How do Terranes Accrete? EarthScope should study North America's actively accreting terrane

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Introduction

Terrane accretion was arguably the most significant geologic/tectonic process affecting western North America during the Mesozoic and Cenozoic, and perhaps long before. Accretion of island arcs and continental fragments represents one of the fundamental mechanisms of continental growth, with numerous examples dating back to Archean time. Most of Alaska and much of western North America consists of accreted terranes. But how exactly do terranes accrete? What are the dominant mechanisms that control where relative motion between the accreting terrane and continent will occur? What is the structure in three dimensions of the accreting terrane and its continental "host"? How is a terrane transferred from oceanic to continental crust? What is the role of the lithospheric mantle, and what happens to this mantle when there is significant shortening in the crust? What determines the balance between transcurrent motion (pre-, syn-, and post-accretionary) and shortening? What roles do localized and regional uplift play in the development of crustal structure? And finally, what effect does erosion have?

Many accreted terranes and terrane boundaries in North America have been studied thoroughly, through a variety of geological methods and geophysical methods like deep seismic reflection. However, North America's one example of active terrane accretion has not received enough attention. The Yakutat terrane is located in the cusp of the southern Alaska margin between the Queen Charlotte-Fairweather transform fault system and the Aleutian megathrust (Figure 1). Geologic evidence suggests the terrane started colliding with North America around 20 Ma, and GPS geodetic data indicate that it is moving about 45 mm/year relative to North America, slightly slower than the Pacific plate and in a significantly more northwesterly orientation; the Yakutat terrane has significant motion relative to both the Pacific and North American plates. The Yakutat terrane is bounded on the north and northeast by the largest area of high elevation in all of North America, the eastern Chugach-St. Elias Mountains, where peaks reach almost 20,000 ft elevation, and the Fairweather Range, with several peaks above 15,000 feet.

Data from the EarthScope facility, combined with geologic and other studies, will provide critical new data that will allow us to understand how the Yakutat terrane is being accreted, where deformation is focused, and develop a mechanical model for its accretion. Such a model can then be tested against the geologic record left by older accreted terranes. We must be able to explain the sequence of events that have led to the present geological structure, the forces that cause deformation to be localized in particular places, the horizontal and vertical motions that result from the interplay of forces and rheology, and the implications of these motions. By developing a complete understanding of this actively accreting terrane, we will also gain insight into what controls the initiation of subduction and the structures left behind as subduction jumps from the leading to the trailing edge of the terrane. Ancient examples of accreted terranes are always modestly to deeply eroded; studying a modern example will allow us to see features that are no longer present in older terranes.

Current Observations

A number of key observations have already been made that bear on the questions raised here. To the best of our knowledge, all of these observations have yet to be synthesized into a complete tectonic model.

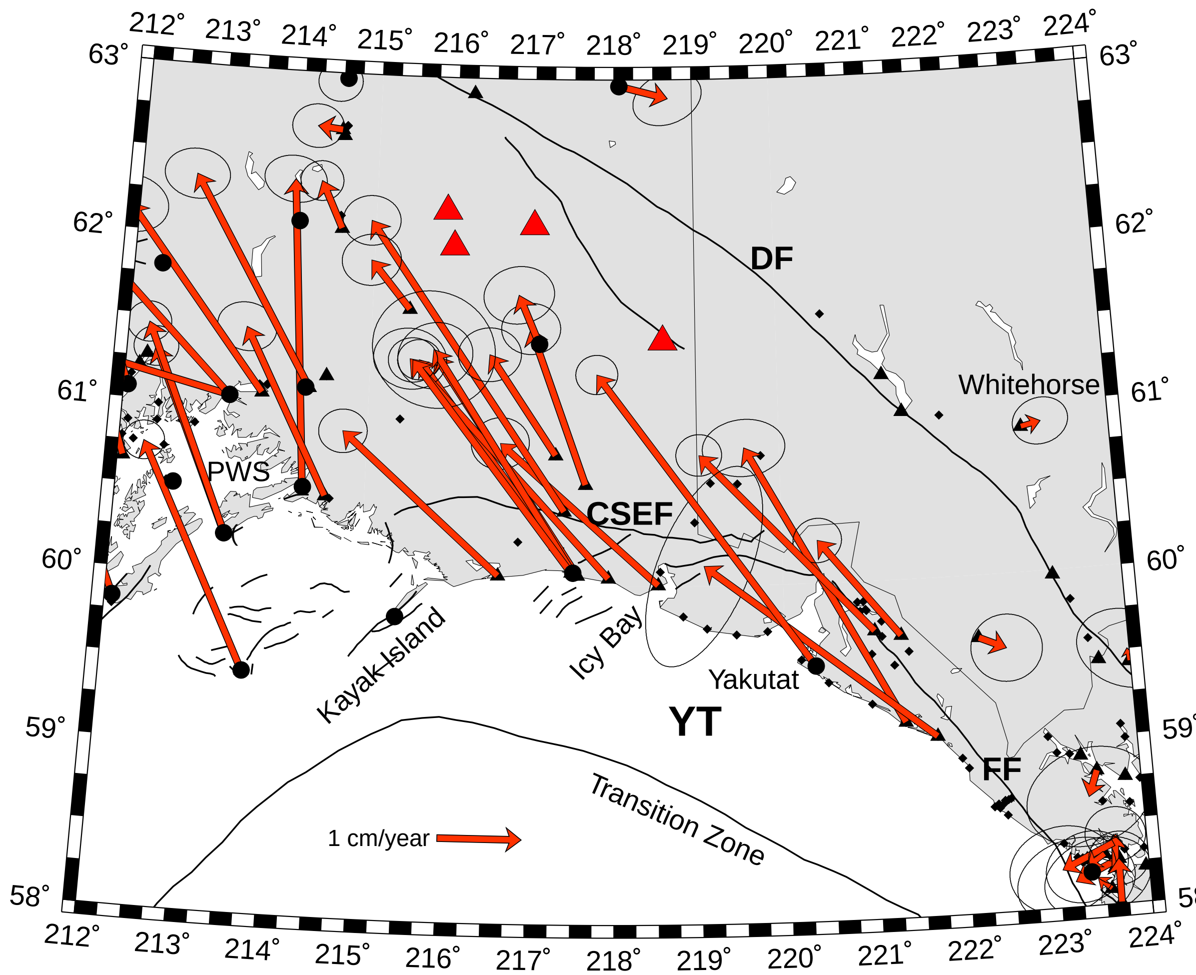

Figure 1. GPS velocities, major fault systems of the area of the Yakutat terrane collision. The area covered by the map is roughly 550x750 km. YT, Yakutat terrane; PWS, Prince William Sound; CSEF, Chugach-St. Elias faults; FF, Fairweather fault; DF, Denali fault. The large red triangles in the upper middle part of the figure show the Wrangell volcanoes. GPS velocities are shown relative to North America, with 95% confidence ellipses. Small circles and triangles are additional GPS sites with no or very imprecise velocities, and black circles are proposed PBO continuous GPS sites (17 within this area). Vertical component short-period seismic stations are distributed along the CSEF and near the town of Yakutat, and the eastern part of the map is largely uninstrumented. Only three broadband seismometers are operational within the area of the map.

Geologic Setting and Crustal Structure

The Yakutat terrane (Figure 1) is bounded on the northwest by the Fairweather fault, a strike-slip fault that accommodates most of the Pacific-North America relative plate motion in the area. The Fairweather fault cuts through the base of the Fairweather Range, with the elevated topography on the North American side of the fault and low topography on the Yakutat side. Rocks on the Yakutat side make up a Mesozoic accretionary complex that underwent subduction zone metamorphism/deformation in late Cretaceous-early Tertiary time. On the north, the terrane is bounded by a series of thrust faults in the eastern Chugach-St. Elias Range, sometimes termed the Chugach-St. Elias faults. South of the Chugach-St. Elias faults, the Yakutat terrane is deformed by a series of NE-striking fold and thrust belts, the westernmost of which (the Kayak Island Zone) corresponds roughly with the eastern end of the Aleutian Megathrust. The terrane probably is bounded on the south by the Transition Zone, a bathymetric feature that has been interpreted variously as an inactive fracture zone [Bruns, 1985] or a thrust fault, which represents the beginning of subduction of Pacific plate beneath Yakutat [Perez and Jacob, 1980]. Although seismicity at the SE end of the Transition Zone and the GPS results (see below) suggests that it acts as a thrust fault, little-deformed sediments drape over parts of the feature, so the Yakutat-Pacific relative motion might be accommodated on an unknown structure or through large-scale deformation of the Pacific plate.

To the north of the Chugach-St. Elias Range lie the Wrangell Mountains, a series of four large arc volcanoes that are presumably related to a poorly-defined Wadati-Benioff zone that dips to the northeast. These volcanoes had Miocene to Pliocene volcanism with one of the highest rates of magma production in a volcanic arc on Earth. The volcanoes are still active today, but at a lower level of productivity. The reduction in volcanic productivity appears to coincide with the initiation of Yakutat terrane collision, which suggests that the Wrangell slab is the remnant of an ocean basin that once separated North America from the Yakutat terrane. According to some (e.g., von Huene et al. [1999]), the western boundary of the Yakutat terrane (on the surface) is moving eastward with time as the terrane is partially subducted.

The TACT seismic line in eastern Prince William Sound [Brocher et al.,1994; Fuis et al., 1991] ran north-south just beyond the western edge (on the surface) of the Yakutat terrane. TACT data have been interpreted as evidence for the existence of a three-plate “sandwich” beneath Prince William Sound, with a thin sliver of North American forearc on top, the Yakutat terrane crust dipping shallowly (~3°) beneath it, and Pacific oceanic crust beneath the Yakutat crust [Brocher et al., 1994]. The Slope Magnetic Anomaly, a prominent magnetic lineation in the Yakutat crust, can be traced westward beneath Prince William Sound for 220 km west of its last exposure on the surface [Bruns, 1985; Griscom and Sauer, 1990]. In this interpretation, argued for by the TACT group and von Huene et al. [1999], in Prince William Sound the leading edge of the western Yakutat terrane is still subducting beneath North America, and the seismogenic interface responsible for the eastern asperity of the 1964 Alaska earthquake may be the North America-Yakutat terrane interface. The relationship between the Yakutat crust and North American crust further to the east is poorly known, but at the eastern boundary of the terrane, the Fairweather fault is a mature, vertically-dipping fault with essentially pure strike-slip motion.

Kinematics

Kinematic data derive from measurements or inferences of rock uplift, and from three-dimensional instantaneous velocities measured by the Global Positioning System (GPS). Quantitative fault offset data in this region are quite limited, and fault slip rates are poorly constrained, if at all, by geologic observations. GPS velocities (Figure 1) show that the Yakutat terrane moves differently from both the North American and Pacific plates. Relative to North America, GPS sites on the eastern part of the Yakutat terrane all move parallel to the Fairweather fault. The velocity of the site at the town of Yakutat is 46 mm/year toward N28°W, roughly equivalent to the full Fairweather-parallel component of the Pacific–North America relative plate motion [Fletcher and Freymueller, 1999].

The Fairweather-normal component of relative plate motion must be accommodated offshore; if any onshore features were responsible for significant Fairweather-normal shortening, sites outboard of those features would be observed to have a convergent component that is not seen. Fletcher and Freymueller [1999], following the suggestion of Perez and Jacob [1980], suggested that the Transition Zone was the most obvious structure accommodating the Yakutat–Pacific relative motion. If this is true, slip is probably largely uncoupled, with slip being dominantly aseismic [Fletcher and Freymueller, 1999]. In this interpretation, the Transition Zone would be, in essence, an incipient subduction zone already undergoing slow subduction and presumably in the future would become the Pacific-North America plate boundary. However, there is clear evidence for deformation of the Pacific plate, in the form of two magnitude 7.7 strike-slip earthquakes in 1987 and 1988, so the southern boundary of Yakutat terrane remains in doubt.

The GPS data show that the NW-directed relative motion between the Yakutat terrane and North America must result in an exceptional rate of shortening within the Chugach-St. Elias Range. North of the range, the region south of the Denali fault moves several mm/year and rotates counter-clockwise (Figure 1). Close to 40 mm/year of shortening must occur between Yakutat and this rotating block (termed the Wrangell Block by Lahr and Plafker [1980]). Although GPS data in the western Yakutat terrane and the area to the north was modeled by Sauber et al. [1997] in terms of strain resulting from offshore subduction, it is clear from the motion of the GPS site in Yakutat that at the eastern end of the Chugach-St. Elias Range there must be ~40 mm/year of contraction within the continental crust [Fletcher and Freymueller, 1999]. Such a rate is one of the highest contraction rates within continental crust anywhere in the world, and is twice as large as the rate of shortening currently accommodated within the Nepal Himalaya [Bilham et al., 1996; Larson et al., 1998].

Such a high rate of shortening is, of course, accompanied by extremely rapid uplift. Mt. St. Elias is one of the steepest mountains anywhere on the planet, rising to a peak of 17,980 feet with its summit only 25 km from tidewater. Inboard lies Mt. Logan, at just over 20,000 feet the second highest peak in North America and a truly massive hulk of rock. However, rapid uplift is not confined to the high mountains. In Icy Bay, near the foot of Mt. St. Elias, the Yakataga anticline is exposed. This anticline is rooted shallowly (~3 km), and is topped by roughly flat-lying sediments [Broadwell, 2001]. Although there are no precise dates for these rocks, the anticline and sediments that overly it are Pleistocene in age (~1 Ma), and were deposited at a water depth of ~4 km. The undeformed and essentially flat-lying rocks above the anticline have been uplifted ~5 km in the last ~1 Ma, suggesting a minimum regional uplift rate of 5 mm/year, as the timing of the uplift is unknown. GPS data from Cape Yakataga, ~100 km to the west, show rapid present-day uplift of 15 mm/year, Higher uplift rates (up to ~40 mm/year) are observed in areas farther east where rapid glacial melting dominates the uplift signal [Larsen et al., in prep.], and the contribution of uplift due to unloading and tectonic uplift at Cape Yakataga is not clear at present.

Critical Questions

Numerous first-order questions about the nature of the Yakutat collision can be addressed by Earthscope:

• How does the structure of the North America–Yakutat–Pacific “sandwich” change from the west, where it has been imaged through the TACT line, through the Yakataga coast where the surface geology is dominated by shallowly-dipping uplifted marine sediments, to the St. Elias-Logan area where the topography is highest, and then to the Fairweather fault. What is the configuration of the subducting Pacific plate beneath the Yakutat terrane? What are the motions of the three plates in 3D?

• Where is strain being accommodated in the collision zone? Which structures are most active? Where are microplate boundaries? Some poorly constrained seismicity suggests the Duke River thrust is a key element, there may be a fault beneath the Bagley icefield, and the Kayak Island zone, but there must be numerous additional structures. The northern extent of the collision zone is unconstrained, although it must lie within the Chugach-St. Elias Range.

• How much internal deformation occurs within the trailing edge of the Yakutat terrane? Is this internal deformation shallowly or deeply rooted? How is this related to the transition from subduction in the west to continental collision in the east?

• Why does the entire Yakutat block, or much of it, appear to be undergoing extremely rapid regional uplift? What drives this uplift? Is it purely a result of internal shortening (even in the areas where surface sediments are only weakly deformed), or is the uplift driven by a deeper cause?

• What factors control the partitioning of strain in the Pacific – Yakutat – North America plate boundary zone? In particular, what drives the almost perfect partitioning of Pacific – North America relative motion along the eastern boundary of the terrane, which results in essentially pure strike-slip motion on an onshore fault and contraction normal to that offshore? Is this a feature common to all terrane accretions where the plate convergence is oblique?

• What is the relationship between collision of the Yakutat terrane and magmatism in the Wrangell Mountains? Is there evidence for magmas at depth?

Strategy and EarthScope Measurements

Data from both PBO and USArray will be critical in allowing us to answer these questions. In addition, EarthScope facility data would help to focus future geologic studies. Geologists (Plafker, Pavlis, Bruhn) have attempted to constrain which structures accommodate contraction at the northern edge of the terrane and have thus far been unable to identify a singular structure or group of structures. The Bagley Icefield lies at the northwestern limit of the Fairweather fault, and it may hide a thrust or strike-slip fault beneath it. Glaciers may hide critical structures in the collision zone, and the motion on these structures will only be clarified by GPS studies. In other cases, faults with significant offsets can be identified, but the timing of fault motion cannot be constrained because suitable young features do not exist. Thus, GPS velocities and high-precision earthquake locations will play a critical role in identifying the active structures. Geomorphic studies of erosion and uplift are underway, and the region has been identified as an associated study area for the MARGINS Source to Sink program. Seismicity and GPS studies will greatly help in narrowing down which structures are active.

Focal mechanisms and moment tensors of well located earthquakes are required, along with tomographic images are needed of the Yakutat terrane, the subducted Pacific plate, the mantle wedge, and the Wrangell magmatic arc. Shear-wave splitting studies would clarify the interaction between the mantle, the subducted slab and its margins, and the roots of the mountains. Receiver functions could clarify the depths to significant velocity boundaries. The existing permanent seismic network is not even remotely dense enough to answer these questions, and consists almost entirely of vertical component, short-period instruments. The eastern boundary of the Yakutat block is almost completely uninstrumented. The flexible part of USArray could augment the Bigfoot array and provide infill for increased resolution. Active source experiments should be considered.

The present plan for the PBO has only a limited number of continuous GPS sites in the region (Figure 1). The proposed PBO network is much more sparse than the limited campaign GPS network, and will be inadequate for resolving important kinematic issues. Some additional continuous GPS sites are justified. However, in much of this area the annual snowfall is many tens of feet (possibly one of the highest precipitation rates in the world), and seismic stations are known to be buried (deeply) in snow every winter, re-emerging with the summer melt. Given that in many locations a GPS site or survey mark would be buried under many feet of snow for months each year, survey-mode GPS is likely to be just as effective as continuous GPS and less expensive. Note that in much of this area, helicopter is the only means of access to sites. We believe that a dense survey-mode GPS network is called for, supplemented by a continuous GPS network dense enough to be capable of measuring seasonal signals that might otherwise contaminate the infrequent survey-mode measurements. Strain rates are expected to be large.

Primary results from these investigations would include:
• Tomographic and structural models that would image: the geometry of the subducting Pacific plate, the Yakutat terrane and its crustal structure, and the mantle wedge beneath the Wrangell Mountains.
• Maps of focal mechanisms and hypocenters that would define the boundaries of crustal blocks, the nature of fault motions, and locations of actively deforming regions.
• An understanding of the relationships between GPS determined velocities, plate boundaries, mantle flow directions, state-of-stress, active faults, deforming regions, and volcanic centers.

These data will allow the formation of a conceptual model for the accretion of the Yakutat terrane and its boundaries, which will spur comparative studies with other collisional orogens.