Trans-Alaska Crustal Transect and continental evolution involving subduction underplating and synchronous foreland thrusting

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ABSTRACT

We investigate the crustal structure and tectonic evolution of the North American continent in Alaska, where the continent has grown through magmatism, accretion, and tectonic underplating. In the 1980s and early 1990s, we conducted a geological and geophysical investigation, known as the Trans-Alaska Crustal Transect (TACT), along a 1350-km-long corridor from the Aleutian Trench to the Arctic coast. The most distinctive crustal structures and the deepest Moho along the transect are located near the Pacific and Arctic margins. Near the Pacific margin, we infer a stack of tectonically underplated oceanic layers interpreted as remnants of the extinct Kula (or Resurrection) plate. Continental Moho just north of this underplated stack is more than 55 km deep. Near the Arctic margin, the Brooks Range is underlain by large-scale duplex structures that overlie a tectonic wedge of North Slope crust and mantle. There, the Moho has been depressed to nearly 50 km depth. In contrast, the Moho of central Alaska is on average 32 km deep. In the Paleogene, tectonic underplating of Kula (or Resurrection) plate fragments overlapped in time with duplexing in the Brooks Range. Possible tectonic models linking these two regions include flat-slab subduction and an orogenic-float model. In the Neogene, the tectonics of the accreting Yakutat terrane have differed across a newly interpreted tear in the subducting Pacific oceanic lithosphere. East of the tear, Pacific oceanic lithosphere subducts steeply and alone beneath the Wrangell volcanoes, because the overlying Yakutat terrane has been left behind as underplated rocks beneath the rising St. Elias Range, in the coastal region. West of the tear, the Yakutat terrane and Pacific oceanic lithosphere subduct together at a gentle angle, and this thickened package inhibits volcanism.

Keywords: Trans-Alaska Crustal Transect, Alaska, plate tectonics, continental growth, subduction, underplating, foreland thrusting.

INTRODUCTION

We present a synthesis of deep crustal structure and tectonics across the North American continent in Alaska, along the Trans-Alaska Crustal Transect (TACT), extending from the Aleutian Trench to the Arctic coast (Fig. 1, inset; Plate 1A[1]). TACT was a collaborative project among the U.S. Geological Survey, State of Alaska, and several academic institutions to collect geologic and geophysical data across Alaska. The data were collected between 1983 and 1990 along a corridor ~1350 km long, following the trans-Alaska oil pipeline, and included seismic (reflection and refraction), potential-field, magnetotelluric, and petrophysical data. Earthquake data collected over the past few decades are also displayed on our transect. The deepest Moho and most distinctive crustal structures are seen near both ends of the transect.

Prior TACT publications focused on regional structure and tectonics, but in this paper we attempt to link the tectonics of northern and southern Alaska together in the Cenozoic. For geology of the terranes crossed by the transect, see the summaries in Plafker and Berg (1994a).

SOUTHERN ALASKA

The transect begins at the Aleutian Trench (Plates 1A, 1B). In the footwall of the megathrust, subducting Pacific plate oceanic crust and sediment are modeled from seismic-refraction data (Plate 1D; Brocher et al., 1994). In the footwall north of the Slope magnetic anomaly (the subducted Transition fault; Fig. 1), oceanic crust of the Yakutat terrane (plus a thin layer of sediment) is modeled from magnetic, seismic, and geologic data to overlie Pacific plate crust (Plates 1C, 1D; Griscom and Sauer, 1990; Brocher et al., 1994; Plafker, 1987). This crustal doubling (15–20 km total thickness) is seen along all offshore TACT lines (Fig. 1), and is assumed to extend throughout the region of unsubducted Yakutat terrane to the east. In contrast, doubling is not observed along our onshore transect, where subducting oceanic rocks reach thicknesses of only 5–10 km (Fig. 1; Plate 1D; Fuis et al., 1991), although doubling is permissible in the southernmost part (Plate 1D, distance range 155–180 km).

The lowest exposures of the Chugach terrane (a Mesozoic accretionary prism) along our TACT route reveal a 1–2-km-thick body of primitive oceanic-arc basalt (Plafker et al., 1994) that can be traced northward in the subsurface in our seismic data (Fisher et al., 1989; Fuis et al., 1991) and magnetic data (Saltus et al., 2007) (Plates 1C, 1D; distance range 200–250 km). This body is observed at the top of a 10-km-thick package of alternating high-

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[1] Plate 1 is a separate loose insert.

Geology, March 2008; v. 36; no. 3; p. 267–270; doi: 10.1130/G24257A.1; 1 figure; 1 inset.

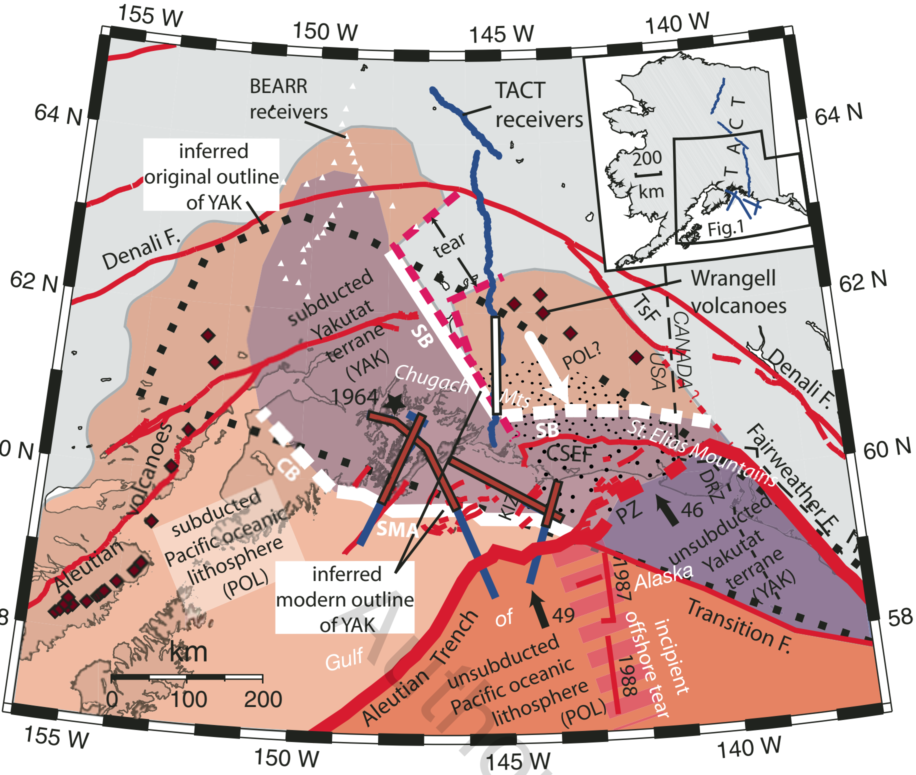

Figure 1. Tectonic map of southern Alaska. Colors—subducted (lighter) and unsubducted (darker) plates and/or terranes. Stipple pattern—underplated rocks; heavier, sparser stipple where outcrops are seen. Heavy dotted black line—interpreted original (Eocene) outline of Yakutat terrane (YAK) translated to its current position in Gulf of Alaska. Heavy white line—interpreted modern outline of subducted Yakutat terrane; dashed where uncertain. SMA—Slope magnetic anomaly (subducted Transition fault); CB—coupling boundary, drawn from Zweck et al. (2002); SB—seismicity boundary (see Page et al., 1989; Eberhart-Phillips et al., 2006). White arrow (parallel to modern subduction)—difference between original and modern north boundaries of YAK in subducting plate. POL—Pacific oceanic lithosphere. Numbered black arrows—plate motion (mm/yr) with respect to North America. White triangles—receivers for study (BEARR) of Ferris et al. (2003). Blue lines—Trans-Alaska Crustal Transect (TACT) receivers. Red lines—faults; heavier red line—plate boundary; CSEF—Chugach–St. Elias fault; KIZ—Kayak Island zone; PZ—Pamplona zone; TsF—Totschunda fault; 1987, 1988—strike-slip earthquakes (Lahr et al., 1988); DRZ—Dangerous River suture within YAK (Plafker, 1987). Black star—epicenter of M 9.2 1964 earthquake. Doubled subducting crust imaged in offshore seismic profiles (red-brown lines with black outlines) is YAK overlying POL. We infer that the single thickness of subducting oceanic lithosphere imaged onshore beneath TACT line (white line with black outline) is POL alone, and that the missing YAK—the difference between original and modern northern boundaries of YAK—has been transferred from subducting plate to North America (stippled areas); see Plate 1D.

and low-velocity, planar, north-dipping layers, interpreted as duplexed sedimentary rocks and mafic to ultramafic rocks that were tectonically underplated (Fuis et al., 1991). We infer from the Late Cretaceous age of the exposed basalt that this package represents fragments of the former Kula or Resurrection plates (Engebretson et al., 1985; Haeussler et al., 2003). No clear seismic evidence is seen of magmatic underplating postulated to have occurred during Eocene subduction of a mid-ocean ridge beneath southern Alaska (cf. Harris et al., 1996); such underplating would have extended across the Contact fault, and is not seen (Plate 1D). The crust of the Peninsular and Wrangellia terranes (island-arc terranes) is anomalously thick (55 km; Plate 1D, ~340 km distance) for either an oceanic or continental arc (Christensen and Mooney, 1995), and its relationship to the abutting underplated sequence to the south remains unresolved. The megathrust has been located at ~30 km depth at distance range ~240–250 km (Plate 1E; Page et al., 1989), based on focal depths in the nearby Wrangell Wadati-Benioff zone (projected onto the transect) and on focal mechanisms (reverse faulting near the megathrust).

CENTRAL ALASKA

Central Alaska, including Yukon-Tanana and other terranes (Plate 1B), was affected by middle Cretaceous plutonism and extension that left a geophysically uniform crust, with velocities of 6.0–6.4 km/s (characteristic of felsic rocks), a thin to absent lower crustal layer (7.0–7.2 km/s), and a shallow Moho (30–33 km; Beaudoin et al., 1992, 1994), except near the Denali fault (Plate 1D). From refraction and wide-angle reflection data, this crust is rather featureless below 5 km depth, with middle- and lower-crustal reflectors seen in places that may be segments of detachment faults or low-angle layering (intrusive or metamorphic). The geophysical signature of this crust is quite similar to that of extended crust elsewhere (e.g., Fuis et al., 2001).

The strike-slip Denali fault developed in a complex Late Jurassic–middle Cretaceous suture zone between the island-arc terranes to the south and continental-marginal terranes to the north (Ridgway et al., 2002); 400 km of strike-slip movement has occurred on this fault (Nokleberg et al., 1985), including slip during the 2002 M 7.9 Denali fault earthquake (Eberhart-Phillips et al., 2003). The Denali fault is a deep conductivity anomaly (Fisher et al., 2004), and there is a poorly resolved crustal root, ~50 km deep, beneath the Alaska Range and Denali fault (Brocher et al., 2004).

NORTHERN ALASKA

The Brooks Range of northern Alaska consists of terranes (Plates 1A, 1B) that have undergone several episodes of deformation, including compression in the Late Jurassic–Early Cretaceous, extension (in the southern Brooks Range) in the middle Cretaceous (as in central Alaska), and pulses of renewed compression in the Cenozoic (Miller and Hudson, 1991; Moore et al., 1994, 2004, 2005). Seismic images (Levander et al., 1994; Fuis et al., 1997) provide evidence for most of these events and especially highlight duplexes, interpreted to be chiefly Paleogene in age, formed in the upper to middle crust, near the crest of the range and above a crustal root (Plate 1D, near 1100 km distance). Reflectivity in the lower crust continues northward and downward into the mantle from the crustal root, leading to interpretations of underthrusting beneath the North Slope. Wissinger et al. (1997) and Fuis et al. (1997) both inferred that the North Slope lithosphere indented northern Alaska (Brooks Range), essentially as a tectonic wedge, although the interpretations differ as to how much lower crust was thrust beneath the North Slope. (See Plate 1D for interpretations of ages of other Brooks Range reflections.)

CENOZOIC TECTONICS

Paleogene Tectonic Underplating and Duplexing

The underplating in southern Alaska and the duplexing in northern Alaska overlapped one another in time in the Paleogene. To view a cross section of the Alaskan lithosphere at that time, one would have to restore 400 km of right slip along the Denali fault and smaller offsets along the Kaltag and Malamute faults (see Plafker and Berg, 1994b, their Figs. 4, 5F, 5G). However, late Mesozoic–Paleogene underplating observed along the TACT route appears to extend more than 400 km along strike to the northwest (Moore et al., 1991), and restoration of right slip on the Denali fault would not qualitatively change the picture shown in Plate 1. The tectonic link between the underplated sequence in the south and the duplexes in the north is, nevertheless, uncertain. At least two tectonic models are possible: (1) flat-slab subduction (e.g., Bird, 1988), and (2) orogenic float (Oldow et al., 1990), in which a décollement extended northward from the subduction zone in southern Alaska to the Brooks Range. For the first model, the expected volcanic signature of subduction as far north as the Brooks Range is missing. The second model predicts a combination of strike-slip and thrust faulting above a décollement and would explain the overlapping periods of strike slip along the Denali, Tintina-Kaltag, and other faults and compression in the Brooks Range (foreland). An orogenic-float model is supported by deep seismic reflection data from the nearby Canadian Cordillera, where regional crustal décollements are observed that approach the surface at the Rocky Mountain front (see data in Cook et al., 2004), in a way similar to the décollement in the Brooks Range. Modeling by Mazzotti and Hyndman (2002) confirms the viability of the orogenic-float model, although they applied their modeling to the collision of the Yakutat terrane (see following).

Neogene Subduction and Underplating of the Yakutat Terrane

The Yakutat terrane was probably underthrust by Pacific oceanic lithosphere as transform motion between the North American and Pacific plates changed from the Transition to the Fairweather faults beginning ca. 35 Ma (Plafker et al., 1994, their Figs. 15F, 15G). The Transition fault is now largely inactive (Gulick et al., 2007). We infer that the Yakutat terrane has since been removed from its position atop the Pacific oceanic lithosphere in the region of the Wrangell volcanoes by tectonic underplating (Fig. 1; Plate 1D). In plan view, we have translated the interpreted original shape of the Yakutat terrane (Plafker et al., 1994, their Fig. 15F) to its current position in the Gulf of Alaska (Fig. 1, dotted outline). Although the current southern boundary of the subducted and unsubducted Yakutat terrane approximately matches the original southern boundary, the current northern boundary appears deformed southward (Fig. 1, white arrow). We infer that the missing Yakutat terrane is now incorporated into the upper plate (Fig. 1, stippled area). In cross section, we place the underplated Yakutat terrane (Plate 1D, light violet unit) structurally below and seaward of the underplated Kula plate fragments.

Evidence supporting underplating of Yakutat terrane in the region of our onshore TACT line and eastward includes 4.5–8 km of denudation of the St. Elias Mountains since the early Pliocene (O'Sullivan et al., 1997) that has exposed the Chugach metamorphic complex (e.g., Harris et al., 1996). Absence of the Yakutat terrane from the subducting Pacific oceanic lithosphere beneath the Wrangell volcanoes is suggested by the abrupt steepening of Wadati-Benioff zone in this region and an apparent tear in the subducting plate between the Wrangell and Aleutian Wadati-Benioff zones (Fig. 1; Plate 1F, cross-section A-A′). In the region west of this interpreted tear, Ferris et al. (2003) found a thick (11–22 km) subducting slab similar to the doubled thickness we observe offshore. An upper limit for oceanic crustal thickness that can be subducted averages ~13 km, but can vary widely (Molnar and Gray, 1979). We interpret that the doubled thickness is under the subductable limit in the Aleutian zone but not in the Wrangell zone. The 400 km gap between the Aleutian and Wrangell volcanic chains, where the doubled slab is inferred (Fig. 1; Plate 1F), is also a region of high slab P- to S-wave velocity ratio (Eberhart-Phillips et al., 2006). Perhaps the processes of slab dehydration and heating required for subduction volcanism are perturbed by this thickening.

Evidence near the coast for the interpreted tear in the subducting plate is not definitive, but is suggested by the sharp bend in the Chugach–St. Elias fault (Fig. 1). One might interpret that the tear has even propagated into unsubducted Pacific oceanic lithosphere farther southeast, where right slip occurred in the 1987–1988 M 7.8–7.9 earthquakes. Note that the source region for the 1964 earthquake extended southwestward from approximately the inferred tear (see Johnson et al., 1996).

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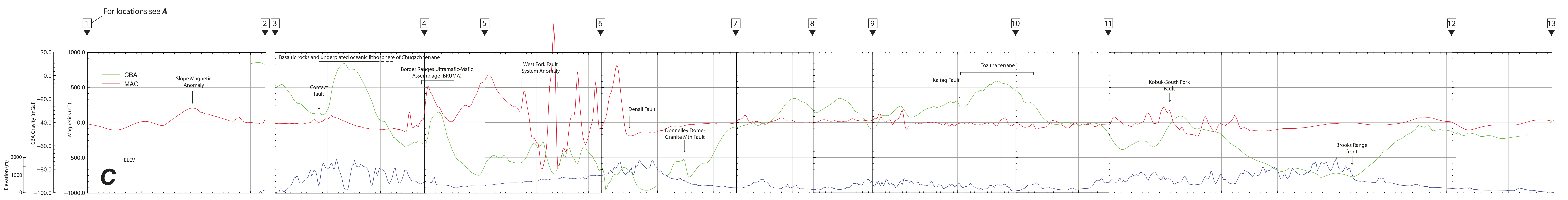
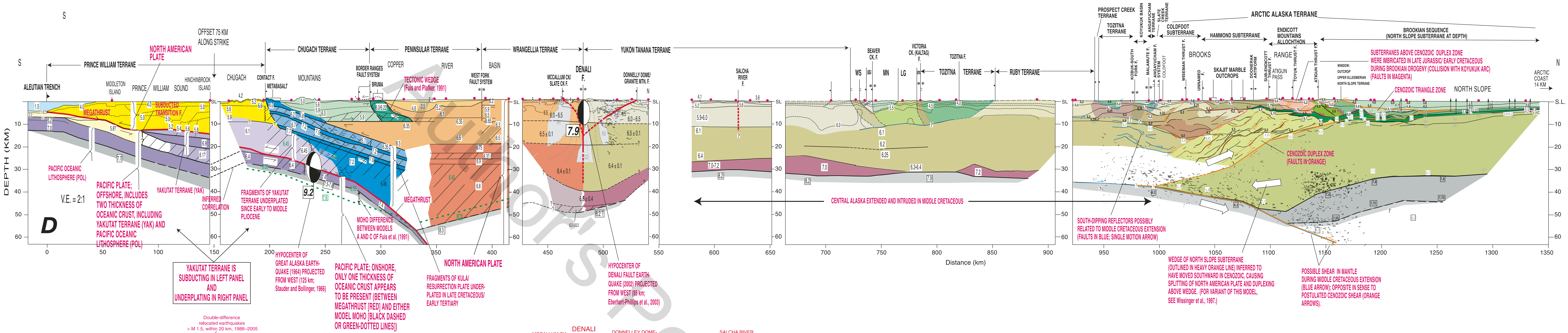
Printed in USA

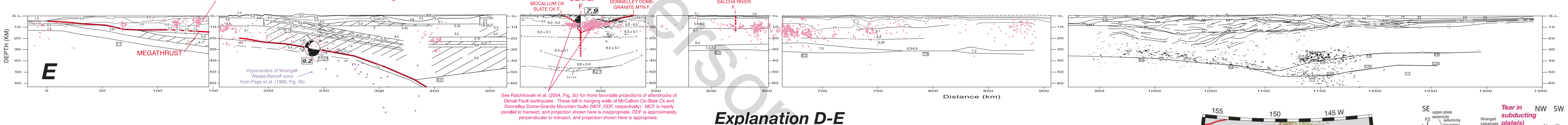
Gravity data (complete Bouguer anomaly, CBA), magnetic data (total field anomaly), and topography along and near the TACT transect. Gravity data from Barnes (1977); magnetic data from Saltus and Simmons (1997).

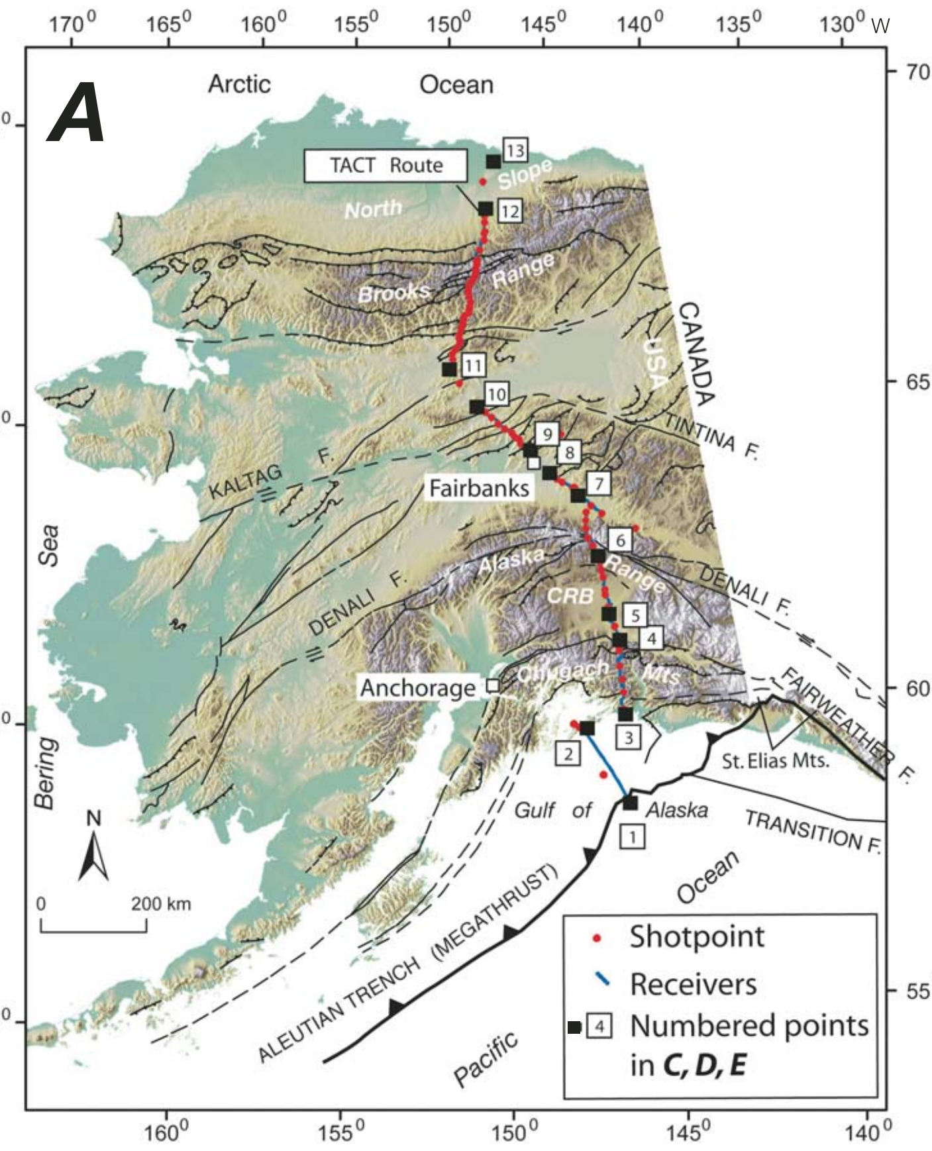


Cross section across Alaska (V.E. 2:1) showing seismic velocities, velocity boundaries, near-vertical-incidence reflections, lithotectonic terranes, faults, and hypocenters of major earthquakes.

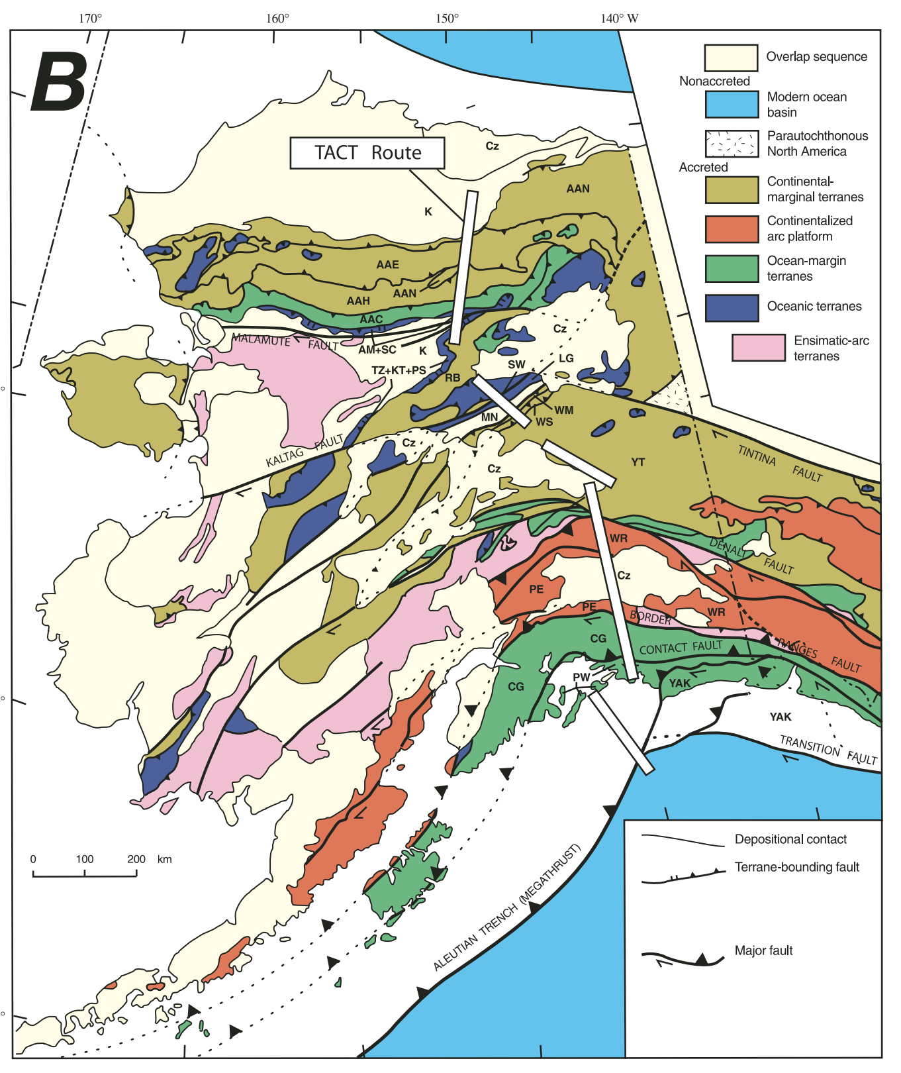


Cross section across Alaska (V.E. 1:1) showing seismic velocities, velocity boundaries, near-vertical-incidence reflections, faults, and earthquake hypocenters.





Colored, shaded relief map of Alaska showing route of Trans-Alaska Crustal Transect (TACT). Faults from http://pubs.usgs.gov/atlas/geologic. CRB, Copper River basin.



Lithotectonic terrane map of Alaska showing TACT route (simplified from Grantz et al., 1991).

ABBREVIATIONS FOR TERRANES CROSSED BY TACT
(in order of appearance from north to south)

Cz	Cenozoic overlap sequence
K	Cretaceous overlap sequence
AAN	North Slope subterrane of Arctic Alaska terrane (AA)
AAE	Endicott subterrane of AA
AAH	Hammond subterrane of AA
AAC	Coldfoot subterrane of AA
SC	Slate Creek
AM	Angayucham
KT	Kanuti
PS	Prospect Creek
RB	Ruby
TZ	Tozitna
SW	Mount Schwatka
LG	Livengood
MN	Manley
WH	White Mountains
WS	Wickersham
YT	Yukon Tanana
WR	Wrangellia
PE	Peninsular
CG	Chugach
PW	Prince William
YAK	Yakutat

Explanation D-E

SYMBOLS

Shotpoints

Oil well

5.6 6.3 6.3 5.6 7.8 Seismic boundary; solid black, first-order discontinuity; seismic P-wave velocity above and below in km/s. Finely dashed, second-order discontinuity; velocity on discontinuity in km/s. Velocities in light gray font, less certain. Velocities in boxes, mantle velocities.

5.6 7.8 Alternate model; velocity as above; dotted green line, alternate Moho

Lateral velocity discontinuity

Wide-angle reflection: prominent; moderate to weak

Near-vertical-incidence reflections

Low-velocity zone

Major faults; arrows denote relative motion; teeth denote upper plate of reverse faults; hachures denote hanging wall of normal fault; dashed where uncertain

Active fault; dashed where uncertain

Major faulting episodes in Brooks Range indicated by colored lines and arrows (panel D):

Cenozoic fault; heavy orange line outlines interpreted tectonic wedge

Middle Cretaceous

Late Jurassic/Early Cretaceous

R3 C2 Resistive (R) and conductive (C) anomalies

Earthquakes; pink, all magnitudes within a 40-km-wide corridor centered on the TACT profile; double-difference relocated; purple, all magnitudes below 25 km depth from special study of Wrangell Wadati-Benioff zone by Page et al. (1989; Fig. 4b)

Focal mechanism of major earthquake; magnitude attached; far hemisphere shown; vertically exaggerated in D

9.2

LITHOLOGY, TERRANES

Accretionary prism: Cz (yellow)--Prince William terrane; Mz (light green)--Chugach terrane

Underplated oceanic crust

Kula (or Resurrection) plate (Late Cretaceous and early Tertiary; light blue, sedimentary and minor volcanic rocks; dark blue, mafic and ultramafic rocks)

Yakutat terrane (Eocene basalt and younger sedimentary rocks [structure unknown])

Actively subducting Pacific Plate oceanic crust and the Yakutat terrane (shades of violet; darker, higher velocity)

Island arc upper crust (shades of orange) and lower crust (shades of red and violet) --Peninsular and Wrangellia terranes

Border Ranges Ultramafic-Mafic Assemblage (BRUMA)--base of Peninsular terrane island arc

Ophiolite:

Livengood terrane--sedimentary rocks, serpentinite, mafic rocks

Tozitna and Angayucham terranes--mafic rocks, sedimentary rocks

Phylonite--shear zone

Prospect Ck/Slate Ck terranes

Continental metasedimentary rocks

Strongly deformed, clastic

Yukon Tanana terrane

Ruby terrane

Coldfoot subterrane of AA terrane

Moderately deformed

Wickersham terrane (WS) (clastic)

Schwatka Mountain terrane (SW) (clastic)

White Mountain terrane (WH) (clastic and carbonate)

Hammond subterrane of AA terrane (clastic and carbonate)

Franklinian basement of AA terrane (clastic)

Arctic Alaska (AA) terrane

Coldfoot subterrane (see above)

Hammond subterrane (see above)

Endicott Mountains subterrane

Post-Lisburne Group clastic sed. rocks of Ellesmerian sequence (includes sed. rocks of Delong Mts subterrane)

Lisburne Group (carbonate)

Endicott Group (clastic sed. rocks)

North Slope subterrane (exclusive of Brookian [foreland basin] sequence)

Post-Lisburne Group clastic sed. rocks of Ellesmerian sequence

Lisburne Group and older rocks of Ellesmerian sequence; chiefly carbonate and clastic sed. rocks

Franklinian sequence.; metasedimentary, metavolcanic, and plutonic rocks. Darker color, interpreted tectonic wedge that moved southward, along with attached mantle, in Paleogene ("Laramide"). Lighter color, Franklinian sequence deformed by duplexing.

Foreland basin sedimentary rocks--Brookian sequence

Rift basin sedimentary rocks--Koyukuk basin sed. rocks and Manley terrane (MN)

Felsic mid-crustal layers of unknown affinity

Mafic lower crustal layer

Mantle

Southern Alaska, oceanic. Northern Alaska, part of North Slope tectonic wedge that moved southward in Paleogene.

Continental

REFERENCES CITED ONLY IN PLATE 1

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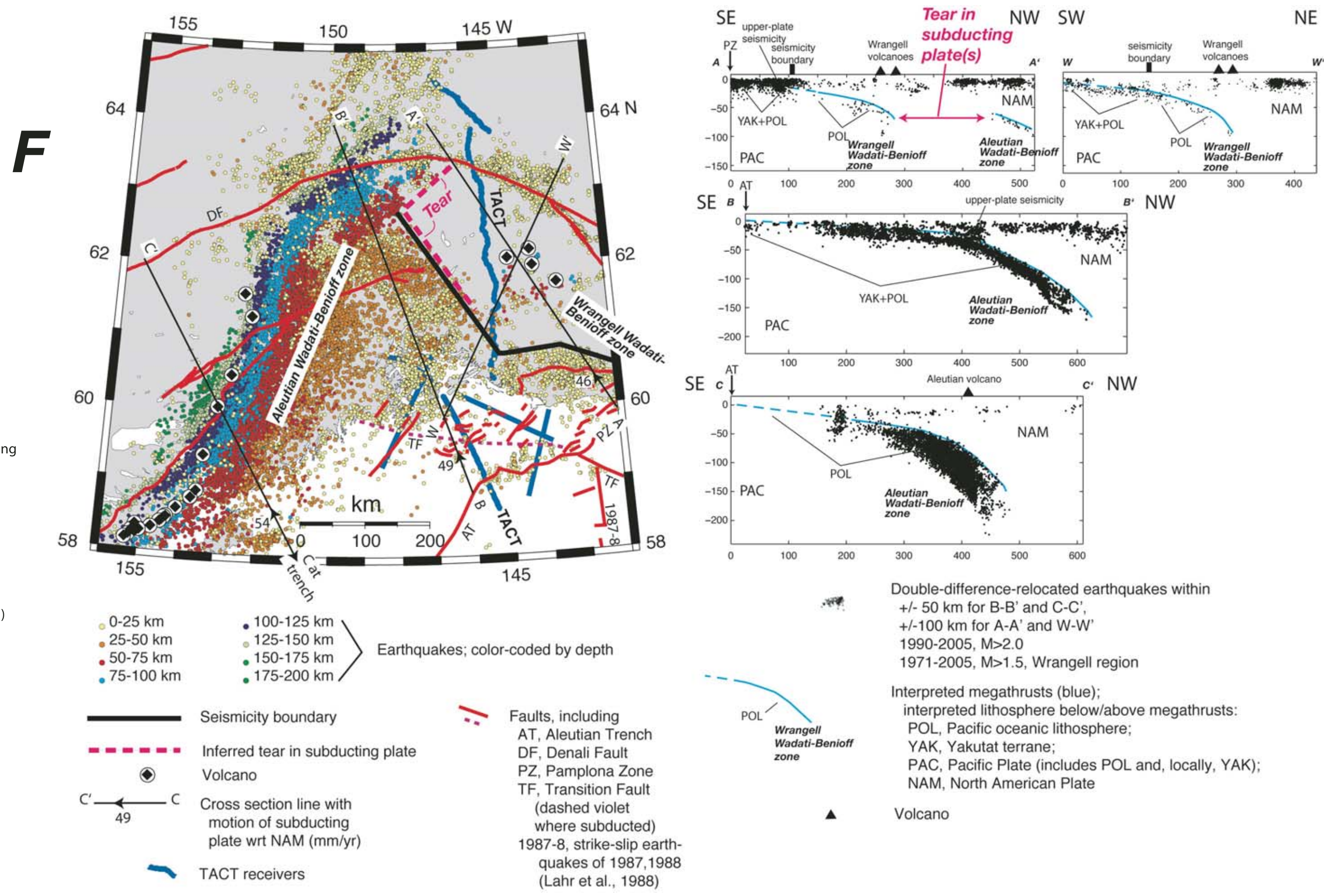
Plate 1. Maps of Alaska and geophysical profiles along Trans-Alaska Crustal Transect (TACT). A. Colored, shaded relief map of Alaska showing TACT route. Black lines, faults; teeth on upper plates of thrust faults; heavy black line, plate boundary between Pacific and North American plates. See explanation for other symbols. B. Lithotectonic terrane map of Alaska showing TACT route. See explanations for other symbols. C. Gravity, magnetic, and topographic profiles along and near TACT route. Profiles are constructed along straight lines joining numbered points in A; numbered points shown at top of C. D. Cross section along TACT route (V.E. 2:1) showing seismic velocities, velocity boundaries, near-vertical-incidence reflections, lithotectonic terranes, faults, and hypocenters of major earthquakes. See explanation below cross section E. E. Cross section across Alaska (V.E. 1:1) showing seismic velocities, velocity boundaries, near-vertical-incidence reflections, faults, and earthquake hypocenters. See explanation below cross section. F. Seismicity map and cross sections of seismicity along directions of modern plate motions (A-A′, B-B′, and C-C′) and perpendicular to strike of Wrangell Wadati-Benioff zone (W-W′). See explanations beneath map and cross sections.



Seismicity map and cross sections of seismicity along directions of modern plate motions (A-A′, B-B′, and C-C′) and perpendicular to strike of Wrangell Wadati-Benioff zone (W-W′). A-A′ reveals apparent tear in subducting plate, giving rise to separate Wadati-Benioff zones (Wrangell and Aleutian). We infer that Pacific oceanic lithosphere (POL) is subducting alone beneath Wrangell volcanoes, having rid itself of "piggyback" Yakutat terrane (YAK) to underplating in coastal mountains. We infer that POL and YAK are subducting together along B-B′. Beneath C-C′, there is no evidence of presence of YAK; POL is subducting alone. High upper-plate seismicity characterizes regions underlain by YAK, either subducted or underplated.

Trans-Alaska Crustal Transect and continental evolution involving subduction underplating and synchronous foreland thrusting—Plate 1
Fuis et al.
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