anchorage	
Gary A. Carver, Ph.D.	Geologic Consultant; Kodiak	
Duane Dvorak	Resource Management Officer, Kodiak Island Borough	
Ann Gravier	Hazard Mitigation Officer, DMVA-DHS&EM; Anchorage	
David Gibbs	Director Emergency Services, Fairbanks-North Star Borough	
Michael Holman	Director Department of Safety, Unalaska	
Laura W. Kelly, P.E.	Civil Engineer, USCG; Juneau	(Vice-Chair)
Robert L. Scher, P.E.	Geotechnical Engineer; Anchorage	(Chair)
De Anne Stevens	Geologist, DNR-DGGS; Fairbanks	
Michael West, Ph.D.	State Seismologist, UAF Geophysical Institute; Fairbanks	

Documents produced by the Commission (e.g. annual reports, meeting agenda and minutes, strategic and operating plans, policy recommendations and white papers, etc.) are available on the Commission's website www.seismic.alaska.gov.

Charge and Context for this Report

In May 2016, Governor Bill Walker's office asked the Commission to lead an effort to compile a summary of the benefits of improved earthquake monitoring in Alaska and potential early warning. The charge was to address benefits at both the Alaska and national level. This request was motivated in part by the congressional request included in the FY16 budget legislation to the U.S. Geological Survey to "conduct a cost benefit analysis and spending plan for the adoption of any remaining seismic stations, including stations in final deployment, if included as part of the Survey's Advanced National Seismic System for Research." Given the breadth of stakeholders—spanning science to engineering to risk mitigation to emergency management to public and private infrastructure—there was considerable need for a document that would provide context for the numerous and varied potential benefits of improved monitoring. The Commission recognizes that these benefits have an associated cost which remains to be assessed. The Commission's task at this time, and this report, focuses on the benefits.

A full treatment of the topic would require an estimated 1-2 years, working groups with expertise in critical sub-disciplines, travel, and the ability to commit substantial staff time from various state agencies. On short notice these were not an option. The timeframe for preparing this document was about six weeks. However, the Commission saw great value in addressing the request from the governor and was eager to respond.

In addressing this task, the Commission had the following goals:

- Ensure open participation from stakeholders
- Avoid prescribing the outcome with pre-selected topics or authors
- Make the document extensible to accommodate new information
- Use the Commission's breadth of expertise to vet stakeholder responses
- Provide a vision that integrates the broad set of stakeholders across the state and nation

The Commission met these goals through an open letter of request. Commissioners circulated this request through their various channels and to stakeholders in their areas of expertise, including state and local government departments, public and private engineering groups, earthquake scientists, emergency response organizations, etc. This distribution approach undoubtedly missed some important stakeholders. However, the professional breadth of the commissioners helped reach into pockets of expertise that no single organization or email list could reach. The diversity of responses suggests that this distribution approach was quite successful.

Responses were edited for consistency (e.g., fonts) and to fit the single-page format. The content represents the opinion of the authoring stakeholders. However, in a handful of cases an individual who submitted content was asked to clarify, revise, or shorten their suggested text. In some sections of technical text, a summary sentence was added to help make the text accessible to a general audience.

The topics included in this document are based on ad hoc responses from the earthquake community and should be viewed as a sampling. They are examples that demonstrate the benefits to specific end users, specific community problems, and specific research areas. They are in no way a comprehensive summary.

The Commission is deeply grateful to the people who volunteered their expertise, time, and energy to contribute one or more pieces to this effort. We hope we have done justice to their interests. The individuals who contributed to this report are listed below:

Geoffrey Abers, Kasey Aderhold, John Aho, Chris Allard, Jason Amundson, Greg Kiah Archibald, Tim Bartholomaus, Jeff Benowitz, Kyle Brennan, Helena Buurman, Charity Carmody, Gary Carver, Rod Combellick, Ian Dickson, Utpal Dutta, Duane Dvorak, Catherine de Groot-Hedlin, David Fee, Douglas Fleming, Andy Frassetto, Jeff Freymueller, Lea Gardine, Matt Gardine, Stephen Gebert, Abhijit Ghosh, David Gibbs, Ronni Grapenthin, Ann Gravier, Michael Hedlin, Michael Holman, Stephen Holtkamp, Laura Kelly, Rich Koehler, Ray Leggett, Ken Macpherson, Elmer Marx, Sara Meyer, Natalia Ruppert, Buzz Scher, Molly Staats, De Anne Stevens, Baird Stiefel, Curt Szuberla, Carl Tape, Aaron Wech, Michael West, Bill Witte, and Bob Woodward.

Summary of Benefits

The Commission binned all of the submissions into five subjective sections. Although these sections are imperfect, they provide some order for the responses to an extremely, and purposely, open-ended request. Note that many submissions could be equally at home under multiple sections. The summaries below address each of the sections, at times calling on submissions that may appear in other sections but are relevant to the topic.

Earthquake characterization

Though baseline earthquake detection capabilities exist across most of Alaska, a number of submissions point out shortcomings in the ability to characterize the basic parameters of earthquake location, depth, and magnitude. In addition, many regions in the state suffer from poor ability to determine the direction of motion of an earthquake (i.e., the focal mechanism or moment tensor). These shortcomings propagate as uncertainties into many of the other topics in this document. Several significant questions concerning the structure and behavior of specific fault systems could be answered directly with more accurate characterization of earthquakes.

There are current shortcomings in the timeliness of earthquake characterization. The current network density in many areas delays detection and assessment when significant earthquakes occur. The higher errors incurred on the fringes of the network add additional delays to timely reporting. Several submissions demonstrate poor performance of automated algorithms in areas lacking network coverage. A few submissions highlight the ability to improve these characterizations after the fact with manual “research-grade” tools. However, these efforts are not suitable for rapid operational use and do not improve the timeliness of earthquake information.

A few submissions here (and in the earthquake early warning section) demonstrate the utility of GPS in assessing the magnitude of large earthquakes. This helps to address a long-standing paradox in seismology: often the largest earthquakes are the most difficult to measure quickly. The vast majority of GPS stations in Alaska are operated under the EarthScope Plate Boundary Observatory (PBO) project but do not provide suitable real time data. The GPS topics submitted here offer strong support for the long-term continuation of the Plate Boundary Observatory as well as a conversion to high-rate real-time dataflow.

At the time of writing, the USArray Transportable Array (TA) has only begun to push into western and northern Alaska. However, a few submissions demonstrate that it has already had an impact on earthquake characterization. Better earthquake characterization is the most basic benefit from improved earthquake monitoring. Though we often take the simple measures of location and magnitude as certain fact, these data are the foundation on which the other four sections in this report are built. Errors and poor performance in earthquake characterization degrade the accuracy of earthquake hazard assessments, post-earthquake response and recovery, our ability to address national science priorities, and the capacity to deliver earthquake early warning. This pervasive dependence of nearly all other topics in earthquake science makes the ability to more accurately characterize earthquakes a significant benefit.

Earthquake hazard assessment

Confidence in assessments of earthquake hazard[1] in Alaska generally lags behind the rest of the nation. There are legitimate challenges that complicate the assessment including: multiple tectonic sources (crustal, offshore, subduction zone, etc.); limited fault mapping and information about the prehistoric activity of faults; and imprecise tracking of earthquakes. The combined impact of these factors means that in much of Alaska there is surely a significant discrepancy between the true and estimated hazard. To fully assess earthquake hazard we need to understand the actual sources of earthquakes, the influence of the geology through which the seismic waves travel, and the response of the soils at the site of shaking.

Identifying recently and currently active faults is a cornerstone of earthquake hazard assessment. Several submissions in this section point to the iterative process of using seismicity to identify targets for geologic field mapping, which in turn informs our knowledge of the seismic potential. This symbiosis is limited in many

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[1] For example, prediction of earthquake-induced ground motions, potential for ground failure, etc.

places (especially northern, western, and southeast Alaska) by the tendency of poorly constrained catalogs to manifest seismicity as fuzzy clouds instead of sharp lineations along faults.

While no one questions the significance of the tsunami threat in Alaska, it is at times unfortunately treated as a separate hazard. This separation reflects in part a division of responsibilities between federal agencies. For the citizens of Alaska's coastal communities, however, earthquakes and tsunamis are inseparable hazards. Robust earthquake monitoring is the foundation of rapid and accurate tsunami warning. The ability to estimate future tsunami hazards is a subtler, but equally important, benefit. Several submissions illustrate how the accurate characterization of earthquakes supports the development of tsunami hazard products such as evacuation routes and inundation zone mapping. These products are the foundation of the public education programs that are so vital to tsunami safety in communities that have minutes, not hours, to evacuate.

GPS measurements play an increasingly important role in earthquake hazard analysis. Because GPS can measure the steady on-going movement across faults even when there are no earthquakes, it can be used to estimate the rate of earthquakes that a particular fault is likely to generate. This rate information is highly complementary to the geologic and seismic constraints.

One submission calls into question the validity of the ground motion prediction equations (often referred to as GMPEs, applied to estimate the shaking from earthquakes) used in Alaska. This concern is especially true for subduction zone earthquakes, which generally control hazard assessments in our coastal areas. In fact, the next version of the USGS Probabilistic Seismic Hazard Map for Alaska has been postponed for several years pending the development of more appropriate GMPEs. These equations are based on observations, not theories, and are limited only by the number of recordings of strong earthquakes. In addition to the in-state need, the rich earthquake dataset in Alaska offers the potential to help build better GMPEs for use globally.

Lastly there is a strong need to better quantify the influence of different soil conditions and site impacts, especially in urban areas. Separate submissions point at this need in Southcentral and Interior Alaska, though the need extends wider than just these locations. Improving earthquake monitoring, especially strong motion, will provide this information. Not only will this support the development of seismic hazard products, the same information will improve the reliability of ShakeMaps following significant earthquakes and ShakeMaps used to support scenario planning and response exercises.

The last decade of observations from the Plate Boundary Observatory (PBO) are vastly improving earthquake hazard assessment by providing the majority of precision GPS in the state. The impact of the Transportable Array (TA) on earthquake hazards will ramp up in the next few years. The need to assess earthquake hazards will always be a part of living and doing business in Alaska. As society and infrastructure grow more complex and interdependent, the need to deliver accurate earthquake hazard assessments continues to grow as well. The combined long-term operation of USArray and PBO is arguably the most significant step Alaska could take toward ensuring the availability of accurate location-appropriate earthquake hazard assessment in the years and decades to come.

Post-Earthquake Response and Recovery

The submissions in this section paint a broad picture of infrastructure monitoring and assessment needs. Alaska has the same standard infrastructure assessment needs as elsewhere—hospitals, bridges, buildings, ports, utilities, military, etc. Compared to other seismically active western states, the number of these facilities in Alaska is lower. It is tempting to extrapolate that the risk associated with these facilities is equivalently lower. These submissions illustrate well, however, that many of these facilities are truly single points of failure without alternatives. For example, to circumvent a compromised bridge on one of Alaska's primary highways—the Parks, Glenn, Richardson—can require a detour of 1000 km (600 miles). Along some other corridors—such as the Seward Highway, the Alaska Railroad, or the northern highways—alternative routes simply do not exist. Several submissions point out the comparable situations that exist in utilities including electricity, pipelines, and communications. Limited redundancy and heavy reliance on individual providers make these facilities more important to the citizenry and the economy than one might infer from population numbers alone.

In the event of a major earthquake, a failure in one of these systems is not only damaging in the immediate aftermath, it is also a barrier to recovery. Alaska's infrastructure is filled with these types of multipliers with the potential to magnify modest physical damage into widespread societal consequences. Though not specifically described in these submissions, the cargo distribution through the Port of Anchorage is the primary cargo hub for the state. Earthquake damage at the port would have ripple effects in every corner of the state. Climate and remoteness are other multipliers. The impact of a winter shutdown in the electrical distribution system in Interior Alaska could become catastrophic in a matter of hours as buildings begin to freeze up. These types of consequences, some unique to Alaska, are hard to capture in typical risk assessments. Standardized formulas for estimating economic loss and casualties fail to account for many of these unique dependencies. As a result, the loss numbers estimated in broad comparison studies, such as the HAZUS MH Estimated Annualized Earthquake Losses for the United States (FEMA, 2008), fail to capture a significant component of the real risk. Though not confirmed quantitatively, risk numbers such as these are surely underestimates.

Major industrial infrastructure adds an additional source of risk. Alaska has, for decades, been home to numerous large-scale mining and oil and gas projects. These facilities are spread across the state and are often in areas far away from population. Reliable earthquake hazard assessments are essential to helping make these facilities both safe and profitable. Accurate assessments at the time of development allow these facilities to "build right the first time" and avoid costly retrofits. Improved earthquake monitoring stands to benefit these facilities by allowing comparisons with engineering plans to rapidly determine whether or not design standards have been exceeded. A few submissions underscore the importance of on-site instrumentation to facilitate these types of comparisons. Integrated into ShakeMaps, these same data can be used to improve the extrapolation to areas of lesser instrument coverage.

Opportunities to advance national science priorities

This section includes a wide variety of applications ranging from the detection of distant nuclear testing to river breakup to tracking sea ice. These applications are a small sampling of the broader uses of data from the existing geophysical networks in Alaska. Enhancing the earthquake monitoring capability in Alaska will have the ancillary benefit of enhancing these science-driven research topics. There are several themes that run through these submissions.

A number of submissions point to natural hazards applications beyond earthquakes. Tracking river ice, sea ice, and glacier calving supports studies of climate and offers the possibility to better navigate the hazards associated with spring breakup of rivers. Another set of submissions examine the role Alaska plays in global seismic monitoring. The Alaska network, when treated as a large array, is particularly well positioned for applications in Asia. Long-term wastewater disposal operations associated with oil and gas development have the potential to advance our national knowledge of induced earthquakes, especially in regions of active tectonics.

Lastly, this section points out ways in which ongoing geophysical operations in Alaska dovetail with the nation's growing interest in the Arctic. The White House, the Department of Defense, the National Science Foundation, and others have all highlighted the need for more extensive monitoring, research, and understanding of the Arctic region. The potential to expand the current monitoring capabilities by leveraging the EarthScope TA and PBO facility aligns well with this growing interest. Enhanced earthquake monitoring would bring with it a wide array of research applications that draw national and international interest and funding.

Earthquake Early Warning

Alaska is very early in the consideration of early warning applications. Several submissions examine some of the areas that should be investigated more thoroughly for earthquake early warning potential. Some industries and companies see potential value while others do not. It is increasingly clear that whether or not earthquake early warning will be deemed societally important and which style of early warning might be most useful will likely be answered by stakeholders and not state and federal agencies. Regardless of when and how earthquake early warning is adopted in Alaska a few broad statements seem appropriate based on the submissions.

Augmenting seismic early warning with GPS capabilities will provide significant performance improvements. The potential for great earthquakes in Alaska (M8 and larger) brings with it a variety of issues. Large earthquakes can take several minutes to fully develop and may begin and end in completely different places. As an example, the 1964 earthquake began under Prince William Sound and propagated ~600 km (375 mi.) to Kodiak Island over the course of about four minutes. Considering the long distance and duration of such a large earthquake forces one to consider what "early warning" even means. It is hard to imagine navigating the complexity of a rapidly evolving earthquake such as this without the clear-cut displacement records afforded by GPS. High-rate real-time GPS needs to be a permanent and fully integrated component of Alaska's earthquake monitoring strategy.

Recent earthquakes including the M7.1 Iniskin earthquake in early 2016 and the M7.9 Denali Fault Earthquake in 2002 demonstrate that broadband seismometers should be expected to go off scale for hundreds of kilometers around large epicenters. Strong motion instrumentation is critical for rapidly assessing large earthquakes since the records stay on scale. For this reason, the continued expansion of strong motion instrumentation is one of the surest ways to help the Alaska seismic network become earthquake early warning-ready.

While early warning of earthquakes is of relatively small benefit to tsunami warning efforts, the move toward faster characterization of earthquakes will be helpful. The steps toward earthquake early warning—improved instrumentation, better coverage, more robust communications, faster assessment algorithms, and near-instantaneous alert mechanisms—all benefit the tsunami effort. Any contributions from these steps that lessen the alert time (whether the alert arrives before the shaking or not) is additional time for citizens and communities to act. Several authors point to the potential for faster, more accurate, tsunami alerts tied to overall earthquake early warning efforts.

Lastly, a submission examining the size of the so-called early warning blind zone for observers in different parts of the state demonstrates huge variability ranging from about 20 km (12 mi.) to many hundreds of kilometers or miles. This is primarily a function of station density. As expected, the size of the blind zone across most of the state shrinks considerably when the Transportable Array is added.

While Alaska's path toward earthquake early warning is not yet known, the steps that will eventually make the network "early warning-ready" are clear. On the instrumentation side these steps are: 1) more comprehensive seismic station coverage; 2) a conversion of the GPS network to high-rate real time; and 3) expansion of the strong motion monitoring at all scales.

Conclusions & Recommendations

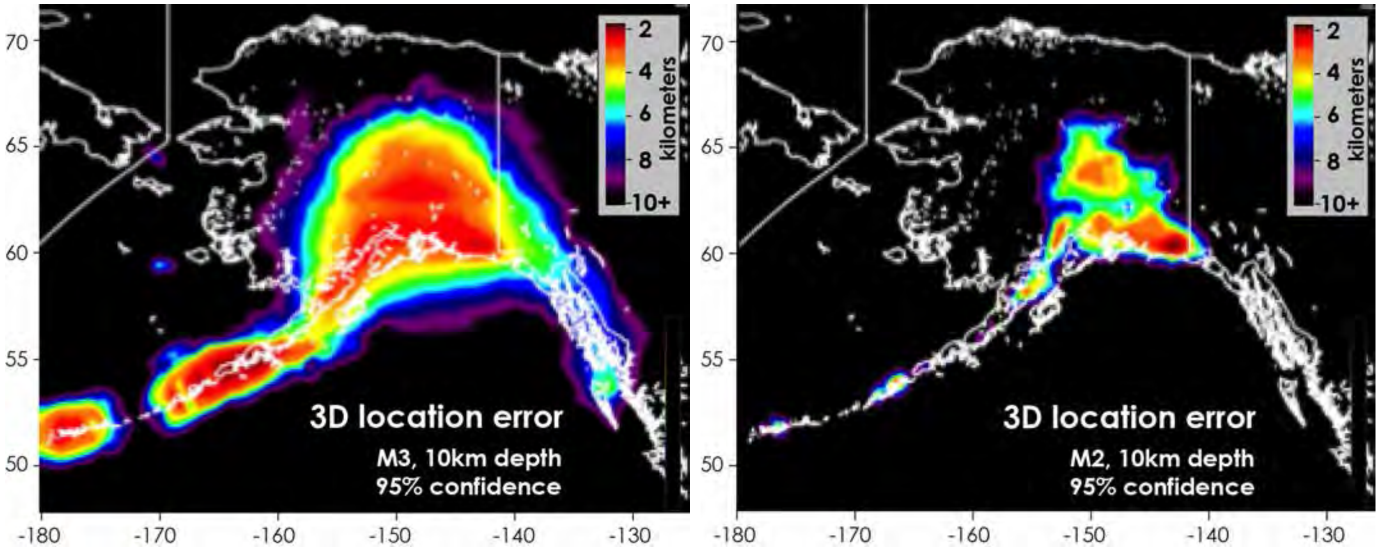
- The number of responses the Commission received, especially under such short notice, demonstrates a wide range of benefits spanning diverse stakeholders in Alaska and across the nation. Planning efforts to enhance earthquake monitoring should make strong attempts to represent the full diversity of these stakeholders.
- The ability to support these five categories of benefits varies widely across the state. While the needs and specific issues also vary across the state, Alaska should have a baseline of earthquake hazards knowledge and capabilities for characterizing earthquakes that apply across all regions of Alaska.
- It is in Alaska's best interests to improve monitoring wherever practicable through the adoption of seismic stations. The USArray Transportable Array offers a proven and unparalleled opportunity to enhance earthquake monitoring and provide more consistent earthquake information.
- Nearly all of the categories in this report would be enhanced by integrating GPS capabilities. Any planning to improve capabilities should specifically address the integration of Plate Boundary Observatory (PBO) data into Alaska earthquake monitoring efforts.
- Alaska has not deeply considered the potential impact of earthquake early warning. Many potential beneficiaries remain new to the concept. A dedicated outreach, education, and planning effort will be required before it is possible to quantify the full benefits. Therefore, the discussions in this report should be considered as presumed benefits of earthquake early warning relative to public safety and industry.

Deficiencies in Monitoring: Earthquake Location Error Across Alaska

Poor earthquake locations have insidious long-term impacts on earthquake hazard studies. Accurate earthquake parameters, including horizontal location, depth, and origin time, are controlled in large part by the distribution of seismic stations. Stations well distributed in azimuth constrain the latitude and longitude. One or more stations close to the source are critical for determining depth.

The absence of seismic stations across much of western and northern Alaska leads directly to poor quality earthquake locations. Accurate depths and locations are necessary to estimate ground motions, such as those distributed in ShakeMap products. They are also needed to properly determine focal mechanisms and constrain the sense of motion on faults.

Decades' worth of poor earthquake solutions produce maps that show fuzzy clouds of diffuse seismicity. Given accurate solutions, many of these clouds turn out to be well-defined lineations that can be interpreted for potential fault length and maximum credible magnitude. When the initial solutions are good, research techniques such as HypoDD relative relocation can sharpen images of seismicity into clear lineations. Once the initial location errors exceed about 10 km, however, these techniques begin to break down.



Three dimensional location errors. Hot colors mark regions with reliable earthquake locations in the shallow crust. (Left) In regions shaded black, magnitude 3 hypocenter locations are uncertain by at least 10 km. (Right) When the magnitude is lowered to 2, the region of accurate locations shrinks to a small fraction of mainland Alaska. Location errors are calculated by the SNES method—Seismic Network Evaluation through Simulation. Figures modified from D'Alessandro and Ruppert (2012).

Sparse Monitoring and Unorthodox Earthquake Sequences

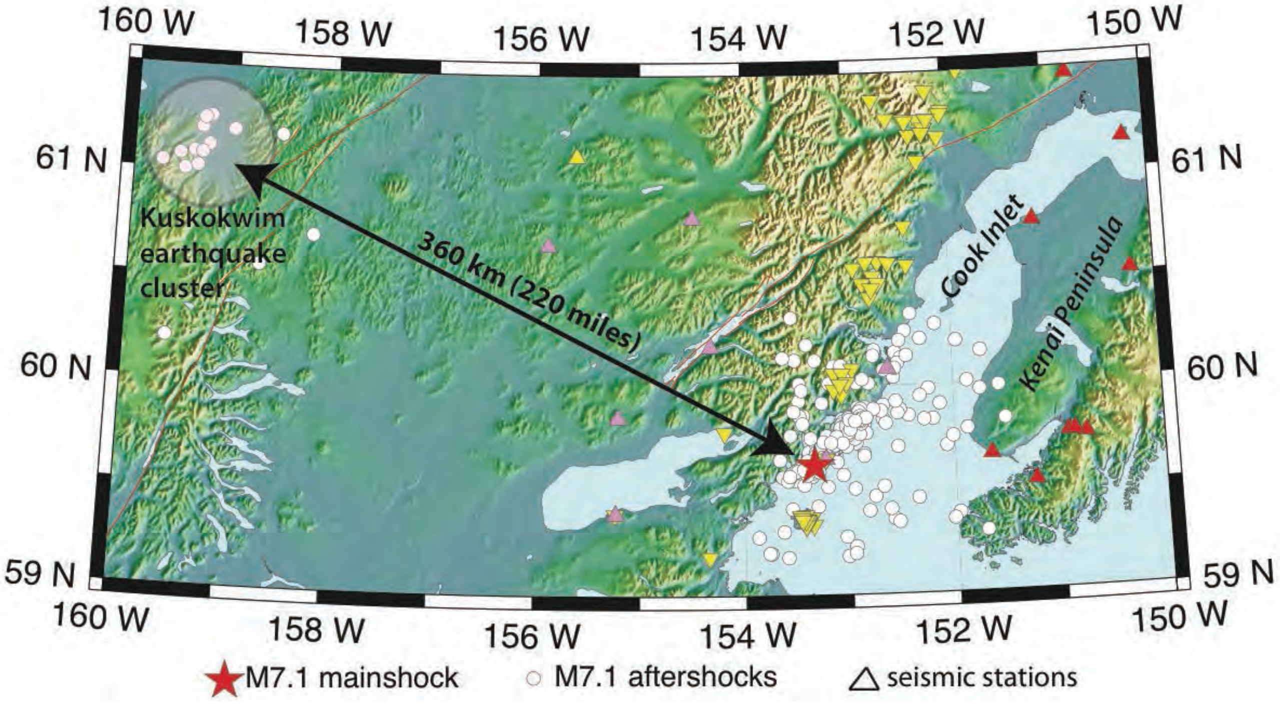
In the early morning hours of January 24, 2016, Alaskans in southcentral and as far away as Fairbanks and Kodiak were awakened by a magnitude 7.1 earthquake occurring 75 miles beneath Cook Inlet. Hundreds of aftershocks would be recorded in the first days after the mainshock, as is to be expected for an earthquake of this size.

However, the passing seismic waves from the mainshock also triggered a cluster of earthquakes hundreds of miles away in the Kuskokwim Mountains. While the phenomenon of distant, triggered earthquakes has been observed in the past, these sequences are nearly impossible to foresee. In this case, the absence of nearby seismic stations made it difficult to detect the earthquakes in this cluster with any precision.

Upon close examination of the Kuskokwim Mountains data, it became clear that the Kuskokwim cluster had been active but completely undetected for a two week period prior to the January event, again due to lack of seismic stations in southwest Alaska. The sequence was greatly accelerated and intensified by the Iniskin Earthquake waves and continued for a few more weeks.

In this case the triggered seismicity occurred in a very remote area and did not affect infrastructure or people. However, given the vast expanse of the state and the multitude of tectonic regimes, we do not know when and where triggered clusters will appear next or how powerful they will be. If the Kuskokwim sequence had occurred in a place where people were able to feel the shaking or infrastructure might have been at risk, residents and authorities would have been left without answers as to what was happening.

This highlights the need for a statewide seismic network without blind spots. Although the broad outlines of major seismicity in Alaska are generally well understood, there are many gaps (in the network and in knowledge) that need to be filled in order to understand the breadth and complexity of seismicity and seismic hazards across Alaska.

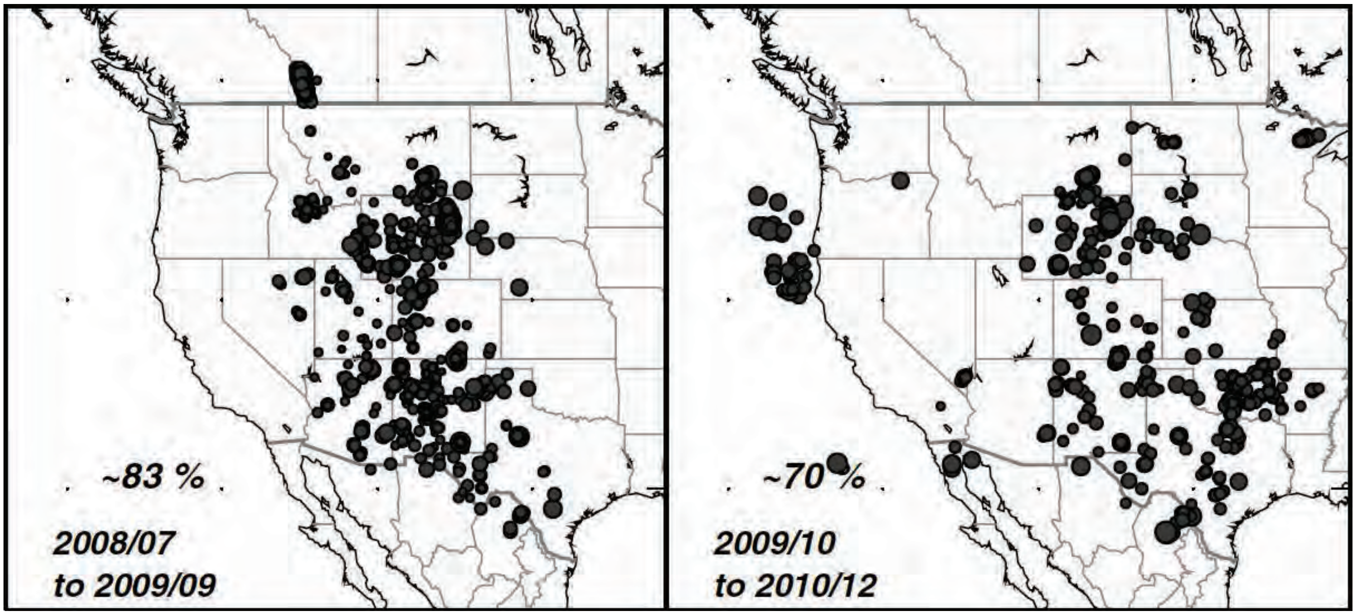


Map showing the Iniskin mainshock-aftershock sequence in Cook Inlet and the triggered sequence 222 miles away in the Kuskokwim Mountains.

Improved Detection and Characterization of Seismic Events in Understudied Regions

From 2004-2015, the EarthScope Transportable Array (TA) in the Lower 48 U.S. involved a rolling footprint of 400+ seismograph stations arranged from east to west with uniform, 70 km spacing. In regions such as the Great Plains, this increased the coverage of seismic stations by an order of magnitude or more, providing a dataset that dramatically improved the ability to detect and characterize small earthquakes and other events. In some regions, the TA was able to detect earthquakes with completeness down to ~M1.2 (Lockridge et al., Bull. Seismo. Soc. Am., 2012), and up to ~83% of its events were uniquely determined (Astiz et al., Seis. Res. Lett., 2014) compared to catalogs using the sparser coverage of existing backbone monitoring stations. Characterizing low-level, background seismicity that is missed by sparser coverage helps to better understand mechanisms of faulting, particularly away from the more densely instrumented plate boundaries. In the Central and Eastern U.S., 158 TA stations remain (http://www.usarray.org/ceusn), providing a much better picture of where small earthquakes and related seismic hazards occur.

In Alaska, most existing seismic stations concentrate near highways and close to the subduction zone. As such, there is an opportunity to improve the monitoring of earthquakes in the northern and western portions of the state, where there are very few stations currently deployed and issues related to distribution of smaller earthquakes and related seismic hazards are not well understood. The TA will deploy stations to these regions of Alaska in 2016 and 2017, and it is expected that the capability to monitor earthquakes in these areas will improve dramatically.



During the migration of the Transportable Array through the western and central U.S. during a two and a half year period, 70-83% of the events located by TA Array Network Facility were uniquely determined – meaning that these events were not initially cataloged by groups that did not routinely incorporate TA data (Astiz et al., Seismo. Res. Lett., 2014).

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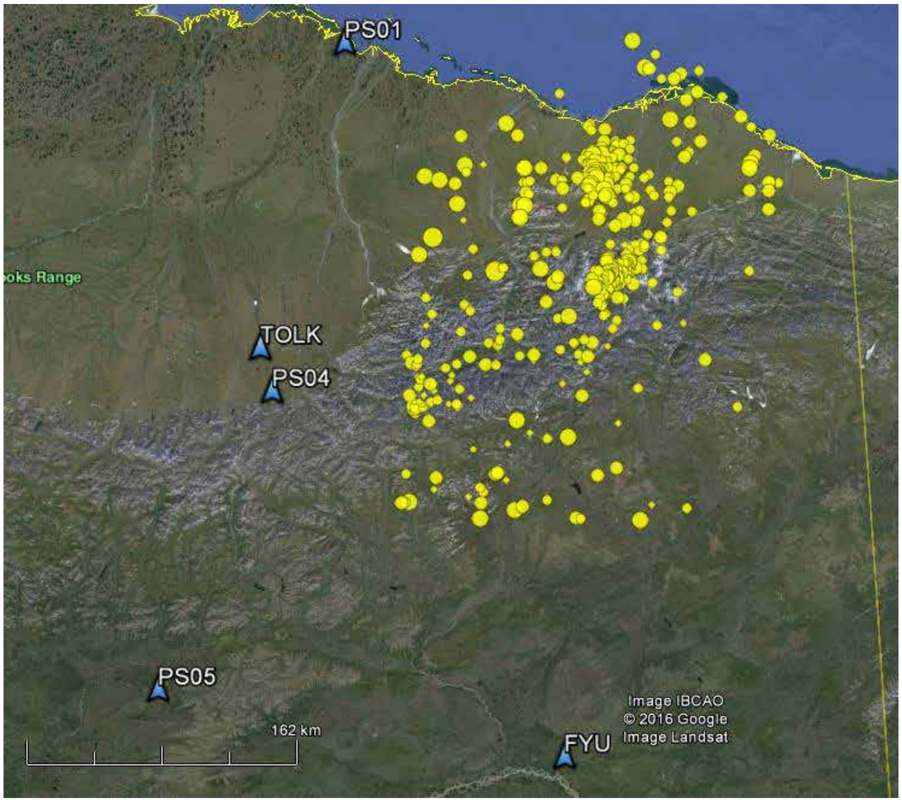
Seismic Sequences in Remote Areas of Alaska

Seismic instrumentation in Alaska largely follows the population corridor, but significant earthquake sequences often occur in sparsely populated regions of the state. These sequences are hazardous to local populations and have the potential to impact remote industry operations such as mining and oil and gas development. Notable recent examples include the 2014 Noatak earthquake sequence, which was strongly felt in the town of Noatak and the nearby Red Dog Mine, and a sequence of earthquakes in 2013 in the Arctic National Wildlife Refuge (ANWR).

Due to the remote nature of these earthquake sequences the closest seismic station is often hundreds of miles from the epicenter. This makes precise determination of earthquake locations impossible, particularly with respect to their depths. Earthquake depth is an important constraint, as shallow earthquakes are more strongly felt and have a higher chance of being associated with a surface rupture. A regional seismic network covering Alaska in a more uniform manner will help assess seismic hazards for remote villages and industrial operations. For example, to protect oil transport methods between the 1002 area of ANWR and the Alaska Pipeline, seismically active structures will need to be identified, which is difficult to impossible when the nearest seismometer is over 200 km away.



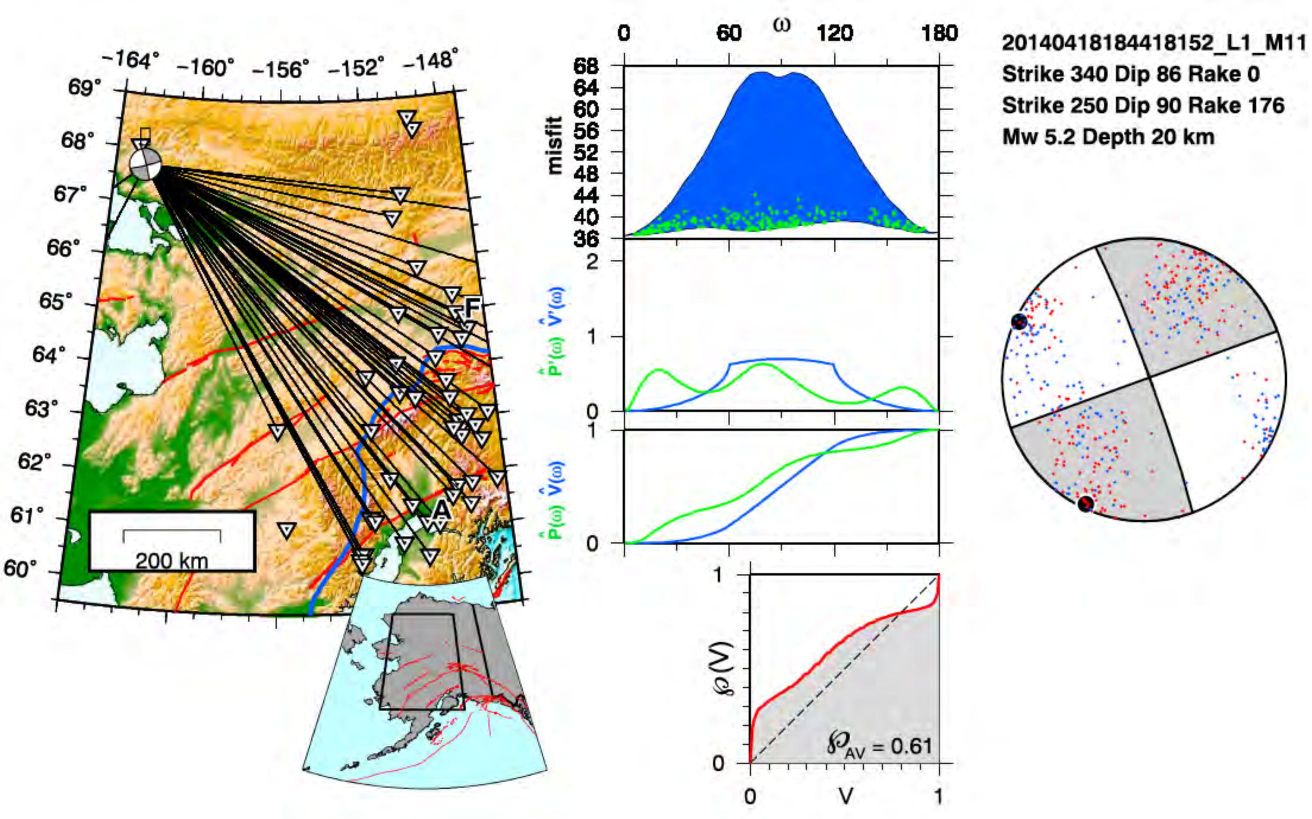
Earthquakes in the northwest Brooks Range (yellow dots) and existing seismic stations (blue triangles, labeled). Seismic stations beginning with "PS" are along the Alaska Pipeline, and are very noisy stations with limited scientific potential.

Note: only earthquakes in the northwest quadrant of this image are plotted. Such "out of network" earthquakes, which occur outside the footprint of the seismic network, are difficult to locate. This is likely one reason why clusters of earthquakes shown here appear as "clouds" rather than linear features, which are expected for earthquakes along fault zones. Precise determination of seismically active structures here would be important for proposed oil and gas operations in the area, but is currently impossible due to the lack of available seismic data.

Earthquake Source Characterization at the Margins of Alaska's Seismic Network

The current ability to assess earthquake source mechanisms across much of Alaska is deeply compromised by the absence of proximal seismic stations.

Alaska is a broad region of nearly continuous deformation manifested by diffuse seismicity on hundreds to thousands of active faults. Using seismic data, we can begin to identify unmapped faults and to characterize the style of faulting (strike-slip, normal, thrust), both of which are fundamental for characterizing seismic hazards. This effort is particularly problematic for earthquakes near the boundary of the Alaska seismic network, since the quality of the source characterizations relies on stations covering all azimuths. With a high-quality network of permanent coastal (and island) stations, we would be able to improve fault and earthquake characterizations throughout all of mainland Alaska.



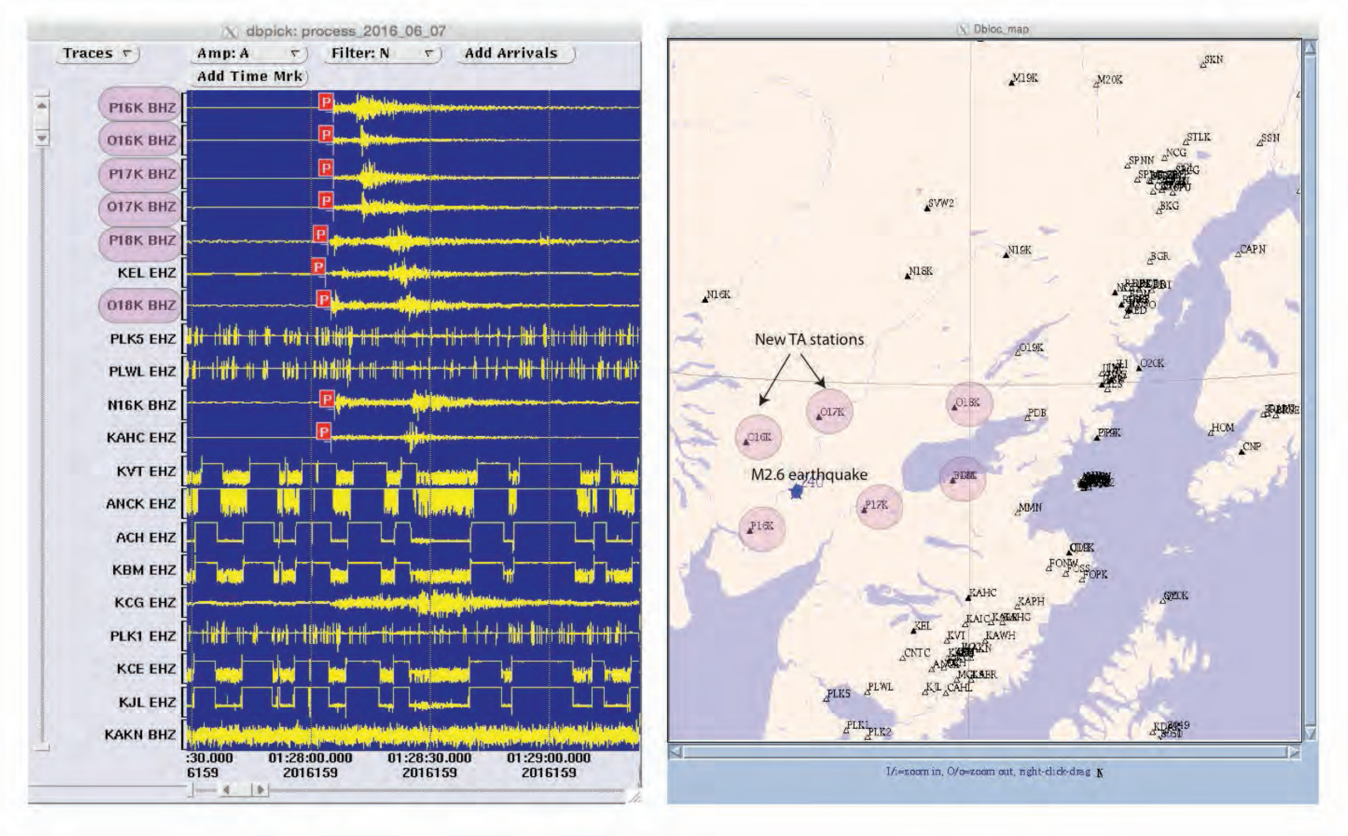
Source estimation and uncertainty characterization for a 2015 M 5+ earthquake near Noatak, Alaska. The example illustrates the challenges of characterizing sources that are outside the network of stations. In this case, having sources in western Alaska would greatly improve our confidence in the source estimation. [Figure 9 of Silwal and Tape, Journal of Geophysical Research, 2016]

Importance of Adopting USArray Stations: Bristol Bay Case Study

On June 6, 2016, the Alaska Earthquake Center detected a magnitude 2.6 earthquake near Bristol Bay using data from six newly installed USArray seismic stations. This was the very first high-quality recording of an earthquake in this economically important region. Prior to summer 2016, the Bristol Bay region was virtually unmonitored.

Not only were these new stations installed in a place where none existed before, the data quality from these digital broadband subsurface installations is far superior to what other regional stations provide. Until now, monitoring southwest Alaska has relied largely on distant analog short period surface sensors on the Alaska Peninsula and Western Cook Inlet, which were installed for volcano monitoring. Without the USArray stations, the June 6 earthquake would never have been detected at all. Even if detected, its magnitude and location would have been impossible to constrain.

This highlights the importance of adopting selected USArray stations into the Alaska seismic network when the Transportable Array deployment ends. Right now, large, economically important regions of Alaska are being instrumented for the first time in history. Failing to make this instrumentation permanent would mean consigning the state to ignorance of these regions' seismic activity and hazards, perhaps permanently.



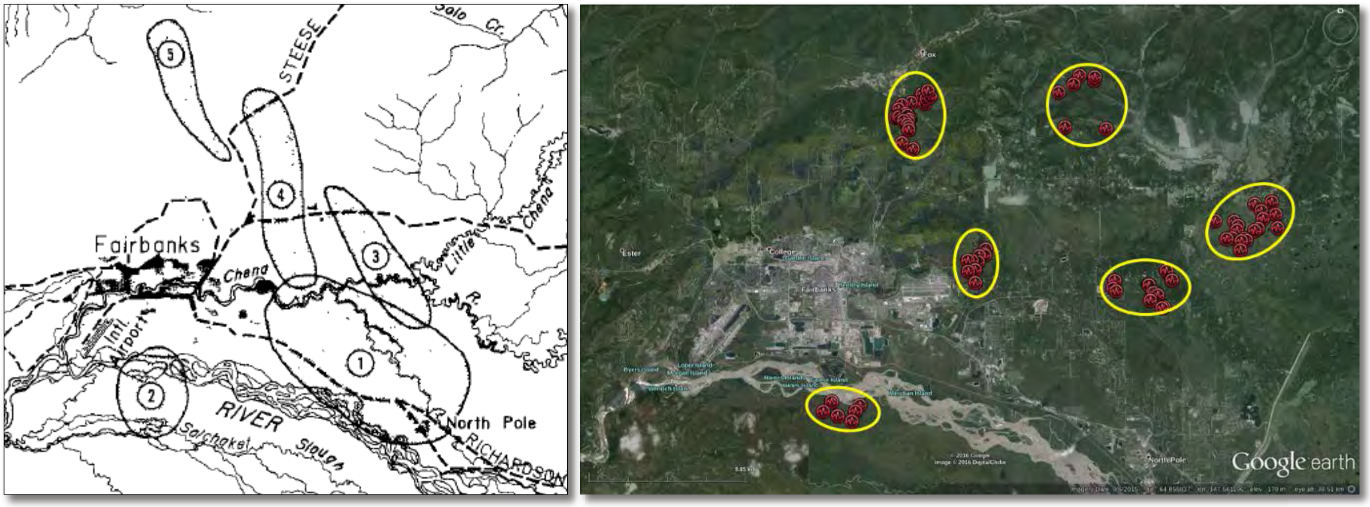
June 6 magnitude 2.6 Bristol Bay earthquake as recorded by newly installed USArray stations. Note the striking difference in data quality between the new TA stations (pink circles) and the preexisting instrumentation.

Earthquake Swarms and Hazardous Faults Near Fairbanks

Several damaging earthquake swarms occurred in the Fairbanks area from the 1960s through the 1980s (Gedney et al., Bull. Seis. Soc. of Am., 1982). Earthquake swarms—sequences of earthquakes that are similar in size and do not follow a larger triggering mainshock—are now thought to be related to aseismic geological processes such as fluid migration and aseismic fault slip. Earthquake swarms can repeat over time as the triggering aseismic process continues.

More recently, much smaller earthquake swarms have been observed in the Fairbanks region. Since swarm activity repeats over time, these smaller swarms are likely part of the same processes that drove the more damaging earlier swarms. Thus, identifying the structures where these swarms occur would lead to a better understanding of seismic hazards in Fairbanks.

Because the recent swarms consist of small events, dense networks of seismic stations are required to detect and locate them precisely. Expansion of the seismic network in and around Fairbanks is necessary to identifying the associated seismic structures and better understanding the hazards they pose, including the size of the largest credible earthquakes that might be generated during these swarms.



Earthquake Swarms in the Fairbanks region, on roughly the same scale.
(Left) Swarms from 1967-1982, from Gedney et al. (1982). The largest earthquake was magnitude 6.0, and Fairbanks sustained damage from these earthquakes in the form of broken shelves and cracked foundations. Significant development has occurred since the early 1980's.
(Right) Recent earthquake swarms in the Fairbanks area. The largest earthquake in these swarms was M3.2, with most events between M0 and M2. Note how the patterns of seismicity are similar between the two time periods

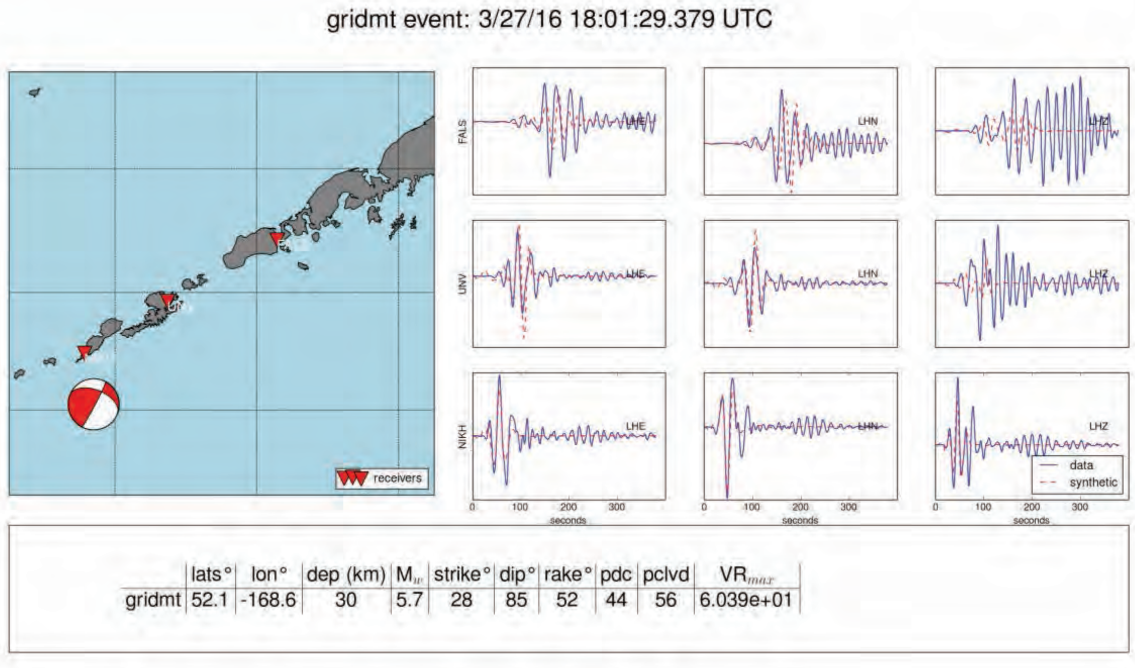
References
Gedney, L. D., Estes, S. A., Biswas, N. N., & Marshall, D. L. (1982). A note on further activity in the Fairbanks, Alaska, seismic zone. Bulletin of the Seismological Society of America, 72(4), 1415–1417. Retrieved from http://www.bssaonline.org/content/72/4/1415.extract

Continuous Moment Tensor Scanning for Alaskan Earthquakes

The threat to coastal Alaska from tsunamis has been appreciated since at least 1946, when a powerful earthquake struck near Unimak Island in the Aleutians and triggered a tsunami that destroyed the Coast Guard lighthouse at Scotch Cap. Tsunamis also caused damage and casualties in Alaska in 1958 and 1964. The 1964 event, triggered by the second largest recorded earthquake, killed more than 100 people and devastated numerous coastal Alaska communities.

While the tsunami hazard in Alaska is clearly formidable, there is a well-developed warning and evacuation infrastructure in the state including sirens, pre-planned evacuation routes, and tsunami shelters that has the potential to minimize casualties during future events. Critical to the functioning of this infrastructure is the ability to rapidly detect earthquakes and evaluate their tsunamigenic potential so that warnings may be issued in a timely fashion. Because of the inherent speed of seismic waves, seismological techniques will give the first indication of an impending tsunami. Continuous moment tensor scanning is one such seismic technique. The algorithm works by using a network of seismometers to continuously scan the long-period wavefield around the Alaskan subduction zone, where large tsunamigenic earthquakes are most likely to occur. The algorithm compares waveforms recorded on the network with theoretical waveforms and finds the earthquake location, magnitude, and sense of fault motion that provide the best fit.

The effectiveness of this technique depends on a widespread and robust seismic network. The Aleutian Islands, which parallel the Alaskan subduction zone, are remote and sparsely instrumented. Additional seismic stations in these areas would facilitate rapid source characterization and enhance tsunami warning for Alaskan coastal communities.



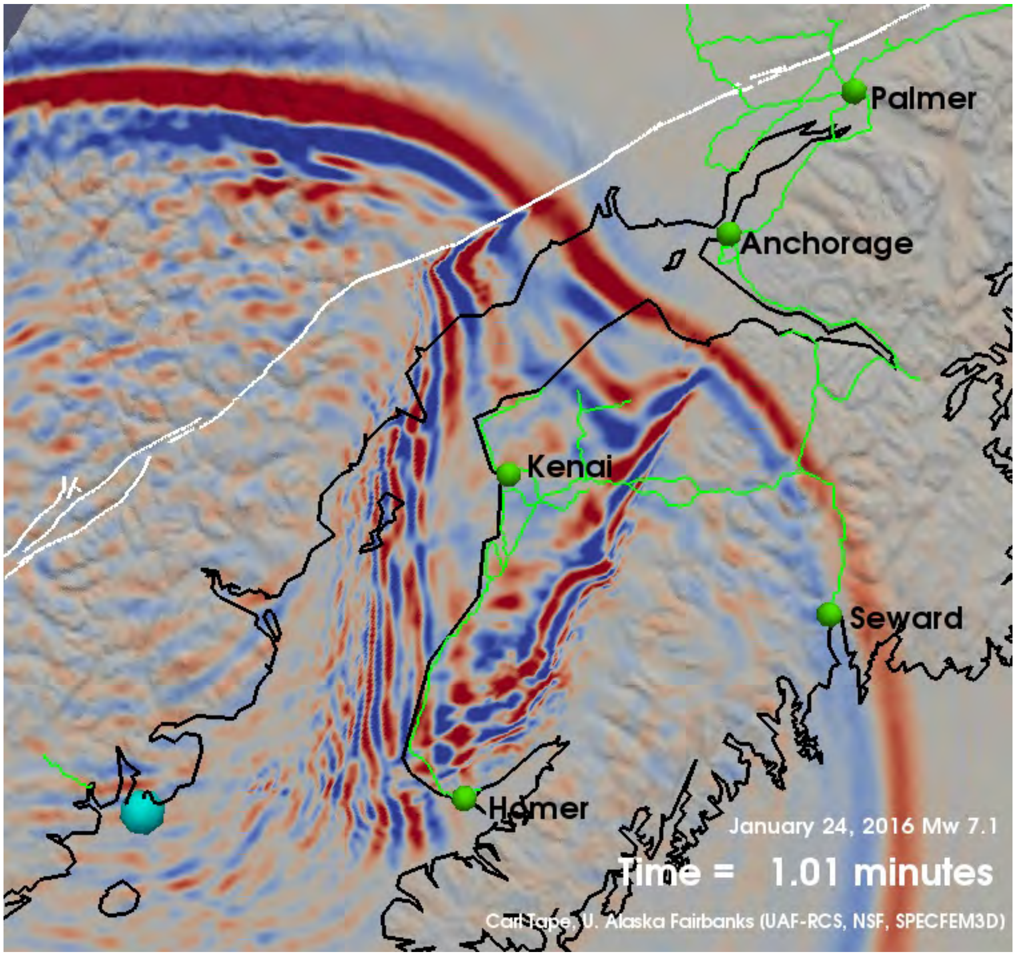
gridmt event: 3/27/16 18:01:29.379 UTC

	lats°	lon°	dep (km)	M_w	strike°	dip°	rake°	pdc	pclvd	VR_{max}
gridmt	52.1	-168.6	30	5.7	28	85	52	44	56	6.039e+01

Example output from a continuous moment tensor scanning algorithm (gridmt).
(Left) The earthquake epicenter location and sense of slip via a "beachball" mechanism.
(Right) The traces show the theoretical waveforms that best fit the data recorded on the Alaska seismic network.
(Bottom) The estimated earthquake parameters listed. Based on the magnitude and sense of slip, an analyst would be able to determine that this earthquake is unlikely to generate a tsunami.

Validation of Ground Motion Simulations for Large Earthquakes

Using the best available descriptions of Earth's structure and earthquake sources, we can simulate seismic wave propagation using high-performance computing. The simulations provide intricate details on how the ground might shake for a given earthquake. However, the value in these simulations depends on how close to reality the simulation is. Denser coverage of seismic stations would allow us to validate the ground motion predictions from numerical simulations. If seismic recordings match the simulation predictions at many isolated points (i.e., stations), then we can have confidence that the simulations provide realistic predictions in regions without stations.



Three-dimensional simulation of earthquake ground motion for the M7.1 Iniskin earthquake in southern Alaska. Seismic waves are amplified and trapped within Cook Inlet sedimentary basin. The simulation predicts amplified ground motion in the western Kenai Peninsula, which was consistent with felt reports and damage. Many more stations are needed in order to test the predictive capabilities of such simulations.

Improving ShakeMaps

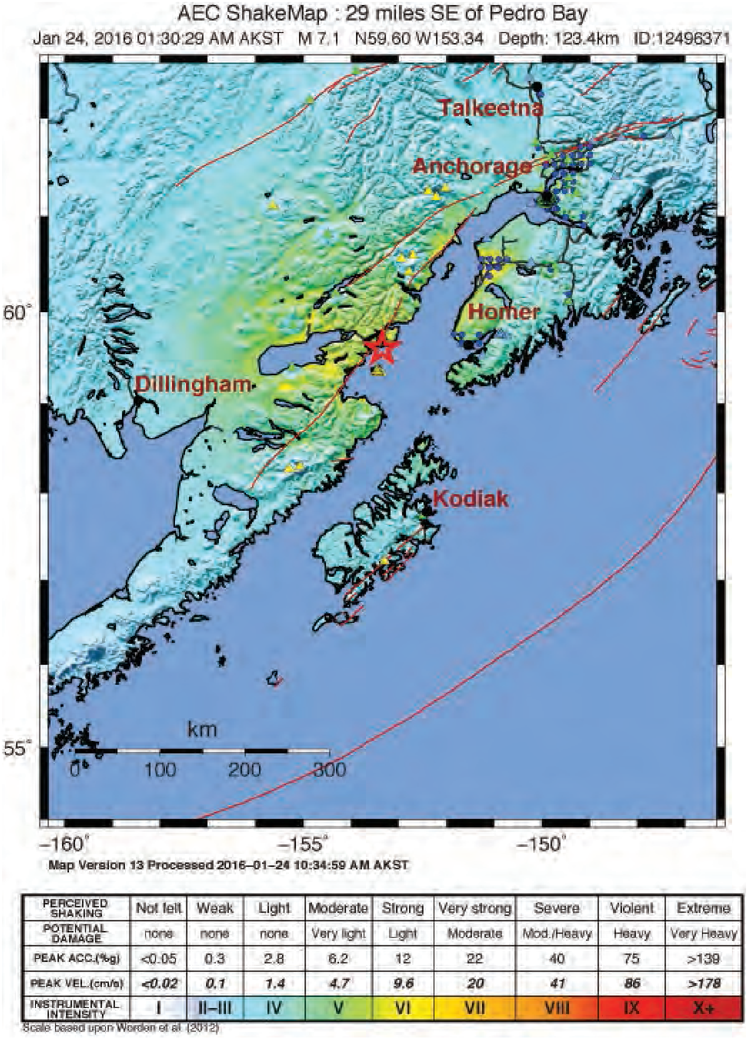
ShakeMaps are a public-friendly data product produced within minutes of a notable earthquake in the state. These maps graphically show shaking intensities and ground motions in a clear and accessible way. Output from ShakeMaps are also used as an important piece of input into risk models produced by the FEMA HAZUS software.

Generating a basic hypothetical ShakeMap requires three pieces of data: the location and magnitude of an earthquake, the shear-wave velocity of the top 30 meters of ground (called Vs30), and a mathematical equation that estimates the amount of ground shaking based on the previous two parameters (called a ground motion prediction equation, or GMPE). Often in Alaska the only reliable parameters for a given event are the location and magnitude. Publically available direct Vs30 measurements are almost completely non-existent, so the data is estimated from topography. Similarly, GMPEs are empirically derived and are typically best suited for particular regions. Alaska does not currently have any GMPEs specifically calculated for the state, so a best-guess global equation is used instead.

With all of these estimated inputs, ground-truthing the results becomes particularly important. ShakeMap does this by incorporating ground shaking values recorded at seismic stations near the epicenter. Real data from these stations is strongly weighted in the final result over the values estimated from the GMPE.

As a result, Alaska ShakeMaps tend to be relatively reliable where there is decent station coverage, such as in the railbelt, but far less reliable areas with sparse coverage such as the northern and western parts of the state. There, the results are merely best guesses based on extremely limited data.

Increasing seismic station coverage in poorly instrumented areas will support ShakeMaps that can more accurately map the intensity of shaking felt in communities and at critical infrastructure around the state.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

ShakeMap for the January 24, 2016 M7.1 Iniskin Earthquake. This ShakeMap incorporated data from over 90 seismic stations as well as "Did You Feel It?" reports from the USGS

Importance of Seismic Station Coverage for Earthquake Response Time

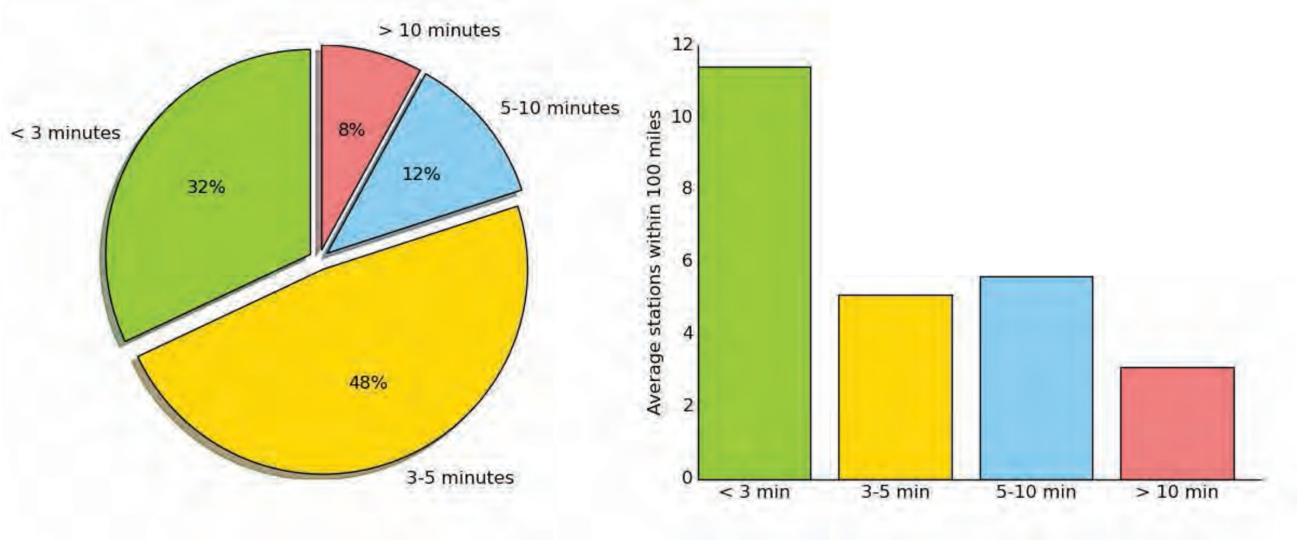
To rapidly assess large earthquakes in the state, it is essential to have seismic stations close to the epicenter. Relying on distant stations dramatically slows response time in situations where every second can matter for first responders and disaster management personnel.

While most earthquakes are quite small and produce no damage, on average three times per week an earthquake occurs that is large enough to warrant immediate review and information release by an Alaska Earthquake Center seismologist.

As soon as the Earthquake Center's automated system detects one of these notable earthquakes, an alarm is sent to the on-call duty seismologist. Because the Earthquake Center is not staffed 24/7, they rely on the alarm system to notify key personnel of such an earthquake, particularly during off-hours.

Over the last three years, there have been over 500 alarms (M3.5 in urban areas, M4.5 in less populous regions). Most alarms have come within 5 minutes of the earthquake origin time; however, a notable quantity (over 40) have taken more than 10 minutes. For alarms sent within 3 minutes, the average earthquake was detected on 11 seismic stations within 100 miles of the epicenter and had an average station-to-epicenter distance of 95 miles. For those that took over 10 minutes, that number drops to a mere 3 stations within 100 miles and an average distance of over 560 miles.

Improved station density is essential to achieving acceptable response times for large earthquakes occurring near all of Alaska's population centers and critical infrastructure.



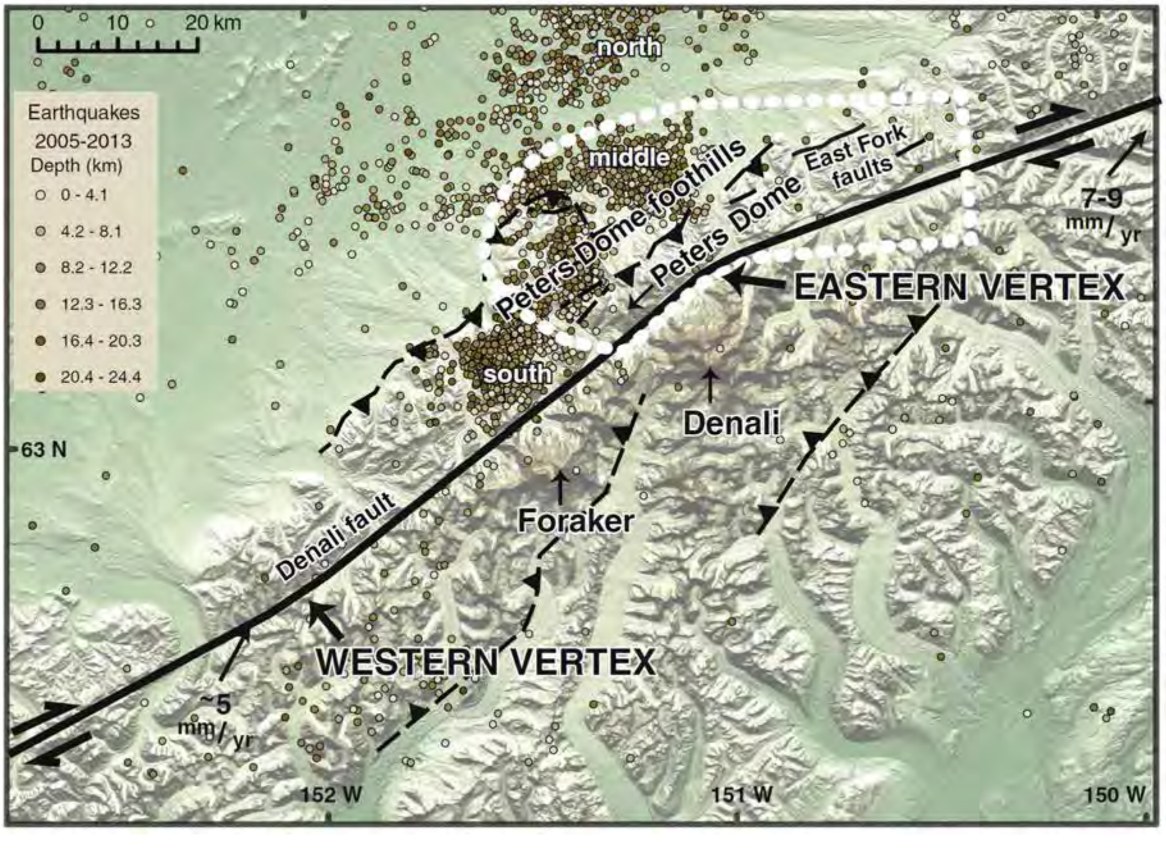
(Left) Percentage of earthquake alarms from 2014-2016 binned by alarm response time
(Right) Number of stations within 100 miles for each bin of alarm response times

Earthquake Behavior Through a Migrating Gentle Restraining Bend

The role that geometric complexities such as fault step-overs and restraining bends play in impeding earthquake ruptures along strike-slip faults has long been debated. The bend of the Denali Fault at Mount McKinley is ~18°, which is the modeled and observed threshold where earthquake rupture will propagate along the fault. A bend sharper than ~18° will limit rupture propagation, whereas a gentler bend will allow a rupture to propagate through the bend.

Combining earthquake patterns with geological observations of long term fault behavior allows us to examine how long-term slip is distributed across the Denali bend. We predict, based on our initial observations, that some large ruptures of the Denali fault do stop within the Denali bend likely acting to promote failure on the subsidiary active faults. These subsidiary or splay faults are seismic hazards themselves, but due to glacial moraine cover cannot be identified in the field.

The current spacing of seismic stations is too sparse to allow us to use the earthquake dataset to discern where these structures are located and their slip histories, but the earthquake dataset has already proven itself to be an invaluable tool set for this work on earthquake behaviors through a migrating gentle restraining bend.



Active structural features and crustal seismicity of the Denali Fault bend near Mount McKinley. Earthquakes shown are a subset from2005 to 2013 of the full dataset used in this study and shown with a maximum depth of 25 km. Hypocenters are colored by depth with a red gradient indicating increasing depth to a maximum of 25 km.

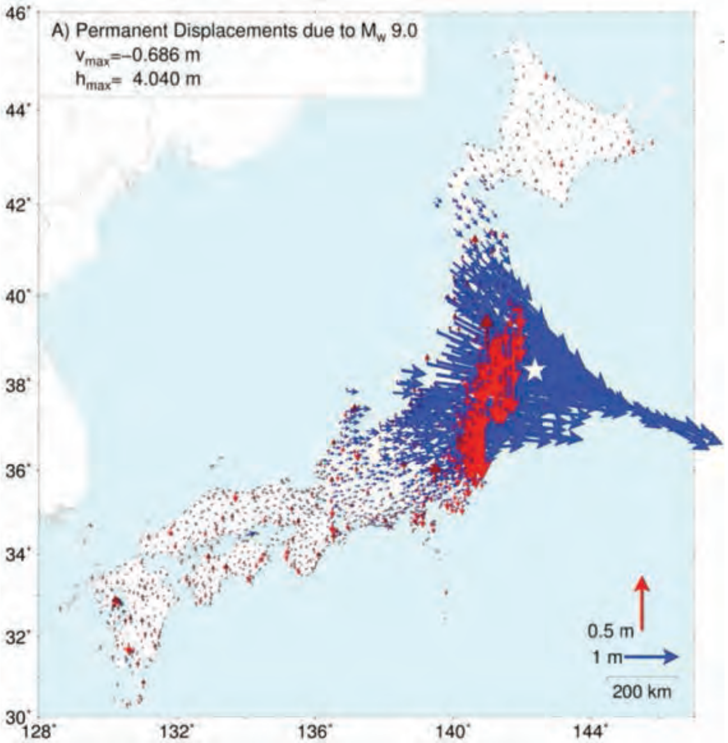
Real-Time GPS Measurements for Rapid Earthquake Characterization

GPS data are a powerful tool for rapid source characterization of large and great earthquakes. For the largest events, such as the 2011 M9.0 Tohoku earthquake, rapidly determined GPS displacements could constrain earthquake magnitude, rupture area, and slip distribution in near real-time, but only if GPS data are available and processed in real time. Several data processing schemes now exist to reliably analyze real-time streams of GPS data, so the main limitations are the lack of real-time data from an extensive GPS network and the personnel time to implement the processing. Since 2011, Japan has implemented systems to exploit this data in real time and use it in earthquake and tsunami warning. Similar efforts are following in the U.S. GPS data products can be available within seconds of receipt of the data, so the latency is limited mainly by communications.

GPS data can be processed into two data products relevant to this problem: ground displacements and ground velocities. Displacements are the more common product, and include both the passing seismic waves and permanent static displacements. The static displacements can be determined accurately as soon as the seismic body waves have passed by the station (see figure below). These displacements make it easy to determine both the moment magnitude of the event and the rupture area or slip distribution. The GPS data can also be processed directly to ground velocity, which produces a seismogram that will remain on scale regardless of the size of the earthquake. GPS receivers are capable of recording data at rates as high as 20-30 samples per second, although 1 sample per second recording is much more common.

The contribution from GPS begins to be significant for earthquakes in the M5-6 range and larger. This is particularly helpful in Alaska, because broadband seismic stations will begin to clip and fail to record earthquake waveforms faithfully at a similar magnitude (for stations near to the fault). There is no upper limit to the magnitude for which GPS can faithfully record earthquake ground motions; only a lower limit based on the noise level of the data.

A large number of continuous GPS sites exist in Alaska already, mostly as part of the Plate Boundary Observatory network, but very few of these are real time. In addition, the financial support to maintain the stations is unclear beyond 2018. Upgrading the power and communications at the sites to support real-time data streaming and ensure long-term operation is of critical importance for the state of Alaska.

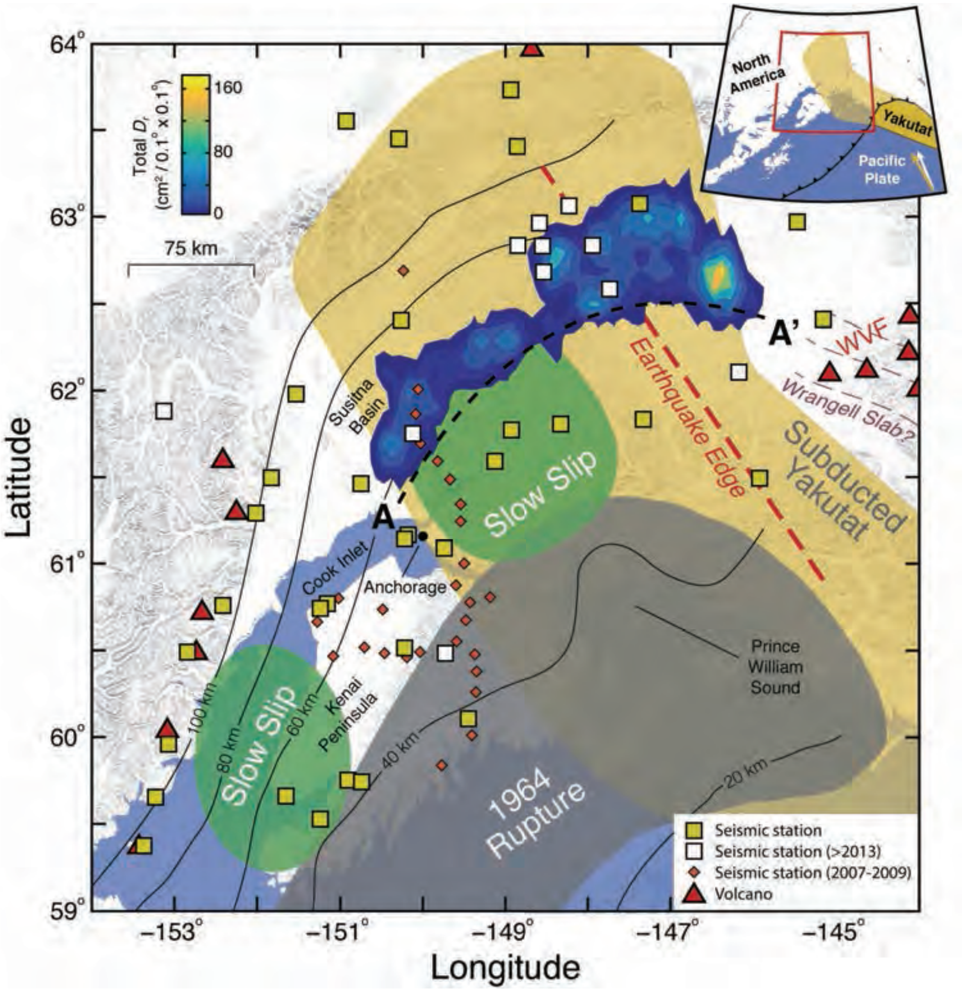


Final static displacements for the 2011 M9.0 Tohoku earthquake based on GEONET GPS data. Blue vectors are horizontal displacements and red vectors are vertical displacements. The earthquake rupture length can be determined easily from these displacements, and even a small fraction of the available sites would be enough to constrain the earthquake magnitude. [From Grapenthin and Freymueller, 2011].

Identifying and Tracking Slow Slip on the Alaska Megathrust

Research in recent years has recognized the important role aseismic processes play at plate boundaries. Slow slip events and the seismic tremors that can accompany them have been increasingly identified worldwide as integral parts of the greater earthquake cycle. These processes are pervasive throughout southcentral Alaska. A recent study found that tremors map out a plate boundary that continues past the presumed edge of the megathrust fault and display a trend from periodic to more continuous slip near the Wrangell volcanic field. This result suggests the fault continues east past the 1964 rupture zone, perhaps dipping beneath the Wrangell Mountains, and has implications for earthquake hazards in this region.

Though not intrinsically hazardous, these phenomena are indicators of subtle fault motion and stress redistribution and may have causal links to large earthquakes. Mapping and documenting their occurrence provides useful information about megathrust fault dynamics and may help place constraints on both short- and long-term earthquake hazards, but doing so requires dense station spacing. Identifying spatio-temporal tremor patterns in southcentral Alaska was greatly facilitated by the arrival of Transportable Array stations and the installation of the WAT1-7 network by the Alaska Earthquake Center.

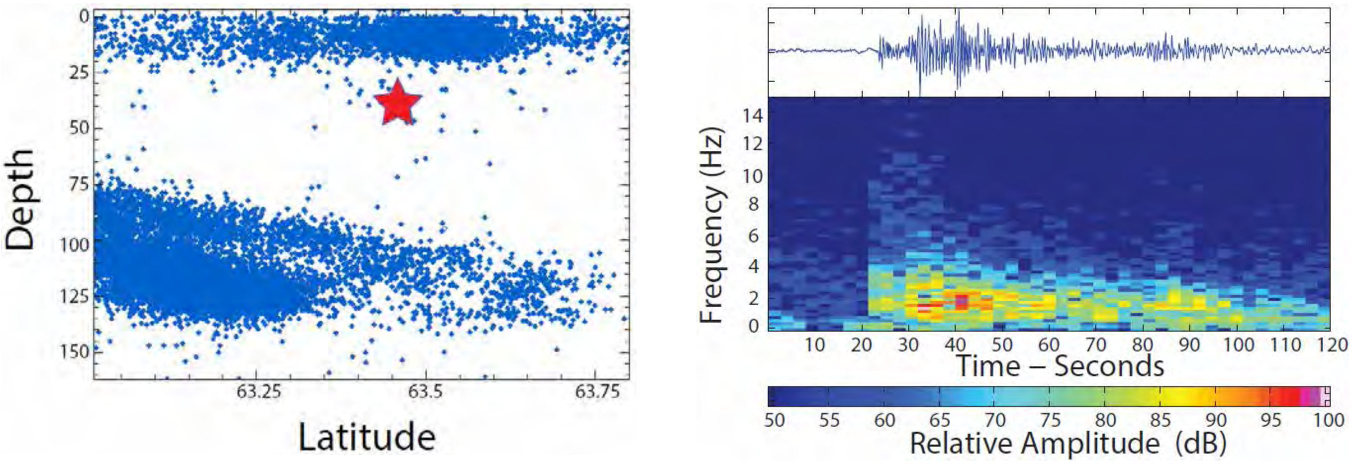


Map of Southcentral Alaska showing cumulative tremor distribution, 1964 megathrust asperity (gray patch) (Plafker et al., 1994), long-term slow slip (green patches) for upper (1998–2001 and 2008–2013) and lower Cook Inlet (2010–2011) (Fu & Freymueller, 2013, and references therein), and the subducted Yakutat terrane (light gold patch) (Eberhart-Phillips et al., 2006). Isodepths to the plate interface (Hayes et al., 2012) are plotted in 20 km intervals with volcanoes (red triangles), seismic stations used in this study (squares and diamonds), the eastern edge of slab seismicity (red dashed line), and the Wrangell Volcanic Field (WVF). [Figure from Wech, 2016.]

Exotic Earthquakes with Potential for Advancing Scientific Knowledge

Alaska is uniquely positioned to host a variety of scientific breakthroughs in the field of earth science. While earthquake hazard is the primary driving force behind seismic instrumentation, Alaska is an ideal natural laboratory for investigating seismic processes due to the variety of tectonic environments present throughout the state. However, instrumentation needs to be expanded beyond the population corridor and southern Alaska to realize this potential. Expanding the seismic network has the potential to stimulate research groups from inside and outside of Alaska to procure research funds for research into new and different types of earthquake sources.

Recent examples of scientifically interesting seismic sequences include: (1) volcanic-like deep long-period (DLP) earthquakes near Denali, which is not a volcano. This observation constitutes one of the first observations of DLP earthquakes outside of active volcanic environments and stands to inform the scientific community about the nature of DLP seismicity. DLP seismicity is an important tool for understanding and forecasting eruptive sequences at volcanoes worldwide. (2) A prolonged major earthquake swarm near Noatak, northwest Alaska. Large earthquake swarms such as this have been extensively studied in other areas of the world, most notably the Vogtland/NW Bohemia region of Western Europe. Expansion of seismic networks in remote areas such as this would allow for robust detection of swarm seismicity and allow researchers worldwide to test theories of earthquake swarm occurrence. (3) Slow earthquakes and earthquake nucleation processes near Minto, central Alaska. A recent federally funded deployment of seismometers near Minto has allowed us to observe a relatively new class of earthquakes called "slow earthquakes," which may be related to the earthquake nucleation process. Expanded instrumentation of this and other fault zones could attract significant attention and research funding opportunities within the seismological community.



Volcanic-like DLP earthquakes in the Denali Volcanic Gap.
(Left) Cross-section of seismicity (blue dots) from south to north near Denali. Red Star indicates location of DLP events between normally occurring deep seismicity in the slab and shallow seismicity in the crust.
(Right) Spectrogram of a DLP event showing most relative energy in the 1-4 Hz range. Regular earthquakes are not band-limited on the high frequency end as this earthquake is.

High Accelerations from Deeper Earthquakes in Populated Alaska

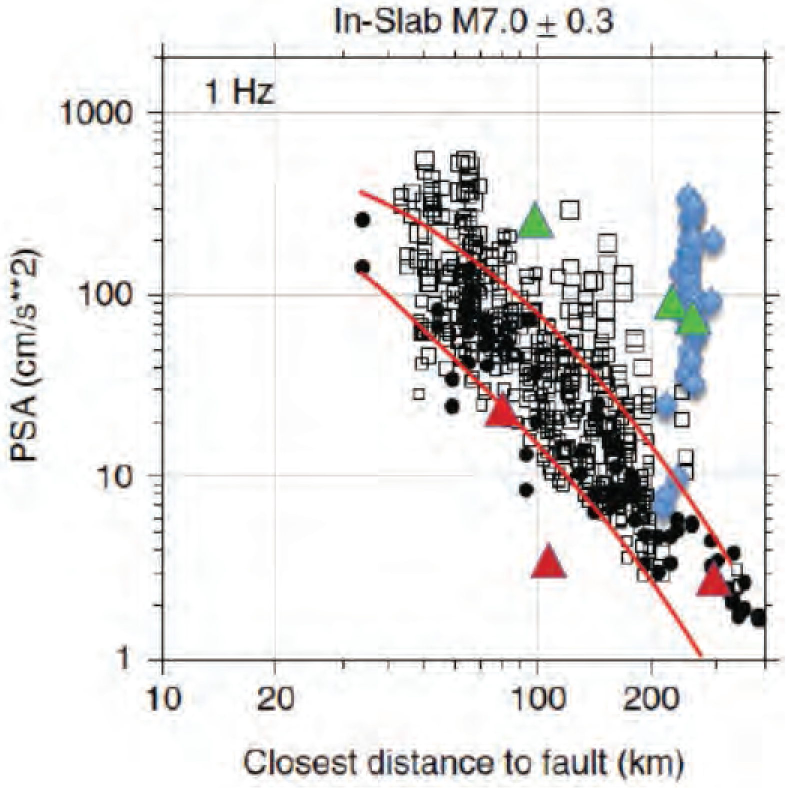
On January 24, 2016, Anchorage experienced the largest shaking since the 1964 Good Friday earthquake (M9.2). Surprisingly, the earthquake was not on the giant offshore megathrust fault or on one of the major crustal faults in Alaska. Rather, it was 129 km below Cook Inlet, over 200 km from Anchorage, and had a magnitude of 7.1.

This earthquake belongs to a class of “in-slab” earthquakes that occur in similar settings worldwide, occasionally reaching magnitudes as high as 8.0. It is the largest such earthquake yet recorded in Alaska and produced shaking exceeding 20% g (one g is the acceleration due to gravity).

Alaska represents by far the largest earthquake population in the U.S. and has the most complex and varied range of potential earthquake sources anywhere. Until this earthquake, “in-slab” earthquakes were not considered a significant threat to Alaska. However, it is clear that past assessments were incorrect and led to underpredictions of shaking of a factor of ten at least (see figure below).

The limited scale and instrumentation of the existing seismic network, particularly away from Anchorage, make it difficult to analyze thoroughly the variations in shaking, but there are hints that deep geology between the earthquake and Anchorage plays a role.

Instrumentation over a broader part of the state, now being made temporarily available through the EarthScope Transportable Array program, is starting to provide some insight (e.g. red triangles on the figure show stations far west of Anchorage). However, this coverage is short-term, coarse, and lacks some critical instrumentation.



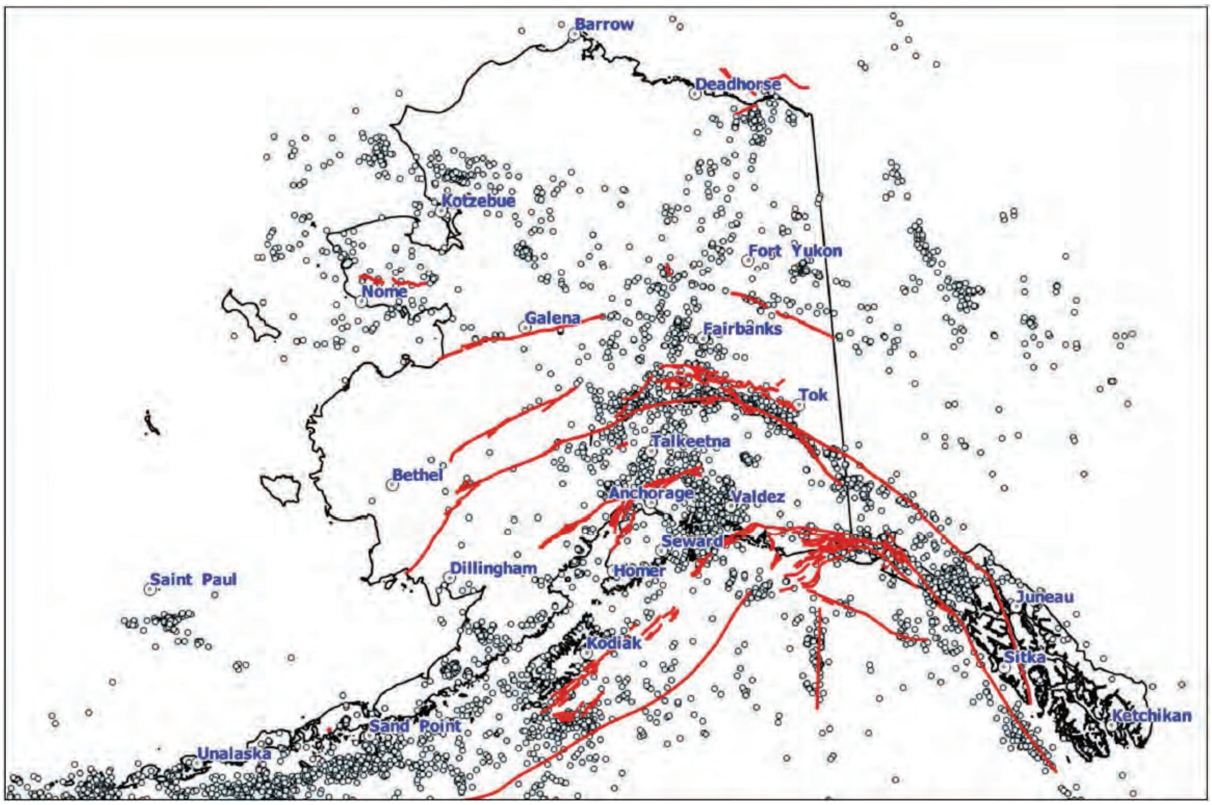
Ground motion predicted for magnitude 7.0 “in-slab” earthquakes, at least 50 km deep, compared with actual observations for the January 2016 M7.1 Iniskin earthquake. Black/white figure from Atkinson and Boore (2003)’s global compilation, largely from Japan and Washington, showing standard psuedo-spectral acceleration at 1 Hz, 5% damping. Red lines show predictions for M6.5 and M7.5. Color symbols show records for the 2016 earthquake from an Anchorage accelerometer network (blue) and from IRIS Transportable Array stations elsewhere in the state (red and green). In some directions, notably toward Anchorage, the predictions underestimate the actual shaking by a factor of 5-50.

Improved Identification and Mapping of Active Faults

Inadequate mapping of active faults remains a persistent problem for evaluating earthquake hazards around the state. Such mapping was mandated years ago by the State of California and has become an integral part of quantifying the earthquake hazards there.

The map below shows that there have been thousands of shallow earthquakes in the state during the past 20 years with no apparent relation to recently active mapped faults. This is especially evident in northern Alaska, where there are few seismic instruments and virtually no detailed geologic mapping of faults. One notable example is the cluster of earthquakes in northwestern Alaska near Noatak, north of Kotzebue, including several events in the magnitude 5-6 range, for which no clear fault source has been identified. The pattern of epicenters is diffuse, partly owing to the sparse distribution of seismometers. A denser network of seismometers would help to constrain the source of these earthquakes, thereby allowing a more accurate assessment of hazards that may affect the town and its critical facilities.

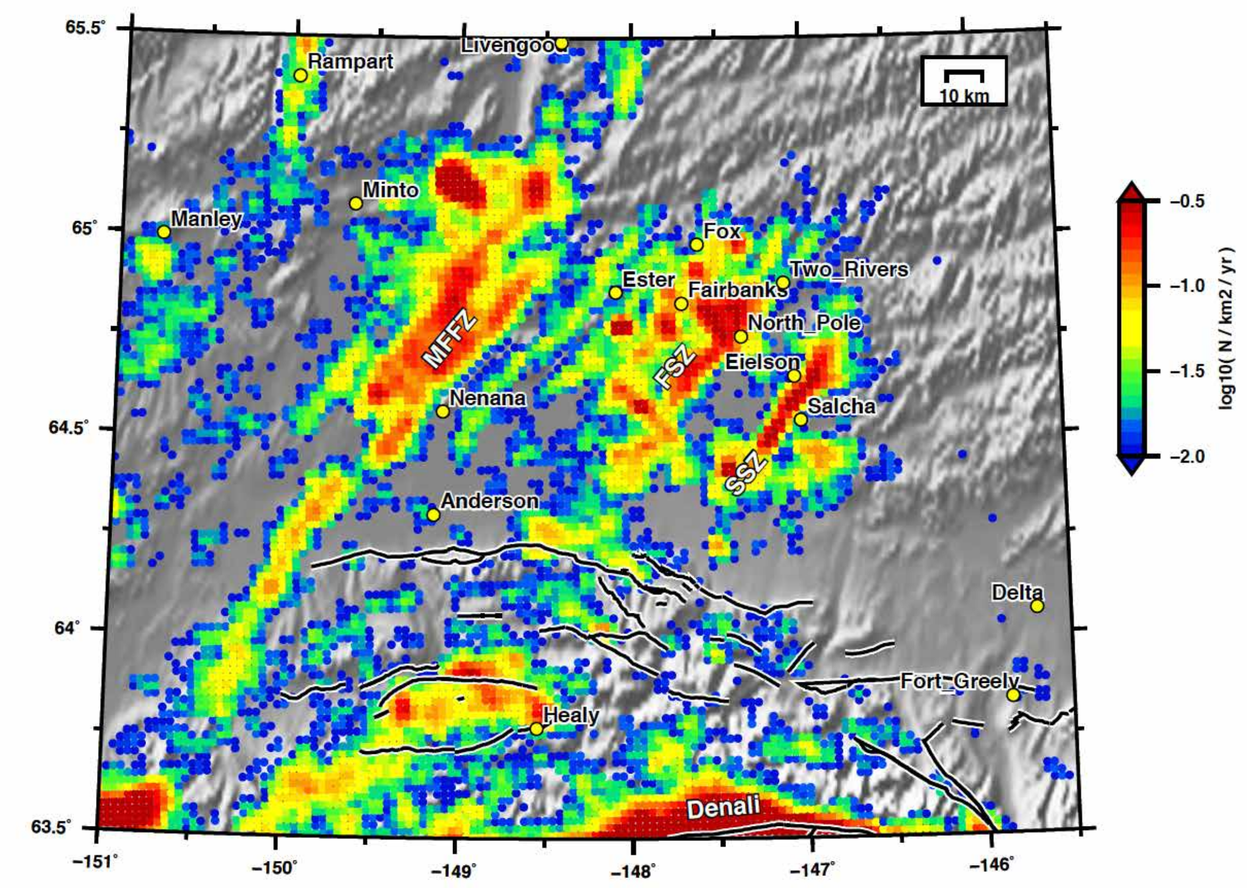
Other areas of shallow earthquakes with no clear relation to mapped faults include the NNE-SSW oriented Minto seismic zone west of Fairbanks, which lies along the route of the proposed natural gas pipeline, and the Talkeetna region, in the vicinity of the proposed Susitna-Watana hydroelectric dam. In all these cases, a denser network of seismometers would help to better locate the source faults, providing for improved assessment of earthquake hazards and, in many cases, pinpoint the areas for on-the-ground geologic mapping and assessment of shallow faults.



Epicenters of shallow (<20 km deep) earthquakes of magnitude 3 and greater during the past 20 years (1996-2016). Red lines indicate mapped faults with known or inferred activity during historic time or recent geologic past (1.6 million years). [Fault data from the Alaska Division of Geological & Geophysical Surveys]

Identifying Subsurface Unmapped Faults with Seismic Source Studies

Existing maps of active faults in Alaska do not seem to "connect the dots" of maps showing seismicity of Alaska. Faults are identified from geological mapping, and earthquakes occur on faults, so why don't these two maps align? The answer is twofold: many seismogenic faults do not have a surface expression (e.g., Minto Flats fault zone) and some geological faults are locked and do not have regular earthquakes (Denali fault, pre-2002). Improved seismic networks provide two fundamental benefits: (1) improved earthquake relocations for characterizing 3D fault structure, (2) improved earthquake mechanisms to characterize the style of faulting. Improved station coverage will sharpen seismicity maps toward identifying active faults. Converting clouds of seismicity into known faults, allows hazard and risk assessments to be dealt with in a deterministic fashion, and not just probabilistic. When a fault lineation is clear, then engineers, planners, emergency managers and others can treat it as an explicit known hazard.



Log-scaled crustal seismicity rate for central Alaska, along with the active fault map for Alaska (Koehler et al., 2012). The parameters from the AEC seismicity catalog are 1990-01-01 to 2015-01-01, M ≥ 0, and depth ≤40 km, in order to eliminate slab events. Fault zones: MFFZ, Minto Flats fault zone; FSZ, Fairbanks seismic zone; and SSZ, Salcha seismic zone. This is an expanded version of Tape et al. (2013, fig. S4). Active faults from Koehler et al. (2012) are plotted. The magnitude of catalog completeness varies from about M = 0.5 to 1.5 over this region (Ruppert et al., 2008, plate 1), so some lack of seismicity could be due to the higher completeness magnitudes.
[Figure S1 of Tape et al., Bull. Seis. Soc. Am., 2015]

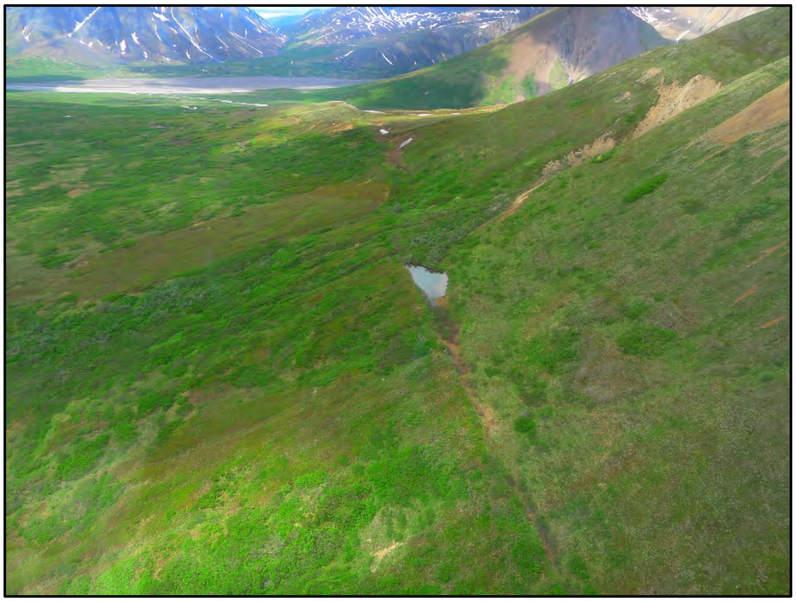
Assessing the Locations of Active Faults and their Associated Earthquake Potential

Geologic and paleoseismic studies focused on better characterizing the location and behavior of active faults in Alaska are essential for estimating the frequency and size of future earthquakes. This information provides critical input parameters to the assessment of future earthquake probabilities and is essential for improving seismic hazard zone mapping, developing earthquake planning scenarios, and implementing earthquake resilient design of the state's infrastructure. Additionally, this information is important to better assess potential earthquake damage and loss estimates due to future large events.

The 2013 release of the Quaternary fault and fold database for Alaska represents a first step in identifying the locations of active faults. However, the database contains only limited information on earthquake parameters for individual faults. Data critical to assessing seismic potential such as slip rate, slip-per-event, recurrence interval, and time since the most recent event are few to non-existent for most faults. Observations on the distribution of slip along a fault, the amount of slip during prior events, and slip rate can provide insight into future rupture potential along a particular fault.

Improvement and expansion of earthquake monitoring capabilities in Alaska will have direct and immediate influence on geologic and paleoseismic studies focused on better characterizing active faults. These studies will benefit from geophysical and seismological data on regional fault behavior, deformation style, and rates of activity. Better information on the locations of small earthquake epicenters can help identify previously unknown faults that may not be clearly expressed at the surface. Well-constrained microseismicity provides information on the width (or depth) of fault planes which when combined with geologic information on fault length and estimated displacement can place constraints on maximum future earthquake magnitudes. Paleoseismic studies of surface ruptures can determine the recurrence intervals of past large earthquakes along well-defined faults. For faults that are poorly defined at the surface, seismological data on the magnitude and frequency of small and moderate earthquakes can be used to develop recurrence models that describe the frequency of larger events.

Thus, data developed through comprehensive earthquake monitoring directly complements geologic efforts to better characterize the seismic potential along active faults and will ultimately lead to reducing Alaska's exposure to seismic risk.

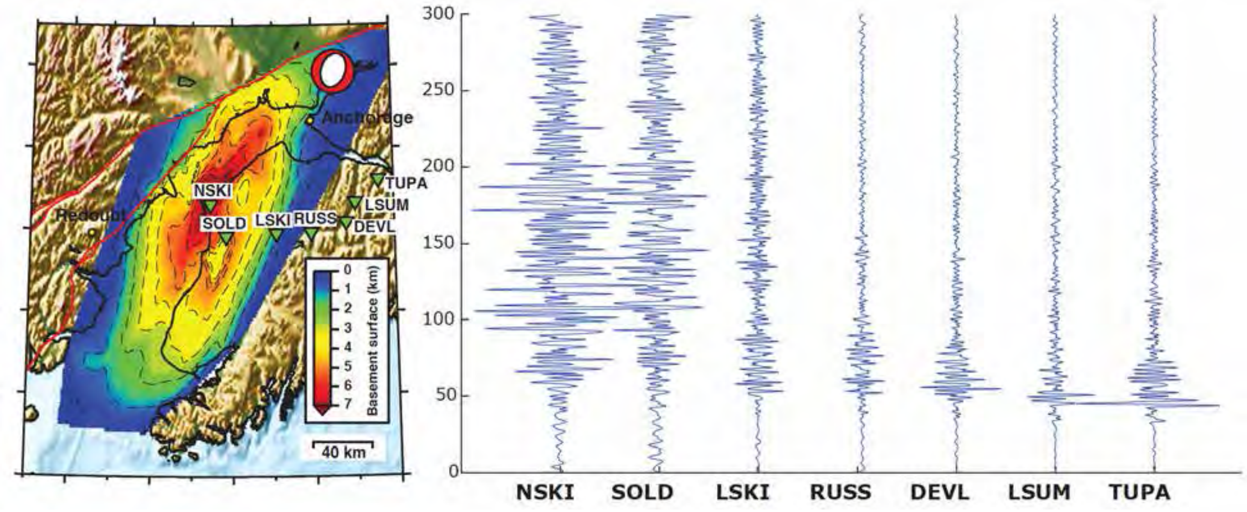


The Denali fault extends through the pond in the center of the photo and is marked by a distinct break in the surface. Paleoseismic studies indicate that this part of the fault generates large earthquakes every 250-400 years; however, the locations of microseismic events along the fault, particularly west of Denali National Park, are poorly constrained due to limited seismic monitoring stations.

Amplified Shaking in Sedimentary Basins: Need for Improved Seismic Instrumentation

Sedimentary basins are deep "bowls" filled to depths of up to several kilometers of unconsolidated sediments and sedimentary rock. Seismic waves slow down and amplify when they enter sedimentary basins, resulting in stronger and longer-lasting shaking during earthquakes. Much of Alaska's population and critical infrastructure are located on or around sedimentary basins.

Sedimentary basins are often avoided as sites for seismic station installation, in part due to the challenging site structure (no bedrock, poor line-of-sight for telemetry, perhaps wet, perhaps permafrost) and in part because of the local noise of the basin, which obscures routine earthquake location monitoring efforts. If ground motions are strong in basins, then more stations are needed to evaluate the variability of ground motion, especially in urban regions such as Anchorage and the western Kenai Peninsula. Historically, seismic stations in major basin structures, including the Cook Inlet, have been avoided because the data are deeply altered by the basin structure. It is specifically for this reason however that stations in the basins, including those of the USArray, are notably valuable.

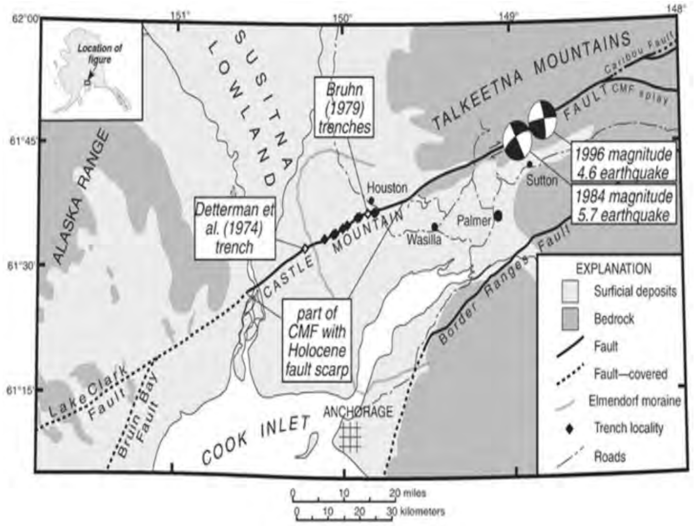


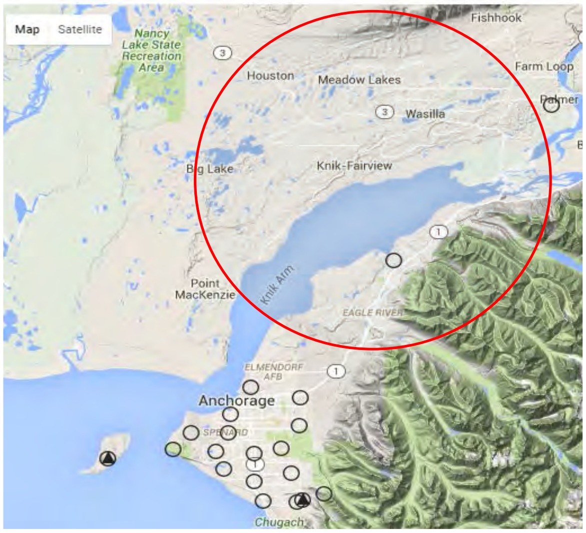
Amplification and extended duration of ground motion for stations within major sedimentary basins. The example is for the Cook Inlet basin in southern Alaska, with six stations from a 2007-2009 temporary deployment. Cook Inlet basement geometry is constructed from large volumes of industry data such as well logs and seismic reflection surveys (Shellenbaum et al., 2010). The vertical axis is time in seconds; the seismograms are ordered from west (left) to east (right); LSKI is near the boundary of the basin

Microzonation needs in the Greater Anchorage Area

Site-specific seismic hazards studies have been conducted for the most populated parts of Anchorage, but data is lacking from the Glen Highway north to the Mat-Su Valley. Given the ongoing port expansion project, the proposed development work in and around Government Hill, the rapid growth of the Mat-Su Valley, and the possible construction of an AK-LNG gas pipeline, improved seismic monitoring is badly needed for assessing seismic hazards in the greater Anchorage area.

Although this area is close to many active faults (left figure below) and is one of the most seismically active in Alaska, a large gap in seismic station coverage exists for the area, as shown in the right figure below. The value of the existing Anchorage strong motion network was demonstrated by the 2016 M7.1 Iniskin earthquake, when drastically different shaking was recorded in different neighborhoods across Anchorage. Northward expansion of the strong motion network, with sensors distributed over various geological units for the purpose of estimating ground motion characteristics and seismic response from various soils, would make possible for the same kinds of hazard assessments for areas north of the city as exist now for the city proper. The University of Alaska Anchorage (UAA) engineering program is well suited to work with these data and incorporate them into our larger efforts in the Anchorage Mat-Su region.





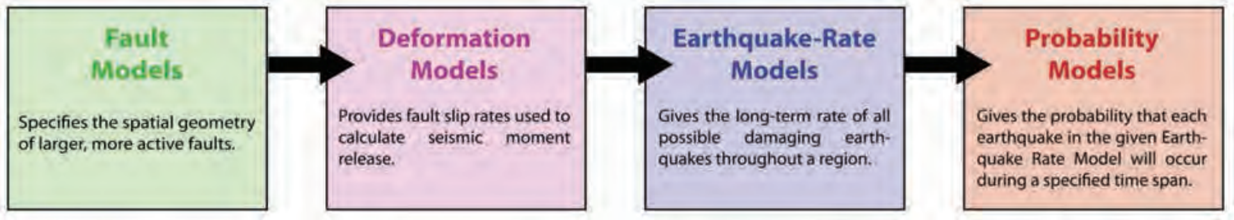
(Left) Distribution of local faults in the proposed study area (Courtesy: BSSA)
(Right) Areas north of Anchorage are almost completely without crucial strong motion instrumentation

Aiding Earthquake Hazard Assessments Using Long-Term GPS Motions

Knowledge of strain rate patterns and fault slip rates is key to the development of accurate seismic hazard assessments. Geodesy, particularly GPS, has revolutionized our ability to estimate present-day slip rates and strain fields and relate them to fault slip and earthquake hazards. The prime reason for this is that the rate of long-term ground motions measured by GPS scale directly with the long-term slip rates on faults, and the long-term rate of earthquake moment does as well. This makes geodetic data a powerful complement to the other data that are used in these assessments, such as seismicity rates and the history of large historical earthquakes. The most recent earthquake rupture forecast model for California, UCERF3, made extensive use of geodetic data, which provided powerful constraints on the long-term rate of large earthquakes (and on where such earthquakes are most likely to occur). The figure illustrates the workflow of how geodetic data from Southern California were used in UCERF3.

Data in Alaska are not as extensive as in California, and existing data are sparse in many areas of Alaska outside the railbelt. Alaska also features a number of complications compared to California, such as the Alaska-Aleutian subduction zone, which produces strain over a large area of southern Alaska and makes it harder to differentiate between upper plate faults and variations in the slip pattern on the megathrust. In addition, Alaska has large areas with significant time-dependent deformation due to post-earthquake responses following the large earthquakes of the last few decades.

Making better use of this kind of data in Alaska requires continuing support for data collection and support for the analysis and modeling of GPS data to estimate velocities, strains, and inferred motions of crustal blocks. Finally, these data products need to be ingested into algorithms for producing hazard maps such as the USGS earthquake hazard maps or detailed regional assessments like UCERF.



Workflow of models used in the UCERF3 earthquake rupture forecast model for Southern California. Geodetic data contribute to the Fault Models box (green), by helping to determine which faults are likely active and must be incorporated in the model. Geodetic data provide the main contribution to the Deformation Models box (pink), which determines the slip rates on all faults and strain rates between faults. These models then lead to estimates of earthquake rates and probability of shaking. [From Field et al., USGS Open-File Report 2013-1165, 2013]

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Improving Knowledge Base for Preparedness

The seismic network in Alaska is tightly clustered in the southcentral and interior regions of the state. The communities and commercial entities in these geographic areas are aware of local seismic hazards and greatly benefit from rapid reporting and scientific interpretation of earthquake activity in the area.

However, in many Alaskan communities, meaningful earthquake monitoring only arrives after a significant earthquake. If a moderate or large earthquake strikes somewhere that lacks station coverage, in response the responding agency (the Alaska Earthquake Center) will deploy one or more temporary sites to monitor the aftershock sequence. These sites are often makeshift by nature, as they are meant to only last weeks or months before being disassembled. These after-the-fact monitoring campaigns are too late to capture the background seismicity, any foreshock activity, and even the mainshock itself.

Below are photos from temporary sites KOTZ (Kotzebue) and PAL (Port Alexander), both of which were installed in response to large earthquakes (M5.7 and M7.5, respectively) felt in their respective communities. These sites were rapid, improvised installations with temporary infrastructure. They were invaluable for capturing aftershock sequences. However, unlike the USArray TA, they provided little long-term value.

Improved earthquake monitoring would help these communities prepare for their specific seismic hazards. Until then, these communities will rely on after-the-fact monitoring efforts, hoping to document a small window of seismic data.

(Left) KOTZ site in Kotzebue
(Right) PAL site in Port Alexander

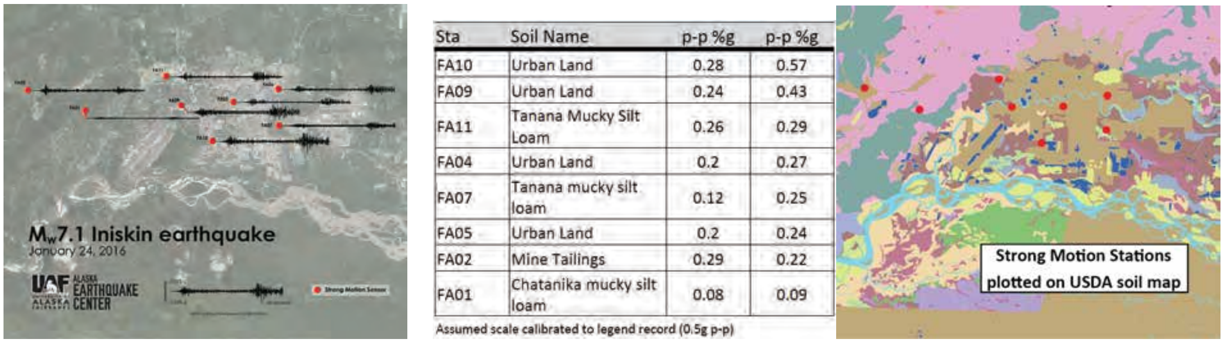
Seismic Microzone Mapping of the Middle Tanana Valley

Although three magnitude 7.0 or greater earthquakes have occurred within 50 miles of the population center in Fairbanks in the last 90 years (Haeussler & Plafker, USGS Open-File Report 95-624, 2004), local seismic response and amplification is poorly mapped. There are over 30 types of soil defined by the USDA, some of which are characterized by water saturated silts, peats or sandy loams and fill—both frozen and unfrozen (Mulligan, Soil Survey of Greater Fairbanks Area, Alaska. Washington, 2010) —which the USGS characterizes as susceptible to seismic amplification (Cassidy & Mucciarelli, Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering Paper No 758, 2010).

An accurate assessment of the liquefaction hazards and site-amplification data is critical for both emergency management and community planning. Characterization of the local seismic amplification would allow planners to answer questions which have historically been ignored: 1) What are the variations of seismic risk on a small geographic scale within the region? 2) Can we develop and encourage new construction best practices for specific zones?

Bolstering the regional seismic instrumentation throughout the valley is crucial to this study. Combining ground shaking recordings with geotechnical and geological data will allow for seismic microzonation maps that will help reduce future losses (Cassidy & Mucciarelli, 2010).

Microzonation maps will assure: 1) New natural gas distribution systems are adapted to sites with high motion potential; 2) initial response damage assessment routes are prioritized; 3) facilities in vulnerable areas are identified and prioritizing for seismic retrofitting and internal facility safety measures; and 4) appropriate risk management measures, such as mandating earthquake insurance in specific zones.



Sta	Soil Name	p-p %g	p-p %g
FA10	Urban Land	0.28	0.57
FA09	Urban Land	0.24	0.43
FA11	Tanana Mucky Silt Loam	0.26	0.29
FA04	Urban Land	0.2	0.27
FA07	Tanana mucky silt loam	0.12	0.25
FA05	Urban Land	0.2	0.24
FA02	Mine Tailings	0.29	0.22
FA01	Chatanika mucky silt loam	0.08	0.09

Assumed scale calibrated to legend record (0.5g p-p)

(Left) Strong motion stations in Fairbanks revealed drastic variations in shaking during the M7.1 Iniskin Earthquake
(Middle) Chart compares soil types and ground motions
(Right) Map of soil variability throughout the Tanana Valley.

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Earthquake Vulnerability of Earthen Structures in a Changing Climate

Many communities in the Y-K Delta have wastewater lagoons and other infrastructure such as roads, runways, and water impoundments that are constructed of the locally available native silt. Appropriately designed and constructed, these structures have, for the most part, served their purpose. The risk of significant damage from earthquakes in the communities of the delta is considered low according to the local hazard mitigation plans.

A number of changing conditions could affect the vulnerability of earthen structures, and this risk could be compounded in combination with the potential for earthquakes. For example, the Y-K Delta is underlain with warm and discontinuous permafrost. Average annual temperatures are rising, and the permafrost is melting. The result will be ground subsidence and potential instability of earthen structures. Sea level rise and an increase in fall storm intensity are not well documented in Western Alaska but are reasonably expected to occur.

Improved earthquake monitoring and assessment in the Y-K Delta would allow for better risk assessment for earthen structures. The Environmentally Threatened Communities program of the Denali Commission is most concerned with flooding, erosion, and permafrost degradation. Communities in the delta face all three of these threats, but the consequences of damage to earthworks is increased by the potential for earthquake activity.

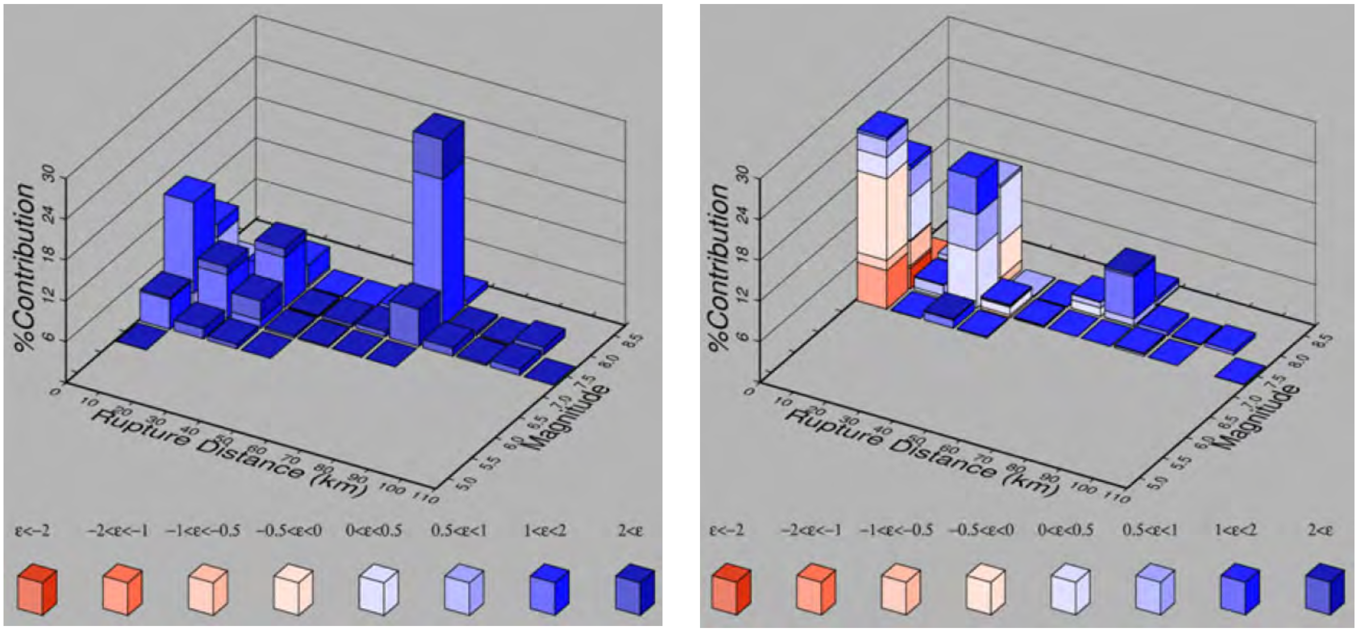
A better understanding of earthquake potential in the Y-K Delta could help guide public policy decisions on infrastructure investment and design as well as hazard mitigation planning. The potential impact on a single community of an earthquake causing soil liquefaction and the failure of a wastewater lagoon or damage to the runway is significant. The impact on the region could be massive.

The Kogniginak wastewater lagoon. As in many Y-K Delta villages, separation of sewage from sensitive waterways and wetlands relies on potentially vulnerable earthen structures.

CyberShakeAlaska: Probablistic Seismic Hazards for Communities and Critical Structures

In 2011 scientists presented a pioneering effort in a paper entitled "CyberShake: A Physics-Based Seismic Hazard Model for Southern California". The concept was to use three-dimensional earthquake simulations for realistic scenario earthquakes in southern California to build a database of shaking expectations for each site in the region. The authors concluded: "Our results indicate that the combination of rupture directivity and basin response effects can lead to an increase in the hazard level for some sites, relative to that given by a conventional Ground Motion Prediction Equation."

Alaska should have CyberShake in its long-term targets. Several ingredients are needed: a database of 3D fault geometries for all scenario earthquakes, earthquake likelihood estimates for each fault (how often? how big?), and a detailed 3D earth structure model. All of these ingredients require dense station coverage. Asking the question, "What is the shaking hazard at this one site?" requires an immense effort if you need an accurate answer. CyberShake Alaska should be the end goal.



Histograms showing magnitude and distance disaggregation at a site in southern California for a period of 3s for an annual exceedance probability of 2% in 50 years. The histograms show how the hazard estimation is partitioned into earthquakes at various distance and magnitude intervals.
(Left) Based on Ground Motion Prediction Equations of Boore and Atkinson (2008).
(Right) Based on CyberShake. For this site, the physics-based approach provides radically different results from the traditional approach. [Figure 8 of Graves et al., 2011, Pure and Applied Geophysics]

Eruptions at Unmonitored Volcanoes: Kasatochi Case Study

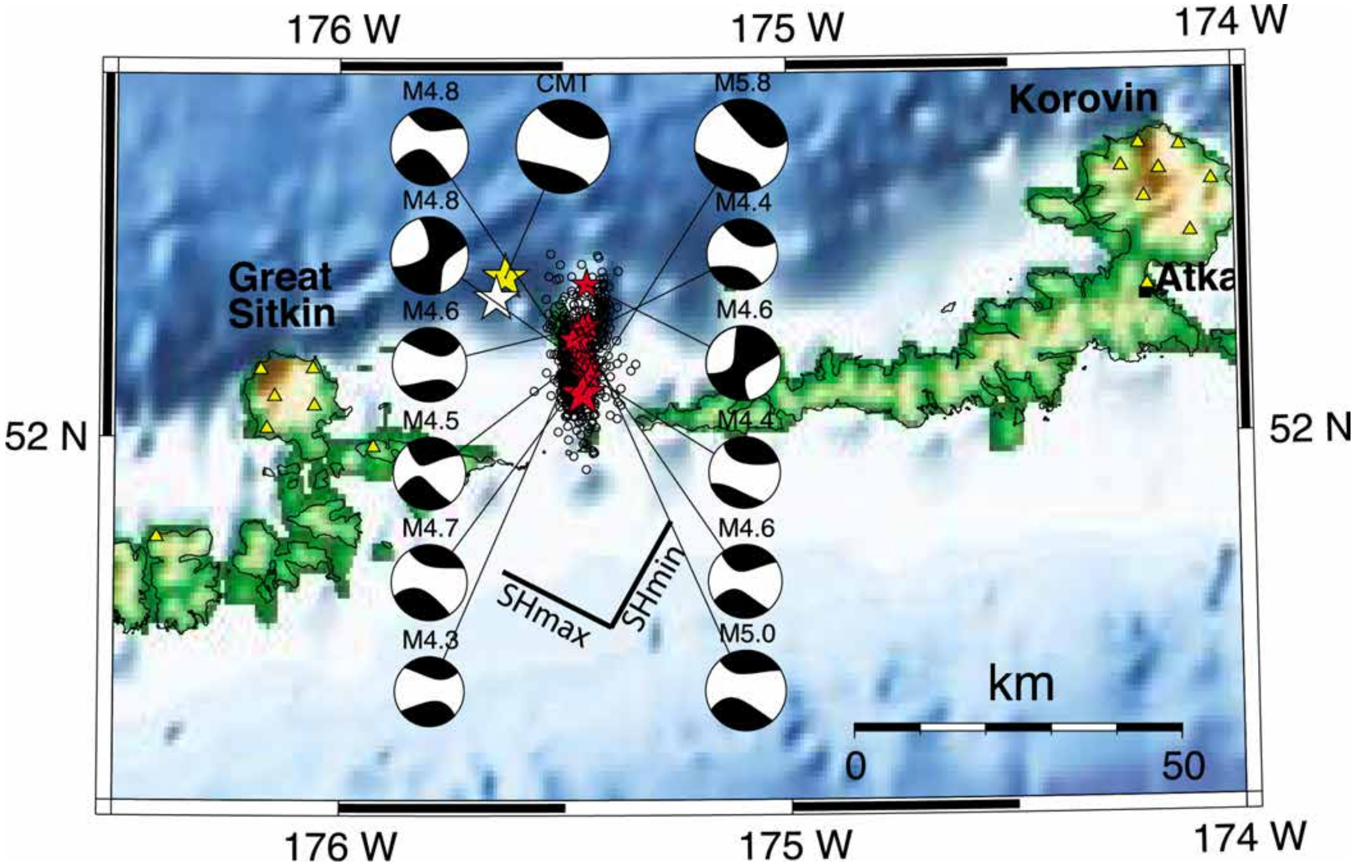
Strong regional seismic station coverage and monitoring is the first line of defense in monitoring volcanoes not considered active.

Of the 92 active volcanoes in Alaska, only 46 are seismically monitored. Many of these monitored volcanoes are among the most frequently active along the volcanic chain. A volcano need not be frequently active to be extremely dangerous, however. Studies have shown that the longer a volcano is inactive or “dormant,” the larger the eruption will be when it comes back to life. This presents a monitoring challenge since these volcanoes are often not yet considered high threat.

The most recent and spectacular case of this phenomenon in Alaska occurred in 2008, with the sudden eruption of Kasatochi Volcano in the western Aleutians. Despite the volcano consisting of just a single cone rising only 1000ft out of the ocean, the eruption produced ash clouds as high as 50,000ft above sea level and pyroclastic flow deposits that covered the entire island to a depth of many meters.

Kasatochi Volcano did not have a dedicated seismic network. The dramatic increase in earthquake activity that led to the eruption was instead detected by the Alaska Earthquake Center’s seismic operation, which monitors the entire state.

Fortunately, the close collaboration between the Alaska Earthquake Center and the Alaska Volcano Observatory meant that the activity was identified as a precursory volcanic sequence, and biologists working on the island were safely evacuated.



Earthquake swarm that preceded the 2008 eruption of Kasatochi volcano. The eruption occurred at a volcano previously considered dormant and lacking any geophysical instrumentation. The earthquakes were picked up and flagged as suspicious by the routine earthquake tracking of the Alaska Earthquake Center. Nearly a dozen foreshocks were large enough to provide moment tensor solutions in advance of the M5.8 earthquake that initiated the eruption.

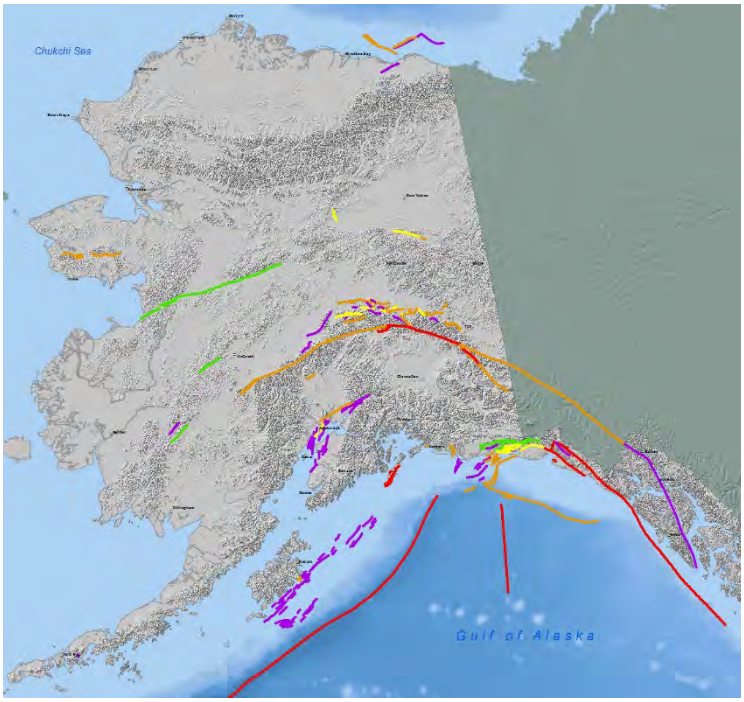
Alaska Division of Geological & Geophysical Surveys Geohazards Mapping

Microseismicity helps target areas for geologic mapping and field investigation to better characterize fault behavior and identify hazards.

The Alaska Division of Geological & Geophysical Surveys (DGGS) is tasked with conducting surveys to determine the potential geologic hazards to buildings, roads, bridges, and other installations and structures. We collect, analyze, and compile geologic data useful for engineering and hazard risk-mitigation purposes; perform studies of major geologic hazards such as earthquakes, active faults, and tsunamis; and produce reports outlining potential hazards in susceptible areas. DGGS advises other State of Alaska divisions and state agencies regarding potential hazard risks to proposed developments and land disposals.

Despite being the most seismically active region of the United States, Alaska has the dubious honor of being the least-mapped state in the nation. Scientists are working to gain a better understanding of the distribution and character of active faults in Alaska, but the state's vast size and remoteness have made this a challenging task. The number and detail of known active faults in Alaska, as currently mapped, are directly related to their proximity to the largest population centers and the railbelt area. This is not because there are more faults in these locations but because these are the areas where researchers have focused their mapping efforts. There are without question numerous active faults that could pose threats to Alaska's people and infrastructure that we are entirely unaware of because no one has yet stumbled across any evidence in the field.

DGGS's mapping efforts would significantly benefit from improved earthquake monitoring and assessment. The data derived from increased seismograph distribution and density would give us valuable tools to help pinpoint areas of suspicious seismicity that could be indicative of active structures that are currently unrecognized and provide targets for mapping, field studies, geophysical surveys, and fault trenching to identify potential hazards.



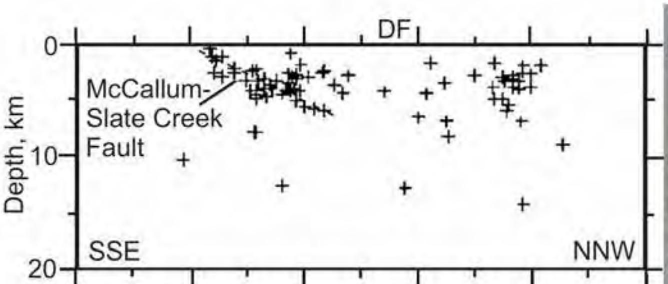
Map showing the distribution of known active faults (colored lines) in Alaska. Generally, mapped active faults are concentrated in developed areas because this is where scientists have accessed these features on the ground or through targeted geophysical or bathymetric surveys. Numerous active faults are likely to exist that have never been mapped and could pose a threat to Alaska's people and infrastructure.

Deep Time, Earthquake Data, and Seismic Hazards

Geologists sometimes refer to research that involves time on the million-year scale as “deep time.” One of the fundamental principles of geology is uniformitarianism—the understanding that processes operating in the present have operated in the past. Hence, our geologic history offers insight into our future. Deep time structural geology is often an iterative process where we use earthquake data to help frame geology fieldwork campaigns. In turn, we can assist with seismic hazard awareness based on our examination of the long-term history of structures and/or the discovery of new structures while in the field.

Given geological faults are never truly inactive, identifying unknown structures is critical to protecting existing infrastructure and planning future development. High-resolution earthquake data is needed not only to help identify potential structures but also to understand the sense of motion on those structures (predominately horizontal vs. vertical displacement) The Trans-Alaska Pipeline was designed to handle strike-slip (horizontal) motion where it crosses the Denali fault system. During the 2002 M7.9 Denali Fault strike-slip earthquake, the engineered mechanism to protect the pipeline performed perfectly.

However, due to sparse seismic instrumentation in the region, there is insufficient high-resolution earthquake data for both accurate epicenter location and depth constraints. Through geological fieldwork and laboratory work, we have already documented two potentially active thrust faults that are crossed by the pipeline that were not identified in the recent seismic hazard map of Alaska nor in the original pipeline seismic assessment. Continued support of an expanded seismic network is needed to fully constrain the potential hazards these structures pose to the Trans-Alaska Pipeline.



Aftershocks of the 2002 Denali Fault earthquakes located in the Delta River valley. plotted as plus symbols.

5 million year old volcanic ash layer (white unit) within sandstone (grey beds) in sediments deformed by the McCallum Fault system.

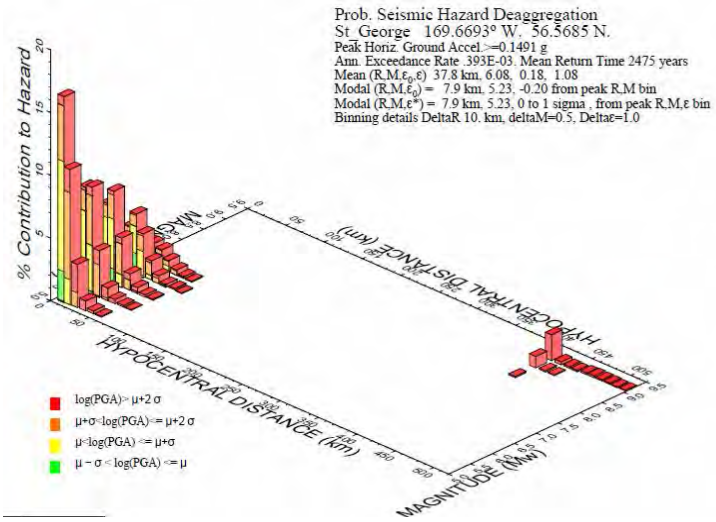
Evaluating Seismic Hazards in Coastal Alaska

The village of St. George and the Alaska Department of Transportation & Public Facilities (ADOT&PF) are improving the island's boat harbor because the complexity of the entrance and its orientation provides navigational challenges and allows for undesirable wave action in the inner harbor areas during strong storms.

The existing harbor entrance is formed by a network of three breakwaters. Improving the harbor will require reconstructing the breakwaters in a different configuration. They will be founded on sea floor sand deposits that, based on explorations and laboratory testing, may be liquefiable under certain seismic conditions. This liquefaction potential had a significant impact on the design slopes, stability, amount of material needed for construction, and project cost.

Unfortunately, the seismic data used to evaluate the liquefaction potential was limited. To establish likely ground motions, a limited probabilistic seismic hazard analysis (PSHA) was conducted using the USGS de-aggregation tool that is available on-line. Because of the lack of seismic and faulting information available in this part of the state, the de-aggregation indicates that the most significant source of seismic activity for the project are "random crustal events" which are not based on actual known seismic sources. In fact, in January 2015 a vigorous swarm of M4-5 earthquakes, including dozens of felt events, took place just offshore of St. George Island. Due to the lack of station coverage, this series of events was poorly tracked and evaded any meaningful explanation.

A firm understanding of the seismic environment is necessary to developing resilient infrastructure. In much of the state, more seismic instruments are needed to achieve this. In the St. George Harbor case, a better understanding of the seismic environment has the potential to cut both ways. Hazard that is higher than anticipated could mean that the new breakwaters were under-designed and thus more susceptible to failure during an earthquake. Conversely, if the seismic environment were found to be less active, that could mean the new breakwaters were over-designed at unnecessarily high cost. These concerns are amplified as northern shipping routes open and strategic coast development increases in those areas of the state where the least is known about the seismic environment.



(Left) USGS PSHA deaggregation output showing the most significant seismic hazard contribution for St. George originating from "random crustal events" (upper left of plot). Such events are not based on known faulting or seismic sources and could be overestimating or underestimating the actual seismic hazard for a given area.
(Right) Outer St. George Harbor breakwater structures from the inner harbor area. (Photo by Thomas Keatts)

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Vulnerabilities of Tourism Resources: Skagway Case Study

Skagway is one of the busiest cruise ship ports in Southeast Alaska. Due to its geographical surroundings, the potential for a catastrophic seismic event is a significant concern.

The port and historic areas of the Municipality of Skagway (MOS) host about one million visitors per year, mainly through cruise ship access concentrated from May until October. In season, up to 4 full-sized cruise ships dock at once between a significant mountainside and a fuel tank farm

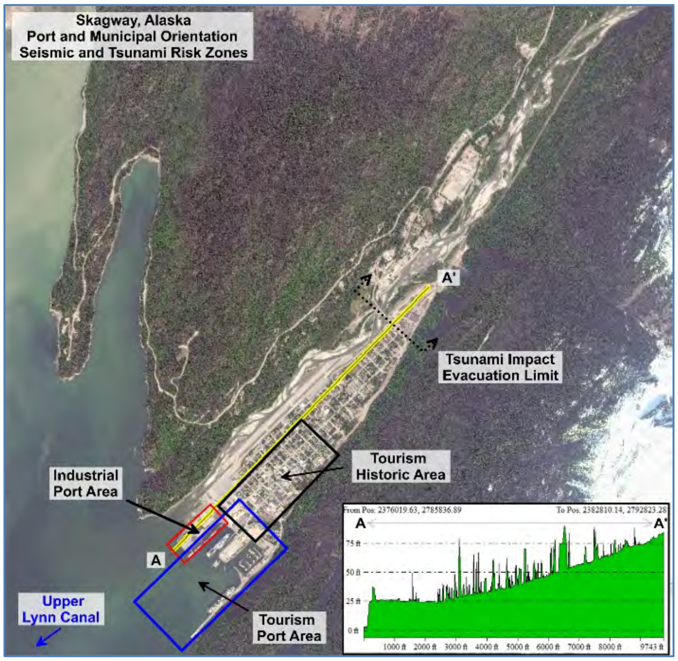
Principal considerations for emergency responses to seismic events are segmented by areas and include:

1. Direct effects of ground motion change,
2. Direct damage to pedestrian access and conveyance structures,
3. Direct damage to industrial structures,
4. Seismic-induced tsunami(s) and inundation(s), and
5. Secondary effects of seismic damage (fire, hazmat release, vehicular accidents, etc.).

The MOS port areas are most prone to the effects of seismic activity, given the proximity of tourist access and industrial port structures such as the storage and transfer points for petrochemical and hazardous materials. Slope failures in this area, which have previously occurred, can cause direct damage and also induce localized tsunami action. Structural failures of docks, conveyances, and storage areas from ground motion/offset and liquefaction of underlying deltaic sediments can also pose direct and indirect human health risks.

The MOS historic area is also at risk from seismic activity, but to a lesser degree than the port areas. This area is principally constructed of relative low-height retail business structures and residences, and it is not used as an industrial materials storage and processing area. Regardless, the historic district is within a tsunami impact area and is also sensitive to structural damage and secondary fires of the predominantly wood-frame buildings. The seasonal increase in population density of this area also increases its risks from seismic activity.

Potential benefits for enhanced earthquake monitoring, assessment, and education are far reaching in terms of life safety as well as the economic stability of Southeast Alaska. It would allow us to more efficiently assess, plan for, and respond to possible threats.



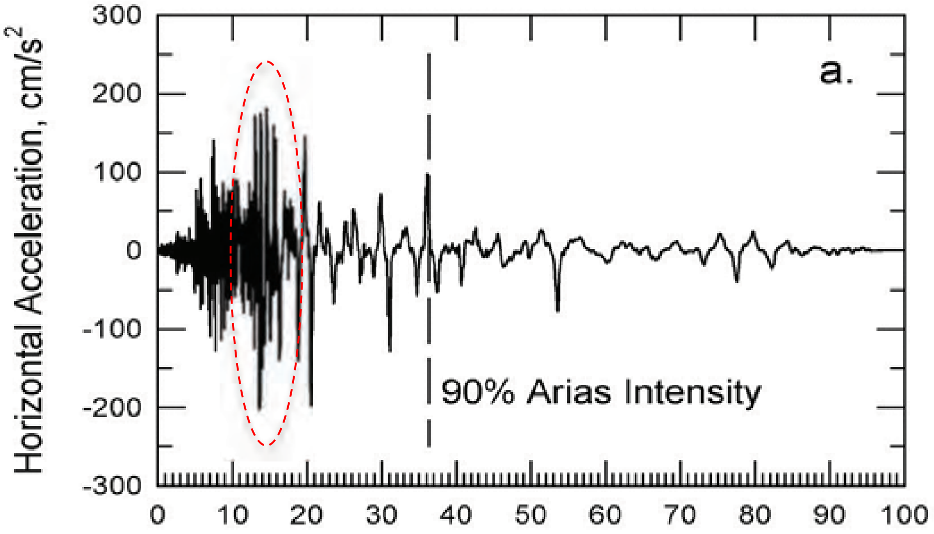
(Left) The main port, business and residential sections of the MOS (2016 population = 920) lie atop a deltaic deposit of the Skagway River, all within an area of ~1.8 x 0.5 miles. The MOS proper starts at the northern edge of the Lynn Canal and slopes upward to the northeast at ~1%.
(Right) Aerial view showing the Skagway Cruise Port.

Post-Earthquake Damage Assessments – Geotechnical[1]

Increasing the number of free-field seismographs in Alaska near populated or industrial areas will improve the ability of engineers to more rapidly and accurately assess the geotechnical stability of infrastructure immediately after a strong earthquake, thereby optimizing the need, scope, and cost for more intrusive investigations, and/or reducing the time for the facility to returned to use.

Following a significant earthquake, the occupancy or operation of a specific facility could be interrupted until such time as the geotechnical stability of the site (e.g. ground settlements and spreading, slope failure, or reduction of foundation bearing capacity associate with liquefaction or cyclic softening) is assessed. Subject to the size and proximity of the earthquake, facilities may remain unoccupied for some time, further delaying important businesses and facilities from resuming operations; especially if there are visible signs of damage that requires more detailed and intrusive investigations. However, since the late 1990s, numerous engineering methods have been devised to utilize actual accelerometer records, if available, as part of post-earthquake inspections to better assess and qualify the geotechnical stability of a site, explicitly to enhance confidence in decisions regarding either the safety and functionality of a structure for resumed use, or if that structure should receive more in-depth investigation.

For example, visual inspection of ground motion records can qualify the peak acceleration and duration of strong shaking actually experienced at the site during an earthquake. These two parameters are very important to geotechnical engineers for estimating the potential magnitude of dynamic earth pressure and inertia loads on retaining walls (including basement walls), waterfront bulkheads, and in slopes during a post-earthquake damage assessment. Additionally, visual inspection of a strong motion record can also sometimes provide a quick indication of liquefaction (see figure below) or significant softening in deeper soils, even when there may not otherwise be obvious evidence of such phenomena visible at the ground surface. The confidence in conclusions drawn from these uses would be directly related to the number and proximity of seismic instrumentation to the subject location.



Time, s

Time history recorded at the Wildlife Liquefaction Array site, Imperial Valley, California, during the 1987 Superstition Hills MW6.6 earthquake. The change in wave amplitude and frequency after about 13-14 seconds of shaking was interpreted to represent the onset of liquefaction effects in the underlying soils.

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[1] *Based on Alaska Seismic Hazards Safety Commission Policy Recommendation 2013-1, Value of Seismic Instrumentation for Critical Structures*

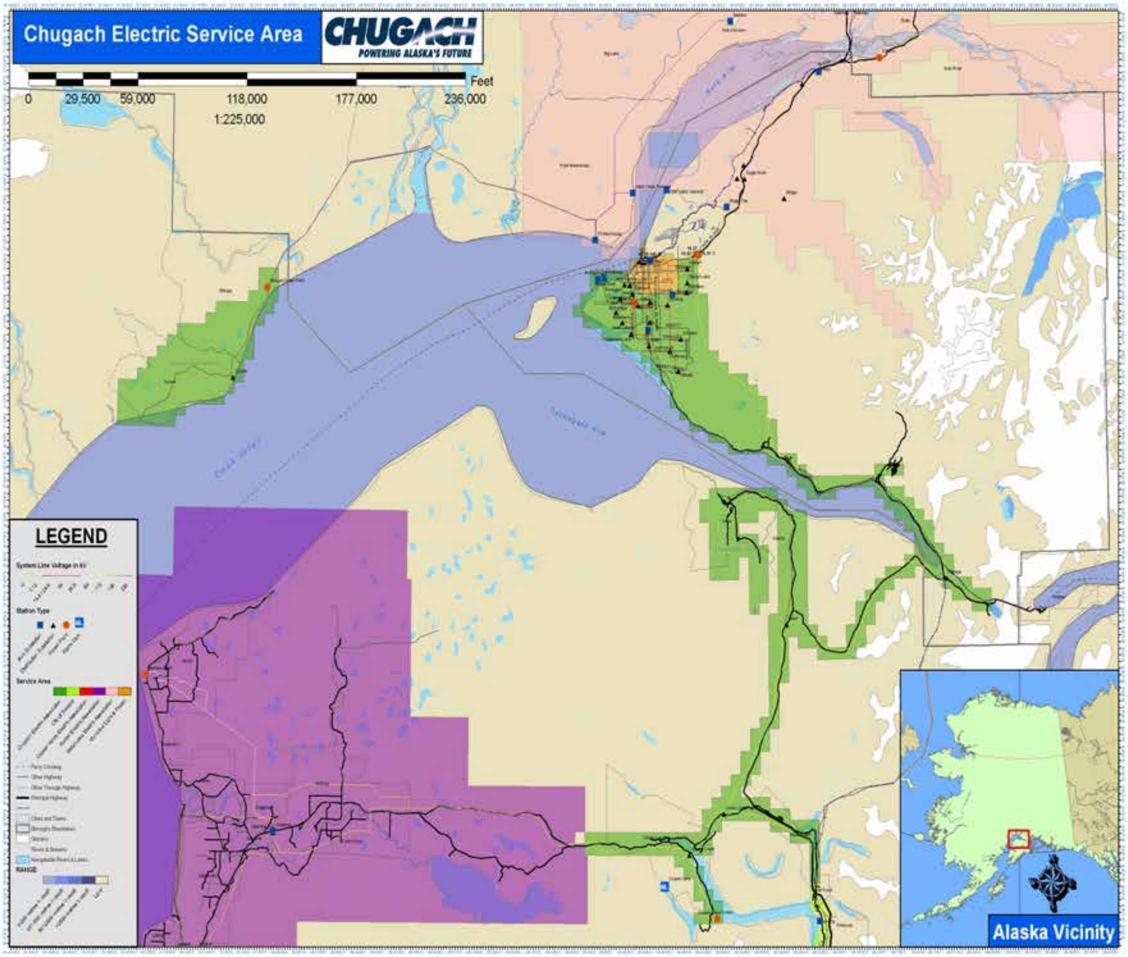
Improved Monitoring and Assessments for the Chugach Electric Association

Accurate earthquake hazard characterization, and related earthquake scenarios, allow Chugach Electric to pursue pre-event structural hardening, pre-positioning of replacement structures and equipment, and system-wide response planning.

Chugach Electric Association facilities produce and deliver power to nearly three-fourths of Alaska's population. Chugach has 531.2 megawatts of installed generation capacity at five power plants. Chugach operates 2,108 miles of energized line made up of 407 miles of transmission line, 897 miles of overhead distribution line and 804 miles of underground distribution line, serving some 80,000 metered retail locations in a service territory extending from Anchorage to the Northern Kenai Peninsula and from Whittier on Prince William Sound to Tyonek on the west side of Cook Inlet.

Chugach regularly provides power from Homer to Fairbanks through wholesale and economy energy sales to Homer Electric Association, Inc., the City of Seward, Matanuska Electric Association, Inc., and Golden Valley Electric Association, Inc. The current grid configuration provides the capability for these utilities to respond to power interruptions throughout the Alaska road system.

These facilities are critical to the life and health of Alaskans and are an essential to any rapid recovery following an earthquake. Improved earthquake monitoring and assessments will provide the data required to improve the durability and integrity of Chugach's facilities. For example, the data will identify seismically active areas for pre-event structural hardening, pre-positioning of replacement structures and equipment, and system-wide response planning.



Benefits of Seismic Monitoring to Bridge Safety

Alaska is one of the most seismically active regions in the world. According to the USGS, as much as 20% of the entire world's seismic energy is released in Alaska. Earthquakes such as the 1964 Anchorage event have caused massive destruction. Despite the major threat posed by earthquakes, Alaska has very limited seismic instrumentation. Improvements to the State's seismic monitoring networks would benefit the safety of our highway bridges in several ways.

Caribou Creek Bridge, Glen Highway (less than a mile from the active Castle Mountain fault)

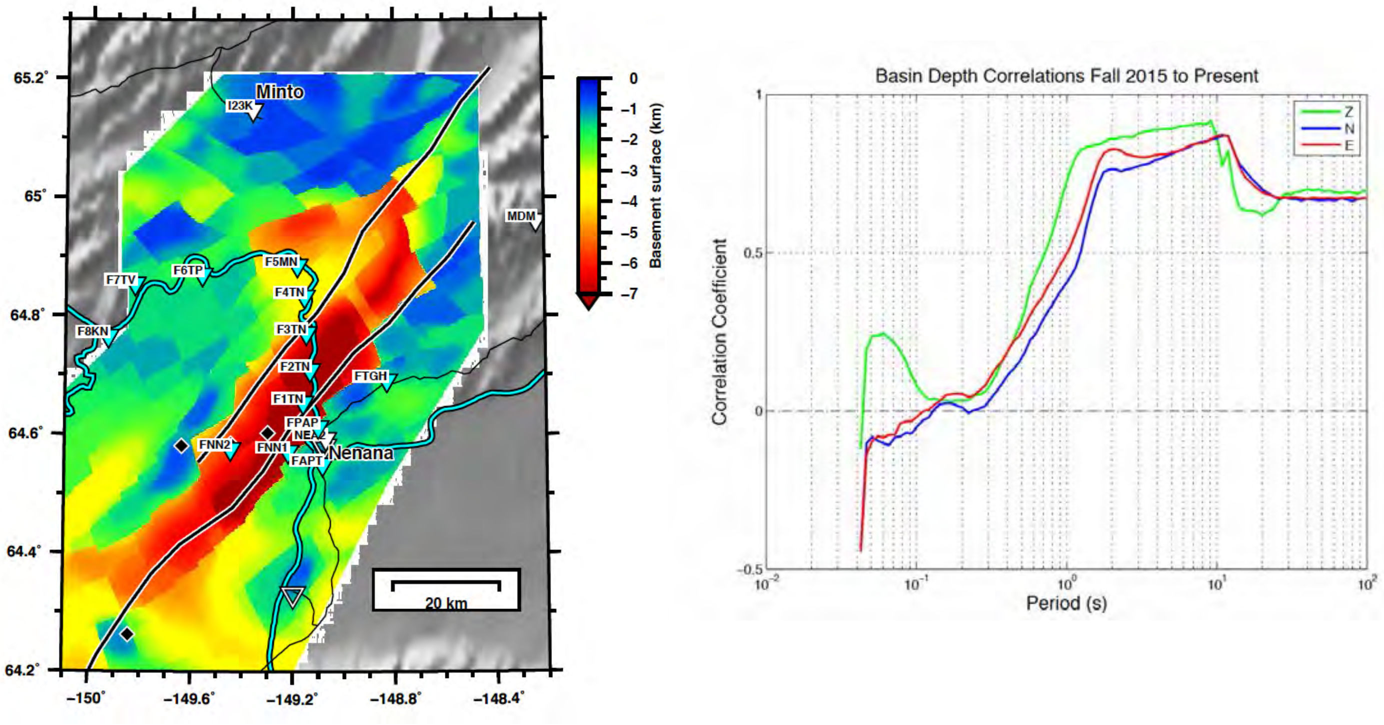
First, seismic instruments provide for the immediate determination of earthquake size, location, and anticipated damage levels associated with a recent earthquake. The Alaska Earthquake Center produces "Shake Maps" within minutes of a detected earthquake. These maps provide the DOT&PF maintenance and bridge design staff information necessary to perform rapid inspections of bridges possibly affected by a strong earthquake so that the transportation routes can more quickly be inspected and opened/closed to traffic.

Second, the recorded time histories of actual ground shaking are invaluable information for inclusion in future designs. The recordings are used to estimate the seismic excitation at a particular site and define the level of ground shaking that is expected. Only a relatively small number of strong motion recordings exist from Alaskan earthquakes. However, these types of recordings are needed to perform sophisticated time-history analyses of bridges as well as updating of seismic hazard maps. Further, increased earthquake records could lead to more accurate, site-specific analysis, thereby better economizing the cost of future bridge designs.

The accuracy and detail of ShakeMaps, as well as the number and quality of time motion records available for the benefit of future design, would be improved by enhancing the current earthquake monitoring and assessment capabilities in Alaska.

Vulnerabilities of Proposed Gas Pipelines: Minto Flats "ASAP" Case Study

The proposed route for the Alaska Stand Alone Pipeline (version 6.1, 2015-08-13) crosses the Minto Flats fault zone (MFFZ) and runs along the eastern margin of the Nenana basin. The MFFZ is defined as a pair of left-lateral strike-slip faults with the Nenana basin in between. Regarding a proposed pipeline, two questions arise: (1) What local earthquakes are possible (e.g., the Mw 6.0 Minto Flats earthquake)? (2) What surface ground motions are expected from local or regional earthquakes? For (1) we need a better understanding of the activity of regional faults. For (2) we need to understand how Nenana basin amplifies ground motion. Temporary stations installed in Minto Flats in 2015 show ground motion amplification in Minto Flats for ALL earthquakes, from the distant M7.1 2016 earthquake in southern Alaska to local M2 earthquakes in MFFZ. The Alaska Earthquake Center augmented this project with real-time telemetry allowing new hypocenters to be fully integrated with the Advanced National Seismic System earthquake catalog. The NSF-funded project in Minto Flats is a textbook example of how improved seismic station coverage provides higher resolution of fault structures and the seismic response of basins.



(Left) Depth to basement for Nenana basin (Doyon, Limited).
(Right) Correlation between ambient seismic noise and basement depth for temporary seismic stations in Minto Flats. The correlation coefficient is plotted as a function of period for three components (vertical, north, and east). The high correlation between periods of 1 s and 10 s is interpreted to represent the seismic response of Nenana basin.

U.S. Coast Guard Infrastructure in Alaska: Earthquake Early Warning Benefits

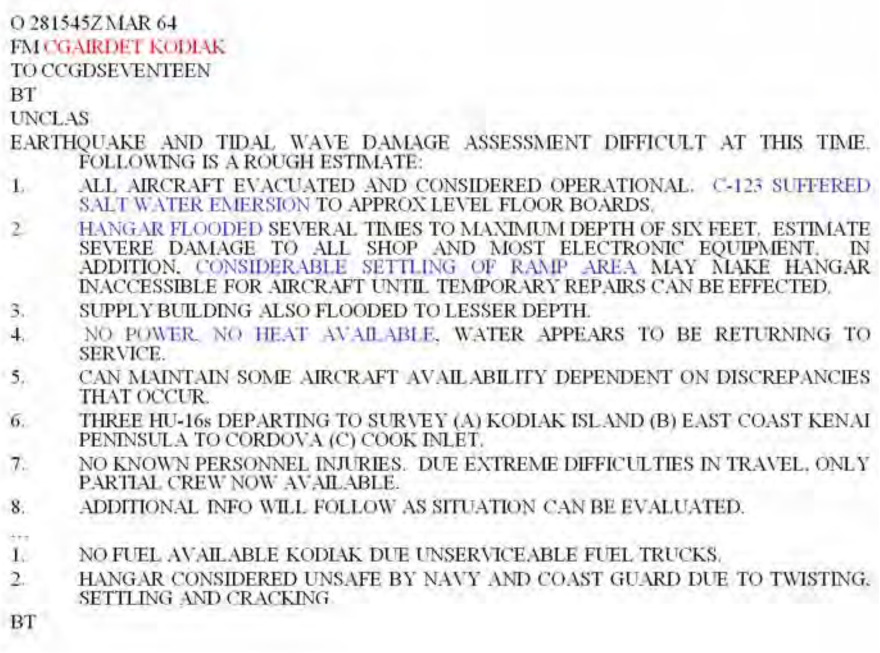
The United States Coast Guard has numerous shore facilities scattered throughout Alaska. Every mission begins and ends at a shore facility in Ketchikan, Petersburg, Sitka, Juneau, Valdez, Cordova, Seward, Homer, or Kodiak. The USCG also has numerous Rescue 21 VHF towers, channel buoys, and forward operating sites along the state's vast coastline. Lastly, the USCG manages several operational response centers that operate 24/7. Nearly all of these facilities are located in areas of high seismicity.

The USCG would benefit greatly from advanced warning whenever a significant earthquake occurs in the vicinity of any of its air station hangars or other key assets in Alaska. A single hangar can house up to four aircraft valued at over $100 million each. Early warning systems on hangar doors would prove invaluable in protecting these critical assets and would help ensure that USCG aircraft remained available for first response, as was needed during the 1964 Great Alaskan Earthquake.

……NAVAL STATION. SOME MINOR DAMAGE. EXTENT OF MAJOR DAMAGE UNKNOWN. SOME BUCKLING AND SETTLING OF ROCKY AREA.

Access to better ShakeMaps and damage forecasts would improve rescue operations both directly and by allowing Damage Assessment Teams to more effectively identify and repair damage to critical USCG assets/infrastructure.

Incorporating historical evidence, science, and cutting-edge technology to avoid and mitigate future losses is considered an important investment for both the US Coast Guard and its parent agency, the Department of Homeland Security.



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EARTHQUAKE AND TIDAL WAVE DAMAGE ASSESSMENT DIFFICULT AT THIS TIME. FOLLOWING IS A ROUGH ESTIMATE:

1. ALL AIRCRAFT EVACUATED AND CONSIDERED OPERATIONAL. C-123 SUFFERED SALT WATER EMERSION TO APPROX LEVEL FLOOR BOARDS.
2. HANGAR FLOODED SEVERAL TIMES TO MAXIMUM DEPTH OF SIX FEET. ESTIMATE SEVERE DAMAGE TO ALL SHOP AND MOST ELECTRONIC EQUIPMENT. IN ADDITION, CONSIDERABLE SETTLING OF RAMP AREA MAY MAKE HANGAR INACCESSIBLE FOR AIRCRAFT UNTIL TEMPORARY REPAIRS CAN BE EFFECTED.
3. SUPPLY BUILDING ALSO FLOODED TO LESSER DEPTH.
4. NO POWER. NO HEAT AVAILABLE, WATER APPEARS TO BE RETURNING TO SERVICE.
5. CAN MAINTAIN SOME AIRCRAFT AVAILABILITY DEPENDENT ON DISCREPANCIES THAT OCCUR.
6. THREE HU-16s DEPARTING TO SURVEY (A) KODIAK ISLAND (B) EAST COAST KENAI PENINSULA TO CORDOVA (C) COOK INLET.
7. NO KNOWN PERSONNEL INJURIES. DUE EXTREME DIFFICULTIES IN TRAVEL, ONLY PARTIAL CREW NOW AVAILABLE.
8. ADDITIONAL INFO WILL FOLLOW AS SITUATION CAN BE EVALUATED.

…

1. NO FUEL AVAILABLE KODIAK DUE UNSERVICEABLE FUEL TRUCKS.
2. HANGAR CONSIDERED UNSAFE BY NAVY AND COAST GUARD DUE TO TWISTING, SETTLING AND CRACKING

BT

(Top) Photos documenting damage caused by the 1964 earthquake to Base Kodiak's Hangar 1, including settlement of the paved apron and structural steel failure as well as lateral spreading along the tsunami-inundated seawall. Hangar 1 presently houses four C-130 fixed-winged aircraft.

(Bottom) Kodiak radio traffic recorded after the March 27, 1964 Great Alaskan Earthquake

Seismic Vulnerabilities of Rural Fuel Supplies: Noatak Case Study

The village of Noatak generates electricity from diesel fuel delivered periodically by air. This fuel is stored in a tank farm on the bank of the Noatak River. The tanks are several decades old and sit on heavily worn wooden platforms. The tank farm is constructed in a shallow retaining pit that is unlined and sited in gravels. The community has long-term plans to rebuild the facility elsewhere in town.

In 2014, a swarm of earthquakes occurred about 15 miles outside of Noatak, with five earthquakes in the magnitude 5.7-5.8 range—the first since 1981. Aftershocks have continued, on occasion, into 2016. The earthquakes alarmed residents and added to concerns about the fragility of the tank farm. The generators fed from the tank farm are the only source of distributed power in Noatak. If the generators are shut down, Noatak has no electricity distribution. There is considerable fear that if a tank were breached, fuel would enter the Noatak River, damaging the ecosystem and compromising subsistence hunting and fishing along the river corridor.

View of the diesel tank farm, retaining wall, and wooded plank support platforms. The Noatak river at lower water level is in the background. At high water level during spring melt, the river is within several feet of the tanks.

Sufficient information does not exist to carry out a meaningful assessment of earthquake hazard. The depth of the 2014 earthquakes is very poorly known. The absence of well-constrained microseismicity challenges any efforts to determine the distribution of earthquakes across the region. Without such data, it is not possible to estimate the size of the largest credible earthquakes for this region.

The inability to assess the earthquake hazard at this site makes it hard to know whether or not the risk warrants expediting the relocation of the tank farm, or whether the risk is minor compared to other factors.

Eielson Air Force Base and the Salcha Seismic Zone

Beginning in 2020, two squadrons of F-35A aircraft will be stationed at Eielson Air Force Base. Preparations for the squadrons, already underway, will cost $500 million. The two squadrons are projected to bring 3,000 new residents to the Fairbanks area and contribute $1.3 billion annually to the Fairbanks North Star Borough.

This important strategic and economic asset faces seismic hazards that are considerable but poorly understood. In 1937, a magnitude 7.3 earthquake was centered fewer than five miles from where Eielson AFB now stands (epicenter estimated at 64.6º N, 147.1º W). In 1937 there was little in the Salcha area that could be damaged, but the highway was closed by landslides and cracks while many structures in Fairbanks suffered broken windows and other minor damage. No surface faulting was found despite extensive ground failure, and the event has not been associated with any mapped Quaternary fault.

Understanding of the hazards posed by the Salcha Seismic Zone remains limited in part to low seismic station density in the eastern Interior. This should be cause for concern so near to a facility with 54 F-35A's costing $100 million each, and which receives 1 million gallons of fuel per day by rail and is accessible by road only via a single highway that is prone to blockage from landslides and ground failure.

While improved monitoring would help to quantify and characterize the risk, earthquake early warning would help to protect this asset in the event of a large earthquake. Warnings from a few seconds to a minute or more could allow for life- and equipment-saving reactions at this very busy facility.

Infrastructure improvements at Eielson AFB include a major rail upgrade to accommodate trains of up to 50 fuel cars delivering one million gallons of fuel per day.

Enhanced Earthquake Monitoring in Support of Performance-Based Engineering

Enhanced strong motion instrumentation and resultant recordings could allow seismic design procedures to be based on measurable parameters. Spectral values would replace peak ground acceleration estimates as the key indicator of the severity of the earthquake hazard. Without monitoring systems, engineers can only speculate about the intensity of shaking based on the resulting damage from past earthquakes.

In-structure and free-field instrumentation yields records that permit a clearer understanding of structural and ground response during strong shaking, much as the "black-box" in an aircraft provides key information about conditions just prior to a crash. Monitoring provides insights into the characteristics and strength of the shaking that can cause damage. Seismic monitoring records show that structures experience earthquakes in a highly dynamic and time-dependent manner, with the resulting structural performance due to complex combinations of the loading history, material strength, and structural design.

Earthquake engineering design techniques can improve after each damaging earthquake and result in increasingly more advanced seismic design standards. When an earthquake occurs and structures experience more damage than their owners and engineers judge acceptable, the engineers adjust design standards to avoid a repeat occurrence. Unfortunately, these advances in design are limited by the quality and quantity of the seismic monitoring records collected. When there are no records, there is a tendency to apply the new techniques to all buildings in all seismic environments. When there are records, the changes often apply only to construction in areas that are expected to experience a similar level of shaking.

For example, new procedures were developed for the design and construction of concrete masonry unit (CMU) buildings based on the damage that occurred during the 1964 Great Alaska earthquake. Unfortunately, no records were available at the sites where significant damage CMU buildings occurred, so the subsequent research and resulting recommendations had to be based entirely on estimates of ground shaking. The resulting recommendations applied to the design of CMU buildings nationwide. These recommendations could have been more reliable if strong motion records were available to calibrate the observed damage.

Damage to the concrete Hillside Apartment Building from the 1964 earthquake. Its wood-frame neighbor appears undamaged.

Post-Earthquake Damage Assessments – Structures[1]

Increasing the number of structures in Alaska equipped with seismographs (Figure 1) will improvement the ability of engineers to more rapidly and accurately assess the potential damage immediately after a strong earthquake, thereby optimizing the need, scope, and cost for more intrusive structural inspections, and/or possibly limiting the time before which the facility can be returned to use.

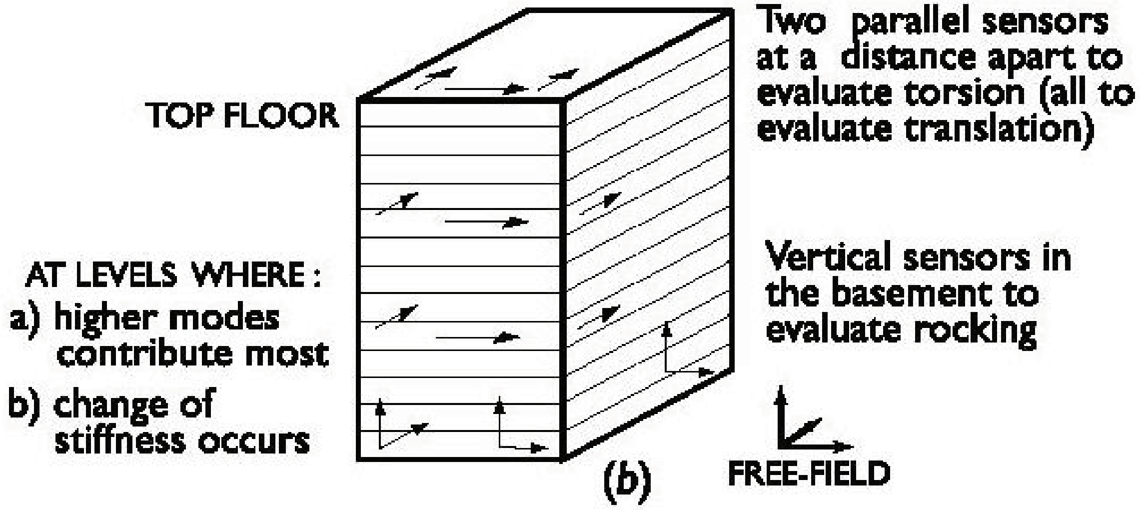


Figure 1: Idealized distribution of seismographs in a structure.

Following a significant earthquake, the occupancy or operation of a specific facility could be interrupted until such time as the structure is screened to assess apparent or potential damage. Subject to the size and proximity of the earthquake, buildings may remain unoccupied for some time, further delaying important businesses and facilities from resuming operations; especially if there are signs of damage that requires more detailed and intrusive investigations. However, since the late 1990s, numerous engineering methods have been devised to utilize actual accelerometer records, if available, as part of post-earthquake inspections to better assess and qualify the potential level of damage sustained in a structure (including buildings, bridges, docks, dams, etc.), explicitly to support and enhance confidence in decisions regarding either the safety and functionality of a structure for resumed use, or if that structure should receive more in-depth investigation.

For example, numerous methods utilize an acceleration response spectrum (ARS) developed from an actual wave-form record to estimate the lateral earthquake load on the structure, and then compare that with the load assumed during design. The complexity and accuracy of these methods range from using a simplified ARS predicted from a *ShakeMap* or from a nearby free-field instrument (limited analysis time but high uncertainty), to using an ARS generated from motions recorded on multiple floors of the subject building (longer analysis time with moderate uncertainty). Another category of methods utilize computer analysis of the actual ARS to identify shifts in the period of the structure's fundamental modes of vibration, or changes in the displacement time-history (e.g. drift between floors and at the roof), either of which could be indicative of non-linear or plastic deformation in the structural frame.

While these methods are not simple or absolute, they can often be completed within days or weeks of the earthquake by engineers well experienced with structural seismic analysis; and improve the ability of engineers to more rapidly qualify the likelihood that the earthquake over-loaded or otherwise damaged the structure. These attributes could in turn be used to optimize the scope and cost of more invasive and in-depth inspections, and thereby possibly reduce the time before the facility is put back into operation.

[1] *Based on Alaska Seismic Hazards Safety Commission Policy Recommendation 2013-1, Value of Seismic Instrumentation for Critical Structures*

Possible Earthquake Early Warning Benefits for the Nikiski Fertilizer Plant

The Kenai Nitrogen Operations plant in Nikiski was for decades a major producer of urea and ammonia, fertilizers that were sold to international markets in Korea, Mexico and the Asia-Pacific region, in addition to local and domestic markets. The facility was shuttered in 2007 due to insufficient natural gas supply from the Cook Inlet, but the legislature is currently considering a tax credit plan aimed at reopening the plant. The plant is at risk from earthquakes, as the state was reminded on January 24, 2016 when a distant M7.1 caused road damage and gas explosions in the immediate vicinity of the plant.

When produced for agriculture, ammonia is compressed into a liquid and must be stored at high pressure in specially designed tanks. If the air temperature around the tank increases, as it would in the event of a fire, the temperature of the liquid inside the tank also increases causing the liquid to expand and increase the internal tank pressure. The resulting explosion can be catastrophic, as was witnessed in a number of fertilizer plant explosions in Texas and elsewhere in the past decade.

Earthquake early warning can play a critical role in preventing disaster during a large earthquake at the Nikiski fertilizer plant, should it reopen. With advanced warning of imminent shaking, equipment can be automatically shut down and chemical processes stopped. These are crucial steps in preventing the outbreak of fires that could trigger catastrophic explosions of the plant's ammonia tanks.

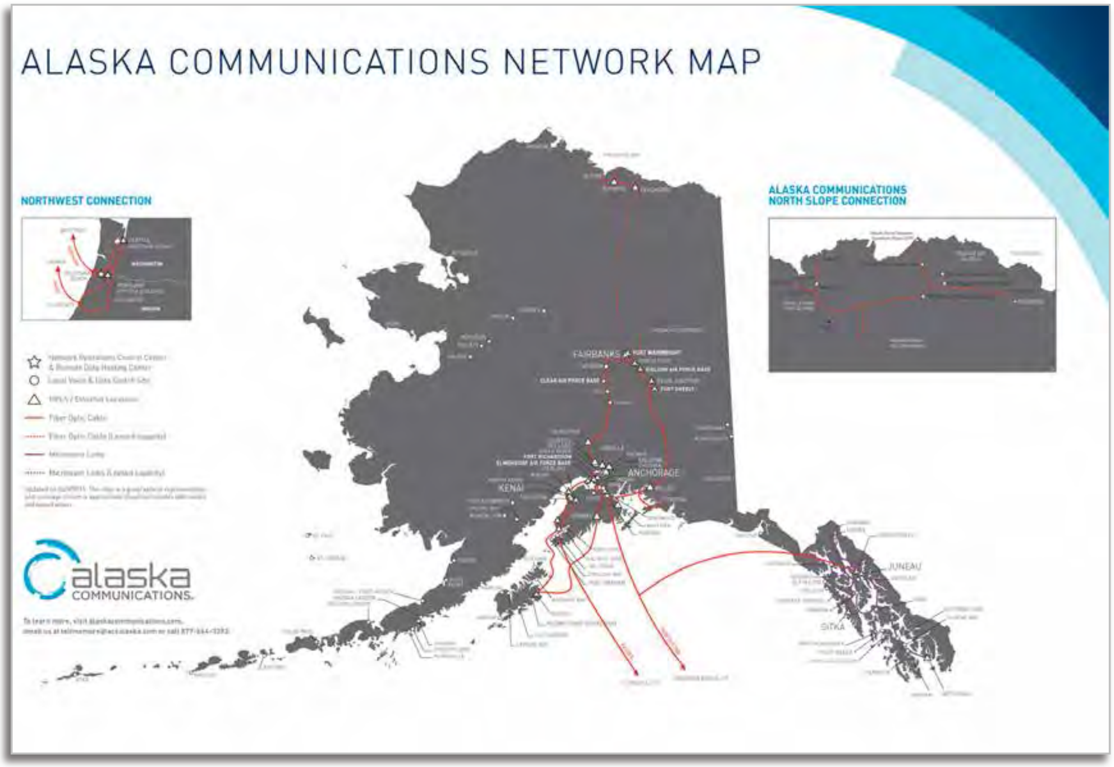
The fertilizer plant in Nikiski, on the eastern shore of the Cook Inlet. The Agrium Corporation which owns the plant has expressed interest in reopening the plant, following its closure in 2007. Photo from www.alaskajournal.com.

Benefits of Improved Earthquake Monitoring for Alaska Communications

As a leading provider of broadband Internet and managed IT services across the state, Alaska Communications would greatly benefit from improvements to the state's existing earthquake monitoring network. An enhanced statewide system would provide better information with which to:

- Reduce risk when planning locations in which to construct new network facilities,
- Plan the prepositioning of critical repair materials in higher risk areas,
- Prioritize the dispatching of repair teams after an earthquake,
- Potentially lower the cost of earthquake insurance riders by providing underwriters with more granular risk information upon which to base their risk assessments.

The 2014 Palma Bay earthquake, which disrupted communications throughout Southeast Alaska by generating a slide that severed an undersea fiberoptic cable, demonstrated the vulnerability of the state's communications networks to even moderate earthquakes. With expansion of high-speed Internet via fiberoptic cable into more remote parts of the state, a better understanding of faulting and earthquake hazards in those areas has become more important. Adoption of USArray stations into the Alaska seismic network could be a significant step toward this achieving this.



Earthquake Insurance for Homes in Alaska

Standard homeowner's insurance does not cover damage and destruction that happens as a result of an earthquake. The 1989 Loma Prieta earthquake in California caused over 6 billion dollars in damage, but insured property damage accounted for only 16% of this loss. In Alaska, about 12% (as of 2014) of homeowners have purchased earthquake insurance.

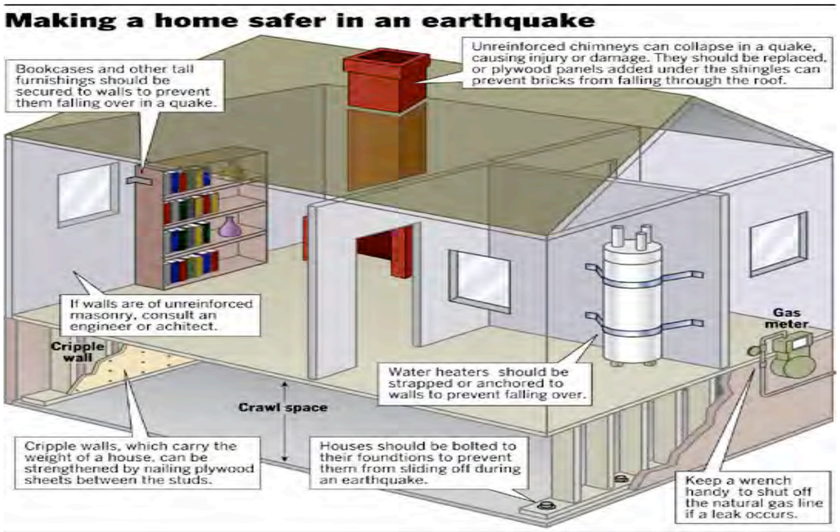
Landslide and slumping effects in the Turnagain Heights area, Anchorage, Alaska, caused by the March 28, 1964, earthquake.

The most common type of earthquake insurance is added as an endorsement on a standard homeowner's insurance policy. Typically, there is a deductible of 10 percent of the value of the home. This means that for a home currently insured at $300,000, a homeowner would have to pay $30,000 in damages before the insurance company would pay anything. Separate deductibles may apply to the contents of the house and the structure. Another important coverage is temporary living expense, which pays for motel and meals if the home is uninhabitable. There is usually no deductible on this coverage.

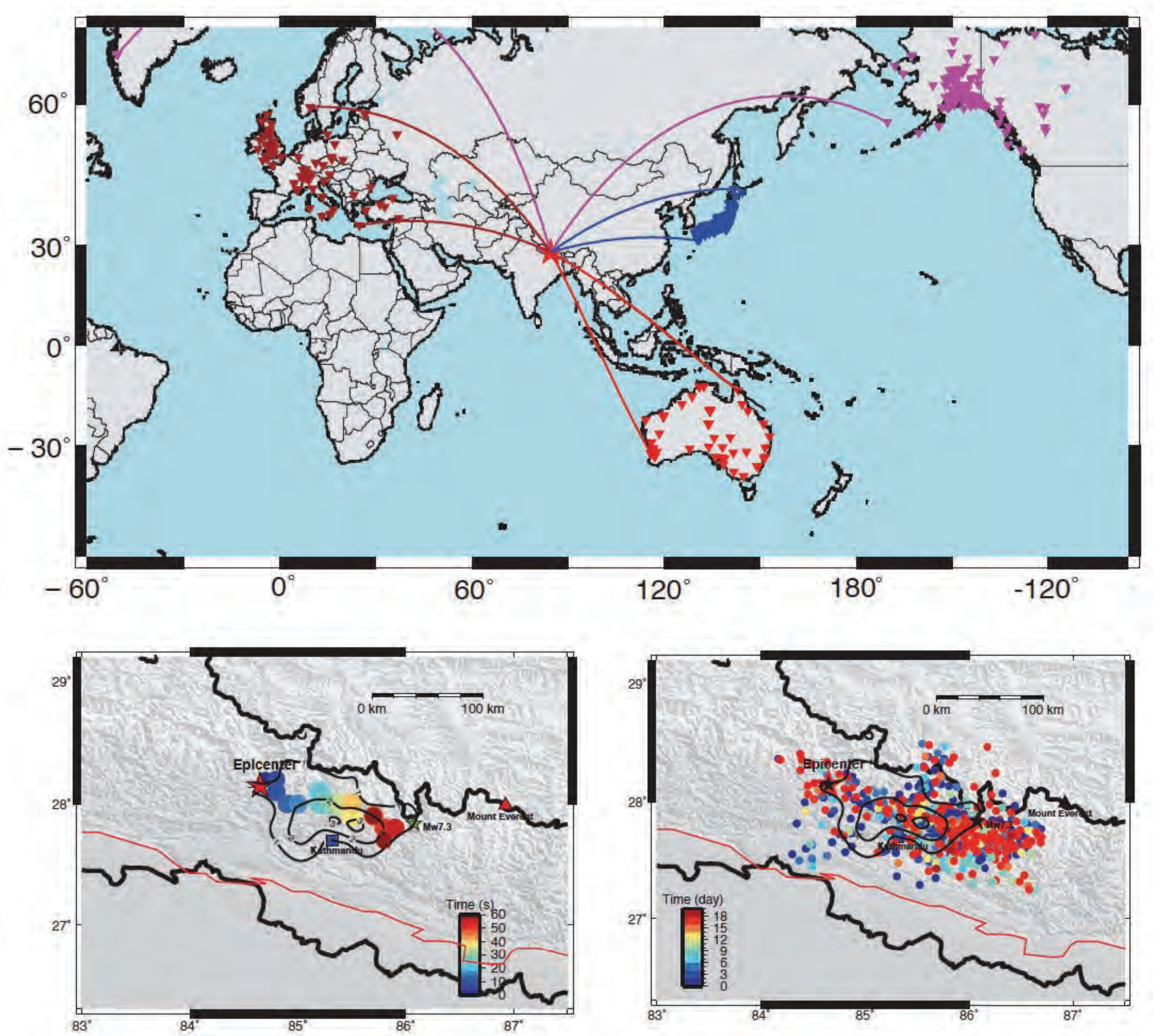
The yearly cost of residential earthquake insurance is normally about $3.00 per $1,000 of coverage on a conventional frame home. However, the rate may rise to $13 per $1,000 of coverage on structures with brick or masonry veneer on the outside. Clearly, the insurance industry considers homes with brick or masonry to be a greater financial risk in an earthquake.

The rates for earthquake insurance depend on the hazard level. Across much of Alaska, including southcentral and the interior, earthquake hazard is not as well constrained as elsewhere in the country. This is due to both limited knowledge of the faults and earthquake histories as well as limited information about the distribution of soil types. These uncertainties undermine the ability of insurance providers to match rates with the hazard level. It is possible that insurers are taking on far more risk than they realize in some locations. Similarly, it is likely that the rates homeowners are paying in other areas are higher than would be warranted if the earthquake hazard were better understood.

Diagram on earthquake safety at home. From the Ventura County Star



Imaging Global Seismic Events with the Alaska Array



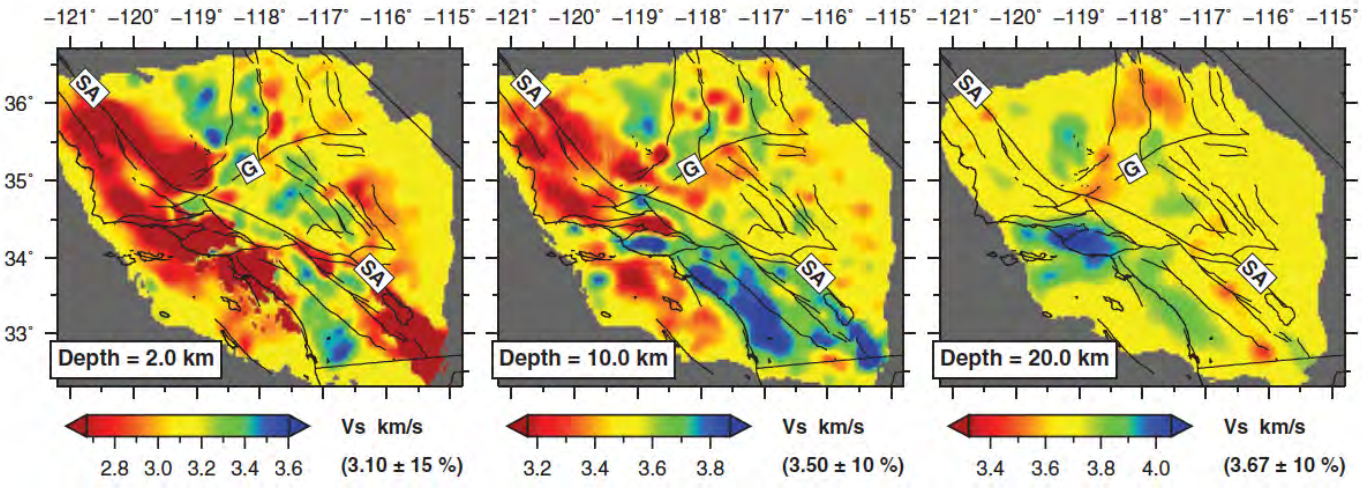
Using USArray seismic stations in Alaska as a large array (like a radar) with three additional large arrays located in different parts of the world to image the rupture process and aftershock distribution of the Mw 7.8 Gorkha earthquake occurred in May 2015. Panel (a) shows locations of the seismic arrays used including the Alaska array in magenta. Panel (b) shows the propagation of rupture during the Mw 7.8 earthquake. Colored closed circles are the location of rupture during this event. Time is color-coded. Contour lines show slip distribution of the mainshock as determined by finite fault model by USGS. Red line indicates the Main Himalayan Thrust. Panel (c) shows aftershocks activities immediately following the mainshock. Circles represent locations of aftershocks determined solely by the arrays. They are color-coded in time.

The full Alaska USArray Transportable Array, once completed, will provide what is arguably the largest uniform seismic array in the world.

Waveform Inversion for Three-Dimensional Seismic Structure of the Alaskan Crust

Advances in high-performance computing and seismic theory over the past 15 years have ushered in a new era of seismic imaging. The techniques, known as full waveform inversion or adjoint tomography, offer two major advances over previous approaches to seismic imaging: (1) use of full-length, three-component (east, north, up) seismic waveforms, (2) use of 3D seismic wavefield simulations with 3D earth structure models. The first application of this technique at a regional crustal scale was in southern California (Tape et. al, 2009, Science). The reason that southern California was chosen was its exceptional coverage of seismic stations and its complex crustal structure. The new seismic images provided an unprecedented view of the crustal structure, as well as unprecedented capabilities for predicting ground motions for earthquakes in southern California.

High-quality seismic imaging in Alaska is currently only possible in the relatively dense regions of the seismic network (southcentral Alaska). And even within the dense regions, the resolution of seismic images is still be limited to the inter-station spacing. The computational cost of full waveform inversion scales with the number of earthquakes, not the number of stations. An increase in station coverage in Alaska would afford higher resolution and more accurate seismic images of the Alaska crust with no additional computational cost.



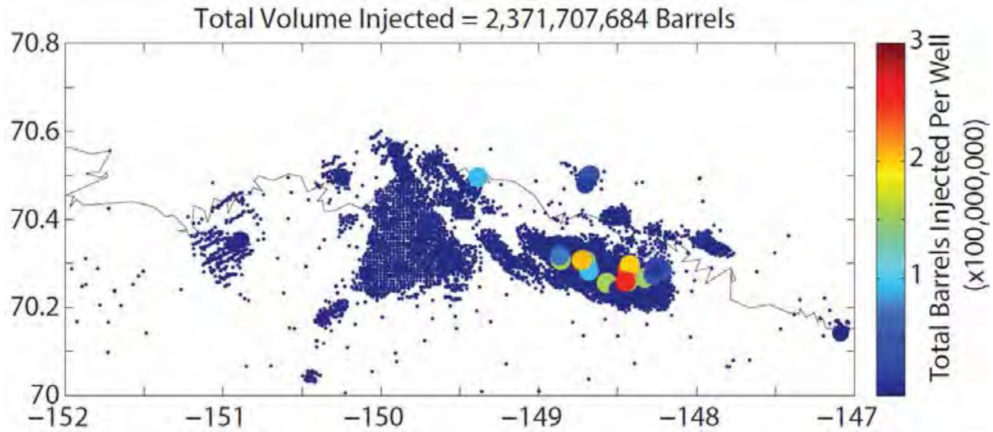
Horizontal cross sections of crustal model of southern California obtained from adjoint tomography (or "full waveform inversion"). The details in the model are afforded by the large number of seismic stations in California in combination with a highly accurate modeling technique for the seismic wavefield. [Figure 4 of Tape et al., 2009, Science]

Induced Seismicity Potential on the North Slope

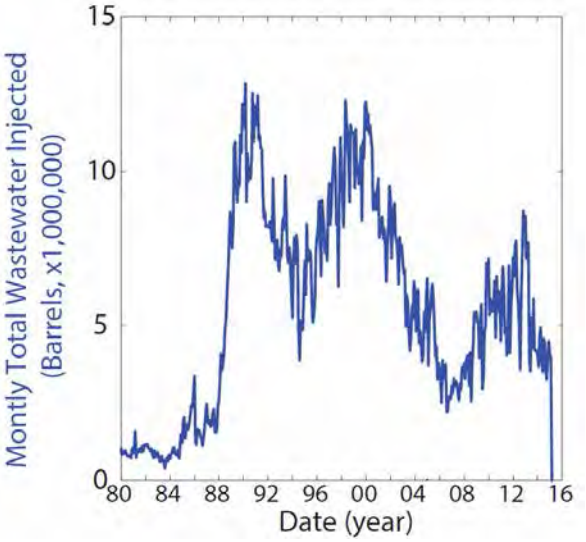
Extensive studies of injection-induced seismicity show that earthquakes large enough to be felt can occur due to underground injection operations with as little as tens to hundreds of thousands of barrels injected. Given the history of wastewater reinjection (2.4 billion barrels liquid) and enhanced recovery (27.0 billion barrels liquid and 79 billion MCF gas) in the North Slope, it is possible that low-magnitude induced earthquakes are occurring. However, if induced earthquakes are occurring on the North Slope, they are at levels below the Alaska seismic network's detection threshold.

While there is significantly less natural seismicity on the North Slope than in southern Alaska, this region does have a history of tectonic earthquakes. Methods for discriminating between natural and induced earthquakes are under active development. Although the seismic hazard associated with industry technologies appears to be low, induced seismicity nevertheless has significant potential to negatively impact the public's perception of industry technologies. An effort to document the natural background rate of earthquakes on the North Slope (currently unknown) would be beneficial to Alaska and to industry in Alaska.

Wastewater injection history on the North Slope. Map of injection wells (colored dots), scaled and colored by total injection volume over the life of the well.



Instrumentation installed under the NSF-sponsored EarthScope USArray project will provide data that make it possible to track earthquake activity in the North Slope region below magnitude ~2. Unfortunately, this is intended to be a temporary deployment, with all seismometers being removed from Alaska following the experiment. Given the national interest, this data will surely be used to assess the potential for induced earthquakes in Northern Alaska. Adoption of EarthScope stations into the Alaska seismic network at the end of the deployment would improve our ability to assess induced seismicity on the North Slope.

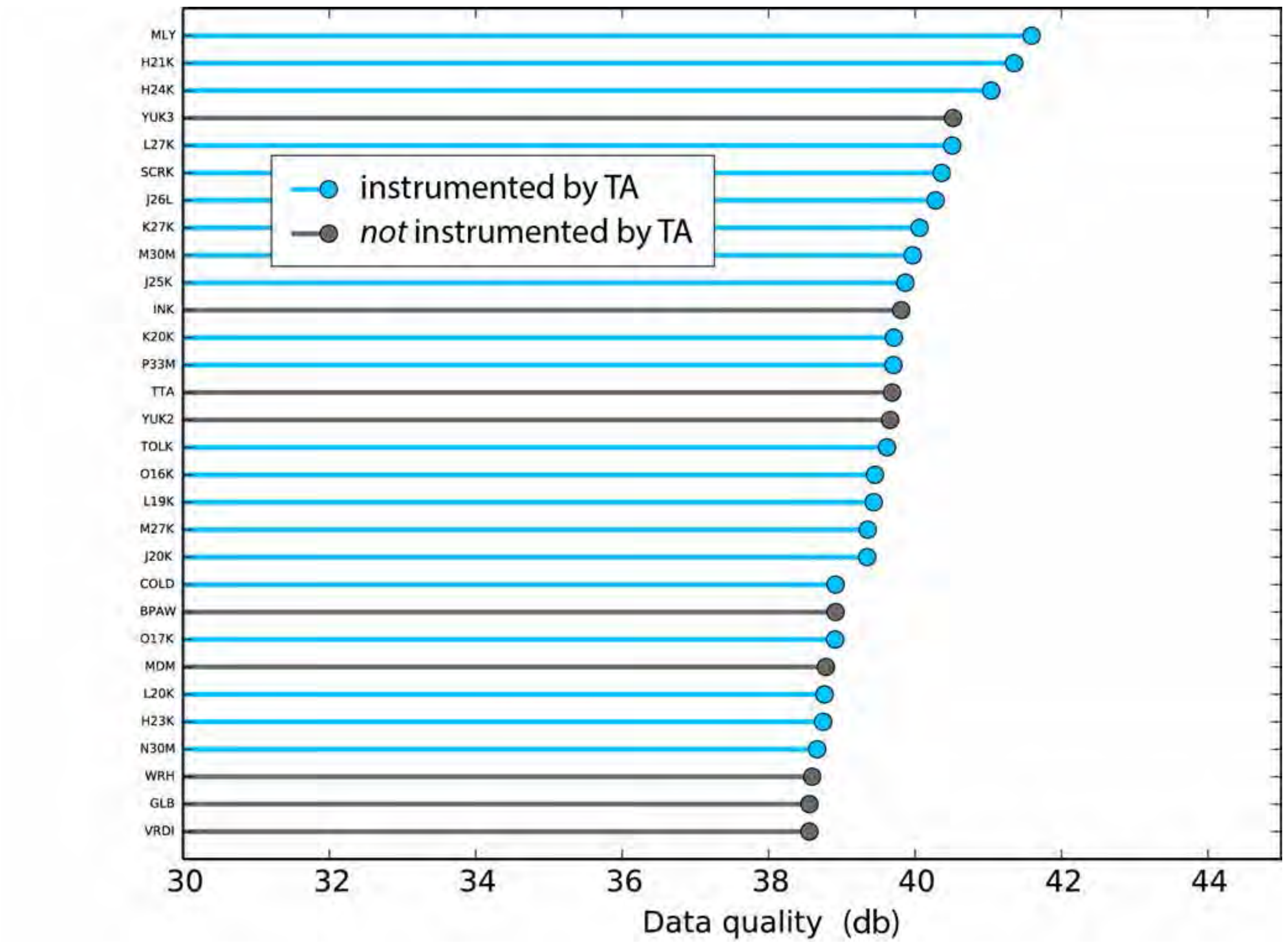


Monthly injection history for Class II disposal wells in the North Slope region.

Superior Data Quality of the EarthScope Transportable Array Project

The EarthScope Transportable Array project utilizes a portable drill rig to install boreholes that house the seismometers. The sensors are placed approximately 8ft below the surface in any type of material, such as solid rock, clays, soils, sands, etc. The result is a marked increase in data quality when compared with existing stations, which are typically installed in hand-dug vaults 1-3ft below the ground.

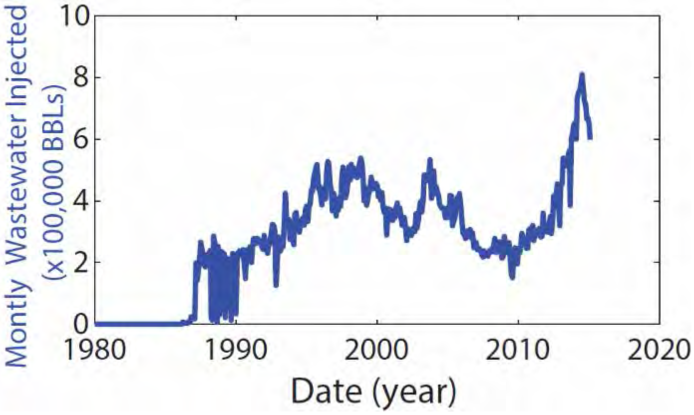
In addition, the seismometers and data acquisition equipment are at the cutting edge of technology. This, combined with a high quality installation method, produces some of the highest quality seismic data in the state (and the nation as well).



The 30 best-performing seismic stations in Alaska. Data quality is defined here as the difference between the average background noise and the new high noise model (Peterson, 1993) on the period band of 0.1 to 100 seconds on the vertical component. Data shown here are for the month of May 2016. Stations installed or upgraded through the EarthScope Transportable Array project are colored blue. Note that the majority of seismic stations in Alaska are not *part of the TA and fall off this chart at lower quality levels.*

Induced Seismicity Potential in the Cook Inlet

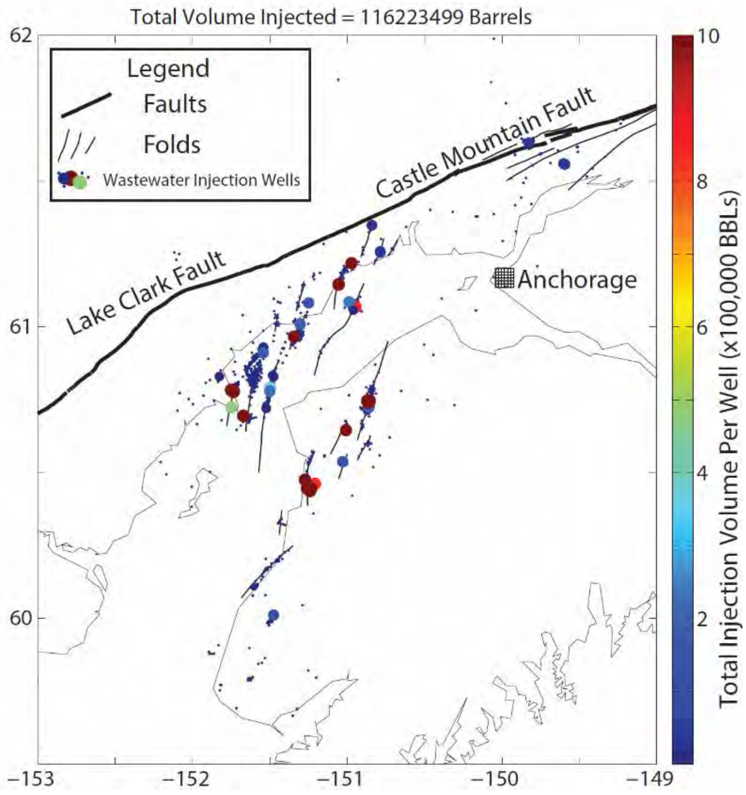
The Cook Inlet basin is seismically and tectonically very active due to its proximity to the Alaska subduction zone. This presents a fundamentally different challenge from the induced seismicity problem as it exists in the Lower 48 because identifying and studying induced seismicity in the Cook Inlet requires distinguishing between natural and induced earthquakes.



Wastewater Injection History in the Cook Inlet Basin. Monthly injection history for Class II disposal wells in the Cook Inlet region.

Quantifying the nature of injection-induced seismicity in the Cook Inlet region is important for a number of reasons. First, there are few case studies of injection-induced seismicity in tectonically active regions, so these studies will advance scientific knowledge of the nature of induced seismicity. Second, proposed regulatory methods are being developed that likely would not be favorable to Alaska because they will originate from seismically quiet regions of the country. Robust methods to separate natural from induced seismicity would protect Alaska's energy industry by decreasing the likelihood that natural seismicity causes regulators to erroneously order the cessation of injection operations.

Since 1986, 116 million barrels of wastewater have been disposed of in the Cook Inlet Basin, so it is possible that low-magnitude induced earthquakes are already occurring. Wastewater injection rates have increased 5-fold from 2010 to 2015, and the possibility of larger induced events will grow as injection rates increase. Researchers are currently exploring methods for identifying potential cases of induced seismicity in the Cook Inlet Basin. Regional seismic monitoring networks in southcentral Alaska are robust, but more local seismic stations are required to determine the precise location of earthquakes relative to injection activities in the Cook Inlet basin.

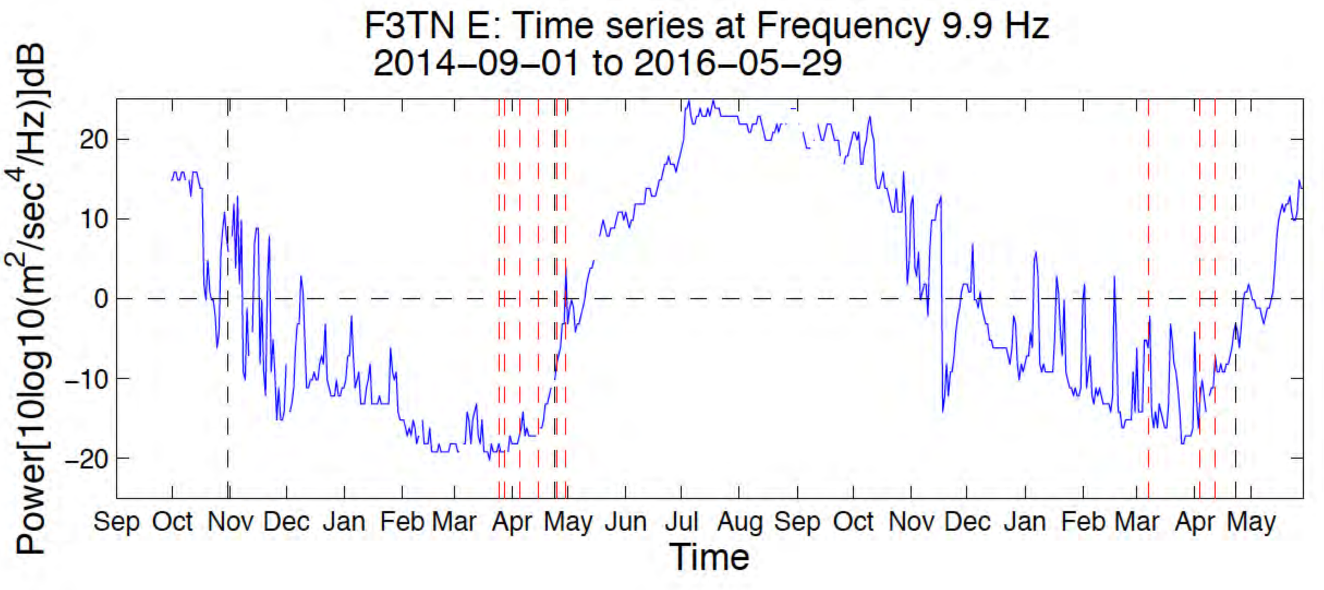


Map of injection wells (colored dots), scaled and colored by total injection volume over the life of the well. Major structures, faults and folds, are shown in accordance with the legend.

Seismic Monitoring of Flow, Flooding, Freeze-Up and Breakup on Alaskan Rivers

Seismic stations located along rivers can be useful in providing advance warning or short-term predictions for breakup flooding disasters such as those in Eagle in 2009 and Galena in 2013. Seismic stations record a wide range of ground motions besides earthquakes. In the past 5 years, several studies have shown that seismic stations near rivers can "hear" the flow of water and the transport of sediments.

With 8 seismic stations along the Tanana River, we have demonstrated a clear seismic signal that tracks the flow within the river (specifically, the amplitude of seismic noise at 10 Hz is highly correlated with river height recorded from regional river gages). The seismic stations provide a stable, constant stream of data that can be used for monitoring rivers, even during winter and breakup, when river gages may not be working or accurate. Our preliminary efforts, which combine seismic data with time-lapse photos and airborne photogrammetric measurements of river ice deformation, show real promise for improving river breakup monitoring.



Time dependence of the amplitude of seismic noise at 10 Hz for a station close to the Tanana river. This large seasonal signal is interpreted to result from turbulent flow within the river; it is only present on stations within 100 m of the river. Vertical dashed lines denote time periods of freeze-up or breakup (black) or of airborne photogrammetric measurements of river ice deformation prior to break-up. The seismic data show an increase in river flow several weeks prior to breakup.

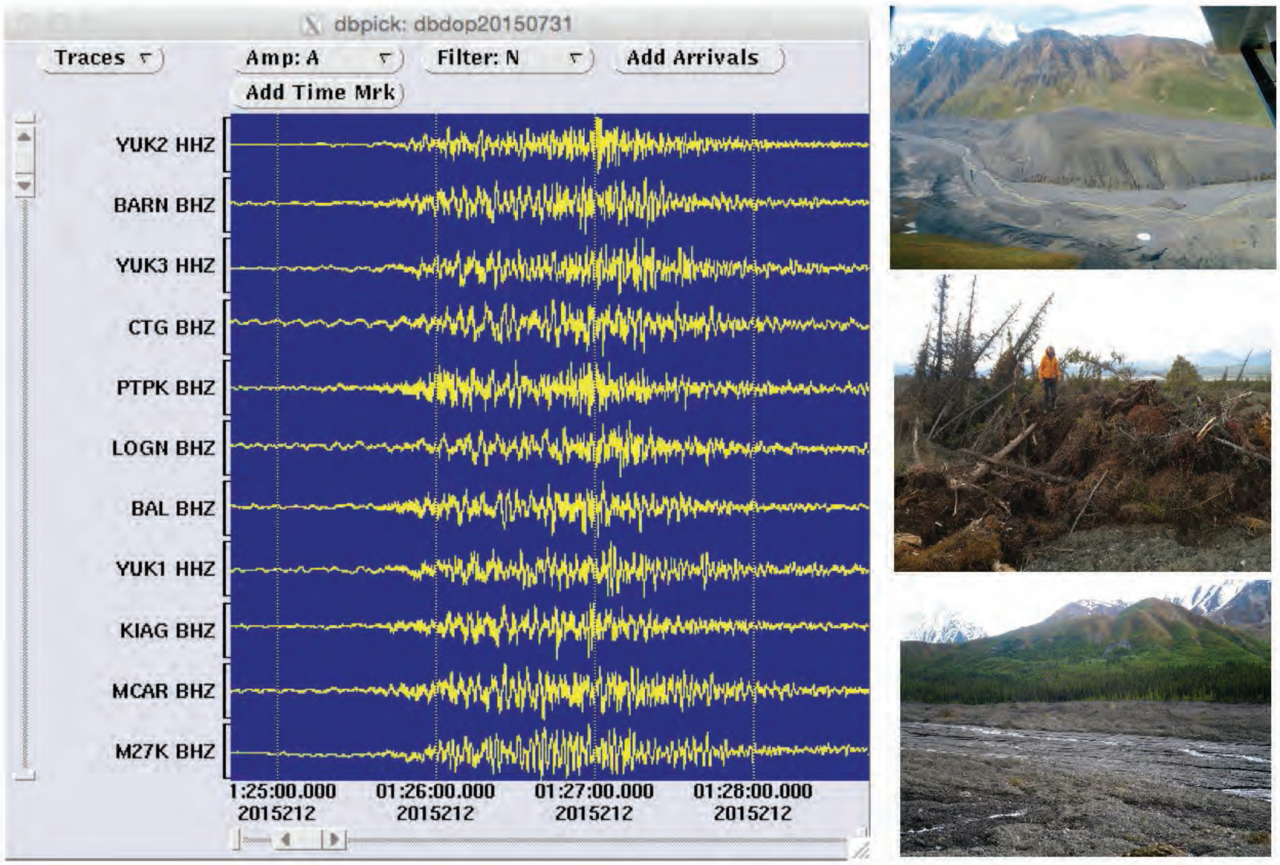
Forensic Seismology in Alaska

Although seismology is mainly concerned with earthquakes, forensic seismology can be used to detect and study other phenomena including explosions, landslides, and movements of icebergs and glaciers. Seismic sensors can also detect sonic waves from explosions occurring in the ground (such as mining blasts or nuclear tests) or atmosphere (such as exploding meteorites or aircraft).

Staff at the Alaska Earthquake Center are often asked to look for signals from landsides after they have been detected visually by the airplane pilots or hikers. For example, rangers at Wrangell-St. Elias National Park could only narrow down the possible time occurrence for a large landslide near White River as between June 22 and August 8, 2015. Seismologists at the Earthquake Center were able to identify a landslide signature in the seismic recordings that showed the slide occurred at 5:25pm on July 30.

On a more somber occasion, the Earthquake Center received a request from Elmendorf Air Force Base in November 2010 asking for help identifying the crash site of an F-22 that was presumed to be lost. The Air Force needed to mount a winter rescue mission in rugged terrain, so anything that could help narrow the search area was urgently needed.

While the Earthquake Center has helped in these and other cases, often telltale signals are impossible to find due to the lack of seismic instrumentation in the area of interest. Increasing seismic coverage in outlying areas would broaden the scope and usefulness of forensic seismology in Alaska.



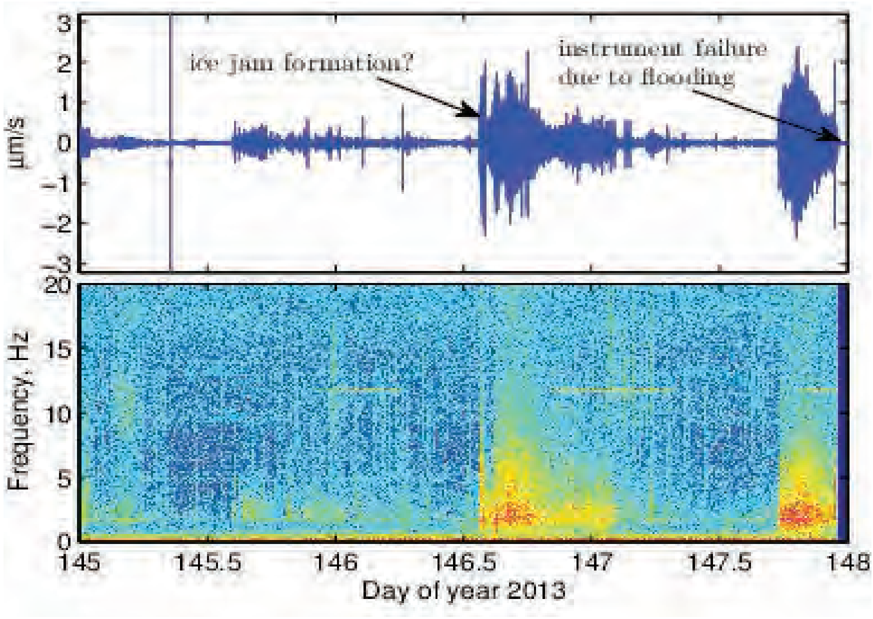
Seismic waveforms from the 2015 landslide in Wrangell-St. Elias Park.

Assessing Ice Jam Formation and Disintegration

During spring breakup, river ice can create a temporary dam when it becomes jammed along a section of river. Rapid and extensive flooding can result either when (1) water pools upstream of the jam or (2) the jam fails and water is rapidly released downstream. Several ice jams on the Yukon River have caused damaging floods in Alaska in recent years. For example, in 2009 and 2013, ice jams formed on the Yukon River near Eagle and Galena, causing flooding that extended up to 10 miles upstream and inundated towns.

Ice jam that formed in Eagle, Alaska, in May 2009.

Ice jams are difficult to study in situ because they are unpredictable and rapidly evolving. Knowledge about stress conditions that lead to ice jam formation and disintegration is therefore largely based on laboratory experiments and numerical models. Seismometers located along rivers such as the Yukon can provide valuable information on the timing of ice jam events and the transmission of stresses through the ice pack. They could also potentially be used to monitor the evolving stress state of an ice jam in real time, providing emergency managers with information to help assess the threat of flooding as an ice jam is forming.

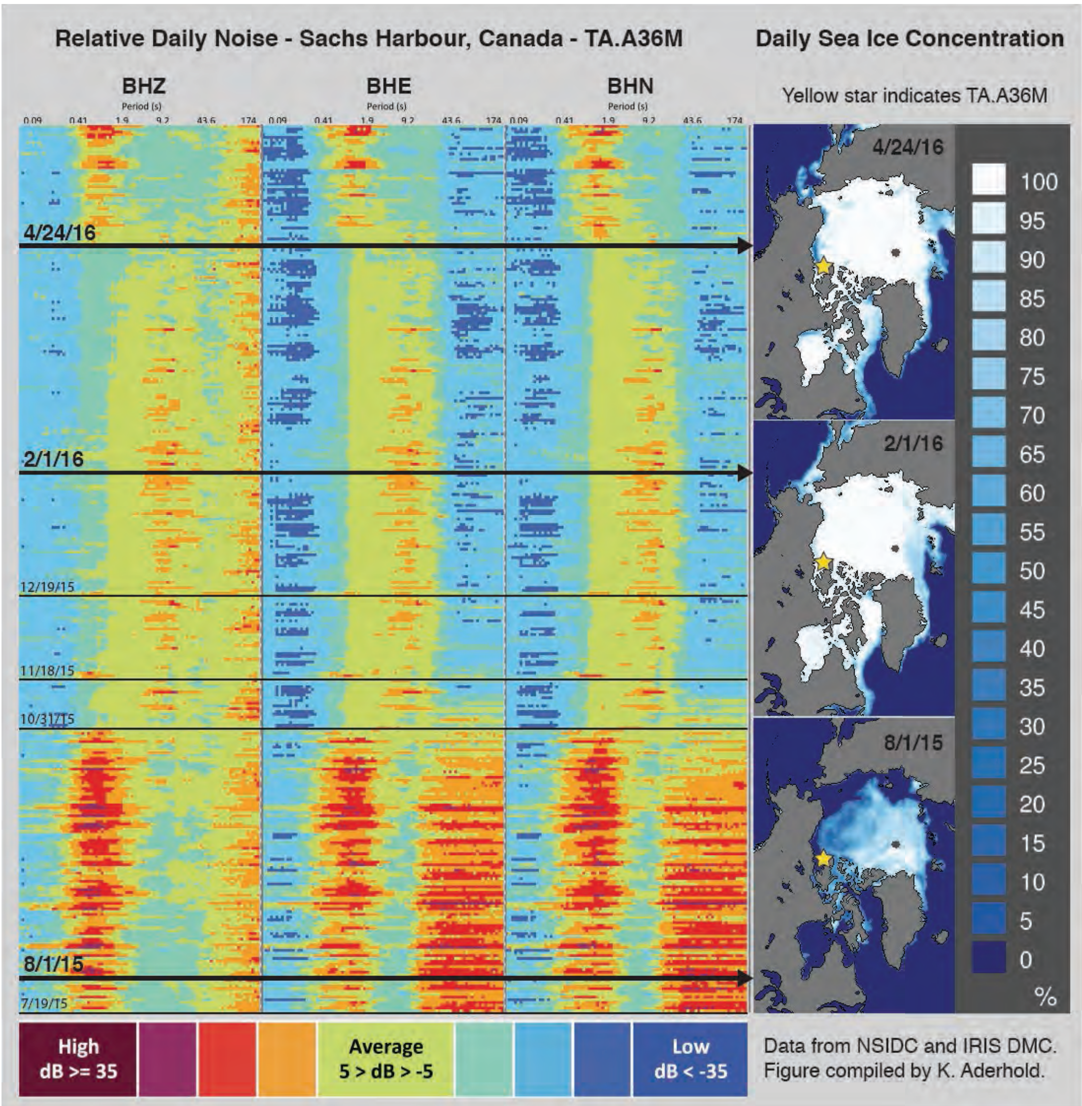


Seismic observations from the ice jam that occurred near Galena, Alaska, in May 2013.

Seasonal Cycles of Arctic Sea Ice Recorded on EarthScope USArray Seismometers

High levels of noise recorded on seismometers correlates with the high frequency ocean waves in open water, while periods of low noise correlates with intact, continuous sea ice. Abrupt changes in the characteristics in seismic noise can pinpoint the timing of both minor and major sea ice break-up. These effects can be quantified to develop models to use seismic stations on land to monitor the mechanical strength of sea ice (Tsai et al., GRL, 2011). The figure below shows the transition from minimum sea ice extent in the late fall of 2015 (high noise in red) to the maximum extent in the early spring of 2016 (low noise in green/blue) as well as the early breakup during the record low extent of May 2016 (Imagery from the NASA MODIS instrument, courtesy NASA NSIDC DAAC.).

Alaska's seismic network does not have adequate station coverage in northern Alaska for this kind of monitoring. Transportable Array expansion in 2016 will change that. Maintaining that new capability will require adopting TA stations into the Alaska network at the end of the TA deployment.



Relative Daily Noise - Sachs Harbour, Canada - TA.A36M

Daily Sea Ice Concentration

Yellow star indicates TA.A36M

Data from NSIDC and IRIS DMC. Figure compiled by K. Aderhold.

Reference

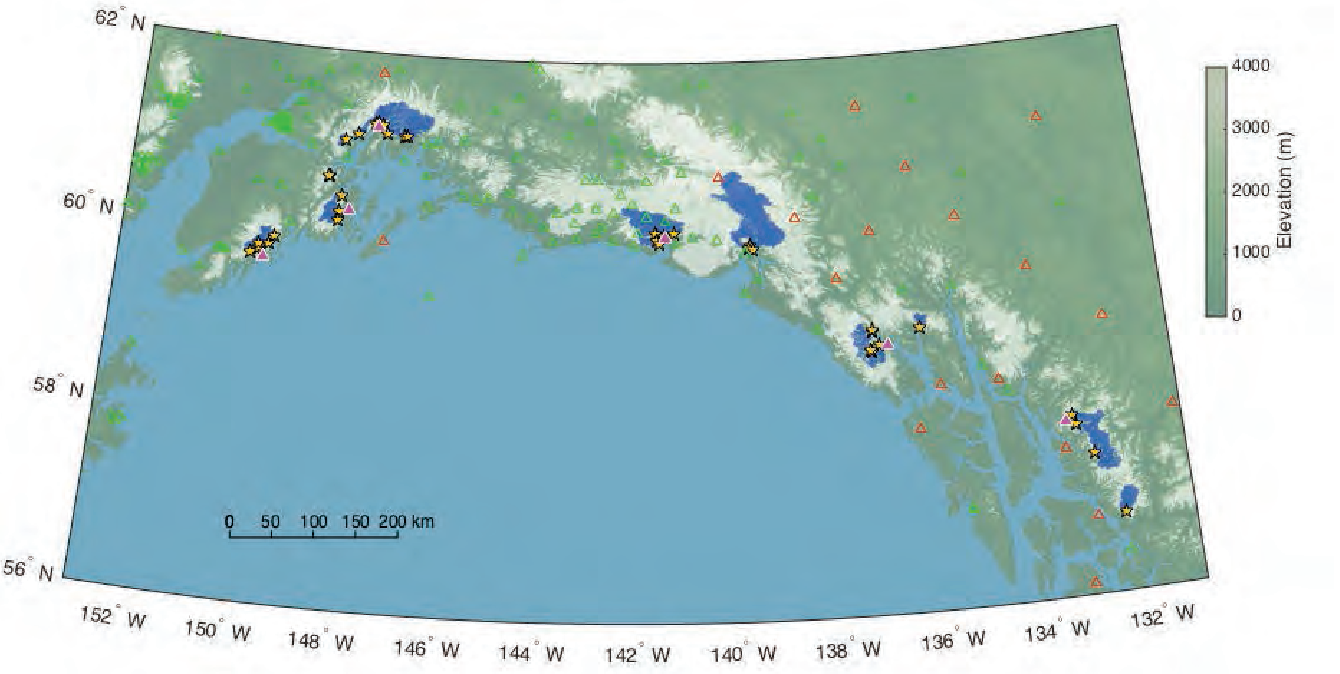
Tsai, V. C., and D. E. McNamara (2011). "Quantifying the Influence of Sea Ice on Ocean Microseism using Observations from the Bering Sea, Alaska", Geophys. Res. Lett., 38, L22502, doi:10.1029/2011GL049791.

Enabling Prediction of Glacier Change in Alaska With Seismology

Alaska's mountains are home to some of the greatest volumes of ice on earth, behind only the Canadian Arctic and the Greenland and Antarctic ice sheets. These glaciers are becoming smaller. However, observations across Alaska show significant variability in the speed with which Alaskan glaciers are losing ice. By far, the greatest variability in ice loss is found in those glaciers that flow directly into the ocean and produce icebergs. The processes responsible for this variability, both over time and across the state, are not entirely clear.

Alaska's existing and expanding seismic network offers a superb avenue through which to understand glacier change. Glaciers produce seismic signals detectable by the Alaska Earthquake Center network in myriad ways. Iceberg calving signals can be tracked across 100+ mile distances. Glacier fracturing and water flow also create seismic signals. The distribution of the Earthquake Center's seismic stations enable the systematic tracking of iceberg calving from the approximately 40 iceberg calving glaciers in Southern and Southeast Alaska (see figure). By comparing long term, seismically observed patterns of iceberg calving at these 40 glaciers, glaciologists and seismologists are better understanding the causes of calving increases and decreases. These studies enable better prediction of glacier change in Alaska.

The study of these changes benefits Alaskans in at least three ways. 1) Studies enable better predictions of how the Alaskan landscape will change in the future. 2) Research on this topic, generally funded by national level grants, has a positive economic impact on the home cities of the researchers themselves, through increased salaries, and brings federal dollars into the smaller towns that serve as the bases for field operations. 3) Education of students in the University of Alaska glaciology and seismology groups trains Alaskans with the technical skills that are valued across engineering, scientific and technical careers.



Glaciers and nearby seismic stations across southcentral and southeast Alaska. Glaciers that end on land are shown in white, while glaciers that end in the ocean are blue (with their iceberg calving faces marked by stars). Green triangles show existing seismic stations, while planned and proposed seismic stations are red and pink. The distribution of seismic stations improves the ability of seismologists and glaciologists to understand the factors contributing to ice loss across the state.

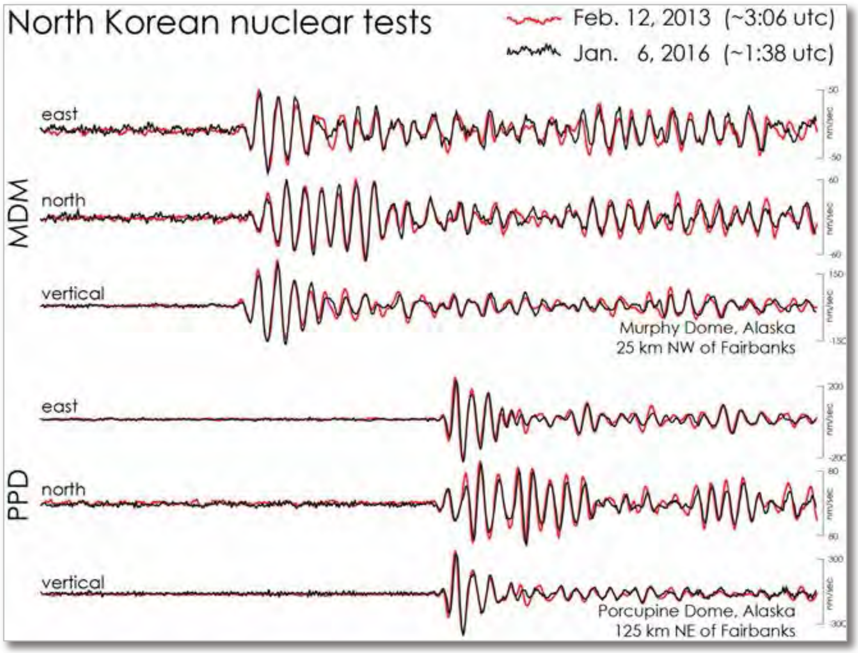
Assessing Nuclear Tests in Asia

USArray stations in Alaska bolster the nation's nuclear test monitoring capabilities. Records of seismic events in Asia, recorded in Alaska, have long been noted for their high fidelity. For decades, the Air Force has operated four short-period seismic arrays in Alaska for precisely this reason. These small-aperture arrays are well tuned for high frequency nuclear explosion discrimination techniques.

Beginning in 2017, Alaska will be home to arguably the largest-aperture seismic array on the planet. The large-aperture array comprises ~220 broadband seismic stations operated by the EarthScope USArray program plus ~130 broadband permanent stations operated by the Alaska Earthquake Center. The combined array has a station spacing at its core of about 20km growing to about 100 km at the edges.

Array aperture with respect to key nuclear test facilities.

The Alaska array will record full seismic wave fields from much of Asia without interference from the core shadow zone. The tiered-array will facilitate array-based processing of the full wave field from body waves (essential for precision locations) to surface waves (critical for assessing yields). Though these data are further away than clandestine stations in Asia, the array provides the ability to vastly improve signal-to-noise characteristics. Unlike other arrays, the Alaska array spans roughly 20 degrees of azimuth with respect to the areas of global interest, effectively giving it the power of an array of arrays.



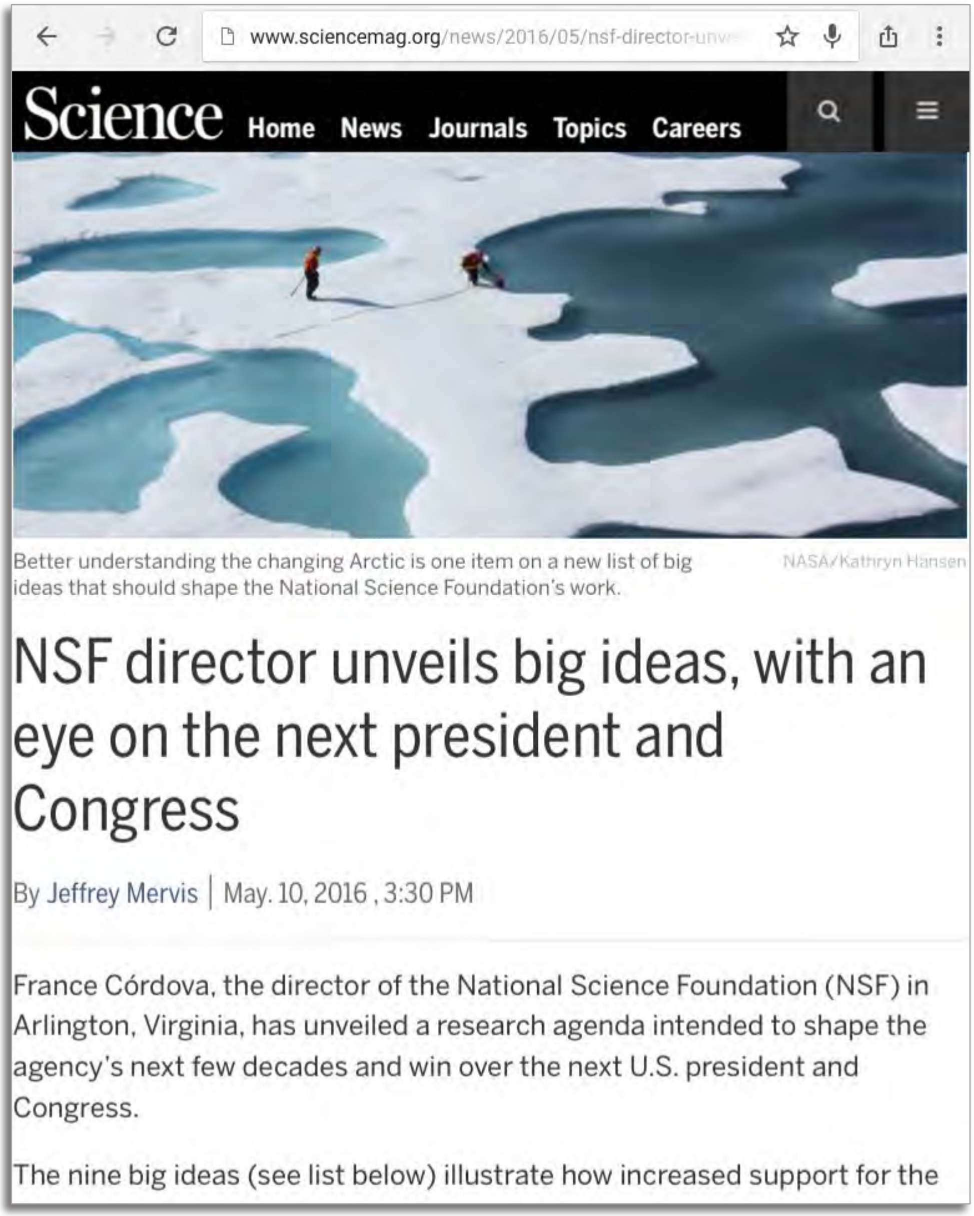
30 seconds of waveform data from three-component broadband stations MDM and PPD. Traces are bandpass filtered on 1-10 Hz. Amplitudes are scaled by trace but using the same scale for both events. The offset between the two stations is precisely the same (about 8 seconds) for both the 2013 and 2016 events.

National Science Foundation Big Ideas: Navigating the New Arctic

In May 2016, the National Science Foundation released nine "big ideas" intended to shape the agency's research over the next few decades. One of these nine, entitled "Navigating the new Arctic," stresses the need for fixed and mobile observing platforms in the Arctic.

Rapid environmental changes are partly driving the desire for better Arctic observation. Arctic observing platforms are also needed in order to keep pace with the rapid growth in fossil fuel development, minerals, fisheries, tourism, and both defense and civil response needs. The NSF statement specifically calls on a strategy of collaboration and leveraged participation with other federal agencies.

The USArray Transportable Array (TA) provides this opportunity in the American Arctic. The TA's real-time communication, hardened long-term installations, and multi-sensor design are already delivering unprecedented atmospheric, meteorological and soil temperature observations. Collaboration and shared objectives with USGS, NOAA, NASA and other agencies give the TA platform the potential to deliver Arctic observing in a responsible and cost-effective manner.



Better understanding the changing Arctic is one item on a new list of big ideas that should shape the National Science Foundation's work.

NASA/Kathryn Hansen

NSF director unveils big ideas, with an eye on the next president and Congress

By Jeffrey Mervis | May. 10, 2016 , 3:30 PM

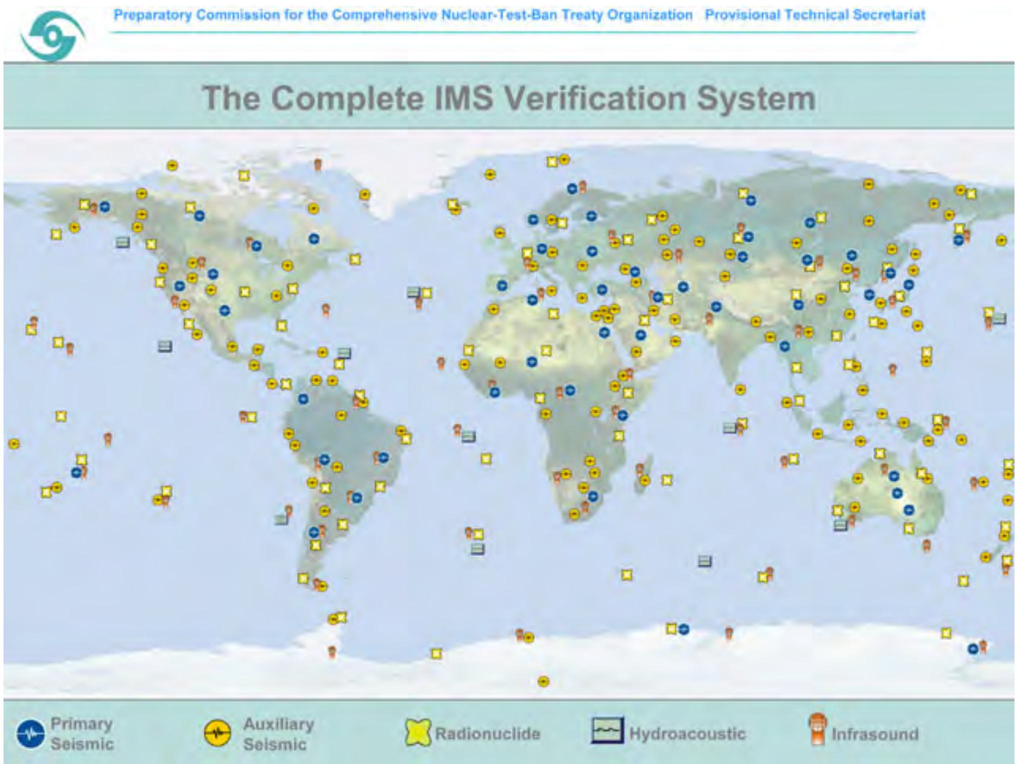
France Córdova, the director of the National Science Foundation (NSF) in Arlington, Virginia, has unveiled a research agenda intended to shape the agency's next few decades and win over the next U.S. president and Congress.

The nine big ideas (see list below) illustrate how increased support for the

May 10, 2016 article in Science magazine highlighting the importance of new Arctic observing platforms in NSF's long-term priorities.
Science, 13 May 2016. Vol. 352, Issue 6287, pp. 755-756 doi: 10.1126/science.352.6287.755

Alaska Seismic and Acoustic Stations for Treaty Monitoring

Alaska is host to many seismic and acoustic stations used to support of the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty Organization and the US Air Force Atomic Energy Detection System. In the event of a nuclear test, the seismic stations are designed to detect associated ground motions while the acoustic stations are tuned to detect the low-frequency sound waves (or infrasound) in the atmosphere. In both cases, the detection can be of an event thousands of kilometers distant. Data from these stations is publically available and is used for far more than treaty monitoring. Research uses in Alaska include natural hazard studies (earthquakes, volcanic ash plumes and landslides) as well as investigations into atmospheric properties and characteristics.



A map showing the worldwide coverage of the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty stations. Alaskan seismic and acoustic stations provide critical coverage of a portion of the circumpolar north. These sites are complemented in Alaska by several USAF Atomic Energy Detection System (not shown here) seismic stations.

An expanded seismic network in Alaska would provide much-needed support to both the nuclear treaty monitoring and basic research communities that require access to such data. In particular, since the IMS stations are operational on a 24/7 basis, experimental modifications to the sites are not permitted, as the US and its international partners closely manage their configurations. A robust Alaska seismic and acoustic network for earthquake hazard monitoring provides sites for research that can be modified to test new ideas, data collection methods, power systems and real-time telemetry links—all without interrupting the operational systems data flow. Experience in the expanded Alaska network can be brought to bear on problems associated with treaty monitoring. The new engineering and designs for the USArray Transportable Array sites hold the potential to eventually inform the construction and operation of IMS sites.

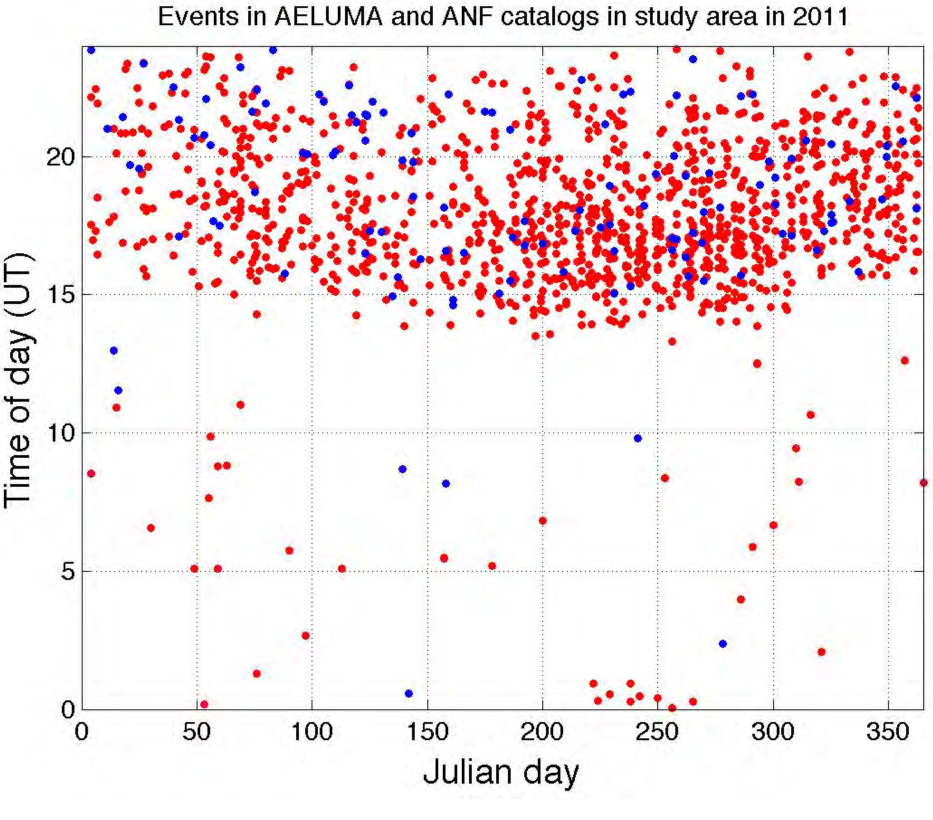
Detection of Earthquakes and Eruptions with AELUMA and the TA

The USArray Transportable Array (TA) has ushered in a new era in seismology and atmospheric science: the era of big data. In the Lower 48, the TA placed a broadband seismo-acoustic station every 70 km across ~2 million square km. This coverage has allowed study and monitoring of earthquakes and atmospheric sources in unprecedented detail.

The network has led to the development of novel analytical techniques, including AELUMA (Automated Event Location Using a Mesh of Arrays), which recasts the TA as a mesh of small arrays, each comprised of three adjacent stations. Data from each 3-element array (or "triad") is processed to detect signals and determine the direction to the source. Results from all triads that have detected a signal at any given time are collectively used to automatically and rapidly provide an accurate estimate of the source's time and location. A test of the method on for a region in the central United States previously thought to be largely aseismic showed a significant number of very small seismic events, mostly due to human activity. For a yearlong dataset, AELUMA located nearly an order of magnitude more seismic events than were detected by traditional techniques (see Figure).

This suggests that AELUMA may be further developed to regularly, rapidly detect small, natural events. Although small seismic events may not themselves be hazardous to people and nearby property, it is important to catalog them to gain a fuller understanding of the physics of seismically active areas and potentially improve forecasting of significant earthquakes. Similarly, the method applied to acoustic data might provide a fuller understanding of potentially dangerous volcanoes.

As the TA moves into Alaska we expect to be able to conduct similar tests of earthquakes using seismic data and volcanoes using acoustic data.

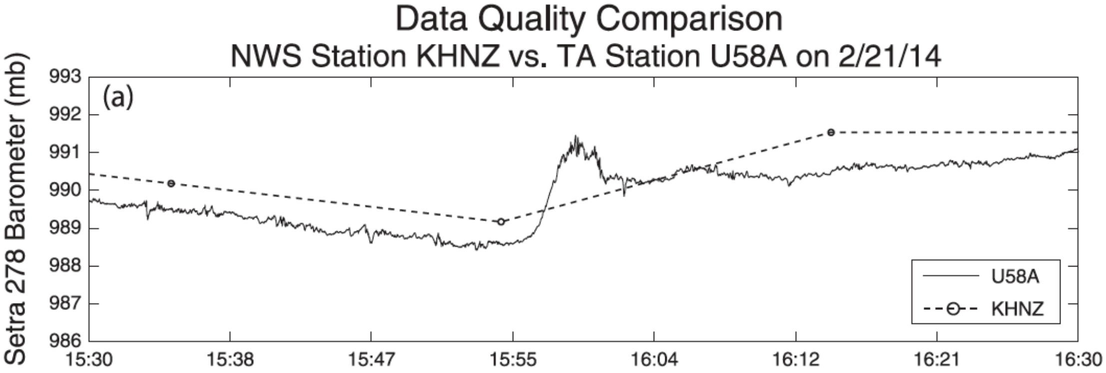


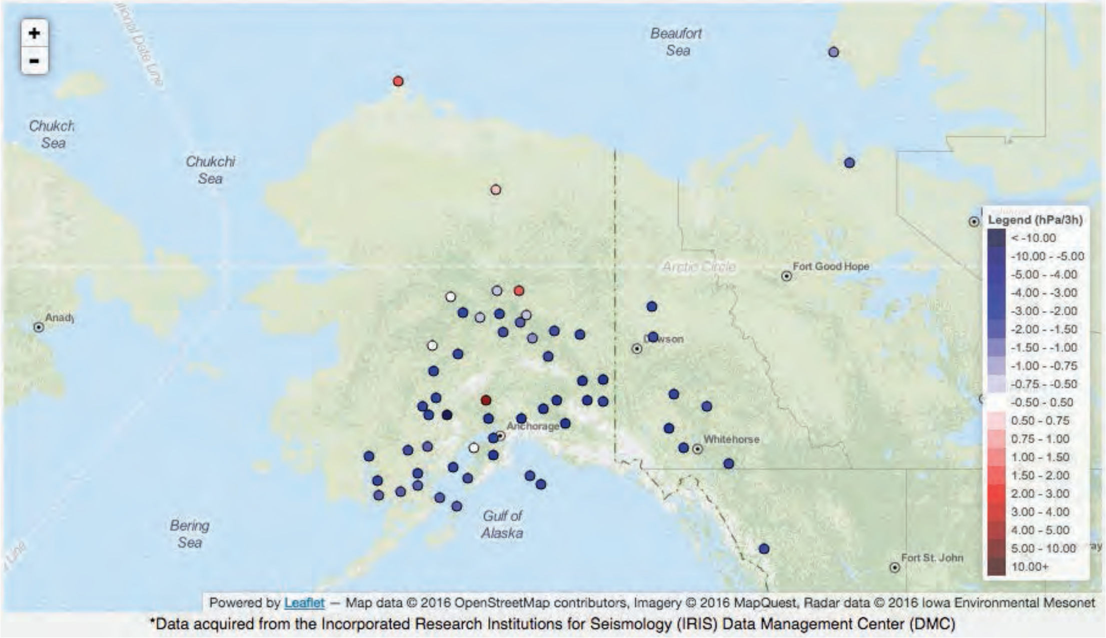
Seismicity in a region encompassing much of Arkansas, Iowa, eastern Kansas, and eastern Nebraska. A standard suite of methods yielded a catalog of 149 earthquakes (blue dots); AELUMA found 1,293 events (red dots). [Figure courtesy of Michael Hedlin and Catherine de Groot-Hedlin, UCSD.]

Seismic Stations as Multi-Instrument Observatories Across Disciplines

From 2004-2015, the EarthScope Transportable Array (TA) in the Lower 48 involved a rolling footprint of 400+ seismograph stations arranged from east to west with uniform, 70 km spacing. East of the Rocky Mountains, all stations also included atmospheric sensors (microbarographs and infrasound microphones). At a handful of stations these were supplemented with meteorological instruments, providing measurements of wind, temperature, humidity, etc. Using real-time telemetry, TA barometric data are incorporated into the Numerical Weather Prediction (NWP) models provided by the National Oceanic and Atmospheric Administration (NOAA). Additionally, the atmospheric science community has used these TA data to characterize natural (meteors, atmospheric gravity waves, hurricanes) and man-made pressure signals (rocket launches, explosions).

Atmospheric and meteorological data from Alaska are considered extremely high value, and there is interest from NOAA, NASA and the Department of Energy to add meteorological sensors on the TA as it is deployed through 2017. Other environmental measurements (e.g. soil temperature) may be collected at TA stations if desired. There is a strong potential for interagency collaboration on observatories that serve multiple missions, as leveraging additional sensors at an established site has considerably lower costs when compared to establishing a new station in a remote location.





Powered by Leaflet — Map data © 2016 OpenStreetMap contributors, Imagery © 2016 MapQuest, Radar data © 2016 Iowa Environmental Mesonet

*Data acquired from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC)

(Top) For a one-hour weather event in North Carolina, high sample rate pressure data from a TA microbarograph (U58A) is compared to a nearby NWS station (KHNZ), demonstrating the un-aliased observations provided by TA-style atmospheric and meteorological instrument deployments (Tytell et al., BAMS, 2015).
(Bottom) Pressure measurements can be filtered for different periods and visualized (e.g. Jacques et al., MWR, 2014) in near real-time across the current TA in Alaska and adjacent Canada http://meso1.chpc.utah.edu/usarray/

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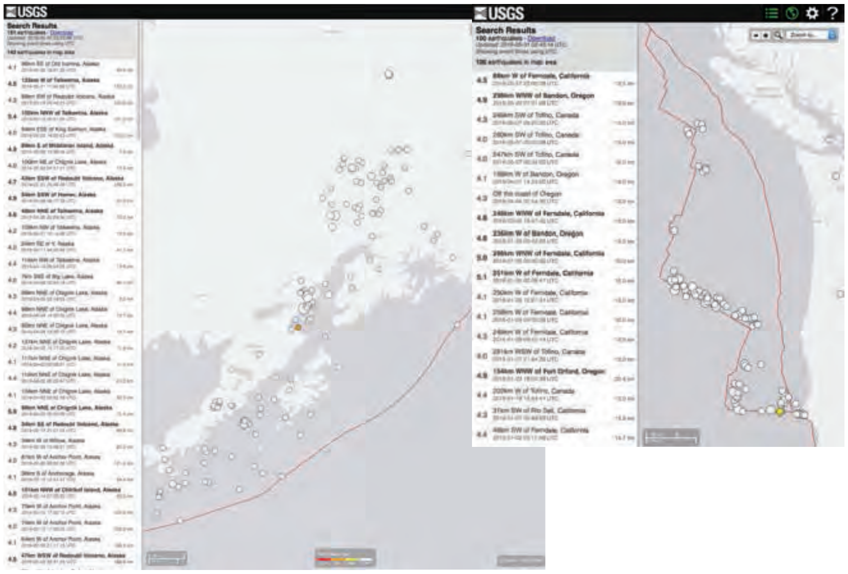
Alaska as a Testbed for US-Wide Earthquake Early Warning

The USGS, together with its university partners along the West Coast (Caltech, UC Berkeley, University of Oregon, University of Washington), are working toward a public earthquake early warning system called ShakeAlert. Planned for public release in 2018, the system's purpose is to provide seconds to minutes of warning for people to take cover and for automated systems to switch to less vulnerable states (stop trains, open firehouse doors, shutdown pipelines, etc.) before the shaking of an earthquake arrives.

In California, the prototype system has been well tested and exercised over the last years by small earthquakes. However, the M_w6.0 South Napa earthquake in Northern California exposed some flaws in the system (e.g., *Grapenthin et al., 2014*). These issues are difficult or impossible to detect in offline tests. For the GPS part of the system we were able to shave off 10 seconds of processing time after addressing the detected issues. However, the system worked in general and provided 10 seconds of warning for San Francisco (light shaking).

While the California system is quite well tested, the subsystem of ShakeAlert for the Cascadia subduction zone that reaches from Northern California past Oregon and Washington State all the way into Canada exhibits very little seismicity that is detectable from land. In fact, most of the seismicity in that region is along the interface between the subducting Gorda & Juan de Fuca Plates and the Pacific Plate further to the West. However, these earthquakes are quite shallow (down to ~25 km), and depth estimates are crucial for subduction zone earthquakes in subduction zones. Waves from a deep earthquake, for instance, lose much of their energy as they travel to the surface; the associated sea-floor displacement is more widely distributed, but at smaller amplitude and as such creates much less of a tsunami threat. Hence, the significant effort that is afoot to instrument the Cascadia coast and get the system ready may end up being tested only with synthetic events. When the dreaded magnitude 9.0 Cascadia megathrust earthquake strikes, the system has to get it right, nonetheless.

Alaska's megathrust system, on the other hand, exhibits M4-6+ earthquakes on a frequent basis over a large depth range. Thus, an Alaska earthquake (and tsunami) early warning system would not only be useful to Alaska citizens, it could become a test bed for the Cascadia subduction zone. While this is important for seismic detection, it is instrumental for the geodetic component. GPS is only useful for large events (M_w6+) that produce surface offsets and these events are rare even in California *(Grapenthin et al., 2014).*



M4+ earthquakes between 01/2014 and 05/2016. Note there are no earthquakes along the Cascadia subduction zone (red line along the coast). [Figures: USGS]

References

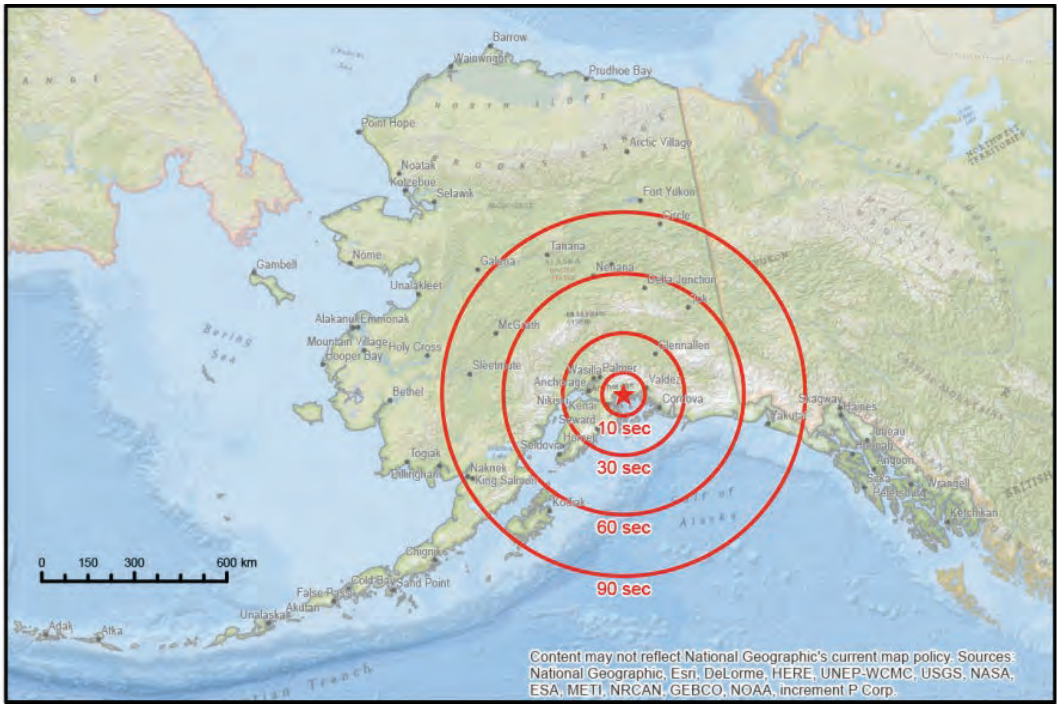
Grapenthin, R., I. Johanson, R. M. Allen (2014) The 2014 M_w 6.0 Napa earthquake, California: Observations from real-time GPS-enhanced earthquake early warning. Geophys. Res. Lett. 41, 8269–8276.

Establishing an Earthquake Early Warning System for Alaska

Earthquake early warning systems use a dense network of seismometers to detect large earthquakes and issue alerts before damaging seismic waves arrive. Warning times vary depending on the distance from the epicenter to the region receiving an alert.

The benefits of even a few seconds of warning are great. With knowledge that strong shaking is imminent, personal safety precautions can be taken ('drop, cover and hold') to avoid injuries from falling objects, heavy machinery and hazardous chemical systems can be shut down, air traffic can be diverted, firehouse bay doors can be opened, and surgical operations can be safely stopped. This list is not exhaustive, but it demonstrates the critical and wide-ranging effect that earthquake early warning can have on society.

Alaska does not currently have an earthquake early warning system. It does, however, already have a strong start on the infrastructure needed to develop earthquake early warning capabilities. The Alaska Earthquake Center operates a network of approximately 200 seismometers that transmit data in real-time. Using this network, earthquake early warning alerts could be issued for large earthquakes occurring on the Aleutian megathrust. Population centers such as Anchorage, Wasilla and the Kenai Peninsula could receive seconds to minutes of warning before damaging shaking begins.



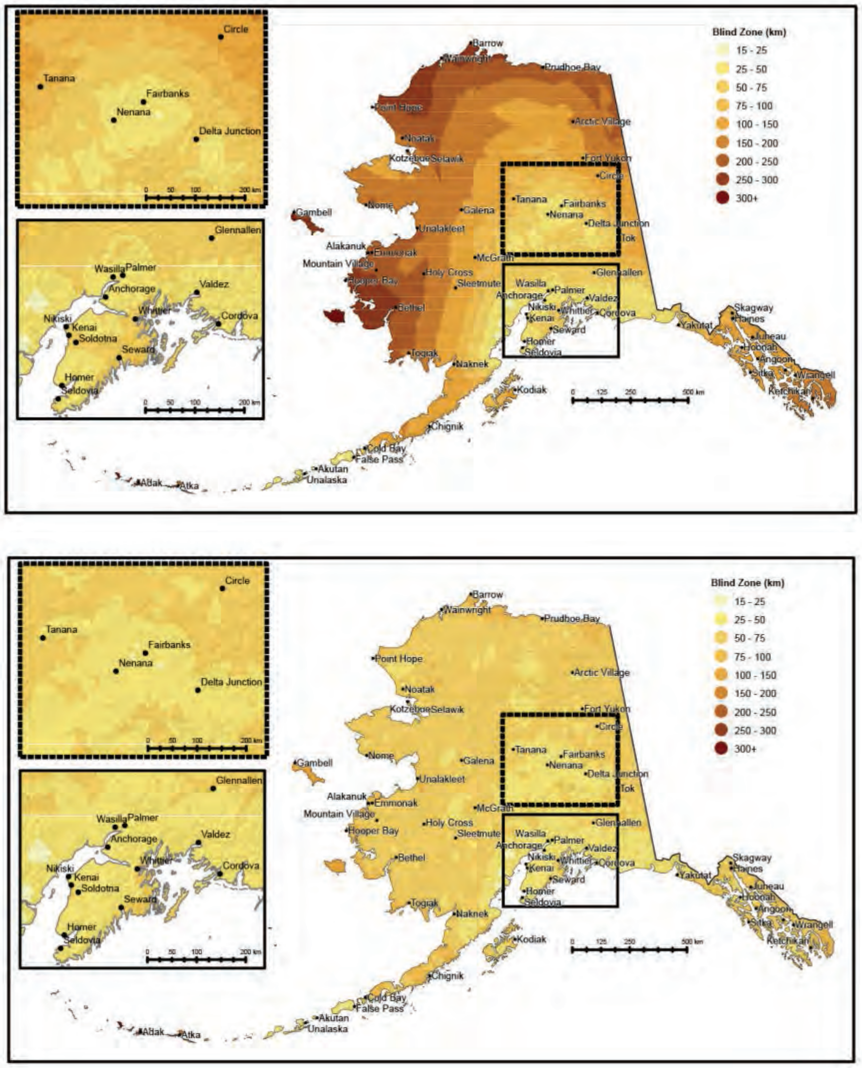
Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Hypothetical alert times for the 1964 M9.2 Great Alaska Earthquake from an earthquake early warning system using the existing seismic network. These warning times are based on the hypocenter. Because the earthquake took 4-1/2 minutes to rupture, the strongest shaking did not occur at the onset, effective adding additional warning time to the estimates in this figure.

Earthquake Early Warning Blind Zones: With and without USArray

Earthquake early warning systems detect the location and magnitude of potentially damaging earthquakes and provide the public with an alert seconds to minutes before damaging waves arrive. The amount of warning possible before the most damaging seismic waves arrive depends primarily on the network configuration and the distance from the earthquake's epicenter. In the area closest to the epicenter, strong shaking begins before an alert can be issued. This area is known as the blind zone. The number and distribution of seismometers determines the size of the blind zone. In areas with few seismometers, the blind zone is extensive.

An earthquake early warning system is not currently in place in Alaska but could be developed using the existing seismic network. The system would be most successful in the central and southcentral regions of the state, where the station distribution is higher. With the addition of the 200 additional seismometers installed by the EarthScope Transportable Array project, earthquake early warning capabilities increase dramatically.



(Top) Map showing the variations in the size of the blind zone – the distance for which an alert will not arrive before strong shaking begins. Lighter colors represent smaller blind zones. Bland zones based on the methodology of Kuyuk and Allen (2014).
(Bottom) Same map but now including the 200 additional seismometers installed by the EarthScope Transportable Array project.

Reference

Kuyuk, H.S., R.M. Allen (2014) Designing a Network-Based Earthquake Early Warning Algorithm for California: ElarmS-2 Bull. Seismo. Soc. Am., 104, 162-173, doi:10.1785/0120130146

Earthquake Early Warning and Missile Defense in Alaska

The Ground-Based Midcourse Defense (GMD) component of the nation's missile defense system launches Interceptor missiles from two sites: Vandenberg Air Force Base in California (4 silos) and Fort Greely in Alaska (26 silos). Additionally, Clear Air Force Station is home to one of the GMD system's Upgraded Early Warning Radar (UEWR) facilities.

Due to the growing threat of missile attack from North Korea, both Greely and Clear are undergoing major upgrades, with about $375 million allocated so far. Fort Greely will get another 14 Interceptors (giving Alaska 90% of the system's missiles), and both bases will get new facilities built to withstand attack from electromagnetic pulse (EMP) weapons.

It is reasonable to assume that Greely and Clear face likelier threats from earthquakes than EMPs. Fort Greely is located only about 30 miles north of the Denali Fault, which generated a M7.9 earthquake in 2002. Meanwhile, Clear Air Force Station sits on the eastern edge of the Minto Flats Seismic Zone, which is believed to be capable of producing earthquakes up to M7.0-7.5.

These facilities are built to withstand large earthquakes. In fact, the Greely silos were under construction in 2002 and weathered the M7.9 without damage. However, the construction phase and ongoing operations at both bases would benefit from earthquake early warning capabilities. Sensitive operations could be halted, machinery could be shut down, and personnel could protect themselves from injury. The GMD system has cost about $40 billion to date, and the most critical component of that investment is at Fort Greely. An earthquake early warning system for Alaska could help safeguard that investment.

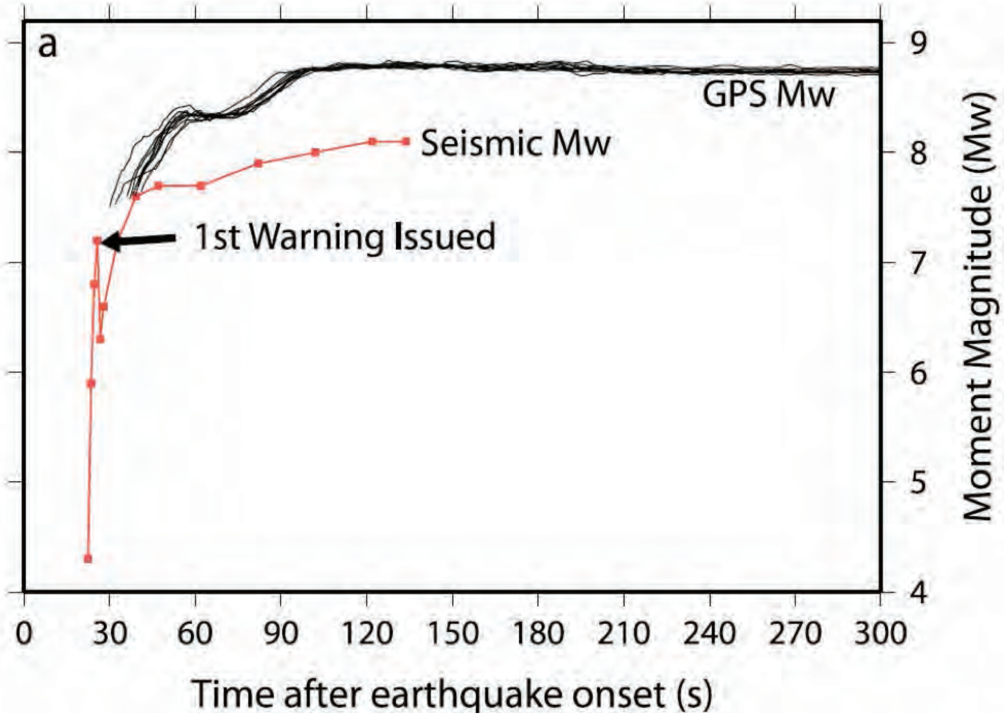
Emplacement of an Interceptor missile at Fort Greely. As part of the planned expansion, 14 Interceptors will be added for a total of 40 silos.

Benefits of Geodetically-Enhanced Earthquake Early Warning for Alaska

The 2011 M_w9.0 Tohoku-oki earthquake in Japan was the best-instrumented great earthquake. Despite the presence of a functional public earthquake early warning system, the earthquake's magnitude remained underestimated at M_w7.9 for the first 20 minutes. This happened because near-field seismic sensors saturated or tilted as they were overwhelmed by the amount of shaking, making it impossible to know the total energy released. High-precision GPS, which can record the full dynamic range of big earthquakes as well as the permanent offset of the ground, was not yet part of the Japanese earthquake early warning system. This meant that, for example, Tokyo did not receive a warning of the strong shaking that was to come. Furthermore, tsunami forecasts tremendously underestimated the wave height, partly due to the low magnitude estimate. The left panel in *Figure 1* shows the magnitude evolution during the event. After ~120 seconds, when the rupture of the event was completed, the GPS-inferred magnitude would have been ~M_w8.9 while the seismic system saturated at M_w7.9.

It is important to note that seismic and geodetic instrumentation complement each other. GPS is not sensitive enough to record the P wave, or primary wave, of an earthquake. The principle of earthquake early warning rests on the detection of this wave, which travels at twice the speed as the S-wave that induces the shaking.

For Alaska, it is thus important to work toward a robust real-time sensor system consisting of both seismic and geodetic instruments with greater density around populated areas. Including geodetic instrumentation not only allows for more precise magnitude estimates for large earthquakes, but the resulting real-time models also give estimates of sea-floor displacements, which is an important input to forecast the resulting tsunamis.



The 2011 M_w9.0 Tohoku earthquake (still smaller than the 1964 M_w9.2 Great Alaska Earthquake) Difference between seismic real-time magnitude, which saturates at M_w7.9 and geodetically derived magnitude, which captures the magnitude at M_w8.9 (Wright et al., 2011).

References

Grapenthin, R., J. T. Freymueller, (2011)The dynamics of a seismic wave field: Animation and analysis of kinematic GPS data recorded during the 2011 Tohoku-oki earthquake, Japan. Geophys. Res. Lett. 38, L18308.

Wright, T. J., N. Houlié, M. Hildyard, T. Iwabuchi, (2012) Real-time, reliable magnitudes for large earthquakes from 1 Hz GPS precise point positioning: The 2011 Tohoku-Oki (Japan) earthquake. Geophys. Res. Lett. 39, L12302.

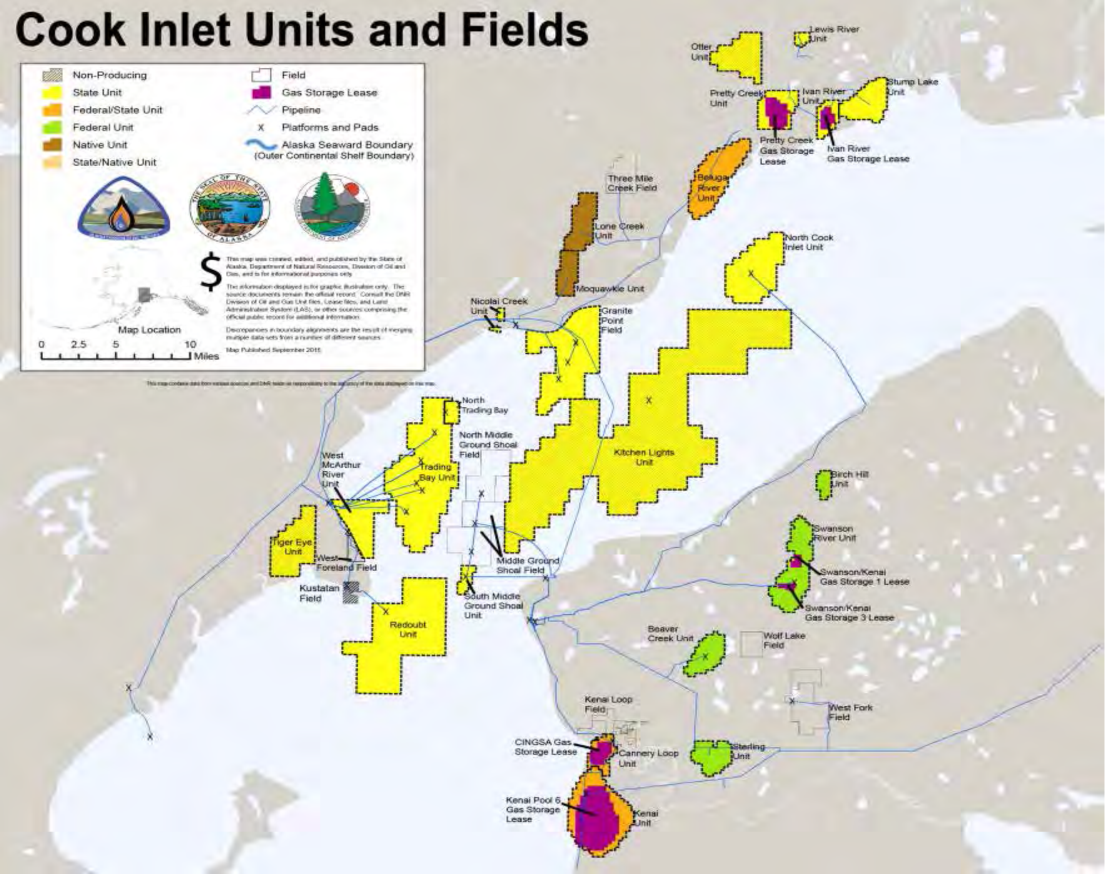
Protecting Cook Inlet Oil Production with Earthquake Early Warning

The 16 operational oil platforms in the Cook Inlet have little or no on-board oil storage. Instead, the oil extracted from these rigs is channeled through underwater pipelines to the Drift River Oil Terminal, where it is stored until enough accumulates to fill a tanker. The facility is capable of storing more than 1 million barrels of crude oil. The underwater pipelines hold an additional 120,000 barrels of crude.

The Drift River Oil Terminal and its pipelines have been built in an area known for its active seismicity. The structure of the subsurface Cook Inlet basin amplifies seismic waves as they pass through it, enhancing the shaking at the surface. The location of the oil terminal at sea level also leaves it potentially vulnerable to seiche activity.

Earthquake early warning alerts could, in theory, save lives and help prevent environmental disasters in a pristine marine environment. Heavy machinery could be stopped. Hazardous chemical systems could be isolated. Oil flow could be halted. Gas valves could be closed. Doors could be opened and elevators slowed to provide egress routes for personnel on site.

Automated controls triggered by earthquake early warning alerts have the potential to enhance the long-term resiliency of these facilities.



Oil and gas production infrastructure in the Cook Inlet. Map modified from the State of Alaska Department of Natural Resources Division of Oil and Gas, http://dog.dnr.alaska.gov/Units/UnitMaps.htm.

Maintaining Hospital Resilience with Earthquake Early Warning

Hospitals face unique risks during large earthquakes, but with only a few seconds of warning, doctors and caregivers could take action to prevent harm to patients. Surgeries could be safely stopped. Radiation sources could be secured and equipment brought to safe mode to protect people in radiography departments. Doors could be opened automatically to provide egress routes, and blinds and curtains could be closed to minimize injury from glass debris.

Anchorage hosts a number of major medical facilities that provide critical care to patients from across the state. Providence Alaska Medical Center is the biggest of these facilities and includes the state's largest emergency department, with LifeGuard air ambulance support. These facilities play critical roles during emergencies. Though Alaska's population is modest, the entire state relies on a small number of major hospital facilities such as trauma centers. Unlike many cities in the lower 48, the next closest hospital is often many hundreds of miles away.

Hospitals can also expect an influx of patients in the aftermath of a large earthquake. Resilient hospitals are a keystone of effective disaster recovery. Though the potential for earthquake early warning has not been meaningfully investigated in Alaska, it is a fair assumption that hospitals stand to benefit more than most facilities.

Inspecting damage to an operating room at a medical facility in Kona, Hawaii, after a magnitude 6.7 earthquake shook the region in 2006. [Photo by Mark Terrill, Associated Press.]

Earthquake Early Warning for Alaska Airports

Strong ground shaking at any airport can have catastrophic consequences. It is extremely hazardous to aircraft that are taking off or landing. Damage to the tarmac or obstructions on the runway will pose an immediate threat to inbound flights. Interruption of air traffic communication can cause chaos to aircraft in the air. On the ground, the heavy machinery used to load cargo can also pose a threat to personnel working on the ground.

Located on the air route that connects Eastern Asia with North America, the Ted Stevens International Airport in Anchorage is the 4th busiest air cargo hub in the world. Federal Express is the airport's largest cargo facility, handling as many as 13,400 packages per hour. The airport also handles around 5 million passengers each year.

The Ted Stevens International Airport is in proximity to numerous earthquake sources, both in the crustal and in the subduction zone. The subsurface structure of the surrounding area also acts to enhance shaking from seismic waves, which likely contributed to the collapse of the air traffic control tower during the great 1964 earthquake.

Earthquake early warning alerts at such a busy airport could play a crucial role in saving lives on an incoming or outbound flight as well as millions of dollars in damage to aircraft and equipment. The vulnerability of air traffic in Alaska has long been recognized as a primary motivator for strong volcano monitoring. The potential value of improved earthquake monitoring and earthquake early warning seem overdue for Alaska's air traffic concerns.

Rank	Airport	Location	Code (IATA/ICAO)	Total Cargo (tonnes)
1.	Hong Kong International Airport	Chek Lap Kok, Hong Kong, China	HKG/VHHH	4,422,227
2.	Memphis International Airport	Memphis, Tennessee, United States	MEM/KMEM	4,290,633
3.	Shanghai Pudong International Airport	Pudong, Shanghai, China	PVG/ZSPD	3,273,732
4.	Ted Stevens Anchorage International Airport	Anchorage, Alaska, United States	ANC/PANC	2,624,312
5.	Incheon International Airport	Incheon, Seoul National Capital Area, South Korea	ICN/RKSI	2,595,674
6.	Dubai International Airport	Dubai, United Arab Emirates	DXB/OMDB	2,505,507
7.	Louisville International Airport	Louisville, Kentucky, United States	SDF/KSDF	2,350,656
8.	Narita International Airport	Narita, Chiba, Kantō, Honshū, Japan	NRT/RJAA	2,122,134
9.	Frankfurt Airport	Flughafen, Frankfurt, Hesse, Germany	FRA/EDDF	2,076,734
10.	Taiwan Taoyuan International Airport	Dayuan, Taoyuan, Taiwan (Republic of China)	TPE/RCTP	2,025,291
11.	Miami International Airport	Miami, Florida, United States	MIA/KMIA	2,005,171
12.	Los Angeles International Airport	Los Angeles, California, United States	LAX/KLAX	1,931,583

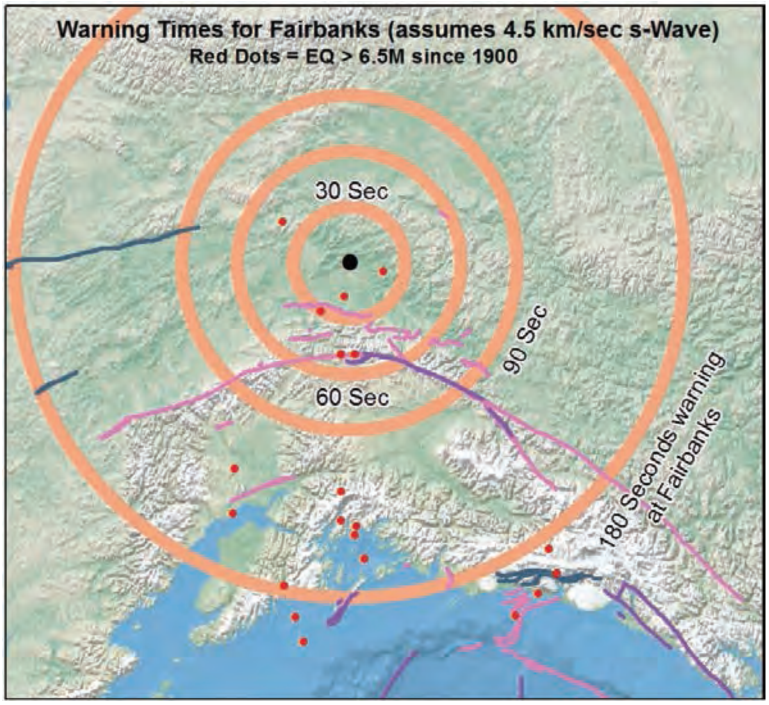
World's busiest cargo airports in 2015. Data from the Airport Council International, presented in Wikipedia. "Cargo Traffic for past 12 months : 12-MONTHS ENDING DEC 2015". Airports Council International. April 11, 2016. Retrieved 2016-04-18.

Alaska Earthquake Early Warning System: Implications for the Middle Tanana Valley

The development of an EEW system for Alaska would benefit the population of the Middle Tanana Valley. The Middle Tanana Valley is home to over 95,000 people and has a large regional hospital, several health centers and road, rail and air connections to the rest of Alaska and the Lower 48. It is also home to an Army base, Air Force base and a major university campus. The region is seismically active, with three magnitude 7 earthquakes occurring within 50 miles of Fairbanks in the last 90 years (Haeussler & Plafker, 2004). The area is dominated by soil types with high shaking amplification and has a depth to groundwater of less than 10 feet on the developed alluvial plain (Glass, 1996). Most critical infrastructure is located on the alluvial plane. Due to these conditions, Fairbanks has felt significant shaking from seismic events occurring as far away such as the 1964 Prince William Sound Earthquake (M9.2), the 2002 Denali Quake (M7.9).

An EEW network could provide enough warning time: 1) for our citizens to take protective actions; 2) to stop delicate mechanical and medical procedures; 3) to open fire & emergency services and prepare personnel; 4) for power and steam generation plants to reduce operating pressure; and pipeline shut off.

The EEW network itself is not a panacea; each organization or function would have to identify and standardize the protective measures they would take based on the time they have until the S-wave arrives. Additionally SCADA systems would need to be programmed for protective measures as well. Therefore, a test, exercise, and evaluation program would be a critical to the success of an Alaska EEW system.



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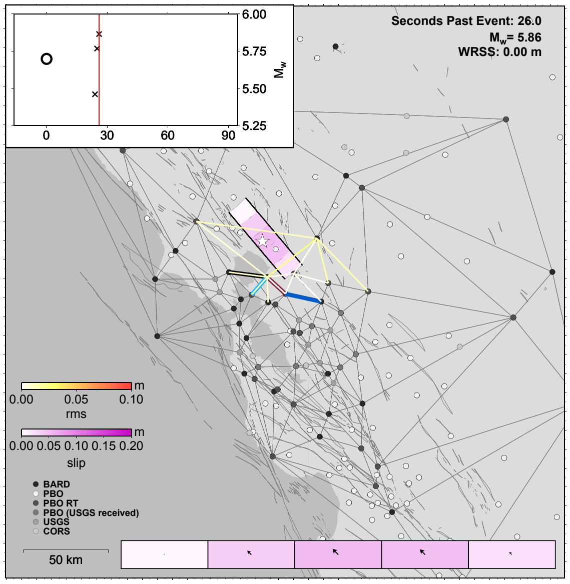
Earthquake Early Warning Systems for Local Tsunami Warnings

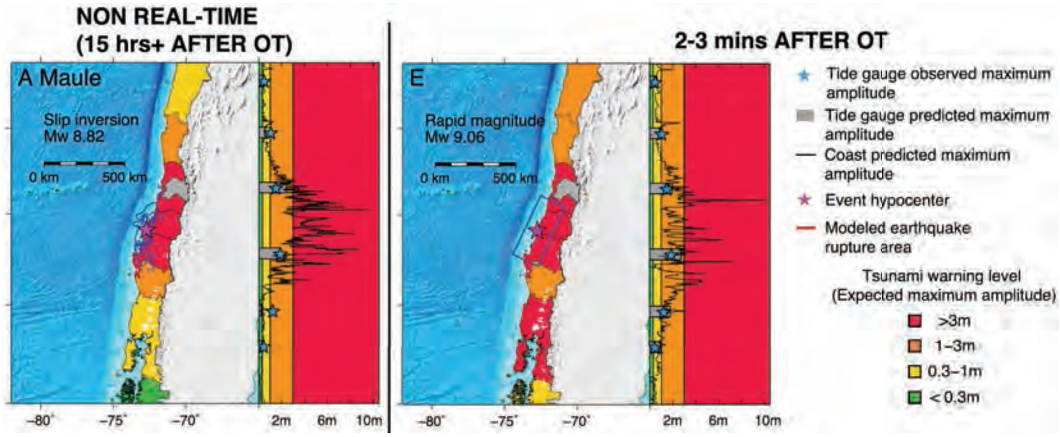
Alaska has a long history of tsunamis following earthquakes; in fact, tsunamis caused most of the casualties related to the 1964 M_w9.2 Great Alaskan Earthquake. Current tsunami warning systems are usually only effective to estimate the far field impact; tsunami sizes are often available only after the waves have already struck the local coastline (Melgar et al., 2016). A benefit of ongoing earthquake early warning efforts that include geodetic methods (GPS) is the rapid availability of a model of slip distribution on the fault that ruptured. We can use the information on depth and amount of slip on a fault to estimate ground motion on the seafloor, which maps directly into tsunami height forecasts.

Melgar et al. (2016) recently demonstrated the possibility for real-time local tsunami warning using offline data for several recent large earthquakes. *Figure 1, bottom,* compares a high-quality model, which takes hours to compute, to a rapidly estimated results, available within minutes of the 2010 M8.8 Maule earthquake in Chile. The left panel shows calculated tsunami run-up heights for regions near the earthquake colored in thresholds from >3 m, between 1-3 m and 0.3-1 m for the high-quality model. The right panel shows almost a similar tsunami height distribution that could be available 2-3 mins after rupture completion if real-time GPS and seismic sensors are available.



(Top) Real-time solution produced 26 s after the M6.0 Napa earthquake in California. White star is earthquake location. Pink colors indicate slip amplitude. Inset shows time series of GPS-based magnitude, black circle shows initial ShakeAlert magnitude. See Grapenthin et al. (2014) for details.

(Bottom) Left panel shows the best solution requiring 10s of hours of computational time. The right panel shows the rapid source mode which can, in theory, be calculated within a couple of minutes of the earthquake based on GPS data. See Melgar et al. (2016) for details.



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The Alaska Railroad (above) provides much of the freight, coal, and fuel to Interior Alaska along a single north-south line. The line crosses major fault systems including the Castle Mountain, Denali, and the Northern Foothills Thrust.

During the 1964 Great Alaska Earthquake, Seward harbor (below) was inundated by a 6-8 meter surge. The initial tsunami was induced by a submarine landslide and struck within 2 minutes, before the strongest shaking had even stopped.