Geophysical insights into the Transition fault debate: Propagating strike slip in response to stalling Yakutat block subduction in the Gulf of Alaska

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ABSTRACT

On the basis of faulting mapped on seismic reflection and bathymetric data, seismicity, current plate motions, and evidence that the Yakutat block may be anomalously thick, we propose a tectonic model for Yakutat-Pacific interactions, including the often-debated Transition fault. To the east, deformation associated with the Queen Charlotte–Fairweather fault system is extending offshore, facilitating westward propagation of strike-slip motion along the eastern segment of the Transition fault. To the west, the oblique-slip Pamplona zone and Transition faults merge at an embayment in the continental margin, where a north-south dextral strike-slip fault within the Pacific plate, illuminated by the 1987–1992 earthquake swarm, intersects the Pacific-Yakutat tectonic boundary. These fault patterns are consistent with modern plate motions and reflect a plate boundary reorganization that may be caused by resistance to subduction by the Yakutat block, a possible moderate-sized oceanic plateau.

Keywords: collision, Alaska, Yakutat, oceanic plateau, Transition fault, subduction.

INTRODUCTION

The Yakutat block in the Gulf of Alaska has been colliding with the North American plate in a 600-km-long orogenic belt over ~10 m.y. (Plafker et al., 1994; Rea and Snoeckx, 1995). This collision has resulted in underthrusting of ~600 km of Yakutat crust and has generated a flat-slab subduction zone with a subhorizontal Wadati-Benioff zone (Fig. 1) that occupies a gap in the Aleutian magmatic arc (e.g., Eberhart-Phillips et al., 2006). The broad Chugach–St. Elias orogeny is formed by this collision, and includes the highest coastal relief in the world; it is bound to the north by the Denali fault system and Wrangell volcanic field. To the south, the Pacific plate slides in a right-lateral sense past the North American plate along the Queen Charlotte–Fairweather fault system to the east and subducts beneath the North American plate along the Aleutian trench to the west. In between, the Pacific lithosphere appears to be subdividing, based on a 1987–1992 earthquake swarm. It is doing so along a north-south lineament that is likely reactivated, spreading ridge-parallel faulting (Pegler and Das, 1996), that we refer to as the Gulf of Alaska shear zone (Fig. 1).

Interpretations of existing data on the Yakutat-Pacific boundary, the Transition fault, are controversial, including whether the fault existed during initial Yakutat–North American collision. The Transition fault (Fig. 1) has been variably described as a rejuvenated left-lateral fault with only minor Pliocene–Pleistocene motion (Bruns, 1983), a dextral-oblique fault (Lahr and Plafker, 1980), and a low-angle thrust (e.g., Perez and Jacob, 1980; Plafker et al., 1994; Fletcher and Freymueller, 2003). Conversely, its lack of seismicity (Page et al., 1989) and local burial by undeformed or weakly deformed sediment (Bruns, 1985) suggest that the Yakutat block is essentially moving with the Pacific plate.

The nature of the Transition fault is critical to understanding the Yakutat collision with its far-field tectonic effects (Mackey et al., 1997; Mazzotti and Hyndman, 2002). We present a revised tectonic model for the Transition fault that uses evidence for an unusually thick Yakutat block, the presence of the 1987–1992 Gulf of Alaska earthquake sequence, and current plate motions to explain seismic and bathymetric observations of faulting.

SEISMIC AND BATHYMETRIC DATA

Methods

In 2005, more than 162,000 km^2 of high-resolution (~100 m) multibeam sonar data were collected along the base of the slope in the Gulf of Alaska in support of a potential U.S. submission for an extended continental shelf (Gardner et al., 2006). These data were collected aboard the R/V *Kilo Moana*, which is equipped with a hull-mounted Kongsberg EM120 (12 kHz) multibeam echo sounder that generates 191 1° × 2° beams over a 150° swath. Frequent sound-speed profiles and an Applanix POS-MV inertial motion unit interfaced with a NovAtel OEM2–3151R global positioning system (GPS) allowed conversion of traveltime to depth, including a water-column refraction correction, and compensation for roll, pitch, and yaw. Spacing of individual soundings is ~50 m and vertical accuracy is ~0.3%–0.5% of the water depth.

In 2004, 1800 km of high-resolution seismic-reflection profiles were collected in the Gulf of Alaska aboard the R/V *Maurice Ewing* as an Integrated Ocean Drilling Program site survey. The sources were dual 45/45 in^3 GI (generator/injector) airguns with a better than 5 m vertical resolution. Processing included trace regularization, normal moveout correction, bandpass filtering, muting, f-k (frequency-wave number) filtering, stacking, water-bottom muting, and finite-difference migration. These profiles add to thousands of kilometers of basin-scale seismic data collected by private industry and the U.S. Geological Survey (USGS) (Bruns, 1983, 1985; Bruns and Carlson, 1987).

Observations

Bathymetry data show linear ridges in the seafloor sediment along the base of the slope that separates the Yakutat block from the Pacific plate (Fig. 2B[1]), where the Transition fault is expected. A single fault trace is observed in the southeast, where it truncates a series of small fans at the base of slope for ~100 km. To the northwest, near the Pamplona fold-and-thrust belt, there are two linear escarpments (including Yushin Ridge) with significant seafloor relief that are interpreted as active faults. The outer strand in the northwest appears in line with the single strand in the southeast, whereas the inner strand lines up with a smaller section of bathymetric relief just southeast of the Yakutat sea valley (Fig. 2B). The transition in steepness between slope (~12°) and Surveyor Fan sediments (~2°) implies that the base of slope is structurally controlled. We suggest that these zones of relief are all part of the Transition fault system.

These observations are consistent with our remigration of a USGS profile (Fig. 3) that

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[1] Figure 2 is provided on a separate insert.

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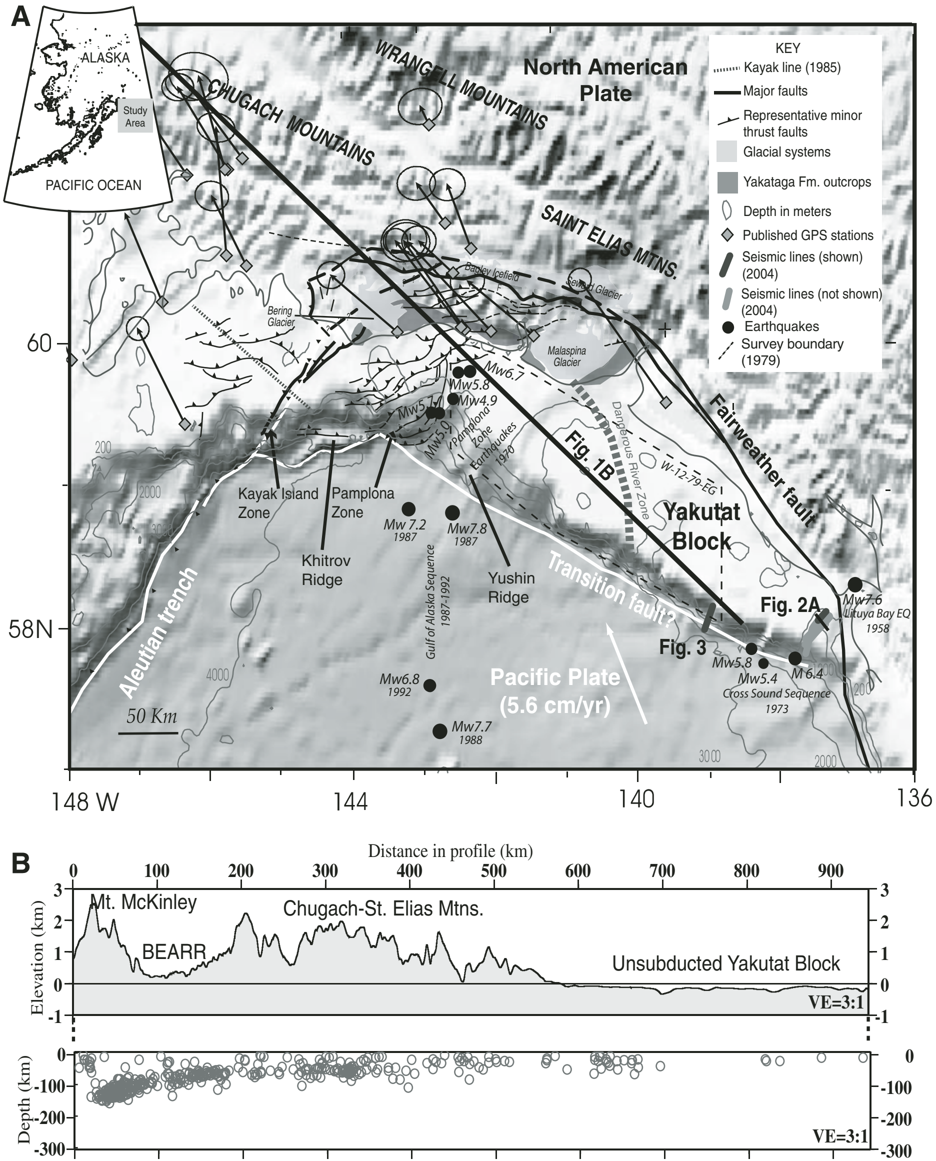

Figure 1. A: Gulf of Alaska study area showing collision of Yakutat block beneath North America and major structural elements. Significant seismic events located near the Yakutat-Pacific boundary are shown from available catalogs. Locations of U.S. Geological Survey and academic seismic lines presented are shown with a box (dashed line) showing industry coverage. B: Topography and seismicity (within 50 km) along cross-section A-A′. Note the nearly flat Benioff zone and ~600 km of underthrust Yakutat block beneath North America. BEAAR experiment from Ferris et al. (2003). GPS—global positioning system; VE—vertical exaggeration.

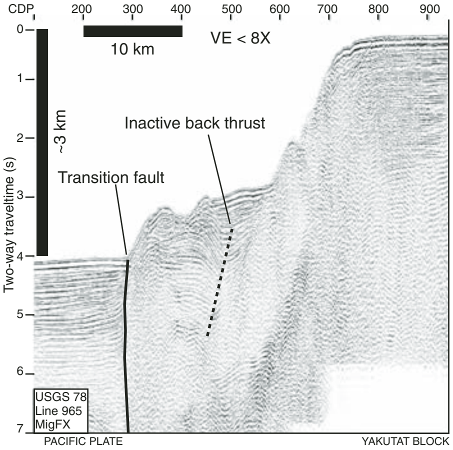

Figure 3. U.S. Geological Survey (USGS) seismic line 965 acquired by Bruns (1985) and remigrated at University of Texas Institute of Geophysics using FX migrated (frequency-depth step) post-stack, time migration algorithm; see Figures 1 and 2 for location. Note the clear high-angle fault at base of slope that offsets sediments to near the seafloor and an inactive thrust fault landward. CDP—common depth point; VE—vertical exaggeration.

crosses the Yakutat-Pacific boundary southeast of the Yakutat sea valley. The migrated image shows an active, near-vertical fault at the base of slope and an inactive backthrust just landward of the near-vertical fault. However, USGS lines crossing the boundary downslope of the sea valley do not show faulting active enough to offset the upper several hundred meters of sediment (Bruns, 1985; Pavlis et al., 2004).

In the southeastern Yakutat block, three high-resolution reflection profiles image a subvertical fault that offsets sediments to the seafloor (one profile is shown in Fig. 2A). This fault was previously imaged at lower resolution on USGS data and named the Icy Point–Lituya Bay fault; no such faults are observed in available seismic data anywhere else within the Yakutat block southeast of the Pamplona fold-and-thrust belt (Bruns, 1983; Bruns and Carlson, 1987). The Icy Point–Lituya Bay fault is southwest of the mapped Fairweather transform fault, is within the Yakutat block (Fig. 2), and strikes southeast to northwest. Based on differential offsets of strata across the fault, lack of any growth strata, and its near-vertical orientation, it is almost certainly a strike-slip fault (Fig. 2A).

On all three profiles, the older sediments beneath the strike-slip fault show convergent folding and faulting; thus, the strike slip is a later phase (e.g., Fig. 2A). Only ~200 m of sediment were deposited during the interval cut by the strike-slip fault. Holocene sediments, observed in depositional lows such as where these profiles are located, as thick as 300 m (Jaeger et al., 1998) and shelf-wide Holocene sedimentation rates estimated to be 7.9 mm/yr (Sheaf et al., 2003) suggest that the 200 m of sediment were deposited in fewer than 300 k.y. While the age of the fault is unclear, the sediments document a recent transition from compression to translation.

DISCUSSION

Bathymetric data suggest that the modern Transition fault is present along the Pacific-Yakutat boundary and that activity is focused on one strand to the southeast and distributed along two strands to the northwest, where it merges with the Pamplona fold-and-thrust belt (Fig. 2B). The southeastern single strand appears to have matured into a true strike-slip fault (Fig. 3), whereas distributed strain to the northwest may be a propagating system still in its oblique-slip phase (e.g., Gulick and Meltzer, 2002).

Any model predicting translation along the Transition fault must explain both the plate kinematics that allow for this translation and how seismicity reflects these kinematics. The existence of a recent change from compression

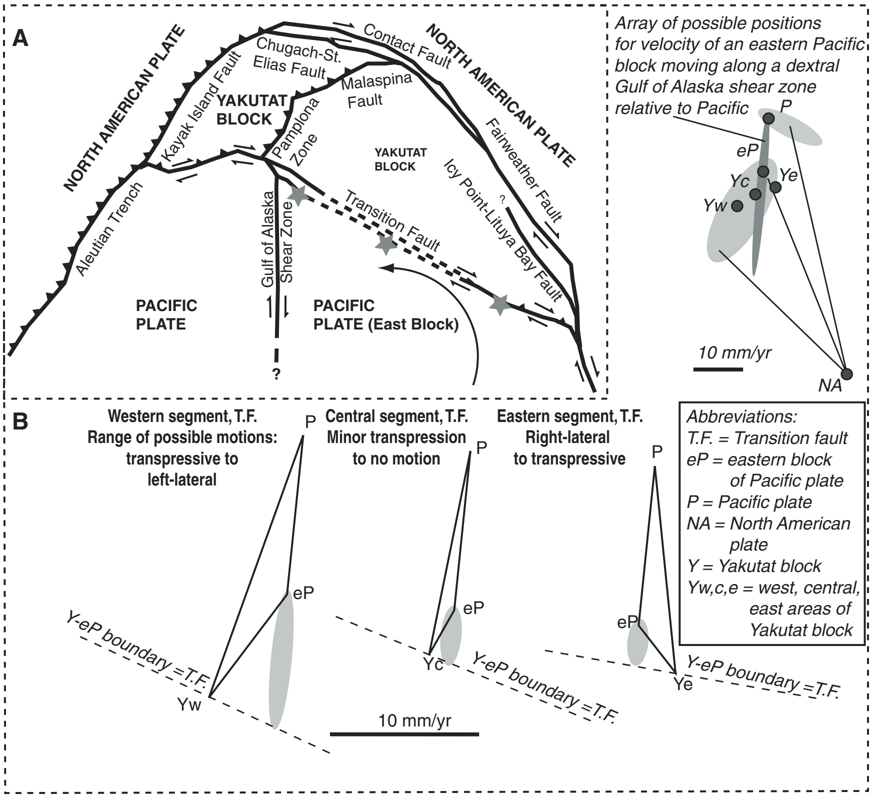

Figure 4. A: Proposed tectonic model where strike-slip deformation is propagating westward along the Transition fault facilitated by a seaward extension of Queen Charlotte–Fairweather fault system. Gulf of Alaska shear zone divides western and eastern blocks of the Pacific plate and separates the merged transpressional Pamplona-Transition fault system to the west from the propagating strike-slip system to the east. B: Upper right figure is summary diagram of published plate velocities. Upper light gray ellipse—Pacific–North America motion; lower light gray ellipse—those suggested by Pavlis et al. (2004) for Yakutat block; dark gray ellipse—array of possible velocity states for an assumed eastern Pacific block with a plate boundary at the Gulf of Alaska shear zone. Assuming Yakutat velocity variation of Pavlis et al. (2004) and an eastern Pacific block model, we present three velocity triangles for different positions along the Transition fault (marked by gray stars in A). Velocity triangles are dependent on the range of motions for eastern block (shown as ellipses), but within this range, kinematics are consistent with our observations and yield consistently low rates of motion along the Transition fault.

to strike-slip faulting within the Yakutat block between the Fairweather fault and the Pacific-Yakutat boundary (Fig. 2A) suggests that the Queen Charlotte–Fairweather fault system is extending offshore and provides a structural mechanism for transferring strike-slip motion to the Yakutat-Pacific boundary.

Three main foci of seismicity (Fig. 1A) help define the plate kinematics: (1) thrust events along the eastern edge of the Pamplona zone (Doser et al., 1997), (2) thrust events at the eastern end of the Transition fault (Doser and Lomas, 2000), and (3) dextral strike-slip events along the Gulf of Alaska shear zone within the Pacific plate (Pegler and Das, 1996). We suggest a tectonic model of the plate boundaries (Fig. 4A) that is consistent with these earthquake sequences, with bathymetric and seismic observations, and with recent tomographic results (Eberhart-Phillips et al., 2006).

Plate velocities based on GPS (Fletcher and Freymueller, 2003) and NUVEL-1A (DeMets et al., 1994), assuming that the north Pacific moves as a single plate, would require significant thrusting along the Transition fault. We propose an alternate model where dextral events along the Gulf of Alaska shear zone highlight the western edge of an eastern Pacific block with implications for motion along the Transition fault (Fig. 4A). Examination of a range of possible plate velocities allows for construction of velocity triangles for three locations along the Transition fault (Fig. 4B). These velocities predict dextral oblique motion in the eastern part of the fault, virtually no motion in the central segment, and transpression in the western segment; none of the predicted velocities exceed 10 mm/yr, a low rate that is consistent with burial in regions of highest postglacial accumulation and limited seismicity.

Our proposed model includes: (1) the dextral Gulf of Alaska shear zone localized along a preexisting zone of weakness in the Pacific plate, (2) transpression between the Pacific plate and the Yakutat block west of this deformation zone, and (3) an evolving plate boundary, the Transition fault, to the east of this zone. From the Yakobi to Yakutat sea valleys (Fig. 2B), the Transition fault is an east-west–propagating strike-slip boundary. From the Yakutat sea valley west, the Transition fault is transpressional and merges with the Pacific strike-slip fault and Pamplona fold-and-thrust belt (Fig. 4A). The overall shape of the continental margin supports this model with a change in width and strike at this location (Figs. 1A and 2B).

Traditionally, the Yakutat block was thought to be flysch and melange east of the Dangerous River zone (Fig. 1A) and oceanic crust west of it (Plafker et al., 1994). However, refraction observations from near Kayak Island (Brocher et al., 1994), tomographic observations onshore collected as part of the BEAAR (Broadband Experiment Across the Alaska Range) experiment (Ferris et al., 2003), and a regional compilation (Eberhart-Phillips et al., 2006) instead suggest that the Yakutat block is a 15–20-km-thick mafic body. The Yakutat block may be an oceanic plateau (Pavlis et al., 2004) whose collision generates flat-slab subduction and the associated gap in the volcanic arc, broad regions of elevated topography, and far-field tectonic effects (Mackey et al., 1997; Mazzotti and Hyndman, 2002).

We envision that the Yakutat block arrived in the Gulf of Alaska attached to the Pacific plate ca. 10 Ma, and that the earliest stage of faulting along the Pacific-Yakutat boundary occurred during the initial phase of collision. The strong, thick mafic Yakutat block may have partially underthrusted the North American plate, causing regional tilting of the plateau and reverse faulting at its seaward edge. This tilting and faulting are exemplified by the ~2 km of uplift near Fairweather ground (Fig. 1A) (Bruns, 1983, 1985) and the seaward thinning of the continental margin sediments (e.g., Bruns and Carlson, 1987). The reverse faulting along the Yakutat-Pacific boundary that existed from the Eocene to early Miocene (Bruns, 1983) likely provided the zone of weakness through which the Pleistocene to modern Transition fault propagated.

It is unlikely that the Pacific plate has underthrust the Yakutat block along the exposed Transition fault (Bruns, 1985), as has been suggested (e.g., Fletcher and Freymueller, 2003; Doser and Lomas, 2000). The 5–7-km-thick Pacific crust abuts the 15–20-km-thick Yakutat crust at mid-crustal depths, making subduction unlikely despite the uplifted edge of the block. Earthquake locations confirm the lack of underthrusting along the Pacific-

Yakutat boundary with the notable exception of Prince William Sound, where, due to the Pacific plate subducting more steeply than the Yakutat block, limited underthrusting is possible (Eberhart-Phillips et al., 2006).

If the Yakutat block is an oceanic plateau, then it is a rare example of in situ subduction of a large igneous province. The Yakutat collision may be representative of a moderate-sized plateau collision, wherein the oceanic plateau initially subducts successfully without its upper layers being peeled or flaked off (Oxburgh, 1972; Hoffman and Ranalli, 1988; Kimura and Ludden, 1995). Due to its buoyancy, a flat-slab subduction zone is formed that is resistant to subduction; if a plateau is large enough, subduction may eventually stall, causing plate boundary reorganization such as we observe in the Gulf of Alaska.

CONCLUSIONS

We propose a tectonic model for Yakutat-Pacific interactions that is based on mapped faults, seismicity, plate motions, and evidence that the Yakutat block may be anomalously thick. To the east, the Queen Charlotte–Fairweather fault system is extending offshore, facilitating westward propagation of strike-slip motion along the eastern segment of the Transition fault. To the west, the transpressional Pamplona zone and Transition faults merge at an embayment in the continental margin where the Gulf of Alaska shear zone within the Pacific plate intersects the Pacific-Yakutat boundary. These fault patterns are consistent with current plate motions and reflect a plate boundary reorganization that may be caused by resistance to subduction by the Yakutat block. Such reorganizations may be illustrative of the effects of moderate-sized plateau collisions, their kinematics being controlled by preexisting zones of weakness, neighboring plate boundary geometries, and plate motions.

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