Report on Workshop USArray-Alaska extension into northwestern Canada

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A two-day workshop was held at the Pacific Geoscience Centre, Geological Survey of Canada, Sidney B.C., to identify scientific objectives and targets for the proposed extension of USArray seismic stations into the Yukon, western Northwest Territories, and northeastern British Columbia (Figure 1). Approximately 45 people attended, about half from US Lower 48 and Alaska, and half from 6 universities and 5 government institutions in Canada, including Yukon and Northwest Territories. In addition to discussions on scientific targets that can be addressed with the USArray seismic stations at about 70 km grid, there was extensive discussion of other types of complementary data collection, analysis, and studies. Most of these would need separate operational funding. There also was considerable discussion on seismic station logistics, permitting, and local outreach.

Possible associated surveys include other seismic stations to extend the geographic footprint of the array (one small temporary array in Yukon/NWT is already separately funded), Flexible Array deployments for focused study areas, ocean bottom seismographs, GPS stations, and magnetotelluric surveys. The workshop provided an important opportunity to establish cooperation and collaboration among scientists, managers and others interested in the northern USArray science, and functioned to encourage science involvement in the exciting opportunity of the USArray data and associated science investigations.

Like Alaska, this region has much different characteristics than most of the previous USArray deployments. There is very strong active tectonics and associated seismicity, there are large variations in crustal and upper mantle structure, and very few current seismic stations and associated data to measure them. The USArray data therefore has the potential of making a very large contribution to our understanding of the structure, tectonics, and seismic hazard of the region. Many of the key tectonic and structure targets cross the Alaska-W. Canada border. The entire region of the Alaska-Yukon deployment features intense seismicity (Figure 2) in combination with active deformation. The deployment will record a large number of local and regional earthquakes in addition to the teleseisms and noise tomography sources for imaging studies, facilitating especially high quality seismic structure data.

Four USArray tectonically active target areas were discussed in some detail, three that cross the US-Canada border, and one further to the east (but linked tectonically to the terrane collision zone in Alaska). They include: (1) the Yakutat collision zone (corner of Alaska, Yukon, NE British Columbia), (2) the Queen Charlotte-Fairweather shear zone to the south, (3) the arctic Beaufort Sea convergent thrust continental margin, between the left-lateral Canning River seismic zone in eastern Alaska and the right lateral Eskimo Lakes-Richardson Mtns at the eastern edge of the Mackenzie Delta, and (4) the Mackenzie Mountains (NWT) which are an active fold and thrust belt driven by the Yakutat collision on the Alaska margin to the southwest. Major crustal and upper mantle structure contrasts are expected, including: crustal thickening in the Yakutat collision zone, and the contact under the Mackenzie Mountains of the thin-crust Cordillera (tectonically active backarc mobile belt), and the thick-crust stable craton. An important target is the deep crustal and upper mantle expression of the terranes that make up the Cordillera. In addition to these expected results, previous USArray experience has shown that many of the most exciting and important results were unexpected.

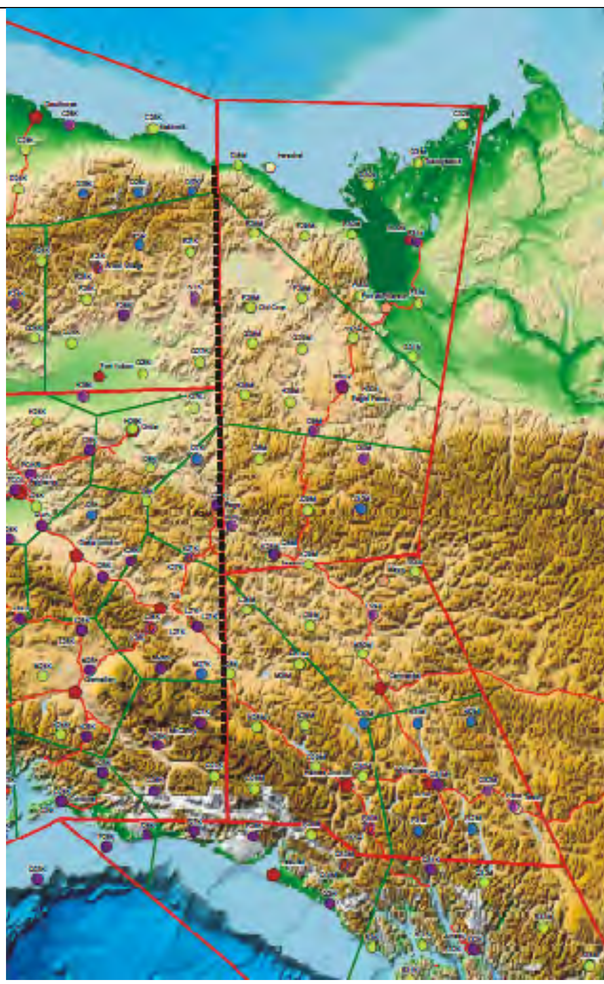


Figure 1. Proposed USArray sites in eastern Alaska and western Canada

The report includes:

(1) A summary of the main breakout group discussions and conclusions. The groups included, (a) logistics: including available access, power and communications, formal permits, and community consultation requirements (especially first nations), (b) community outreach and education, (c) seismic data management and standard analysis, (d) structure and tectonics.

(2) The agenda, including a list of presentations. There also were a number of very short “pop up” presentations.

(3) The list of participants.

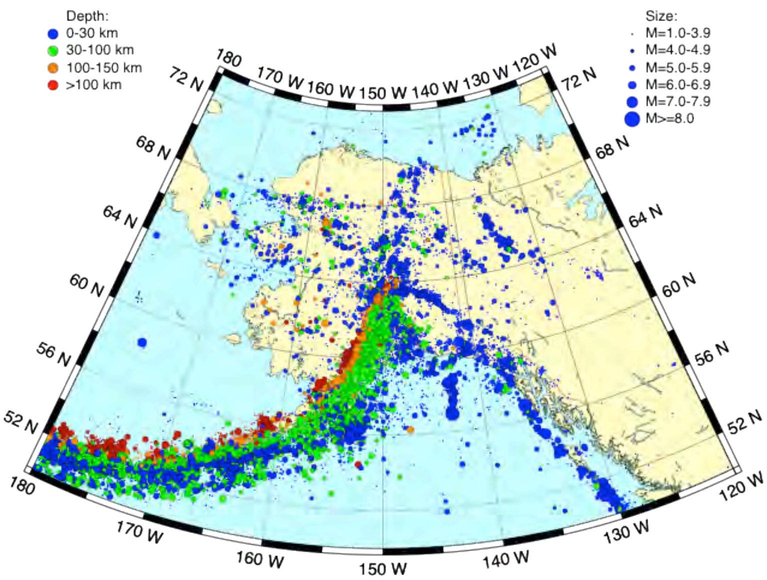


Figure 2. Seismicity of Alaska and the adjacent part of Canada. Earthquakes are from a combination of the Alaska Earthquake Information Center (AEIC) catalog and the USGS PDE catalog in Canada.

Science Targets

Following one of the early EarthScope tag lines, we divided the science targets into two broad categories, *Making the continent* (structure and geologic history) and *Breaking the continent* (active tectonics). The categories are not mutually exclusive, as modern active structures in many cases reactivate much older structures.

A. Making the continent (structure and geologic history)

1. Boundary of the Canadian Shield with the modern deformation front.

The TA deployment in Alaska and NW Canada offers the opportunity to study the difference between the Archean lithosphere of the Canadian Shield and the actively deforming lithosphere of Northern Cordillera (Figure 3). Differences in seismic velocity and other material properties are expected to be profound, and may extend to a few hundred km depth. The present TA proposal includes stations that may cross over the modern deformation front along the Arctic coast, but additional stations would be required to cross over the front further south, as the front bulges out to the east. Additional seismic array data on the Canadian Shield has been collected by Canadian researchers and agencies (e.g., Snyder and Bruneton, 2007), and data collection continues. This will allow comparative studies of lithospheric and mantle properties between locations, and a new 7-station seismic array to be operated by the University of Ottawa will cross over the modern deformation front. **Additional data could be proposed as a FlexArray experiment.**

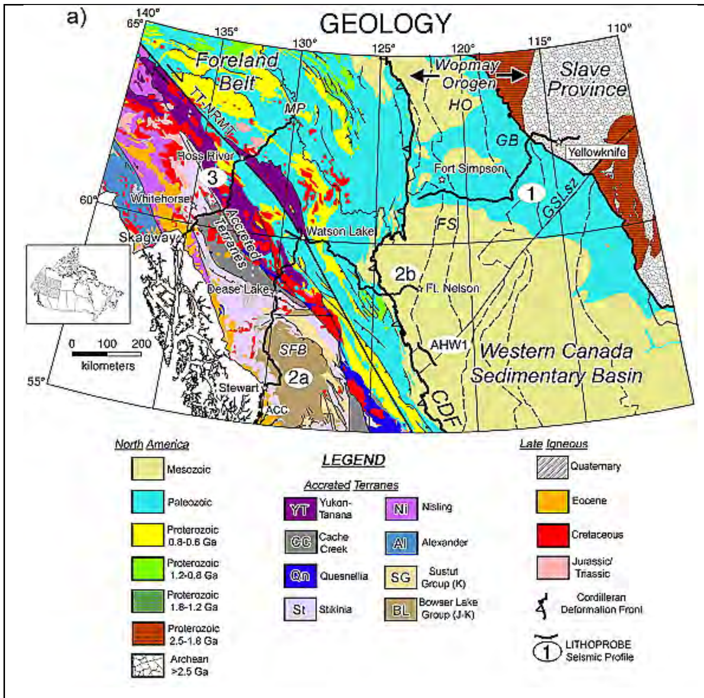


Figure 3. Geologic map of the region, from Cook et al. (2004).

Does the location of the modern deformation front at the surface coincide with a fundamental boundary in lithospheric structure and strength? The arcuate front of the Mackenzie Mountains is thought to represent the active structures rather than an oroclinal bend. Is the mountain front located there because of a contrast in structure, or does shield-type lithosphere continue for some distance beneath the active thrust belt? The "orogenic float" model proposed by Mazzotti and Hyndman (2002) featured a weak detachment in the mid-crust. If this model is correct, how far does this particularly weak zone extend and what lies beneath it? Is the edge of Shield-type lithosphere abrupt or gradual?

2. How deep are terrane boundaries?

For many years, the standard description of the geology of both Alaska and the Canadian Cordillera has divided the region into a number of terranes, which have moved substantially relative to each other and to the stable part of the continent. Rapid motion of one such terrane (the Yakutat block; see Fig. 4) continues today, and motion may continue on some of the terrane boundary faults at lower rates. However, it is not clear whether all identified terrane boundaries truly represent lithospheric-scale structures, or instead are confined only to crustal or upper crustal levels. How deep do these boundaries extend? How different are rocks at lower crustal or mantle lithospheric levels across different terranes? In thrust zones, the key question is whether the thrusting represents motion of a thin sheet (or an orogenic float as proposed for the current Northern Cordillera deformation) or a lithospheric-scale thrusting akin to a subduction zone. Gravity anomalies (Figure 4; and Cook et al., 2004) in concert with seismic velocity measurements can provide relevant constraints.

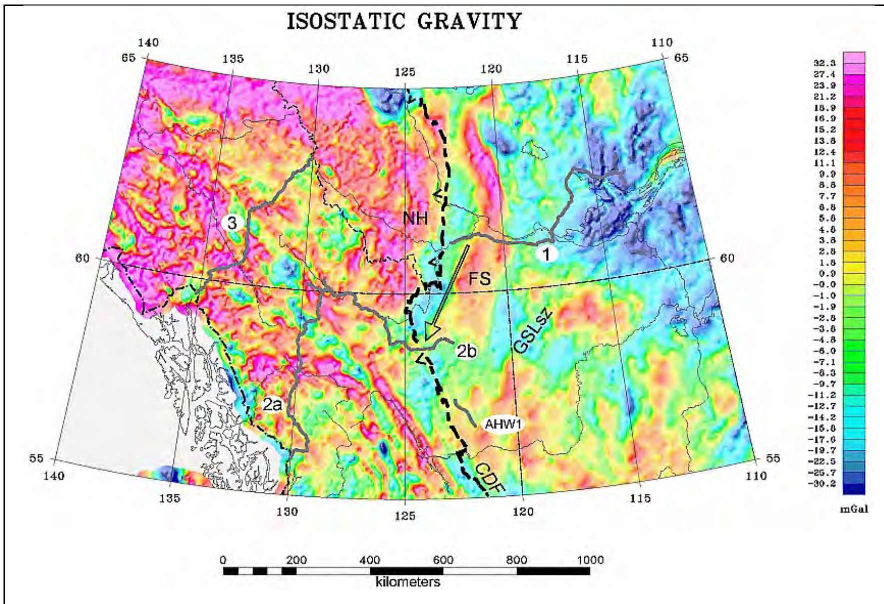


Figure 4. Isostatic gravity for northern B.C., Yukon, and W. NWT, from Cook et al. (2004). The dashed line is the Cordilleran deformation front. Solid lines are Lithoprobe deep reflection lines.

Several strike-slip faults have been terrane boundaries in the past, and some are active structures today. Are these lithospheric scale, and what is the structure of these boundaries at depth? Are they vertical faults cutting the entire lithosphere, or do they have a more complex structure at depth? Examples include the Queen Charlotte-Fairweather fault, and the Denali and Tintina faults. Are the terrane bounding structures that are currently active (or reactivated) today different in some fundamental way than those that are not?

Very extensive geological and geophysical studies were carried out across northern B.C. and southern Yukon as a part of the Canadian Lithoprobe program (see Cook et al., 2004;

Lithoprobe SNORCLE, 2010). The work included a series of Vibroseis multichannel deep seismic reflection lines, wide-angle seismic refraction lines, geothermal measurements, gravity, magnetics, and numerous other geophysical and geological studies.

3. The paleo-subduction zone

Prior to the development of the current tectonic regime, the coast of southeast Alaska and Canada had been a subduction zone. Subduction of the Kula plate to the northwest prior to the Eocene meant the entire Cordilleran margin was a subduction zone, and the motion of the Pacific plate has changed over time such that there have been periods of oblique subduction and periods of strike-slip motion since the Eocene. At least one, and perhaps as many as three, spreading ridges have subducted along this margin, impacting the thermal structure. The remnant slabs (and paleo slab windows) should be in the mantle beneath the Canadian Cordillera.

Subduction causes substantial modification to pre-existing lithospheric structure, in large part through its perturbations on mantle flow and heat tranport. Mantle flow in the wedge, and mantle flow around the corner at the edge of a slab can fundamentally alter the temperature distribution within and beneath the lithosphere. In addition, hydration of the mantle wedge by fluids brought down in the slab lowers the viscosity of the asthenosphere in the wedge. Changes in the subducting plate, migrating triple junctions, or tears in the subducted plate can lead to the formation of slab windows; the thermal impact of a slab window can also alter the structure and properties of the lithosphere. Thus the lithospheric and asthenospheric structure of the region has been thoroughly altered by this history of subduction, and some of these alterations are detectable via seismic imaging.

Specific targets for seismic imaging include delineating the landward extent of the old subducted plate, imaging relict slabs, changes in lithospheric thickness, and changes in the velocity or attenuation structure of the mantle. Estimates of the mechanical properties of the lithosphere and asthenosphere can be made from geodetic studies of glacial isostatic adjustment and postseismic deformation, and this information can be combined with the structural imaging to provide a complete and consistent rheological model of the Earth in this region.

Further inland a frozen subducted slab has been mapped by Cook et al. (1999). See also the tomographic mapping of relict slabs by Sigloch and Mihalynuk (2013).

4. Eastern edge of Pacific plate under Alaska-Yukon

In addition to the case of past subduction, the location and structure of the eastern edge of the currently subducting Pacific plate and Yakutat block need to be determined. This edge most likely lies underneath Alaska, but data from both Alaska and BC/Yukon will be required to image it properly.

The eastern edge of the subducting Pacific plate has commonly been inferred from the prominent edge (Figure 2) of Benioff zone seismicity (e.g., Fuis et al., 2008). However, recent work as part of the multidisciplinary STEEP project cast significant doubt on this interpretation, and identify subducted material farther to the east. Elliott (2011) showed that the interseismically locked area on the subduction interface extends well to the east of the edge of the seismicity. Seismic imaging also identifies slab-like material coincident with the weakly defined Benioff zone dipping beneath the Wrangell volcanoes. One significant limitation of these studies is that they see this slab only from one side, from the southwestern direction. New data from the area to the east and northeast are required to provide paths that pass to the east of the slab edge, if the slab is not actually continuous. Stations providing these paths would need to be located in the Yukon Territory. This slab edge and corner are targets with a high likelihood of scientific return. Data from the STEEP project has shown that there are azimuthal velocity variations at scales of ~100km that are larger than velocity variations observed in the entire Lower 48 US Array deployment; large signals will be observed by any array that properly covers this region.

5. Is the Beaufort Sea margin thrust belt "subduction-like"?

There is an enigmatic cluster of thrust earthquakes in the southern Beaufort Sea, north of the Mackenzie River (Figure 5). What is the structure associated with these earthquakes? One hypothesis is that the earthquakes represent failure within the oceanic crust beneath the edge of the sediment pile of the Mackenzie delta, but another is that they are related to the hypothesized Canning-Mackenzie thrust front, a larger thrust zone that may indicate incipient subduction (Hyndman et al., 2005b; see active tectonics section). A full exploration of this boundary would require a complementary Ocean Bottom Seismometer (OBS) deployment. However, the landward component of the boundary can be imaged through location of microseismicity and imaging of velocity contrasts.

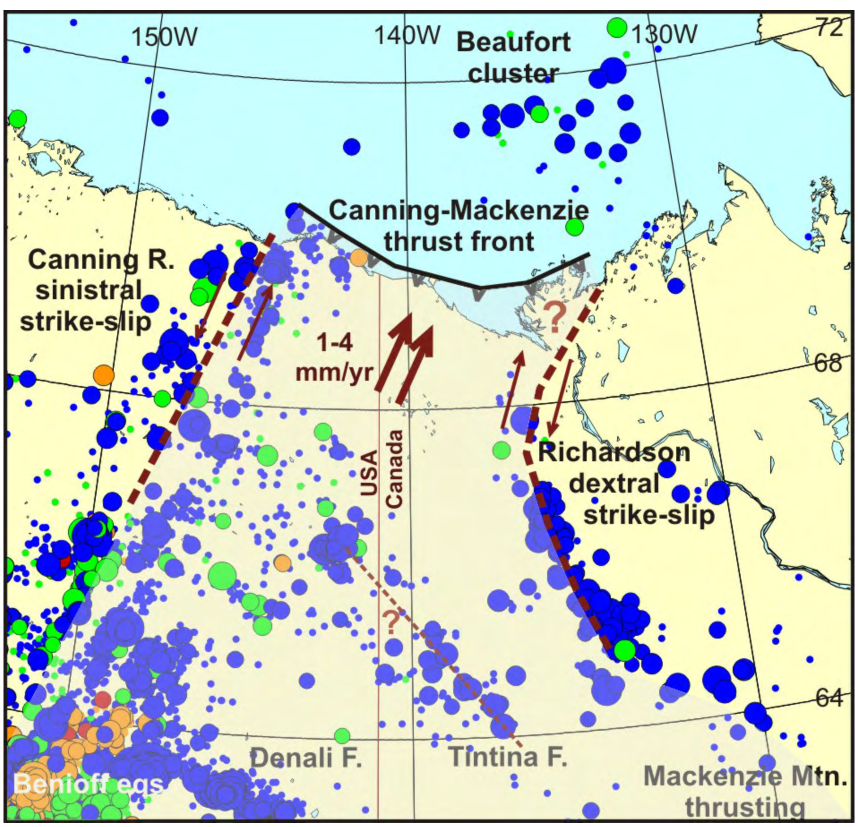


Figure 5. Seismicity of the northern part of Alaska and the Yukon. An inferred mobile block is bounded by diffuse strike slip faulting on each side of a presumably rigid block (Canning River zone in Alaska, Richardson Mountains zone on the Canadian side). Deformation rates are inferred from Leonard et al. (2007,

2008) and Mazzotti et al. (2008).

B. *Breaking the continent* (active tectonics)

Alaska and the southwestern corner of the Yukon Territory feature some of the most spectacular topography on the planet, a result of rapid ongoing tectonic convergence. The entire region is seismically active and mobile (Figures 2, 5, see also Freymueller et al., 2008; Mazzotti et al, 2008; Hyndman et al., 2005a; Leonard et al., 2007; Leonard et al., 2008). Here we divide the discussion into two sections, the Collision Zone or the outboard edge of the active deformation, and the Craton boundary, or the inboard edge of the active deformation (Figure 6). The collision zone is mostly related to the collision of the Yakutat block and the transition from the strike-slip regime of southeast Alaska to the subduction regime further west. We include the Denali fault system in this category. The Craton boundary encompasses all of the active inboard systems from the Arctic coast through the Richardson and Mackenzie Mountains into the Canadian cordillera (Figures 5,6).

Figure 6. Topography of the Northern Cordillera, illustrating the Yakutat collision zone and other tectonic elements.

Collision zone

1. Structurally, how is the convergence of the Yakutat block accommodated?

The leading edge of the collision zone of the Yakutat block features very rapid contraction over very narrow zone (Elliott, 2011). The Yakutat block occupies the corner or cusp that joins the strike-slip Fairweather fault (Fig. 4) to the northeast with the convergent boundary to the west. Strain rates at the leading edge of the collision zone are among the most rapid globally. Investigations from the STEEP project over the last decade suggest that the leading edge of the collision involves a number of active structures and deformation processes at shallow depth. Sediments on the downgoing Yakutat block are laterally compacted and dewatered, then a series of active thrusts strip off most of the sedimentary cover and some of the Yakutat basement, with the remaining basement underthrust (Worthington et al., 2010; Elliott, 2011; Worthington et al., 2012; Pavlis et al., 2012). The deeper structure of this system is less clear, mainly because of a lack of data on the Canadian side. In addition to the leading edge deformation, the lateral (northeast) edge of the Yakutat terrane is being crumpled (Elliott et al., 2010).

The impact of the collision also causes substantial deformation of the North American crust north and east of the Yakutat block itself. Koons et al. (2010) described the predicted strain patterns resulting from oblique collision and a crustal indenter corner geometry. These strains result in active seismicity and modifications to the crustal structure and architecture. A substantial amount of the deformation predicted from the corner effects occurs within Canada, and will be reflected in seismicity, seismic velocity contrasts resulting from offsets along active structures, and other observable impacts.

Key questions that remain from the collision zone, in addition to the structural architecture of active deformation, include an assessment of the forces acting on the Yakutat block and the overriding plate, and the strength of thrust and other faults in the system.

2. Are "small" tectonic blocks rigid, fault-bounded blocks?

Present-day GPS motions are described well by an elastic block model (Figure 7), which features a set of elastic blocks that undergo permanent deformation only on the faults that bound them (Elliott et al., 2010). As with the question about terrane boundaries, a key question is whether these block boundaries are lithospheric scale boundaries, such that the faults cut through the entire lithosphere. The alternative would be that some of the faults are distinct structures within the crust only, or within the upper crust only. In the latter case, discrete faults at the surface would be connected with broad deformation zones at depth. For example, the model of Elliott et al. (2010) features several small blocks or slivers at the northeastern margin of the Yakutat block, which are bounded by thrust faults in the foothills of the Fairweather range. Elliott et al. (2010) noted that these structures quite possibly represent a broad deformation zone that would include multiple faults and folds, given the small scale of the blocks. However, the same question should be asked of other block-bounding faults in this or future competing models.

Which of these structures are of lithospheric scale? This question will be easier to answer for structures with large offsets, which may juxtapose lower crustal or lithospheric mantle rocks of different properties. Seismically observable properties such as seismic velocity, anisotropy and attenuation may be diagnostic for testing these differences. Larger-scale structure of the crust and upper mantle may be used to test the structural implications of particular models. Precise hypocentral locations will help to delineate the active structures at shallow depths.

In the long term, information from seismology, geodesy and geology should be merged to provide a unified representation of the active deformation processes. Terrane boundaries from the geologic past affect the distribution of active faulting today and the present pattern of seismicity, and may impact the 3D seismic velocity structure where different materials are juxtaposed. Integration of additional data will allow a refinement of block models such as Figure 7 and will make for a stronger connection between the present-day deformation and the long-term geologic record.

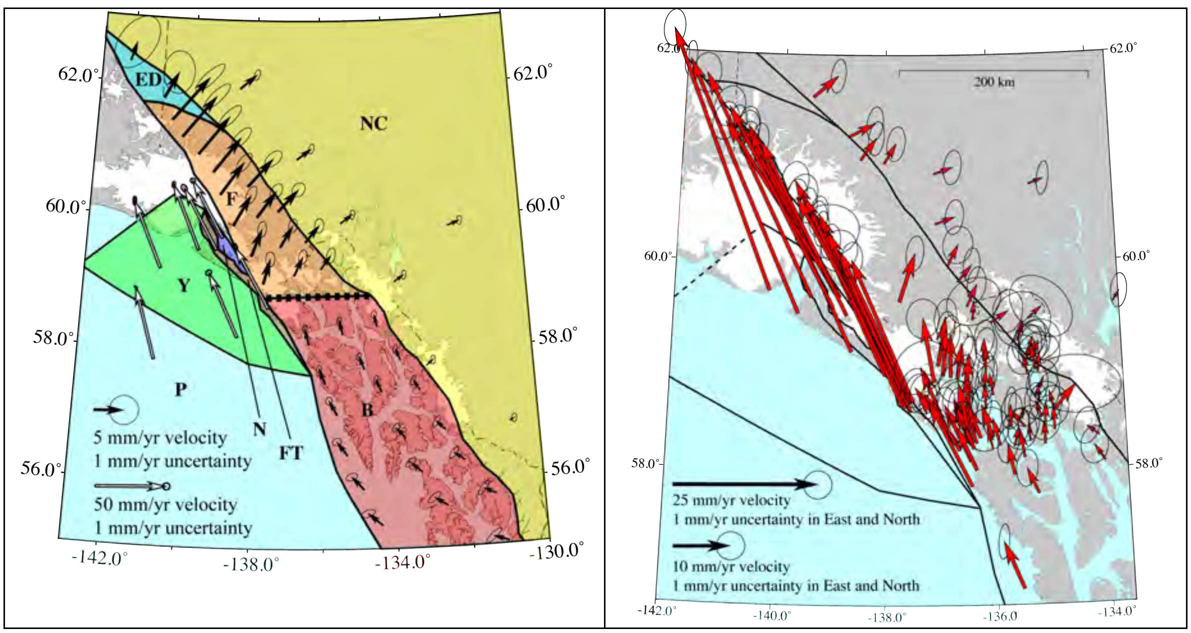


Figure 7. (left) Rigid block motions predicted by the elastic block model of Elliott et al. (2010). (right) GPS velocity field used to derive the model.

3. Partitioning of deformation into strike-slip and thrust faulting

At the Yakutat collision zone part of the northwesterly motion is partitioned into strike-slip motion around the Gulf of Alaska corner (e.g., slip on the Denali fault), part is partitionined into nearly orthogonal shortening across the St. Elias Range (e.g., Elliott, 2011). The corner effects of the collision also result in northeasterly-directed motion on the "continental" side of the corner (Koons et al., 2010), and some of this motion is conveyed across the whole Cordillera (Mazzotti and Hyndman, 2002). This partitioning provides important constraints on the strength of the strike slip fault and on the terranes themselves. There are similarities to forearc slivers (see McCaffrey, 2002 and references therein, for forearc sliver behavior.

4. Glacial Isostatic Adjustment (Post-glacial Rebound)

The coastal glaciers and icefields of Alaska and adjacent British Columbia and the Yukon have lost a tremendous volume of ice over the last 200 years, and the rate of mass loss remains high today. The changing surface load due to deglaciation produces rapid deformation that impacts GPS observations, and represents a substantial stress change that can bring faults closer to or farther from failure. Changes in stress offer unique opportunities to study the mechanical properties of the Earth and its materials.

GIA is caused by the combined elastic and viscoelastic responses of rock beneath glaciers and icefields. GIA contributes uplift or subsidence to GPS or altimetry measurements, and gravity change to GRACE measurements, and a proper explanation of the data requires accounting correctly for both the present-day and past mass changes. Developing these GIA models requires accounting for the mass load history and the physical (elastic and viscoelastic) properties of the earth, and thus is an activity that integrates glaciology, geodesy and seismology through numerical modeling.

Bettinelli et al. (2008) studied the seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. Seasonal strain and stress variations in the Nepal Himalaya, are of the order of ~2-4 kPa. They found that the seismicity rate is twice as high in the winter as in the summer, and correlates with stress rate variations. Seismicity variations in parts of southern Alaska are connected with surface load variations due to glacial surges and deglaciation (Sauber-Rosenberg et al., 2004; Doser et al., 2007). The impact of glacial unloading has not been studied as much for southeast Alaska or the Yukon, but dramatic glacier changes and some rapidly moving faults provide a great opportunity to do so. Good catalogues of microseismicity are required for this.

GIA modeling also provides important constraints on crustal and mantle rheology. The time-delayed viscoelastic response to past ice loss depends on the thickness of the elastic lithosphere and on the viscosity structure of the mantle. Due to the spatial scale of the ice loads in Alaska, BC and the Yukon, the response is mainly sensitive to the viscosity of the asthenosphere, which is low, on the order of 10^{19} Pa-sec (Sato et al., 2011). There is some tradeoff between the asthenospheric thickness and its viscosity. Comparisons of the seismic and rheological structure of the upper parts of the Earth will help in developing more realistic models for both.

5. Weak zone in the lower in the Cordillera mobile belt.

Mazzotti and Hyndman (2002) proposed an orogenic float model for the Northern Cordillera. In this model, there is a weak zone in the lower crust that allows the upper crust to move northeastward relative to the lower crust, transferring deformation from the collision zone to the Mackenzie and Richardson Mountains in the north. An alternative model might view the motion of this mobile Northern Cordillera as a lithospheric block, as in section 2 above. In the latter case, faults cutting the entire lithosphere would be required both at the inboard edge of the collision zone and at the Mackenzie Mountains.

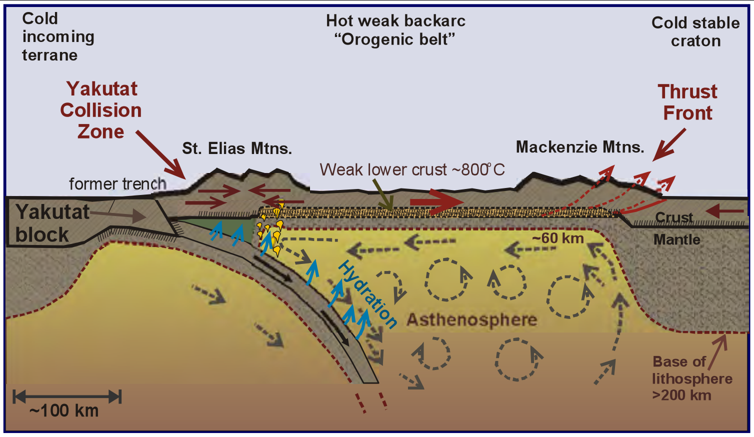


Figure 8. Yakutat collision model with strain transferred across the Cordillera in thin upper crustal sheet (after Mazzotti and Hyndman (2003)

These models may be testable in a couple of ways using USArray data. First, the lower crustal shear zone might be detectable in the form of horizontal reflective bands, as suggested to the south. Patterns of anisotropy might also reveal the presence of such a zone. Changes in lithospheric thickness or seismic properties within the lower crust or mantle lithosphere may also reveal the presence of faults that cut the entire lithosphere, which would support the block-like model over the orogenic float model.

6. Implications for earthquake hazard.

The Alaska-Canada border area is heavily earthquake-prone, especially in the collision zone. Fault slip rates are high, in excess of 40 mm/yr for the Fairweather fault and for the sum of all the thrust faults in the leading edge of the Yakutat collision zone; the frequency of large earthquakes is thus relatively high compared to slower moving faults. The Denali fault extends into the Yukon, and is capable of large magnitude strike slip ruptures. Other faults within the actively deforming system have lower slip rates, but may be capable of large and damaging earthquakes. The impact of large earthquakes may be small in lightly populated areas, but when damage occurs it may be especially harmful because of the limited infrastructure, long distances to help, and harsh climate.

Seismicity rates and their spatial variations are an important input to models of earthquake hazard, and this region has been poorly monitored in the past. The USArray deployment will provide a time window with an excellent seismic network for locating regional seismicity more accurately and to lower magnitudes than before. Not only will seismicity rate estimates be based on a wider magnitude range that should make them more robust, the ability to locate smaller earthquakes should help reveal seismogenic structures that may have been unrecognized before.

Arctic Margin

The northeastward motion of the Northern Cordillera causes convergence at the Arctic margin of Alaska and the Mackenzie delta (Figures 2, 5) (e.g., Hyndman et al., 2005a,b). This convergence may be the latest phase of ongoing thrusting on this margin (e.g., Lane, 2002; Houseknecht and Bird, 2011). At its northern end, the mobile block is bounded on the west by a zone of left-lateral strike slip faulting (the Canning River zone), and on the east by a zone of right-lateral strike slip faulting in the Richardson Mountains. Kinematically, these two systems must be linked by a thrust system. Active seismicity indicates that this thrust front is likely located at near the Arctic coast. Essentially, a piece of the continent is being thrust northward over the Beaufort Sea (Figure 5).

Is this model correct? Can we find evidence for or against the thrust front as shown in Figure 5? Current estimates of the rate of motion on these fault systems is based on seismicity rates and on GPS rates in the southern Yukon (Leonard et al., 2007, 2008; Mazzotti et al., 2008). How fast are these motions, and how long has this motion been occurring? What is the total offset on these structures?

Additional questions that could be addressed, especially if the TA is augmented by a deployment of Ocean Bottom Seismometers, include the origin of the earthquakes of the Beaufort cluster. Are these related to the same thrust system, or do they represent failures within the Mackenzie delta sediment pile? What is the thickness and depositional history of Mackenzie delta?

An IODP-ICDP workshop on continent-ocean drilling across the Beaufort Sea margin was held recently in Kananaskis, Alberta. This project would be very complementary to the USArray studies in the adjacent continent.

Continental Shield boundary

The boundary between the undeforming continental shield has been discussed earlier in the "Making the Continent" section. Such a boundary may be defined in terms of either the present-day deformation front or the Cenozoic deformation front. How different are these? Is the deformation front a roughly vertical boundary cutting through the lithosphere, as might be the case if its location is purely defined by a strength contrast, or does shield-like lithosphere extend at depth for some distance west of the deformation front, as might be the case if the deformation front marks the limit of thin-skinned deformation?

Within the Northern Cordillera, the present-day deformation front is thought to lie at the eastern front of the Mackenzie Mountains. Where is the limit to the north and to the south? The model of Elliott et al. (2010) predicts that the convergence rate between the Northern Cordillera and stable North America should decrease to the south, which means that the present day deformation front may be harder to define there. What is the southern limit of present-day deformation associated with this inboard boundary? It may detectable through changes in structure, through microseismicity, or through additional GPS measurements. The northern limit of the inboard boundary is inferred to be a thrust fault located at the edge of the Beaufort Sea (Figure 5). Is this model correct, or is there active tectonism involving a larger part of the Arctic?

Associated Studies

The co-location of additional instruments with the TA package opens up the opportunity to convert the TA into multi-disciplinary observation sites. In addition to making new types of science possible, this may increase the likelihood of maintaining some of the TA sites for the long-term, as a permanent increase in the seismic network capabilities. **Especially promising co-located instruments and measurements include GPS, a surface meteorological package, and permafrost monitoring (downhole temperature).** The basic TA instrument package already has pressure measurements, with a surface meteorological package that could be augmented by temperature, humidity, wind, and precipitation. GPS adds measurements of surface deformation for many different signals, and also environmental monitoring (snow depth, vegetation height, soil moisture), estimates of integrated atmospheric water vapor, and space weather (TEC) measurements. Real-time or low-latency data delivery for multi-instrumental sites would be desirable, and would be required for some applications, such as assimilation of meteorological data into weather forecast models.

The logistical “hub” sites that IRIS proposes to use are obvious first candidates for additional instrumentation in both Canada and Alaska. IRIS field crews likely will be staying there, and the additional field time needed for other instrumentation likely can be provided within the time budgeted for bad weather at the “spoke” sites. Thus the cost for installing additional instruments may be minimal beyond the costs for instrumentation and materials. **We recommend that IRIS specifically prioritize these locations for multi-instrument sites. Very easy and inexpensive add-on measurements include MT observations and campaign GPS surveys. Installation of instruments for the long term would require more effort but should be considered. IRIS should explore the possibility of using these hubs as bases of opportunity for collaborative geological studies.** Probable Yukon hubs are Whitehorse, Haines Junction, Eagle Plains (EPYK), Carmacks, Haines Junction, Dawson City, Inuvik, plus likely one more. Meteorological stations are an obvious add-on to the basic TA package at these sites. In addition to GPS, MT, and meteorological measurements, greenhouse gas measurements or other such measurements could be considered at hubs.

Extra consideration for associated studies needs to be given to Canada-specific priorities, which have a chance of attracting significant funding from the Canadian side. These include earthquake hazards, minerals, permafrost, hydrocarbons, and climate/weather/met. Climate is a particularly big opportunity. IRIS needs to interface with key people in that community in Canada. Permafrost changes are another area of significant importance in Canada. Permafrost conditions depend on surface temp, precipitation, wind and other atmospheric conditions. Studies of permafrost need quantification of surface conditions and the subsurface response.

Addressing some Canadian needs and priorities would require expanding the network in some targeted locations. Such expansion would require additional resources, either from Canada or from FlexArray proposals. These include:

- Arctic coast east of Inuvik, extending to shield and to Arctic Islands
- Mackenzie Delta to Alaska North Slope across actively convergent margin
- Across Mackenzie Mountains (FlexArray plus Pascal Audet's array, GPS?)
- Greater densification in the Yakutat collision zone
- Better sampling in general onto the Canadian Shield

OBS deployments would be needed to address some targets. Promising OBS targets include:

- Seismicity in Beaufort sea – flexural breakage or incipient underthrusting/subduction?
- Seismicity on the active thrust belt along the Alaska/Canada Arctic coast.
- Image margin structure on the Arctic coast and on the Alaska side of the Yakutat collision.
- Linkage with active source efforts, which are being carried out in the Arctic Ocean to delineate the extent of the outer continental shelf for UNCLOS claims.

Breakout Group Discussion of Seismic Catalogs and Data Handling

This breakout group focused on identifying the data products required by the research discussed at meeting. A key objective is to obtain uniform capability across the whole area spanned by the USArray deployment. Given that multiple organizations are responsible for producing these products, a significant degree of coordination will be required.

Products

The basic data products that must be produced include:

- Teleseismic and regional phase arrivals with error bars
- Regional seismicity (arrivals, hypocenters, magnitudes)

While these products are currently produced by organizations in both Alaska and Canada, the combination of high seismicity rates and additional Earthscope stations require a clear plan to minimize overlap while providing uniform data products. Modifying procedures to create uniformity in processing, analysis and completeness will require significant coordination and collaboration among the organizations involved.

Techniques

The data products identified in the preceding section are used as input to a wide range of data analysis techniques and applications. Again, these applications are applied over the entire area encompassed by USArray in Alaska and Canada (and beyond), so it is critical that the input to these applications be as uniform as possible.

- regional travel-time tomography
- attenuation tomography
- Gutenberg-Richter based strain estimates
- focal mechanisms
- moment tensors
- statistical analysis (ie. B-values, earthquake decay curves, etc)
- relative hypocenter relocations
- rupture potential estimates
- seismic hazard
- probabilistic seismic hazard analysis
- earthquake swarms

Science Goals

Many of the key science goals identified in the workshop require products that can be realized through the application of the techniques enumerated above. These include:

- YK-Beaufort-North Slope seismic zone connections
- Incipient subduction versus sediment loading versus other processes in the Beaufort sea
- Microblock interaction in ak-sw yt (Yakatak block, fair-weather block, south-central alaska, st elias/wrangell block, etc) include Jeff's figure of micro-tectonic blocks
- Don Murphy's terrain boundary structure in the YT (affects current seismicity, important for velocity model boundaries)
- McKenzie mountain thrusting/active faulting parameters: Boundary between tedtonic and stable north america.
- Active faulting and Seismic potential of specific faults: Denali, Fairweather, Tintina, Duke River, Queen Charlotte.

Breakout Group Discussion of Outreach and Identification of Other Stakeholders

A general strategy for USArray-related outreach is to add context to existing outreach structures and efforts, rather than trying to create new structures. This is particularly critical given the relatively rapid rollout of the USArray effort in Alaska and Canada, and its finite duration. It was also noted that it is important to focus on a small number of outreach strategies to ensure impact, as opposed to spreading efforts too thin.

Several broad strategies were identified as a means to maximize outreach and broader impact. A strategy, well known in education and outreach efforts, is "teaching the teachers". Training teachers results in many more students impacted, over a longer period of time, than efforts to reach students directly.

It was also noted that many routine opportunities for outreach require good science communicators equipped with relevant and appropriate materials and information. These communicators do not need to be research scientists - the priority is on good communication. Towards this end it is important to **identify the outreach materials that are required and to make these available to project personnel** and others working with the project. **Consideration should be given to providing relevant training to these personnel in communicating the science information that is part of the project**.

Finally, it was noted that personal connections are important. When working in small communities the time must be taken to interact with villager residents and others.

The sections below provide an initial inventory of existing outreach-related structures and activities.

Identification of organizations that have active efforts / POCs in outreach

One key objective is to identify those organizations with well-established outreach programs. In Canada these programs and contacts exist at multiple levels.

- Yukon Geological Survey has an outreach lead (Sarah Laxton?); they have established contacts in communities.
- Yukon College (in Whitehorse, with satellite campuses elsewhere)
- Yukon Science Institute sets up public lectures on science
- Northwest Territories Geological Survey (correct name?) has an outreach contact (Diane Baldwin?) who works on community-based outreach programs, including a summer field experience.
- The Geological Survey of Canada has had people focused on outreach, including outreach focused around field activities.

Specific ideas for enhanced outreach impact

A variety of ideas were discussed for enhancing outreach as part of routine USArray operations or via specific activities aimed specifically at outreach.

- Where possible and appropriate the hiring of a local person for specific field assistance tasks can serve both project needs, achieve outreach impact, and build community engagement and interest.
- Engaging students in the geospatial/GIS aspects of the project could be an excellent way to build interest in the project and provide training in useful career skills. Such training might require that the necessary hardware and software be provided.

- Displaying real-time seismograms in schools is a good way to build student interest and engagement. Several strategies exist for doing this, including providing software, providing displays via the web, and providing display kiosks (which can be run on ordinary PCs). The existing IRIS '*Seismographs in Schools'* program could also be relevant in this environment. The high seismicity levels in / near the USArray deployments will ensure a steady stream of events of interest for real-time data feeds and school-based seismometers.
- Vladimir Romanovsky at UAF is very actively engaged in outreach around a field research project that is operating permafrost temperature probes in far northern Alaska. Evidently data from this project are being streamed into schools, so this may be a good opportunity for leveraging an existing activity.
- The Active Earth Display system (http://www.iris.edu/hq/programs/education_and_outreach/museum_displays/active_earth) provides a simple web-based delivery of Earth Science content that is particularly useful in school environments and informal education settings. Some number of these kiosks will be distributed as part of USArray, but the kiosks content can be run through an ordinary web browser and a "kiosk" can be created from with any PC with a touch screen display. Other science organizations can customize the AED content, or add locally specific content.
- It was noted that in many rural areas feasts are an important tool for bringing people together and creating an informal science education opportunity.

Meetings and events that may provide an opportunity for further outreach

- Equivalent of NSTA annual meeting in Canada (need to research the name & location)
- Yukon Geosciences Forum is good place to showcase USArray science and activities. This meeting includes an industry trade show, so is a good place to make contacts with industry regarding our science, and a good place to make contact with potential vendors. This meeting is held every November in Whitehorse.
- Northwest Territories Geoscience Forum – held in conjunction with, and is similar to, the YGF. This meeting is held in Yellowknife.
- 2014 Seismological Society of America meeting will be held in Anchorage.
- 2015 GACMAC (sp?) national meeting will be held in Whitehorse.

Logistical and Permitting Issues

Within Yukon, and to a lesser degree within the proposed area of the NWT there is existing data available from:

- GPS Campaign sites
- GPS CORS sites
- Seismic CNSN

- Seismic – Temporary

Figure 9 provides a general overview of these.

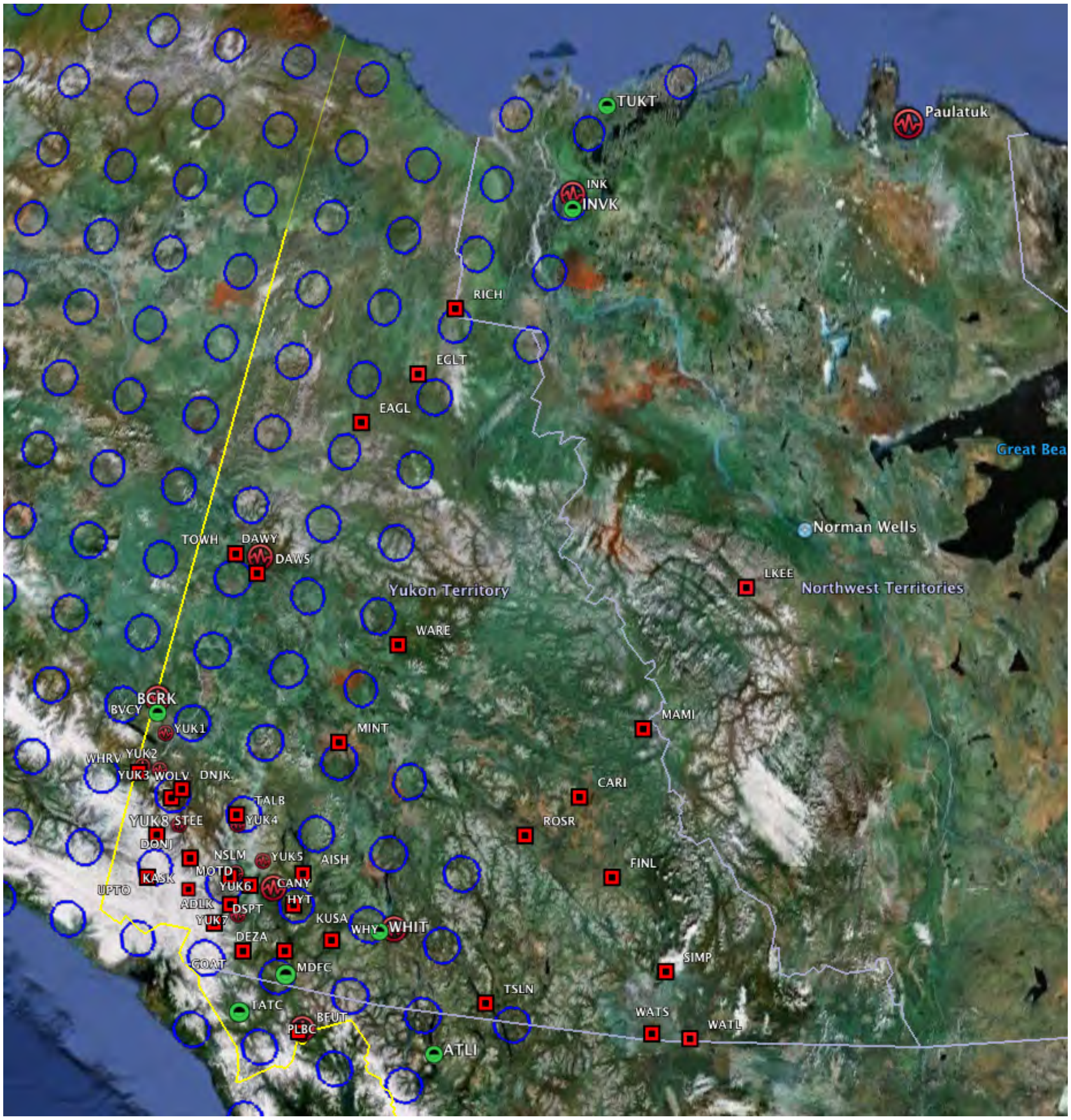
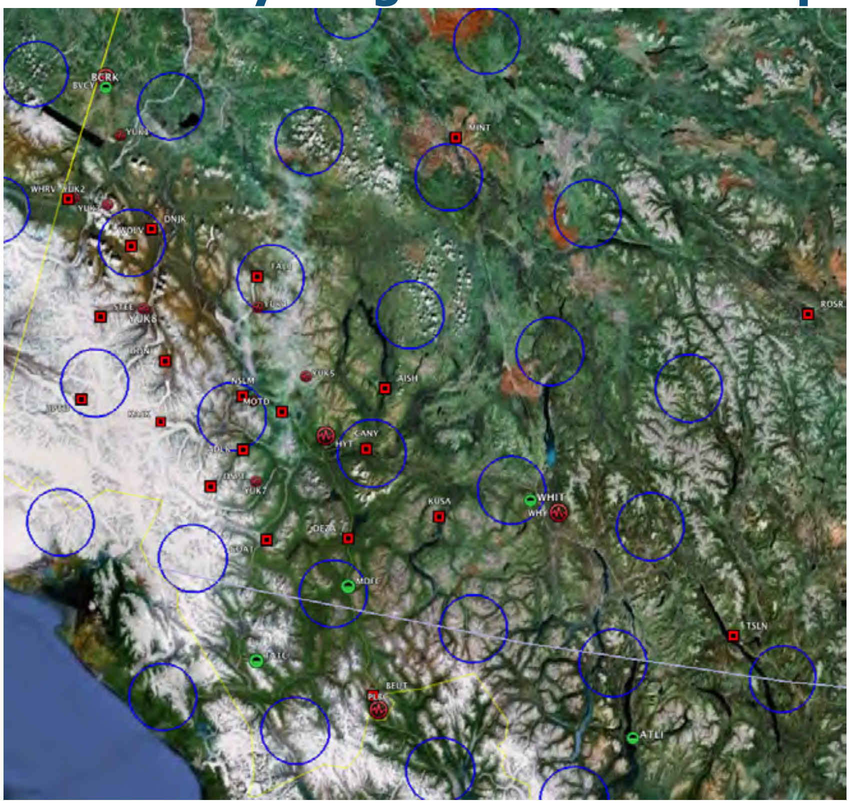


Figure 9. Existing seismic and GPS sites in the region. Blue circles are proposed TA stations, seismogram symbols are permanent seismic stations, red squares are campaign GPS, and green circles are continuous GPS.

The SW corner of the Yukon, one which in particular presents logistical challenges, there are considerable number of options that can be considered for TA sites, including a network of eight temporary seismic station (YUK sites) already on-line with line-of-sight communication as well as an extensive network of GPS campaign sites all with existing information available to facilitate the reconnaissance process (see Figure 10).

USArray Target Area – Overlap –SW. Yukon



- GPS Campaign Sites
- GPS CORS
- YUK Seismic Sites
- CNSN Sites
- Possible sites:
  - K30M: WARE
  - M28M: YUK1
  - M30M: MINT
  - N28M: WOLV
  - N29M: TALB, YUK4
  - O28M: UPTO
  - O29M: ADLK, YUK6
  - O30M: HYT, CANY
  - P29M: GOAT, DSPT
  - P30M: MDFC
  - P32M / Q32M: ATLI
  - P33M: TSLN
  - Q30M: TATC
  - O31M: WHIT/WHY
  - Other: (e.g. PLC, BCVY, ATLI, etc.)

Figure 10. Site overlap in the southwest Yukon. Symbols are the same as Figure 9. Specific site overlaps are listed to the right of the map.

Within the Yukon, NWTel operates a network of microwave repeater sites. While DSL is not currently available at most of these, NWTel is open to installing and providing hub linkages. Cost may be a barrier but follow-up is recommended.

First Nations Consultation and Permitting

As is demonstrated in Figure 11 the proposed TA deployment is within the areas of several Yukon and NWT First Nations. The red rectangle approximates the region proposed for TA deployment.

Particular attention will have to be paid to the consultation process with each First Nation as each will have concerns relative to their territory. These range in complexity based on cultural, environmental and other factors.

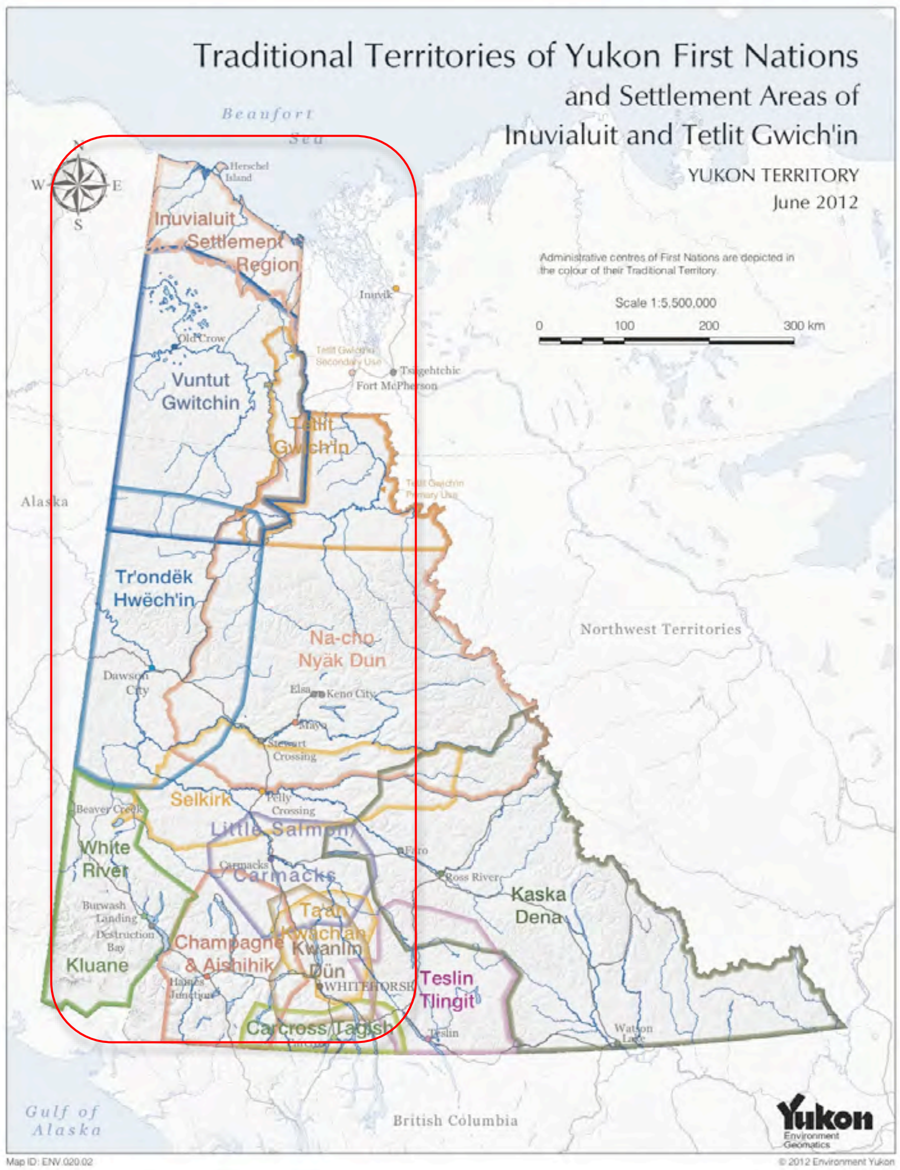


Figure 11. Map of traditional territories of First Nations in the Yukon Territory.

The permitting process in Yukon, includes the following organizations:

- Yukon Scientist and Explorers License, which falls under the Yukon Department of Tourism and Culture - http://www.tc.gov.yk.ca/scientists_explorers.html
- Requirements for Environmental Assessment falls under YESAB http://www.yesab.ca/ , the Yukon Environmental and Socio-economic Assessment Board, established under the *Yukon Environmental and Socio-economic Assessment Act* (YESAA).

- Additional permitting may be required under Yukon Land Services, Yukon Department of Energy, Mines and Resources. http://www.emr.gov.yk.ca/lands/index.html

Similar permitting processes, with different agencies exist for the NWT through the Aurora Research Institute http://www.nwtresearch.com/licensing as well as local community councils, Hunters and Trappers Associations, etc. (to be confirmed based on locations).

To facilitate the permitting it is recommended that a Canadian individual or agency, familiar with working in the Canadian north, First Nation protocols, and the permitting processes be engaged to help facilitate and ease USArray into the Yukon and NWT.

Hub / Spoke sites – concept of 'super' hub sites with multiple instrumentation packages

The concept of super hub sites with multiple types of instrumentation packages was discussed – the various types included GPS, meteorological, strong motion, etc. in addition to the "nominal" instrument package. It was recognized that this would involve multiple partners from academia as well as other institutes including for example, Environment Canada, Natural Resources Canada, and others. In the Canadian context, the idea (as with the permitting) to engage a Canadian individual or agency to help coordinate this was discussed.

Miscellaneous Other Logistical Topics:

- Customs clearances: the clearance of the Eagle Plains Instrumentation was facilitated through GSC contracted customs brokers. The lessons learned from this include:
    - Clear and timely documentation for broker;
    - Defining port of entry;
    - Documentation that provides the appropriate information to ensure the instruments are declared in such a fashion so as to avoid paying duties (geophysical and related instruments enter duty free – subject to confirmation by broker, etc.); some taxes may be payable;
    - Canadian contact would be useful here as well;
- Identifying Staging areas and contacts:
    - Some preliminary staging (ship to) locations identified include:
        - Whitehorse;
        - Haines Junction
        - Dawson City
        - Eagle Plains
        - Inuvik
- Hub Deployment Sites:
    - Discussion of optimizing deployments via "hub" staging areas;
    - To be determined / located;

- Identification of:
    - Roads and landing strips in the remoter regions;
    - Settlements, infrastructure with power and communication;
    - Aircraft charter companies (location, type of aircraft, contracting information);
    - Vehicle rental companies (as required);

Additional background and site information has been shared with USArray, including site photos, maps, etc..

Moving forward:

Required in the short term:

- Time frame and requirements for:
    - Reconnaissance and permitting;
    - Setting deployment priorities (regional: north or south?);
        - Currently there is more information available on deployment sites in southern Yukon and logistics are relatively easier here;
- Establish the Canadian point of contact and support for this project for practical issues as outlined above.
        - (This was proven particularly effective on recent (March 2013) reconnaissance trip to the NWT with both USArray and Canadian (GSC) personnel);

Conclusions

The USArray extension into Yukon, western NWT, and northern British Columbia provides an outstanding scientific opportunity for addressing important scientific targets in structure and tectonics. The wide distribution of seismicity will provide especially good sources for determining high-resolution seismic structure, and much more accurate earthquake location and characterization should substantially improve our understanding of the tectonics of this fascinating region that is bounded by two oceans-- strike-slip faulting, terrane collision, and long-distance transfer of deformation. Most of the most important geoscience targets cross the international border so international monitoring and study is essential. Many complementary measurements, monitoring and study have already been initiated or are planned, but much more can be done. The meeting provided the opportunity for discussion of scientific objectives by participants from a large number of groups, as well as initial discussions of the critical logistics, permitting, outreach and public communication.

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Attachments

Meeting Announcement

USArray-Canada Planning Meeting
19-20 February, 2013 – PGC, Sidney, BC, Canada

This meeting will present plans related to the proposed deployment of the USArray Transportable Array to Alaska and the Yukon (see www.usarray.org/alaska) and will bring together US and Canadian scientists to identify collaboration opportunities and key science targets and objectives with cross-border impact. The goal is to help all involved leverage the presence of the TA in Alaska and Canada and to enable USArray to continue refining deployment plans. Discussion will also encompass USArray Flexible Array and Magnetotelluric capabilities.

Attendees will contribute to a report / whitepaper that identifies key cross-border collaborative science opportunities that can leverage EarthScope activities in the Arctic region.

Agenda

Jeff Freymueller and Roy Hyndman, co-chairs

Tuesday, February 19

- Welcome, introductions, logistics (Roy Hyndman and PGC Director)
- US Array (program background, budget, instruments, spacing, etc.:
  Bob Woodward, USArray Director
- USArray: Operations, logistics, etc.
- Plenary session 1: Science context / inspirational / framing discussion
  - Roy Hyndman, Large scale curren tectonics and large scale crustal structure of the Northern Cordillera; areas of possible special focus
  - Jeff Freymueller and Lucinda Leonard: GPS and Active Deformation in Yukon and adjacent Alaska; also PBO *(Stephane cannnot attend)*
  - Garry Rogers/John Cassidy: Seismicity of the Yukon and adjacent Alaska, large events, earthquake mechanisms etc.
  - Taimi Mulder and Natalia Ruppert, Current Seismic Monitoring across the US-Canada border
  - Frank Vernon: seismicity; accurate locations to small magnitude, locations of active faults, stress directions, seismicity rates, relation to GPS-defined deformation, better seismic hazard characterization, etc.
  - Honn Kao, Noise tomography with USArray stations, what can be

obtained; previous work
    - Mitch Mihalynuk: Fundamental advancements in Cordilleran tectonic evolution - 3D tomographic images of fast domains beneath North America
    - STEEP project: Terry Pavilis?
    - Magnetotellurics, what has been done, what planned in area (Alaska MT person?; & Martyn Unsworth, Univ. Alberta?)
    - Large scale geological structures and tectonic history of Yukon and adjacent Alaska (Don Murphy Yukon Geol. Surv.)
    - Geological structures and tectonic history W. Northwest Territories (John Ketchum, NWT Geosci. Office)

Morning Break *(coffee etc. brought to outside of meeting room, by cafeteria contractor)*

- Plenary session 2: Existing and Planned Facilities
    - USArray
        - Transportable Array plans
        - Seismic Flexible Array; What can be done with it? Where? targets?
        - Magnetotellurics; what has been done, planned?
    - Plate Boundary Observatory (GPS), now in place and planned?
    - Other community (non-USArray) plans and/or activities
        - Stephane Mazzotti (cannot attend but sent GPS etc. plans)
        - Pascal Audet (Canadian Foundation for Innovation, CFI) funded seismic stations proposed for area to east
        - Yukon Geol. Survey (Don Murphy)
        - Northwest Territories Geol. Office (John Ketchum)
        - Offshore; what is being done, planned, proposed. Where stations needed; IODP-ICDP Kananaskis workshop for drilling across the Beaufort Sea margin
        - Industry

Lunch *(Hot buffet in cafeteria)*

- Feature: Recent Large Earthquakes – Haida Gwaii and Alaska Panhandle (Craig)
    - What we have learned (Garry Rogers, Jeff Freymeuller, others)
    - Implications for USArray planning
    - Possible summary of Denali M7.9 earthquake work?

- Plenary Session 3: Science Pop-ups
    - Five-minute talks on any aspect relevant to meeting (facility, plans, science, etc.)

- Plenary Session 4: Framing for the breakout
    - Some ideas
        - This will be a huge investment – how do we maximize the impact?
        - Perhaps framed as an inventory of topics that should be considered
        - Geographic based

        - Discipline based
        - Impacts?
        - Thinking ahead to legacy of this project 10 years from now

- Charges to breakout groups
    - Talk that leads into charge (big questions)
    - What does IRIS need for this report? Guide preliminary investigations and set stage for larger collaboration.
    -

Afternoon Break

- Breakouts
- Yukon logistics breakout (Mike Schmidt, Don Murphy et al.)

Some ideas for breakout topics:

1) International collaboration
2) Identifying and engaging other stakeholders
    a. extractive industries
    b. federal / state / provincial / local agencies and organizations
    c. other science communities
3) Leveraging USArray plans and activities
4) Science motivators and potential for synergistic multidiscipline aspect
5) Recommendations to US and Canadian funding agencies
6) Funding opportunities
7) Outreach opportunities

Wednesday, February 20

- Report on breakouts, discussion

Break

Organizing writing committee

The way forward, group brainstorms next steps

Lunch *(buffet day at cafeteria)*

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