Introduction

We propose complementary EarthScope (USArray/PBO) investigations of a broad region of south-central Alaska from Cook Inlet to Denali (Mt. McKinley), with focused studies to address: 1) the relationships between subduction zone seismicity, strain transients, and volcanism, 2) the nature of mountain building near, and away from, Denali – the tallest peak in North America, and 3) forearc basin crustal structure, evolution, and seismic hazards.

In south-central Alaska, the Pacific Plate is sliding to the NNW past southeastern Alaska on the Queen Charlotte-Fairweather transform fault and then is subducting beneath southern Alaska at a rate of about 5.5 cm/yr on the Aleutian megathrust. In the region between the Queen Charlotte-Fairweather transform and the Aleutian megathrust, a microplate, the Yakutat terrane, is colliding with the southern Alaska margin. Northwesterly GPS-determined velocities of 4.6 cm/yr demonstrate that the Yakutat terrane is mostly attached to the Pacific Plate. Collision of the Yakutat terrane is inferred to be the cause of rapid and high uplift of the eastern Chugach-St. Elias Mountains, faulting in interior Alaska along the Denali and Totschunda fault systems, uplift of the highest part of the Alaska Range, and deformation in, and extrusion of, the forearc to the southwest. These far-reaching effects of the Yakutat terrane collision are superimposed upon normal subduction zone earthquake and volcanic processes. The 1964 Mw 9.2 earthquake was the second largest earthquake ever recorded and the last significant subduction zone earthquake in this region, where an 800-km long patch along the megathrust slipped an average of 10 m. There are several active volcanoes along the magmatic arc in this region including: Illiamna, Redoubt, Double Glacier, Spurr and Hayes Volcanoes. Although there is subducted slab east of the volcanoes in the Denali region, there are no volcanic edifices until much further east in the Wrangell volcanic field, with the exception of a small maar.

This area is ripe for more detailed EarthScope studies. It is one of the few in North America where substantial background work has been done, but many first-order questions remain to be resolved. Various university and
USGS research groups have examined aspects of the regional geology, deformation field, uplift history, paleoseismology, volcanology, volcano seismology, forearc basin deformation, subduction zone slip and seismicity, historical seismicity, and potential field geophysics. EarthScope data can provide the critical information needed to answer those questions.

Moreover, because of the active tectonic setting of south-central Alaska, it is the best place in the United States to understand volcanism, subduction zone earthquakes and strain transients, mantle flow, near-field and far-field deformation from terrane collision, and mechanisms of mountain building. The proposed studies would be strongly complimented by the proposed EarthScope studies of the Yakutat region (Freymueller, Haeussler, et al.). The proposed scope of studies do not cast as broad a net around as many different volcanoes and subduction zone asperities as the proposed EarthScope study of Aleutian volcanoes (Power et al.). However, this study would be complimentary because it will examine controls on ascent and emplacement of magmas in regions where there are, and are not, Quaternary volcanoes, despite a subducting plate beneath both regions.

**Goals**

We propose two focus areas within the larger south-central Alaska region: Denali and upper Cook Inlet. Below, we discuss the scientific issues relevant to both regions, although the general approach to both would be similar: deploy seismometers and GPS instruments across the region of interest with more instruments in areas of greater focus. The backbone network of permanent GPS sites, which is focussed on seeing strain transients associated with the subduction zone, would be augmented by campaign GPS. And the backbone seismometer network operated by the Alaska Earthquake Information Center (AEIC) and the Alaska Volcano Observatory (AVO) will be augmented by the ANSS (Advanced National Seismic System) and USAArray instruments.

**I. Cook Inlet focus area**

South-central Alaska is the population and infrastructure center of Alaska. It has significant natural hazards from Cook Inlet volcanoes, and subduction zone and crustal earthquakes. Anchorage lies on the margin of the Cook Inlet forearc basin, which has been an active oil and gas province for 40 years. An EarthScope project in this region
would necessarily have numerous goals, primarily focussed on earthquake hazards, forearc basin evolution, and controls on ascent and emplacement of magmas. Previous studies on forearc basin geology and potential field geophysics, crustal, Benioff zone, and volcano seismicity lay a strong foundation for further studies in the area. Goals and important scientific questions include:

- Observing transients in subduction zone aseismic slip and understanding their relationship to updip seismicity
- Understanding forearc basin development and evolution
- What is the origin of crust beneath the Cook Inlet basin? It is highly magnetic and conductive, but has low density and thus is probably serpentinite. Is it trapped and altered oceanic crust? Underplated mafic magmas?
- What is the nature of shallow seismic sources, and their relationship to mid-crustal seismicity between 15-30 km depth in the forearc basin? A similar pattern of seismicity is in Puget Sound. Because great subduction zone earthquakes have recurrence intervals of roughly 700 yrs, these crustal faults may constitute a greater short-term seismic hazard to south-central Alaska than subduction zone earthquakes.
- What is the tectonic setting of Cook Inlet volcanoes – are they located on crustal faults?
- Can magmas be identified beneath Cook Inlet volcanoes?
- What are the flow directions in the mantle wedge and surrounding the volcanic axis?
- Can refined tomography of the Benioff zone delineate changes in slab dip associated with mineral phase transformations?
- What is the orientation of the stress field? How does it relate to strains measured with GPS?

**Strategy**

To address the issues raised above, tomographic images are needed of the downgoing slab, the mantle wedge, the forearc basin, and the magmatic arc. The existing AEIC network is not even remotely dense enough to answer these questions. The flexible part of USArray would augment the bigfoot array and provide infill for increased resolution. Passive sources would be primarily used, but active sources would be needed in a few key areas, such as across the axis of the volcanic arc and across the Cook Inlet basin. Logistics are easiest in this area of all the proposed Alaskan studies. The Alaska Wadati-Benioff zone is highly productive, so it should be possible to study the mantle wedge above the slab using earthquakes generated within the slab. Comparing measurements of, for example, anisotropy, made using slab events and teleseisms should make it possible to separate anisotropy coming from within the mantle wedge from anisotropy coming from the rest of the mantle.

The PBO will have ~50 (37 in the 1964 rupture zone plus another 10 or so from the backbone) permanent GPS sites in this region, which will augment the 3 already installed by the UAF/GI. The PBO network is focused on the goal of observing strain transients and postseismic deformation in the 1964 earthquake rupture zone. It is not dense enough to study in detail active structures in the overriding plate, and in fact it will be substantially less dense in the road-accessible areas than the present UAF campaign GPS network. The PBO network will need to be densified through either more permanent sites or campaign measurements in order to maintain the spatial density required to study faults in the overriding plate. The PBO network will be critical in separating time dependent deformation from transient processes from the steady state deformation. Campaign GPS will be necessary to augment the permanent sites, and more sites off the road network (and particularly on the NW side of Cook Inlet) are required.

The new geophysical measurements would be integrated with growing potential field and seismic reflection datasets, as well as with new geologic mapping being conducted in the region.

**Results**

Primary results from the investigations would include:

- GPS velocities in the region where strain transients above the subduction zone have been observed. There is a high likelihood of observing further transients.
- New tomographic models that would illustrate the downgoing slab and Yakutat terrane (if present), the overlying mantle wedge, the magnetic and low density crust beneath the forearc basin, the forearc basin sediments, and the roots of the western Alaska range.
• Seismicity maps and focal mechanisms that would help to identify: structures that control the location of the Cook Inlet volcanoes; deep-seated structures beneath young fault-cored folds in the Cook Inlet basin; and whether there is seismicity along the front of the Alaska Range southwest of Denali.
• A map of the state-of-stress in the crust. This will result in an improved understanding of stress and the location of Cook Inlet volcanoes and crustal structures, as well as the relationship between overpressured zones in oilfields and regional stresses.
• An improved understanding of the rates of forearc basin deformation and its origin and evolution.

Figure 3. North America’s tallest mountain, Denali (Mt. McKinley) from the north. It is 20,320 ft. tall and has 17,000 ft. of relief. Surrounding peaks are around 9,000 ft.

II. Denali focus area

The Denali focus area would examine mountain building in the highest mountains in North America and the regional deformation producing these mountains. There are two primary mechanisms for building mountains: 1) a deep-seated mechanism in mountain ranges where tall summits are roughly at the same elevation (i.e. the Sierra Nevada in California, the Rocky Mountains in Colorado, the Chugach-Kenai Mountains in Alaska, and the Talkeetna Mountains in Alaska). Coulomb-failure models appear to accurately describe the topography of such mountain belts. 2) A shallow mechanism in which a few summits are much taller than surrounding peaks. Examples include Nanga Parbat and Namche Barwa in the Himalaya and Denali (aka, Mt. McKinley) and Foraker in the Alaska Range, which are 3-4 km above surrounding peaks. In all cases, crustal faults that accommodated the uplift have been identified or suspected. It has recently been proposed that downcutting on the Indus-Tsangpo River system drives the uplift of Nanga Parbat and Namche Barwa, as well as young metamorphism and magmatism, forming a “tectonic aneurysm.” Beneath Nanga Parbat there is also a decrease in the depth to crustal earthquakes and a low velocity zone beneath, indicating advection of heat to the Earth’s surface during uplift. An investigation of crustal structure, velocities, and rates of deformation around North America’s tallest mountain will help to identify what processes are responsible for uplift of the Denali massif in Alaska. A comparison of results to those in the Himalaya would help to identify which factors influence uplift of massifs above surrounding peaks.

The role of the Denali fault in the deformation of interior Alaska and uplift of the Alaska Range also needs to be examined. It has been proposed that motion on the Denali fault in central Alaska, and reduced or no slip on the western part of the Denali fault, west of the Denali massif, is taken up by uplift of the Alaska Range. Campaign GPS data along two highway transects across the fault, 100 and 200 km east of the Denali massif, show that the western part of this right-lateral fault system is moving faster (10±2 mm/yr) than the eastern part (6±2 mm/yr). This result is enigmatic—it is opposite what is expected by the mechanism described above. Could this be explained by a version of the “tectonic aneurysm” model? Or could both the uplift and possible changes in the rate of strike-slip motion be
driven by forces related to the westward extrusion of western Alaska? Or is the uplift of Denali and changes in the Denali fault slip rate due to the interaction of the right-lateral Denali fault and rotating blocks to the north? Or could it be due to coupling between the crust and mantle, and mantle flow drags the western part faster? The regional extent of this pattern of deformation, and the mechanism that is driving it, needs to be investigated.

North of the Denali fault is a young northward-propagating fold and thrust belt. Initial geologic studies demonstrating deflection of streams around the Kantishna Hills and tilting of stream terraces are underway, as are earthquake seismology studies that are beginning to image the master faults at depth. GPS measurements show that strike-slip motion on the Denali fault system must be distributed, with some strike-slip motion occurring within the fold and thrust belt. A recent sequence of M~5.5 earthquakes also show activity on a right-lateral strike slip fault parallel to and well to the north of the Denali fault. What is the relationship between the strike-slip faults and the fold and thrust belt? An understanding of strain partitioning, and the relationship of this area to the Denali fault to the south, will require detailed investigation of crustal structure and velocities.

In addition, this region has a major volcanological puzzle. Arc volcanism in Alaska is strongly correlated with the 100-km depth contour of the Benioff zone. However, in the Denali area there is a distinct lack of volcanism above the slab (the “Denali volcanic gap”). This gap has been attributed to extensive de-watering in the very wide ‘arc’-trench gap, possibly caused by infertile slab lacking the necessary fluids for arc magma generation, or a thick continental crust under the Alaska range that inhibits the rise of arc magma.

**Strategy**

To address the issues raised above, both seismological and geodetic studies are required. GPS data from the backbone network of permanent stations would be augmented by campaign GPS to determine the regional velocity field. The PBO network around the Denali fault consists of only a handful of sites beyond the ~200 km spacing of the backbone network. Campaign GPS sites observed over a period of several years to a decade should be able to resolve along-strike changes in the slip rate of the Denali fault. This would be compared to seismotectonic maps that would better identify the location and types of structures that accommodate deformation. Tomographic images are needed of the subducting plate, the mantle wedge, and the crust. The existing AEIC/AVO network is not even remotely dense enough to provide the detail needed. The flexible part of USArray would augment the Bigfoot array and provide infill for increased resolution of earthquake locations and tomographic models. Passive sources would be primarily used, but active sources would be needed in a few key areas. Shear-wave splitting studies would also be conducted to determine the relationship between GPS determined velocities and mantle flow directions. It will be important to examine if there is evidence for 2-D entrained flow associated with the subducting slab, the relationship of mantle flow to crustal roots and to the subducted part of the Yakutat terrane, and to evaluate coupling between the crust and upper mantle.

**Results**

Primary results from the investigations would include:

- A map of GPS-determined crustal velocities in, and around, the region of rapid uplift and major faults.
- A new tomographic image beneath the Denali region would help to define the thermal state of the shallow crust from the slab to the region of rapid uplift.
- Studies of seismicity would identify which shallow and deep structures are responsible for young uplift of the highest topography of the Alaska Range and surrounding regions, and would help us to examine if the base of crustal seismicity is anomalously shallow beneath the high peaks.
- Maps that would better characterize seismicity around Denali, on the Denali fault, and in the northward-propagating Kantishna fold and thrust belt, north of Denali.
- Studies of Poisson’s ratios would help to identify if there are regions with magma ponded in the crust, and if any earthquakes are low frequency ‘volcanic’ events.
- Shear-wave splitting studies would show the relationship between mantle flow, the subducted slab and Yakutat terrane, and crustal motions.