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Mapping the megathrust beneath the northern Gulf of Alaska using wide-angle seismic data

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Abstract. In the northern Gulf of Alaska and Prince William Sound, we have used wide-angle seismic reflection/refraction profiles, earthquake studies, and laboratory measurements of physical properties to determine the geometry of the Prince William and Yakutat terranes, the Aleutian megathrust, and the subducting Pacific plate. In this complex region, the Yakutat terrane is underthrust beneath the Prince William terrane, and both terranes are interpreted to be underlain by the Pacific plate. Wide-angle seismic reflection/refraction profiles recorded along five seismic lines are used to unravel this terrane geometry. Modeled velocities in the upper crust of the Prince William terrane (to 18 km depth) agree closely with laboratory velocity measurements of Orca Group phyllites and quartzofeldspathic graywackes (the chief components of the Prince William terrane) to hydrostatic pressures as high as 600 MPa (6 kbar). A landward dipping reflector at depths of 16-24 km is interpreted as the base of the Prince William terrane. This reflector corresponds to the top of the Wadati-Benioff zone seismicity and is interpreted as the megathrust. Immediately beneath the megathrust is a 4-km-thick 6.9-km/s refractor, which we infer to be the source of a prominent magnetic anomaly and which is interpreted by us and previous workers to be gabbro in Eocene age oceanic crust of the underthrust Yakutat terrane. Wide-angle seismic data, magnetic anomaly data, and tectonic reconstructions indicate that the Yakutat terrane has been underthrust beneath the Prince William terrane for at least a few hundred kilometers. Wide-angle seismic data are consistent with a 9° to 10° landward dip of the subducting Pacific plate beneath the outer shelf and slope, distinctly different from the inferred average 3° to 4° dip of the overlying 6.9-km/s refractor and the Wadati-Benioff seismic zone beneath the inner shelf. Our preferred interpretation of the geophysical data is that one composite plate, composed of the Pacific plate of a fairly uniform thickness and the Yakutat plate of varying thickness, is subducting beneath southern Alaska.

Introduction

Significant portions of western North America consist of terranes interpreted to have traveled hundreds to thousands of kilometers [e.g., *Jones et al.*, 1982; *Plafker et al.*, 1989]. Onshore seismic reflection and refraction data collected in southern Alaska and southern British Columbia revealed prominent landward dipping seismic reflectors and interbedded high- and low-velocity layers [*Fisher et al.*, 1989a; *Hyndman et al.*, 1990; *Fuis et al.*, 1991]. These layers and reflectors and refractors have been interpreted as evidence that terranes accreted at the subduction zones in these two areas dip landward beneath the continents and that tectonic underplating has formed significant fractions of the crust beneath these regions. We acquired more than 1000 km of seismic reflection and refraction profiles in the northern Gulf of Alaska for the Trans-Alaska Crustal Transect (TACT) program to examine the nature of the crust beneath accreted terranes north of the Aleutian trench. These data were designed to address important questions related to the accretion of continental terranes in southern Alaska. These questions include (1) what is the geometry of the Pacific plate beneath the accreted terranes, (2) to what depths do terranes extend, (3) what is the nature and geometry of the terrane boundaries at depth and their relationship to current seismicity and the Aleutian megathrust, (4) how are currently accreting terranes related to the interpreted older underplated terranes, and (5) how are terranes metamorphosed and deformed by tectonic underplating? The resolution of these questions would clearly advance our understanding of the process of terrane accretion and hazards posed by large earthquakes on the Aleutian megathrust.

Prior to our study, the crust north of this trench had been explored using gravity and magnetic anomaly profiles [*Bruns*, 1985; *Griscom and Sauer,* 1990], conventional seismic reflection profiling [*Bruns*, 1985], seismic refraction

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profiling [*Bayer et al.*, 1978], investigations of the Wadati-Benioff seismic zone [*Page et al.*, 1989; *Estabrook et al.*, 1992], and combinations of these techniques [*Plafker et al.*, 1982; *Bruns*, 1985; *Plafker*, 1987]. In the following, we briefly review the geology of the northern Gulf of Alaska and describe the 1988 field work in Prince William Sound. We then present the results of forward modeling of the wide-angle reflection/refraction data, and we use the velocity models derived from this analysis to constrain tectonic interpretations of the subduction of the Yakutat terrane at the northeastern end of the Aleutian trench.

Tectonic and Geologic Setting

Within the northern Gulf of Alaska (Figure 1), Pacific plate crust of late Eocene age (anomalies 15-20) is being subducted at the northeastern end of the Aleutian trench at about 54 mm/yr [*Taylor and O'Neill*, 1974; *Schwab et al.*, 1980; *Bruns*, 1985; *DeMets et al.*, 1990]. Magnetic anomalies on the seafloor trend N-S and can be traced west of the Aleutian trench for at least 200 km beneath the overriding plate [*Bruns*, 1985; *Griscom and Sauer*, 1990].

Southern Alaska is composed of a series of accreted terranes [*Jones et al.*, 1987]. These terranes include the Prince William, Yakutat, and Chugach terranes (Figure 1).

The Prince William terrane is a 100-km-wide belt of Paleogene rocks extending southwestward from Prince William Sound to Kodiak Island and beyond (Figure 1). The Aleutian trench forms the approximate southeastern boundary of the Prince William terrane and the Kayak Island zone is the eastern boundary across the continental shelf. The terrane basement consists of the Orca Group, an accreted late Paleo-

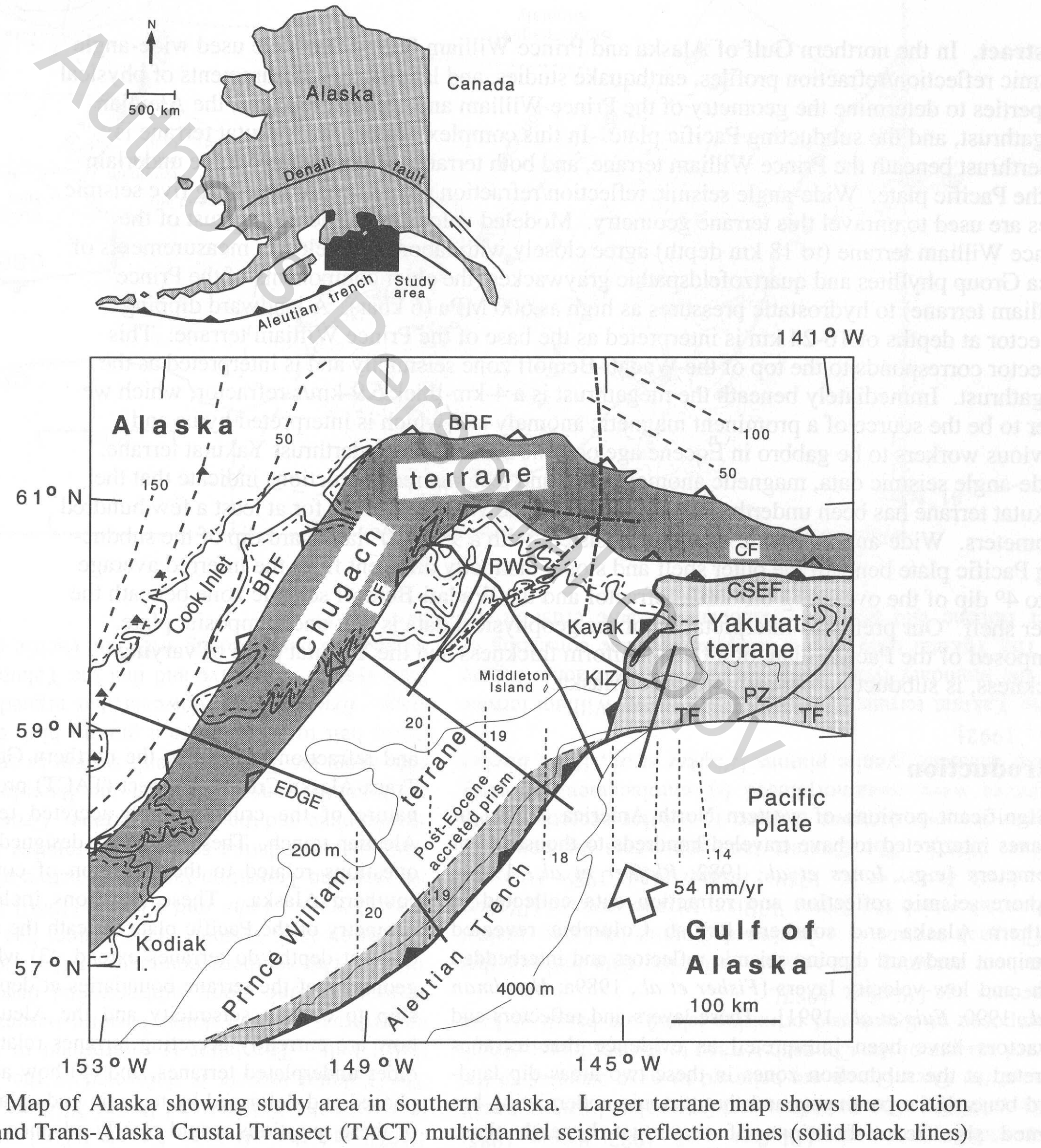


Figure 1. Map of Alaska showing study area in southern Alaska. Larger terrane map shows the location of EDGE and Trans-Alaska Crustal Transect (TACT) multichannel seismic reflection lines (solid black lines) in the northern Gulf of Alaska [*Moore et al.*, 1991; *Fisher et al.*, 1989b]. Dashed-dotted lines show locations of TACT seismic refraction profiles described by *Fuis et al.* [1991]. Abbreviations are: PWS, Prince William Sound; BRF, Border Ranges fault; CF, Contact fault; KIZ, Kayak Island zone; CSEF, Chugach-St. Elias fault; TF, Transition fault; and PZ, Pamplona zone. Magnetic anomalies 14-20 on the Pacific plate and beneath the Prince William terrane, from *Naugler and Wageman* [1973] and *Taylor and O'Neill* [1974], are shown as light dashed lines. Depths of Wadati-Benioff zones in kilometers (heavy dashed lines) and Aleutian volcanoes (solid triangles) are from *Page et al.* [1989].

cene through middle Eocene deep sea fan complex with interbedded coherent slabs and blocks of oceanic volcanic rocks and associated pelagic sediments [*Plafker*, 1987; *Lull and Plafker*, 1990]. On the continental shelf and slope near Middleton Island the Orca Group is overlain by as much as 4 km of relatively undeformed late Eocene to Quaternary siliciclastic sedimentary rocks [*Plafker et al.*, 1982; *Bruns*, 1985; *Plafker*, 1987]. The turbidites and intercalated pillow basalt flows of the Orca Group are believed to have accreted to the seaward margin of the Chugach terrane to the northwest, which is composed of flysch and primitive island arc basalt of Late Cretaceous age [*Plafker,* 1987].

Onshore mapping and seismic reflection data indicate that the Chugach terrane is a landward dipping backstop against and beneath which the Prince William terrane accreted [*Plafker et al.*, 1982; *Fisher et al.*, 1989a; *Plafker et al.*, 1989; *Fuis and Plafker*, 1991]. The Contact fault represents the boundary between the two terranes (Figure 1). After accretion, both sequences were metamorphosed by emplacement of early Eocene anatectic granite plutons [*Plafker et al.*, 1989; *Barker et al.*, 1992].

The Yakutat terrane lies east of the Prince William terrane with the boundary lying along the Kayak Island zone (Figure 1). The Yakutat terrane is a composite terrane consisting of lower Eocene and possibly Paleocene oceanic crust in the western part and, outside of our study area, a probable displaced fragment of the Chugach terrane in the eastern part [*Plafker*, 1987]. The oceanic basement rocks in the Yakutat terrane are overlain by a dominantly clastic sequence of lower Eocene to Quaternary sedimentary rocks up to 9 km thick. The onshore Wingham Island-Ragged Mountain faults [*Plafker*, 1987] and the offshore Kayak Island zone [*Bruns*, 1985] juxtapose the Yakutat and Prince William terranes (Figure 2). The Yakutat terrane is deformed in the Pamplona fold and thrust belt. The latter is interpreted to have resulted from underthrusting of Yakutat basaltic basement beneath Prince William terrane along subhorizontal decollements [*Plafker,* 1987]. The southern boundary of the Yakutat terrane is the Transition fault system. This system has been interpreted in several ways. *Lahr and Plafker* [1980] and *Plafker* [1987] interpret the Transition fault as an active oblique dextral thrust fault accommodating some of the relative motion between the Pacific plate and the Yakutat terrane. *Grantz et al.* [1991], in a north-south transect through the Pamplona fold and thrust belt, show the Transition fault system as an imbricated oblique thrust belt to accomodate a gravity high over the continental slope. *Bruns* [1985], however, has argued that the Transition fault system is inactive and that the Yakutat terrane is welded to, and has been moving with, the Pacific plate for at least the past 5 m.y.

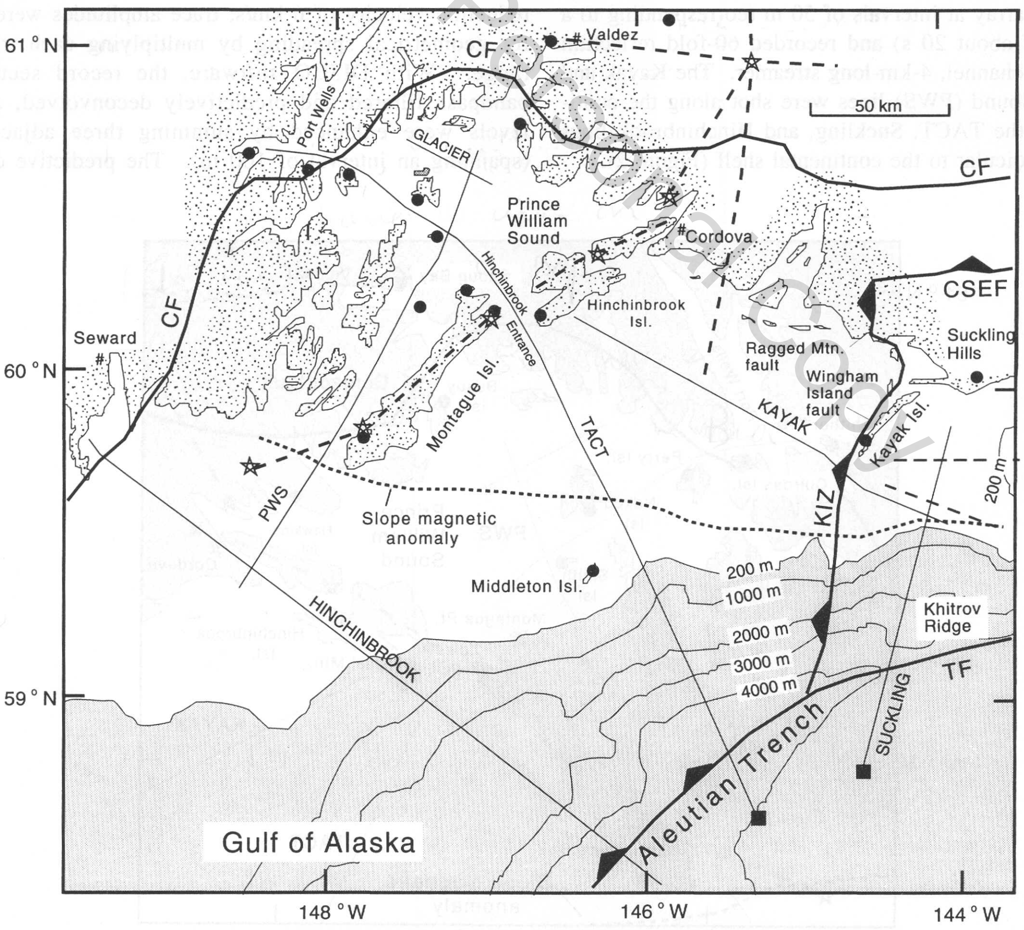


Figure 2. Map of study area within northern Gulf of Alaska showing location of TACT seismic reflection lines (named light lines), temporary seismic 5-day recorders (solid circles), and sonobuoys (solid squares) used to obtain wide-angle seismic reflection/refraction profiles. Heavy dashed lines show locations of seismic refraction lines described by *Fuis et al.* [1991]. Stars show shot points along the Montague refraction line described in the text. Abbreviations are defined in Figure 1.

A prominent magnetic anomaly along the slope of the Yakutat terrane trends ESE-WNW for 500 km along the continental margin across both the Pamplona and Kayak zones as far west as Montague Island (Figure 2). The slope anomaly has been interpreted as the subducted southern boundary of the Yakutat terrane [*Schwab et al.*, 1980; *Bruns*, 1985; *Giscom and Sauer*, 1990]. This interpretation suggests that at least 200 km of the lower crust of the Yakutat terrane has been subducted beneath the Prince William terrane [*Griscom and Sauer*, 1990].

The amount of northward motion of the Yakutat terrane has been variously estimated as from 5° to as much as 30°. On the basis of geologic correlations with southeastern Alaska and British Columbia, *Plafker* [1987] suggests about 600 km of northward displacement of the Yakutat terrane. *Keller et al.* [1984] infer about 30° northward displacement of the Yakutat terrane on the basis of the foraminifers in the Eocene and younger strata.

Data Acquisition and Processing

Over 1100 km of marine multichannel seismic reflection data were acquired for TACT along six profiles in the northern Gulf of Alaska during July, 1988 (Figure 2) [*Fisher et al.*, 1989b]. The multichannel vessel M/V *Geotide* deployed a 40-element air gun array totaling 126 L (7700 cubic inches) producing a nominal peak pressure of 178 bars m. The *Geotide* fired the air gun array at intervals of 50 m (corresponding to a repetition rate of about 20 s) and recorded 60-fold reflection data using a 240-channel, 4-km-long streamer. The Kayak and Prince William Sound (PWS) lines were shot along the continental shelf and the TACT, Suckling, and Hinchinbrook lines were shot perpendicular to the continental shelf (Figure 2).

Temporary seismic stations to record the air gun signals were deployed by plane and by helicopter in 16 locations along the coast of the northern Gulf of Alaska, in Prince William Sound, in the Suckling Hills, on Middleton Island, and in the Chugach Mountains (Figures 2 and 3) [*Brocher and Moses*, 1990]. We deployed stations at 20- to 30-km intervals along the TACT and PWS lines in Prince William Sound and more sparsely along two other reflection lines. Average uncertainties in station locations and elevations are approximately 50 m. Three identical Kinemetric True-Time Satellite Clock Receivers (model 468) provided a common time base accurate to a millisecond for all seismic recorders and the multichannel seismic vessel.

Two offshore wide-angle recordings of the seismic reflection lines were obtained using the R/V *Big Valley*. The *Big Valley* was first stationed at the seaward end of the TACT line to record data from along the TACT line and then sailed to the seaward end of the Suckling line to record data from along the Suckling line. On the R/V *Big Valley* we deployed and digitally recorded signals telemetered from a series of sonobuoys.

All data were converted to SEG-Y format, and the common receiver gathers were processed using DISCO seismic reflection software [*Brocher and Moses*, 1990]. The common receiver gathers were processed either as refraction profiles or as reflection gathers, depending on the arrivals being investigated. Refraction record sections were plotted using a reduction velocity of 6 km/s; trace amplitudes were corrected for geometrical spreading by multiplying each trace by its range. With DISCO software, the record sections were bandpass filtered and predictively deconvolved, and signal levels were enhanced by summing three adjacent traces (spanning an interval of 100 m). The predictive deconvolu-

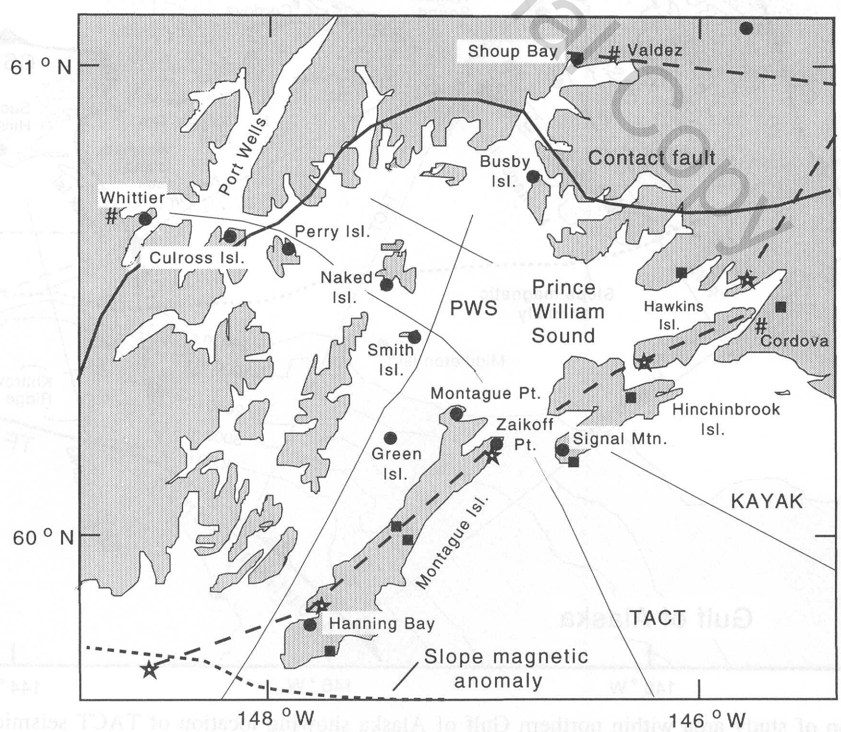


Figure 3. Map of Prince William Sound showing location of TACT seismic reflection lines (named light lines), temporary seismic recorders (solid circles), and hand samples used for laboratory measurements (solid squares). Dashed lines show locations of seismic refraction lines described by *Fuis et al.* [1991]. Stars show shot points along the Montague line described in the text.

tion reduced the reverberation of the wide-angle data and allowed midcrustal reflections and wide-angle refractions to be more easily identified.

Description of the Wide-Angle Data

The onshore recordings of the TACT, PWS, and Kayak lines show a number of refracted and wide-angle reflected arrivals from the crust and upper mantle. Refractions from the upper crust, *Pg*, having apparent velocities between 4 and 6 km/s, can be traced to source-receiver offsets as great as 100 km (Figure 4). A midcrustal refraction, having an apparent velocity of 6.9 km/s, emerges as a first arrival at an offset of 100 km and can be traced as a first or second arrival for over 100 km. We shall refer to this arrival as *Pi*. Refractions from the top of the upper mantle, *Pn*, cross over *Pi* and become first arrivals at ranges of between 120 and 150 km. *Pn* arrivals observed on lines PWS and Kayak have apparent velocities close to 8 km/s at maximum source-receiver offsets of 230 km (Figure 4b). *Pn* arrivals are observed to maximum ranges of 290 km southeastward along the TACT line where they have an apparent velocity of 8.9 km/s, indicating a substantial northwestward dip of the Moho of the subducting Pacific plate.

As found in the marine multichannel seismic reflection profiles, few wide-angle reflections from the upper crust (0-4 s two-way travel time or twtt) were observed. In the midcrust, however, a large-amplitude wide-angle reflection, *PiP*, can be traced from near-vertical incidence to wide angles, over a total aperture more than 100 km (Figure 4). This *PiP* reflection, which dips landward over the length of the TACT line between 6 and 8 s twtt, is from the same midcrustal reflector as observed on the multichannel seismic reflection profiles within Prince William Sound [*Fisher et al.*, 1989b; *Brocher et al.*, 1991b]. A second, low-amplitude wide-angle reflection, labeled *PiiP*, can in a few places be observed at wide angles about 1 s later than *PiP*. *PmP* reflections from the upper

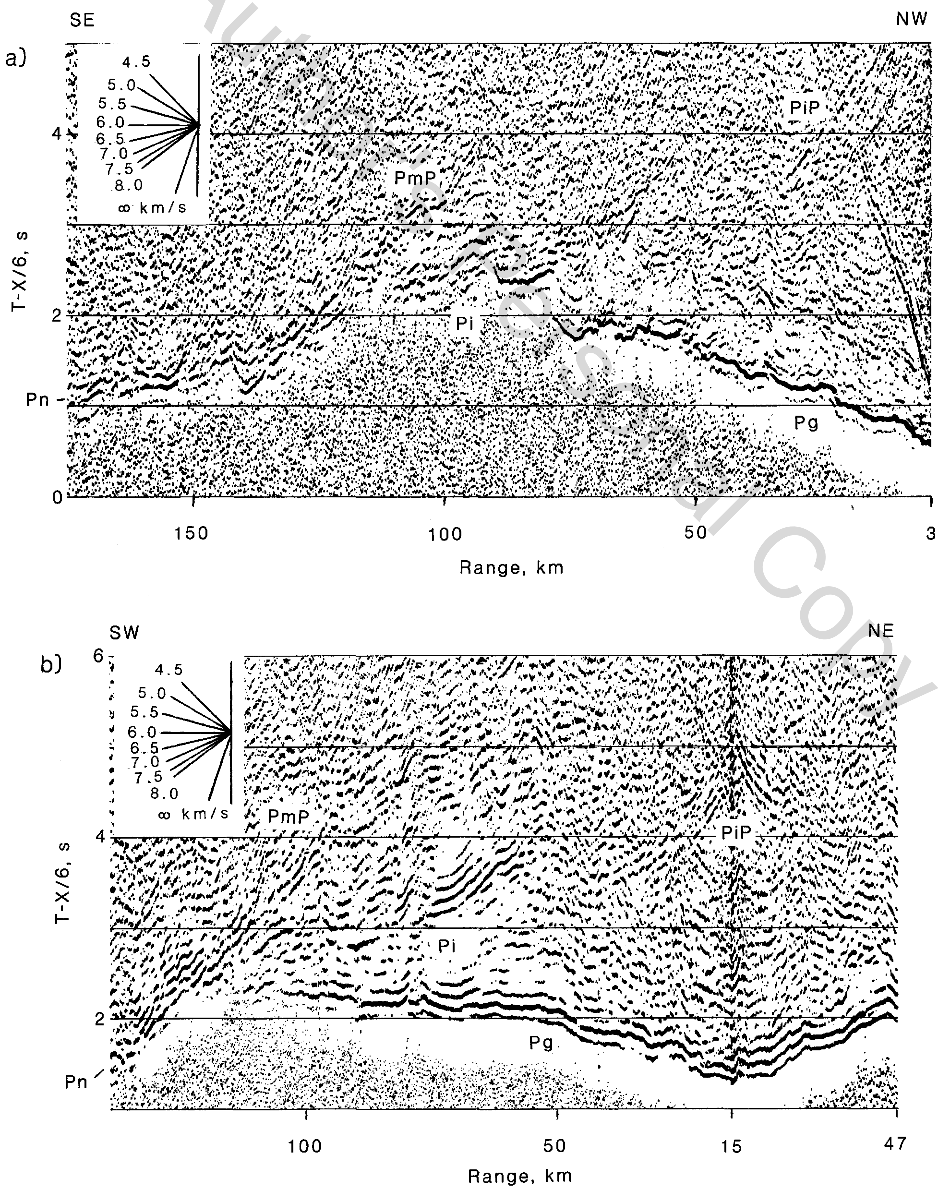


Figure 4. (a) Common receiver gather for shots along the TACT line recorded at Naked Island. Identified arrivals, *Pg, Pi, Pn, PiP*, and *PmP* are described in text. Each trace represents the sum of three adjacent air gun shots (a distance of 100 m). Data have been deconvolved and plotted using automatic gain control (AGC). (b) Plot using identical format for shots from the PWS line recorded at Montague Point.

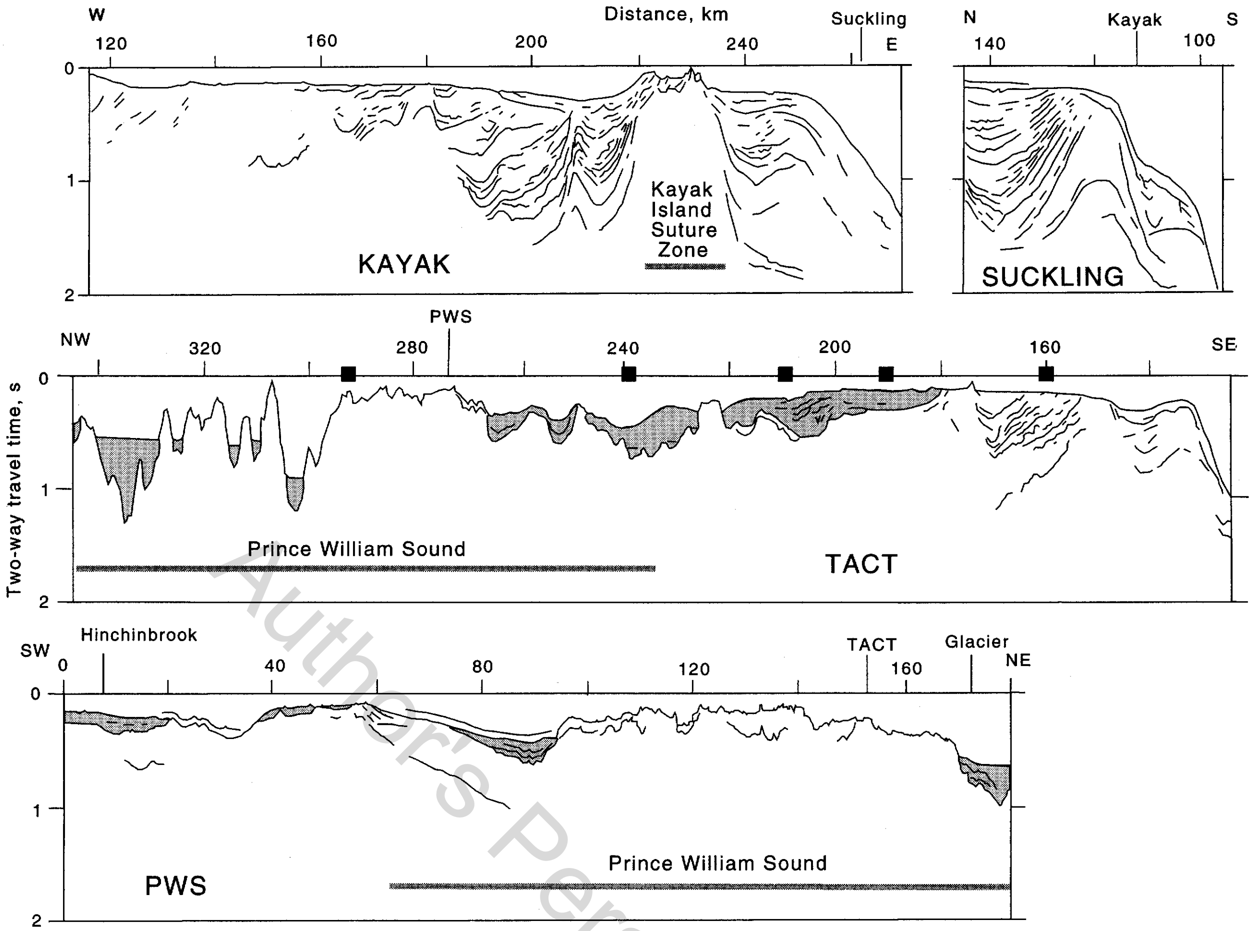


Figure 5. Line drawing interpretation of upper 2 s two-way travel time (twtt) of Kayak, Suckling, TACT, and PWS unmigrated seismic reflection profiles showing bathymetry and Neogene sediments (shaded) on the continental shelf. The profiles are plotted with a vertical exaggeration of approximately 39:1. Solid squares along TACT line shows locations of common shot gathers shown in Figure 6.

mantle are prominent at wide angles and can rarely be traced discontinuously to near-vertical incidence at 10-11 s twtt. Neither *PiiP* nor *PmP* can be easily observed at small source-receiver offsets in the record sections presented here, and thus details of the lower crust are poorly resolved by these data (see appendix[1]).

Forward Modeling

Observed travel times were generally matched to within 0.10 s to 0.2 s by forward modeling using computer algorithms described by *Cerveny et al.* [1977], *Hill et al.* [1985], and *Luetgert* [1988]. The velocity model consists of layers with internal, linear velocity gradients and velocity discontinuities of varying magnitude between layers. The modeling proceeded by fitting first the direct arrivals and then the refractions recorded nearest the receiver. These arrivals constrain the uppermost layers of the model near each receiver; interpolation of these models between receivers yields a two-dimensional (2-D) model for the entire seismic line. Subsequent arrivals are then fit, always working downward through the model, ensuring that all previous arrivals are matched by the model. The model was constructed along a straight-line segment that approximates the source-receiver geometry. Source and receiver locations were projected onto this line, although true source-receiver distances were used in modeling.

A detailed discussion of the estimated uncertainties for each of the velocity models to be presented is provided in the appendix. We estimate from trial-and-error perturbations of model parameters that *P* wave velocities for the best determined parts of the models are resolved to within ±0.1 km/s by this forward modeling procedure and that in the poorly determined lower crust uncertainties in the velocities approach ±0.5 km/s. We believe the depths of interfaces to be resolved to within 5 to 10% of the total depth of the interface. The spatial resolution in upper crustal structure near the receiver is determined by the shortest wavelength on the record and is several hundred meters. The resolution of the velocity-depth model varies depending on the density of ray paths along the profile. The landward ends of the profiles lack ray coverage degrading the resolution of the forward modeling in these areas. For a more detailed description of model parameterization and error estimates in this type of forward modeling the reader is referred to *Hill et al.* [1985], *Fuis et al.* [1991], and the appendix.

[1]Appendix is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document B94-002, $2.50. Payment must accompany order.

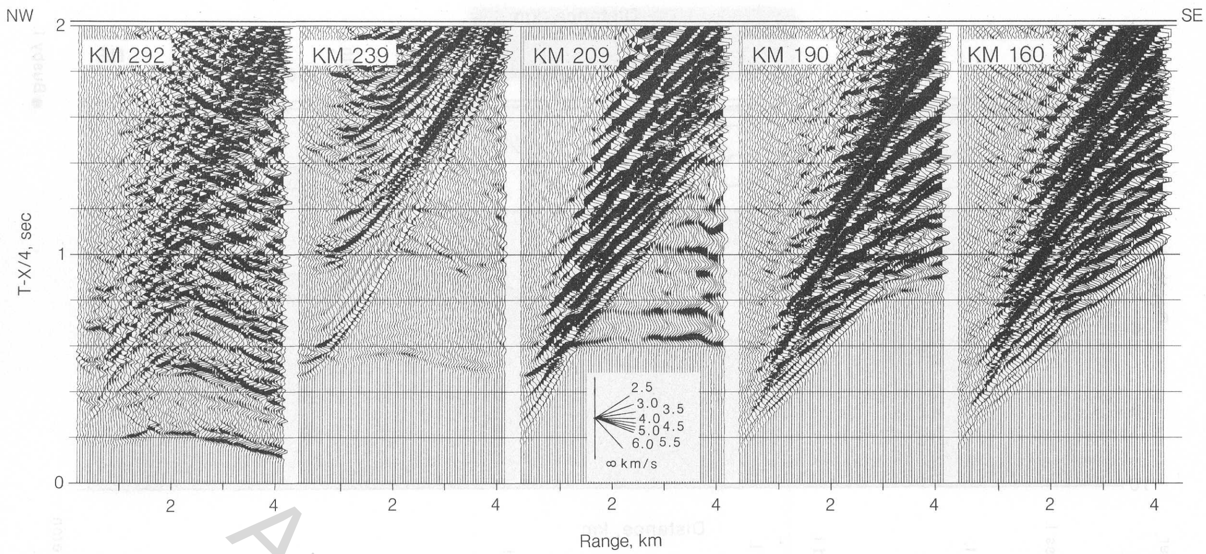


Figure 6. Examples of common shot gathers from the multichannel seismic reflection streamer showing refracted first arrivals used to determine velocities of the rocks near the seafloor. The gathers are reduced at a velocity of 4 km/s, showing data recorded at offsets from 0.3 to 4.2 km. Amplitudes of the gathers have been corrected for geometrical spreading using a factor of range$^{1.5}$. Common shot gathers are from the TACT reflection line where the seafloor is relatively flat at model km 292, 239, 209, 190, and 160 (Figure 5).

The resolution of the final velocity-depth model depends most critically on correlations of arrivals between receiver gathers and on the choice of diving, refracted, or wide-angle reflected waves, and refracting horizons used to model these arrivals. To minimize the ambiguities associated with these choices, we tied these correlations to the more continuous reflection events imaged by the marine seismic reflection profiles. The geometry of the most shallow crustal structure in terms of two-way travel time was digitized off the seismic reflection profiles (Figure 5) and converted to depth using a velocity of 2 km/s for Neogene sedimentary rocks determined from first arrivals on shot gathers obtained during multichannel profiling. These gathers indicate that near-bottom velocities within Prince William Sound increase landward from about 3.5 km/s near the entrance of the sound to about 4.8-4.9 km/s near the coast of southern Alaska (Figure 6). Velocity models for the upper 10 km of the crust along the TACT and PWS lines based on these gathers and *Pg* arrivals are presented in Figure 7.

Velocity Structure of the Oceanic Crust

Oceanic crust beneath the sedimentary sequence on the continental slope has been mapped on seismic reflection line 425 (which the TACT line reoccupied) for a distance of at least 15 km and possibly as much as 40 km [*Plafker et al.*, 1982]. Lower-frequency, diffractive reflections from the top of the igneous oceanic crust are observed on both the TACT and Suckling lines, but they cannot be traced as far landward beneath the continental slope as on line 425. Our ability to trace the subducted Pacific plate landward of the Aleutian trench is facilitated by our wide-angle recordings made over the Pacific crust seaward of the trench (Figure 2). We focus on sonobuoy data acquired along the TACT line (Figure 8b), as the locations of the sonobuoys used to record the Suckling line are of lower quality.

The TACT sonobuoy data contain arrivals characteristic of the igneous oceanic crust as described by *Spudich and Orcutt* [1980]. Precritical and postcritical reflections from the top and bottom of the igneous crust are well imaged by this profile (Figure 8b). Refractions from the oceanic upper mantle, *Pn*, crossover the refractions from the middle to lower crust, *P3*, at a source-receiver offset of about 35 km and can be faintly traced to ranges of 50 km.

The velocity model shown in Figure 9 yields calculated travel times that match the observed travel times to within 0.05 s. The igneous oceanic crust was modeled as two layers with a second-order velocity discontinuity between them and lower velocity gradient in the lower layer. The total thickness of the igneous crust is 6.5 ± 0.5 km.

Velocity Models for Prince William and Yakutat Terranes

The following sections describe the five velocity models presented in Figure 10 for reflection lines within the Prince William and Yakutat terranes. Our discussion is focused on the widespread *Pi* refractor having a velocity of 6.9 km/s and on the structure beneath the *Pi* refractor. The depth to the *Pi* refractor varies both along strike and dip lines, but generally dips landward. Velocities between the *Pi* refractor and the Moho are poorly resolved by the wide-angle data, due to the absence of refracted arrivals from the lower crust. We therefore assumed the 6.1- to 6.6-km/s velocities in the lower crust beneath the 6.9-km/s layer to minimize the thickness of the lower crust (Figure 10) and to match the total crustal thicknesses found onshore in the Chugach terrane [*Fuis et al.*, 1991]. If higher velocities are assumed for the lower crust, the lower crust and total crustal thickness would be increased. If we use relatively low velocity lower crust (compared to many continental crusts) within Prince William Sound and on the continental shelf the crustal thickness determined from *PmP* and *Pn* arrivals varies between 28 and 34 km, which is close to the thickness inferred from onshore TACT lines in the

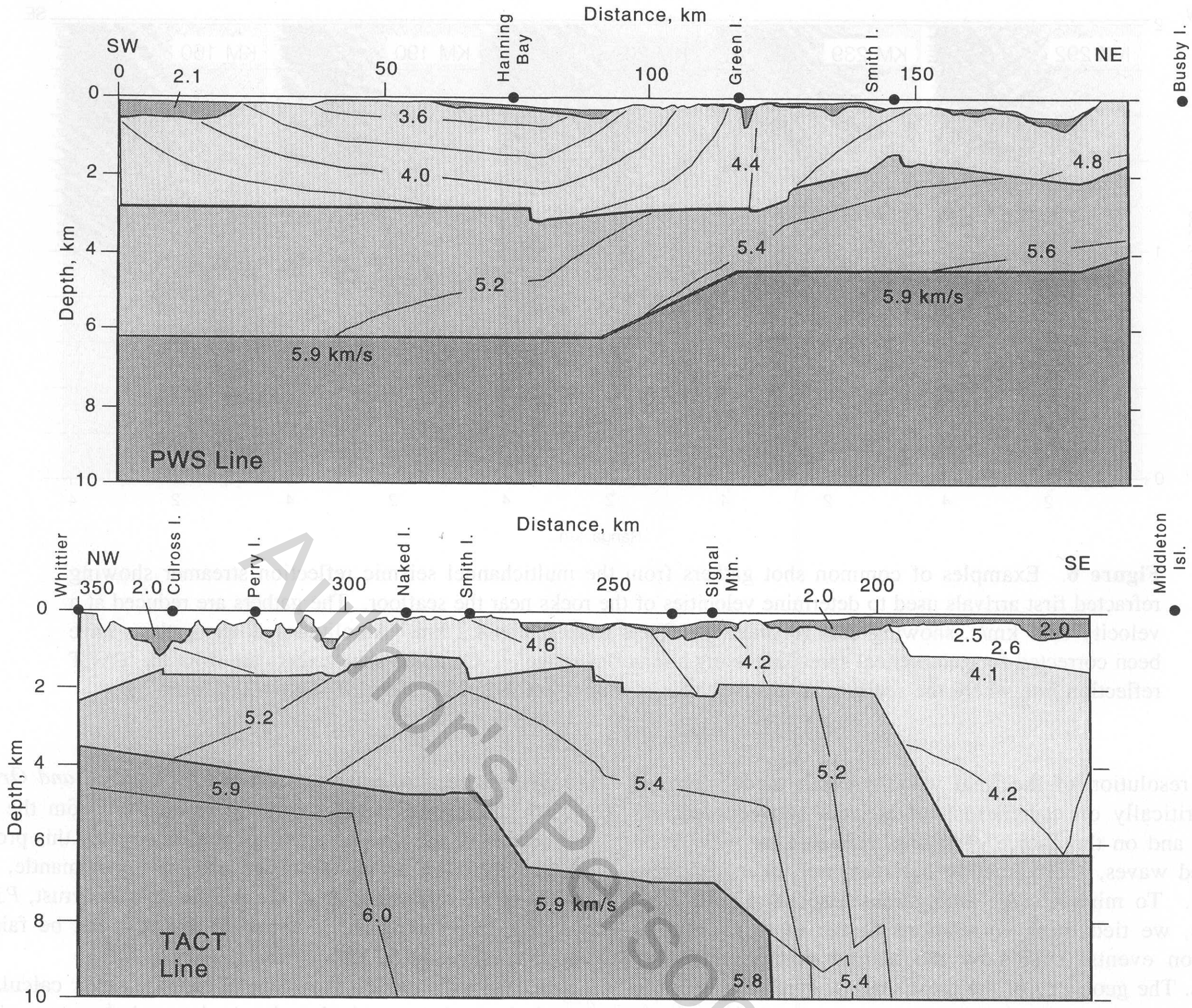


Figure 7. Shallow crustal velocity models for the Prince William terrane in Prince William Sound (PWS) determined from the forward modeling of *Pg* arrival times recorded along the PWS and TACT reflection lines. Station locations used for this modeling are indicated by solid circles at the top of each model. Velocity contours are shown at intervals of 0.2 km/s. Velocities increase toward the northeast and northwest edges of the sound; Orca Group rocks are thought to extend to depths exceeding 10 km in the sound. There is little or no evidence for azimuthal velocity anisotropy where the lines intersect near Smith Island in Prince William Sound (Figure 3).

Chugach terrane [*Fuis et al.,* 1991]. A more detailed discussion of the uncertainties associated with each of the models is presented in the appendix.

The PWS Line

We first describe our interpretation of the wide-angle data recorded during the acquisition of the 180-km-long PWS reflection line. Perhaps because these data were obtained along regional geologic strike entirely within the Prince William terrane, they reveal the clearest examples of the arrivals described in this study. Wide-angle data were recorded by six receivers along or off end of the PWS reflection line, including stations at the northern and southern ends of Montague Island, and on Green, Smith, and Busby Islands, and in Shoup Bay, Valdez Arm (Figure 3). Source-receiver offsets ranged from 3 to 195 km. Data recorded by the receiver at Shoup Bay in the Chugach terrane, northeast of the Contact fault, connect the crustal model for the PWS line to previous TACT refraction models for the Chugach terrane [*Flueh et al.,* 1989; *Wolf and Levander,* 1989; *Fuis et al.,* 1991; *Wolf et al.,* 1991]. No receivers were located on the southern end of the PWS line meaning that the velocity model lacks reversed ray paths for the southernmost 80 km; hence we attempted to satisfy these data using a simple, horizontally layered model.

Nowhere along the PWS line do the apparent velocities of *Pg* exceed 6 km/s (Figure 11). As shown in Figure 7, *Pg* travel times were modeled using three layers having velocities between 3.5 and 6.0 km/s. These arrivals sample the crust to a depth of about 6 km.

The base of the 5.9- to 6.0-km/s layer is defined by the large-amplitude *PiP* reflection (Figure 11) which correlates to the prominent vertical-incidence reflection observed between 6 and 8 s twtt on the PWS reflection line. The observed normal move-out of *PiP* is consistent with the topographic relief of the reflector observed on the PWS reflection line, including the upward doming of the reflector that peaks between km 150 and 160 (Figure 10a). The curvature of the

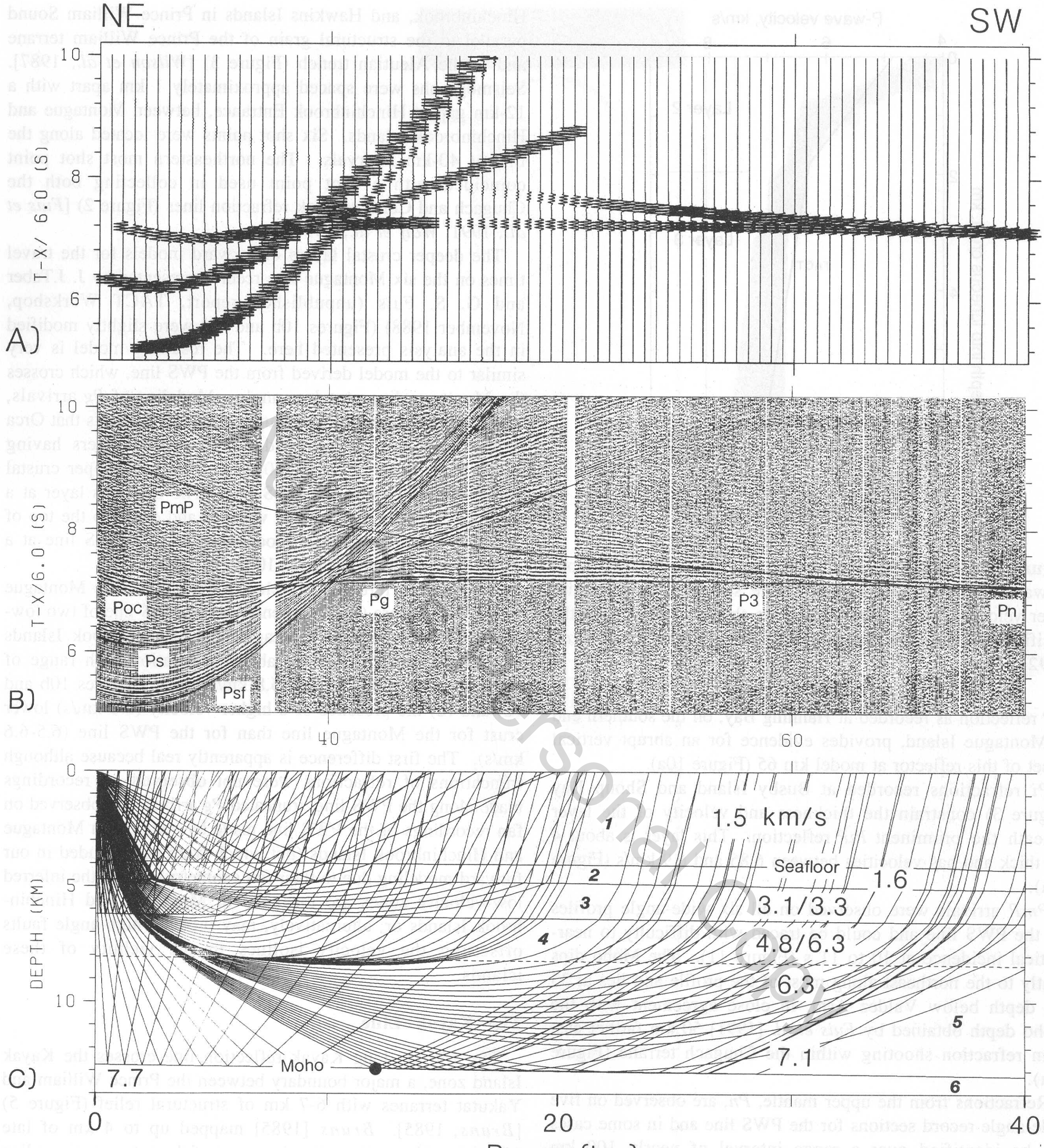


Figure 8. (a) Synthetic and (b) observed wide-angle profiles and (c) ray diagram for data recorded along the TACT line by sonobuoy over the Pacific plate. Synthetic seismograms were calculated using ray theory [*McMechan and Mooney,* 1980]. Calculated travel times are superposed on the data. Numbers of major layers beneath thin surficial units are given in bold italics. Labeled arrivals *Pg, P3,* and *Pn,* respectively, are modeled as refractions from layers 4, 5, and 6, respectively, of the velocity model. *Psf, Ps, Poc,* and *PmP* represent reflections from the seafloor, post upper Eocene sedimentary rocks, top of the igneous crust, and the upper mantle, respectively. The seismic reflection data acquired by TACT and previous surveys in the northern Gulf of Alaska [*Bruns*, 1985; *Plafker,* 1987], reveal that the oceanic crust of the Pacific plate is covered by two layers totaling up to 2 s twt of post upper Eocene sedimentary rocks. Layer 2 of the velocity model, representing the uppermost sedimentary unit lying between *Psf* and *Ps,* Pleistocene turbidites [*Bruns*, 1985], did not produce identifiable refracted arrivals so we simply assumed a 1.6-km/s velocity for this layer. Layer 3 represents pre-Pleistocene pelagic and hemipelagic sediments [*Bruns*, 1985; Plafker, 1987]. Layers 4 and 5 of the velocity model represent the extrusive and plutonic components of the igneous crust, respectively. The profile has been reduced at 6 km/s and plotted using automatic gain control (AGC). Critical points are indicated by solid dots along the tops of layers 3 and 6.

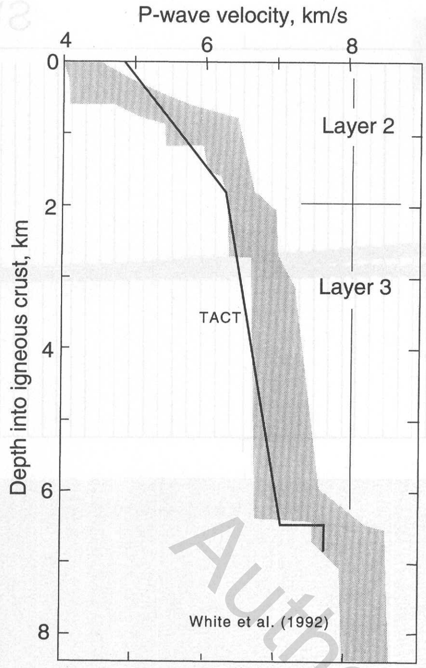


Figure 9. Comparison of velocity model obtained from forward modeling of the TACT line sonobuoy profile with other velocity models (summarized as shaded region) from the Pacific ocean for crustal ages greater than 29 Ma [*White et al.*, 1992].

PiP reflection as recorded at Hanning Bay, on the southern end of Montague Island, provides evidence for an abrupt vertical offset of this reflector at model km 65 (Figure 10a).

Pi refractions recorded at Busby Island and Shoup Bay (Figure 3) constrain the thickness and velocity of the layer beneath the prominent *PiP* reflection. This layer is about 4 km thick and has velocities between 6.85 and 6.9 km/s (Figure 10a).

PmP arrivals were observed on all six wide-angle profiles for the PWS line and could be traced with difficulty to near-vertical incidence at 10 to 11 s (Figure 11). The Moho dips gently to the northeast along most of the profile and lies at 33 km depth below Valdez Arm, in close agreement with the Moho depth obtained by *Fuis et al.* [1991] 50 km farther east from refraction shooting within the Chugach terrane (Figure 11a).

Refractions from the upper mantle, *Pn*, are observed on five wide-angle record sections for the PWS line and in some cases can be identified over a range interval of nearly 100 km beyond their crossover range at 110 km. The apparent velocities of the *Pn* arrivals can be satisfactorily matched using an upper mantle velocity of 7.8 km/s (Figure 11), in agreement with the upper mantle velocities reported by *Fuis et al.* [1991] for a dip line within the Chugach terrane.

There are no clear reflections from the top of the oceanic crust (layer 6) at the northeast end of this model to definitively indicate the presence of this slab of oceanic crust (layers 6 and 7). Its existence is compatible with *PmP* and *Pn* observations and was incorporated solely to be consistent with the interpretation of the TACT line where it crosses the PWS line.

The Montague Line

In 1985, the TACT program collected refraction data along the Montague line, which extends 135 km along Montague, Hinchinbrook, and Hawkins Islands in Prince William Sound parallel to the structural grain of the Prince William terrane and to the Aleutian trench (Figure 3) [*Wilson et al.,* 1987]. Seismographs were spaced approximately 1 km apart with a 12-km gap at Hinchinbrook Entrance, between Montague and Hinchinbrook Islands. Six shot points were located along the line at 40-km intervals. The northeastern most shot point coincided with a shot point used in collecting both the Chugach and Cordova Peak refraction lines (Figure 2) [*Fuis et al.*, 1991; *Wolf et al.*, 1991].

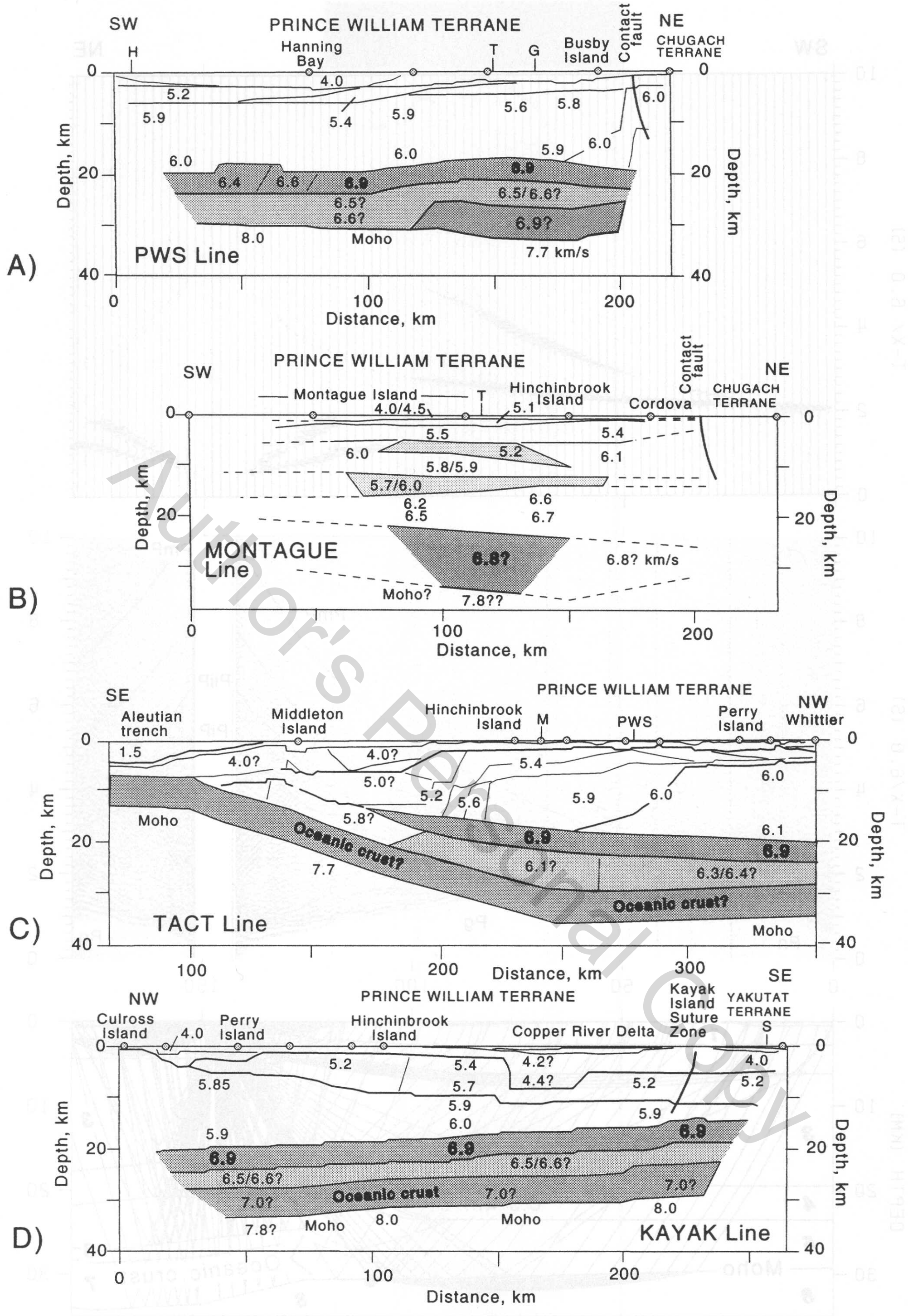
The deeper crustal layers of forward models for the travel times on the six Montague line records presented by J. J.Taber and G. S. Fuis (unpublished report, TACT Workshop, November 1988) (Figures 10b and 12) were slightly modified in the analysis presented here. The resulting model is very similar to the model derived from the PWS line, which crosses the Montague line at a low angle. Modeling of *Pg* arrivals, which can be traced to offsets up to 110 km, suggests that Orca Group rocks can be subdivided into several layers having velocities between 4.0 and 6.0 km/s, similar to upper crustal layers modeled along the PWS line. The 6.8-km/s layer at a depth of 22 km resembles the velocity and depth to the top of the *Pi* (6.9 km/s) refractor modeled along the PWS line at a depth of about 20 km (Figure 10b).

The chief differences in velocity models for the Montague and PWS lines are (1) the absence on the PWS line of two low-velocity zones beneath Montague and Hinchinbrook Islands that were inferred from the abrupt truncation with range of refractions from the 5.5 and 5.8 km/s layers (Figures 10b and 12) and (2) the presence of a higher-velocity (6.8 km/s) lower crust for the Montague line than for the PWS line (6.5-6.6 km/s). The first difference is apparently real because although truncations of refractions were not observed on recordings made along the PWS line, truncated *Pg* arrivals are observed on fan recordings of the PWS line made by stations on Montague and Hinchinbrook Islands (but which were not included in our forward modeling due to their fan geometry). Thus the inferred low-velocity zones are localized to Montague and Hinchinbrook Islands or, alternatively, may indicate high-angle faults offsetting the velocity isolines in the vicinity of these islands.

The Kayak Line

The 140-km-long Kayak reflection line crosses the Kayak Island zone, a major boundary between the Prince William and Yakutat terranes with 6-7 km of structural relief (Figure 5) [*Bruns*, 1985]. *Bruns* [1985] mapped up to 4 km of late Miocene and younger strata just west of the suture zone on line 417, and the Kayak line imaged more than 2 s twtt of these sedimentary rocks. We modeled wide-angle data recorded at seven stations including stations at Culross, Perry, and Naked Islands, the northern end of Montague Island, and the southern end of Hinchinbrook Island (Figure 3). Source-receiver offsets ranged from as little as 13 km to as much as 265 km.

Even though both stations on Kayak Island and in the Suckling Hills recorded the Kayak line in a fan geometry from the eastern end of the line (Figure 2), we modeled only data from the Suckling Hills because the data from Kayak Island were too severely disrupted by complex structure associated with the Kayak Island zone. Thus, although the Suckling Hills station was located 57 km north of the line, it provides the only data used to reverse the Kayak line. The fan geometry of the Suckling Hills station introduces a significant bias in the



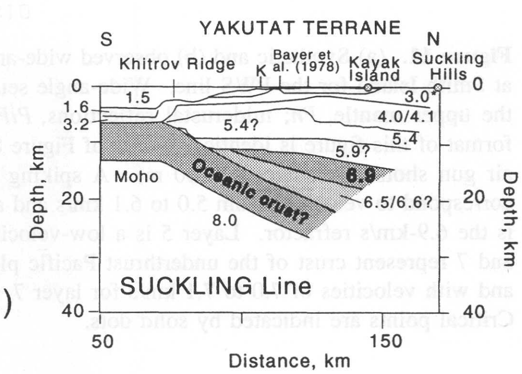


Figure 10. Velocity models for Northern Gulf of Alaska based on the (a) PWS, (b) Montague, (c) TACT, (d) Kayak, and (e) Suckling lines. Models for the PWS and Montague lines are aligned where the lines intersect at Hanning Bay. The 6.9-km/s layer is shown in the dark shading; inferred Orca Group rocks above this layer are not shaded. Horizons are truncated where no rays sample the horizon. Models are plotted with a vertical exaggeration of 2:1. Stations used to determine the velocity model are shown along the tops of the models as open circles. The velocity of the 3.0* km/s layer near the Suckling Hills on the Suckling line was assumed. Ties to other seismic lines are indicated by abbreviations H, Hinchinbrook; T, TACT; G, GLACIER; M, Montague; PWS; S, Suckling; and K, Kayak lines.

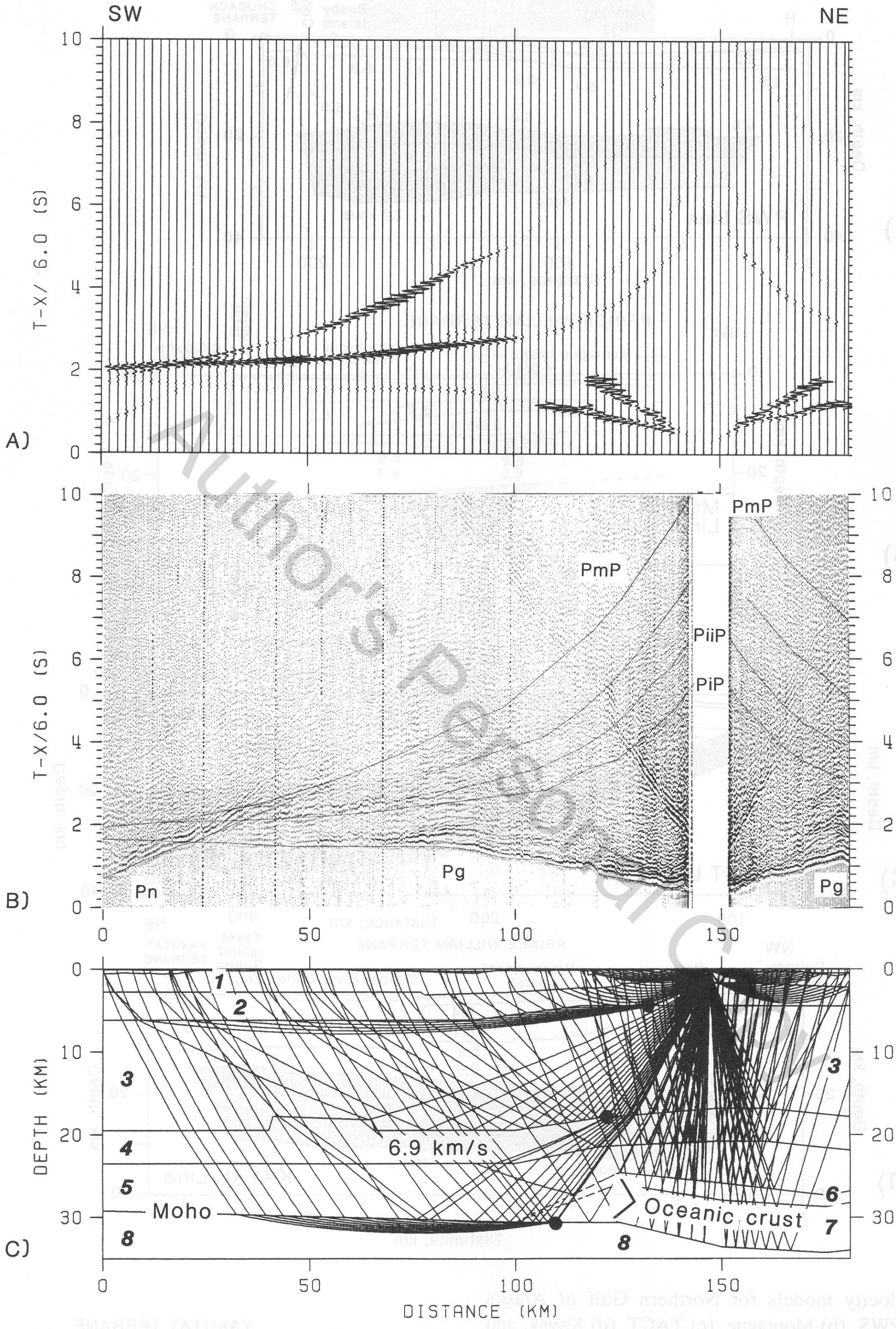


Figure 11. (a) Synthetic and (b) observed wide-angle records and (c) ray diagram for the recording obtained at Smith Island for the PWS line. Wide-angle seismic data reveal refractions from the upper crust, *Pg*; and the upper mantle, *Pn*; midcrustal reflections, *PiP* and PiiP; and the reflection from the Moho, *PmP*. The format of this figure is identical to that of Figure 8 except that each trace represents the sum of six adjacent air gun shots (a distance of 200 m). A spiking deconvolution has been applied to the data. Layers 1-3 correspond to velocities from 5.0 to 6.1 km/s and are inferred to represent rocks of the Orca Group. Layer 4 is the 6.9-km/s refractor. Layer 5 is a low-velocity zone having velocities from 6.5 to 6.6 km/s. Layers 6 and 7 represent crust of the underthrust Pacific plate, with velocities between 6.5 and 6.6 km/s for layer 6, and with velocities of 7.0 to 7.1 km/s for layer 7. Layer 8 is the upper mantle, with a velocity of 7.8 km/s. Critical points are indicated by solid dots.

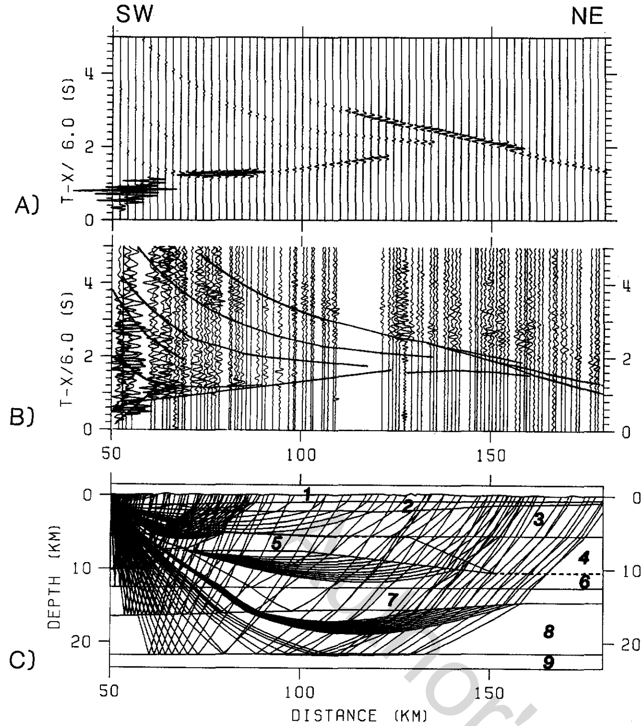


Figure 12. (a) Synthetic and (b) observed wide-angle records and (c) ray diagram for the recording of the Montague line for the shot point at Hanning Bay. Format of this figure is the same as for Figure 11; traces represent recordings made at individual receivers. Layers 1-7 have velocities less than 6.1 km/s and are inferred to represent rocks of the Orca Group. Layers 5 and 7 are low-velocity layers, with velocities of 5.2 km/s in layer 5 and 5.7 to 6.0 km/s in layer 7. Layer 8 has a velocity between 6.2 and 6.7-km/s. Layer 9 has a velocity of 6.8 km/s.

inferred velocity model for interfaces which dip landward which include the 6.9-km/s refractor; the latter appears to be 2 or 3 km deeper at the eastern end of the Kayak line than is suggested by previous reversed refraction profiling [*Bayer et al.*, 1978], which placed the top of a 7.0-km/s refractor at 10 to 11 km. A shallower refractor depth than inferred from the wide-angle recording of the Kayak line is also suggested by vertical incidence reflections from the Kayak line which indicate that the top of the 6.9-km/s refractor is at 4.2 s twtt (about 4.25 s twtt on line 417; see *Bruns* [1985]), corresponding to a depth of about 9.7 km, using an average velocity of 4.6 km/s (Figure 10d).

The absence of receivers along the Kayak line limits our ability to resolve details of the velocity structure in the upper and middle crust. The northwest ends of the TACT and Kayak lines are nearly colinear (Figure 3), and thus *Pg* arrivals from parts of the TACT line recorded at Culross, Perry, and Naked Islands constrain the velocities in the upper to middle crust of the western end of the Kayak line. Direct *Pg* arrivals from the Kayak line were recorded only at stations on Montague and Hinchinbrook Islands. Observed *Pg* and *Pi* refractions are consistent with velocities less than 6 km/s extending to the top of the lower crustal refractor at 14 to 21 km depth (Figure 10d).

Pi and *Pn* refraction arrivals were recorded by all seven stations. *Pi* can commonly be observed on the profiles as a first and secondary arrival for a range interval of about 100 km, placing bounds on the velocity of the refractor of 6.9 km/s (Figure 13). Most of these stations also recorded *PiP* reflections and a few recorded *PiiP* reflections from the top and bottom of the *Pi* refractor, providing evidence that the refraction originates from a layer approximately 4 km thick (Figure 13). *PiP* reflections from the top of this layer suggest that it dips to the northwest from a depth of about 14 km at the southeastern end of the line to nearly 21 km depth beneath Culross Island on the northwestern end of the model. *Pn* emerges as a first arrival at source-receiver ranges of about 150 km (Figure 13) and is consistent with a crust that thickens to the northwest from 28 to 32 km (Figure 10d). *Pn* can be traced both as first and second arrivals for distances of more than 100 km, providing an accurate upper mantle velocity of 8.0 km/s. *PmP* arrivals recorded by five stations confirm the gentle northwesterly dip of Moho along this profile (Figure 13).

There are neither strong reflections nor observed refractions from the slab of oceanic crust which is assumed to underplate the Yakutat terrane [*Plafker*, 1987; *Fuis and Plafker*, 1991; *Fuis et al.*, 1991; *Grantz et al.*, 1991]. Faint wide-angle reflections from the lower crust, perhaps representing the top of the oceanic crust, however, are observed at the station located on the southern end of Hinchinbrook Island (Figure 13). Thus, there is only limited evidence favoring the presence of oceanic crust underlying the continental crust along the Kayak line.

The existing wide-angle data do not require a major velocity contrast in the upper or middle crust across the Kayak Island zone (Figure 10d). Our preferred velocity model indicates that the 6.9-km/s refractor and the Moho are offset by this suture zone. Although they are consistent with both the observed travel time and amplitude-range distributions, neither of these offsets are strongly required by the forward modeling, and the Kayak line data are consistent with no offset of these horizons in the middle and lower crust. The Suckling line described below provides better evidence for an offset of the 6.9-km/s refractor at the Kayak Island zone.

The TACT Line

Air gun shots along the 315-km-long TACT reflection line, extending from the Pacific plate to the Contact fault (Figure 3), were recorded by eight stations deployed around Prince William Sound, by one station on Middleton Island near the shelf edge, and by a free-floating sonobuoy over the Pacific plate (Figures 2 and 3). The curvature of the TACT line at its northwestern end (Figure 2) violated our assumption of 2-D geometry, resulting in ray path deviation from the reflection line by as much as 10° and introducing range errors up to 5% in the correct location of velocity features. A preliminary interpretation of the TACT line was presented by *Brocher et al.* [1991b].

Upper crustal velocities on the continental shelf seaward of Prince William Sound are as much as 1 km/s lower than those within Prince William Sound at comparable depths (Figures 7 and 10c). On the shelf, upper crustal velocities nowhere exceed 5.0 and 5.1 km/s (Figure 10c). The thickness of sedimentary units having velocities less than 3 km/s increases toward the shelf edge (Figure 7), consistent with observed thickening of late Miocene and younger strata along line 425 [*Bruns*, 1985], nearly coincident to the TACT line.

As for the PWS and Kayak lines, the base of rocks having

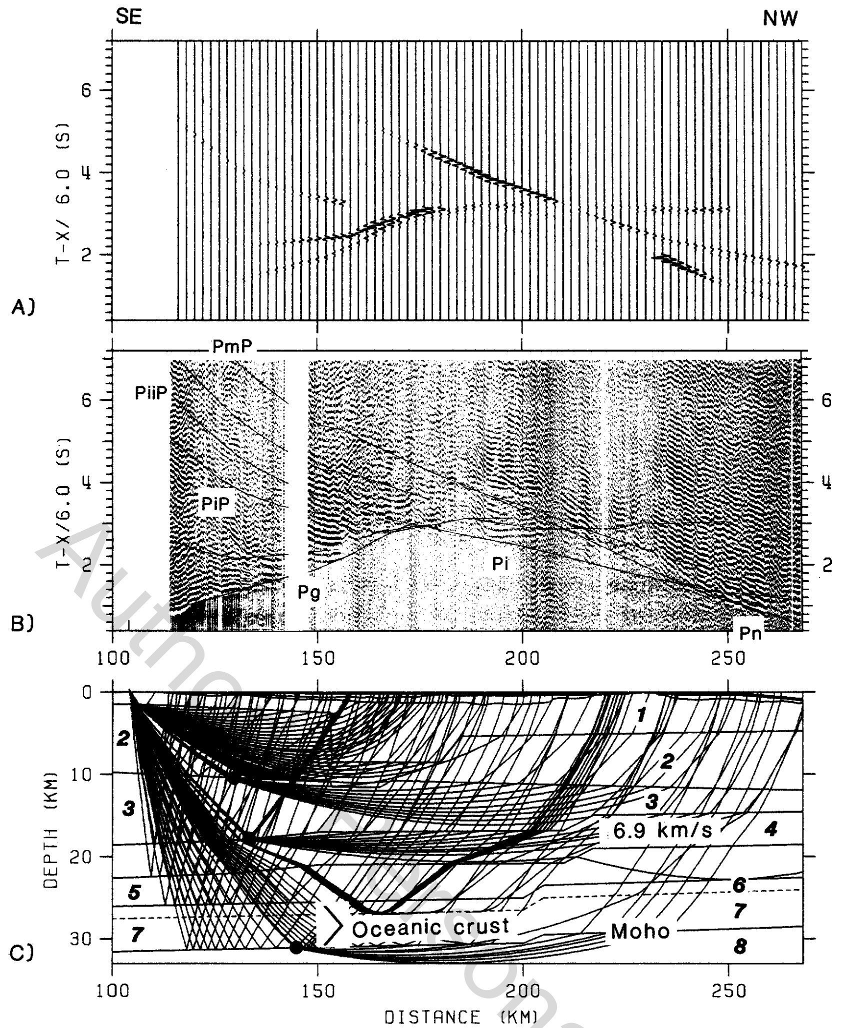


Figure 13. (a) Synthetic and (b) observed wide-angle profiles and (c) ray diagram for data recorded on Hinchinbrook Island for shots along the Kayak seismic reflection line. Format of this figure is the same as for Figure 11 except that each trace represents the sum of three adjacent air gun shots (a distance of 100 m) and was not deconvolved. Layers 1-3 correspond to velocities between 5.2 and 6.1 km/s. Layer 4 is the 6.9-km/s refractor. Layer 5 is a low-velocity zone having assumed velocities from 6.5 to 6.6 km/s. Layers 6 and 7 represent crust of the underthrust Pacific plate, with velocities of 6.2 to 7.0 km/s and 7.0 to 7.1 km/s, respectively. Layer 8 is the upper mantle with a velocity of 8.0 km/s. Solid dot indicates critical point.

seismic velocities between 5.9 and 6.1 km/s (Figure 10c) is defined by a large-amplitude *PiP* reflection. Along the TACT reflection line the *PiP* reflector dips landward from about 5 s twtt beneath the projection of Middleton Island (model km 150) to nearly 8 s twtt beneath the Contact fault near Whittier, corresponding to an average 3° dip from 15- to 24-km depth over a distance of 210 km.

Pi refractions are observed on several records from stations between Culross and Montague Islands. The 6.9-km/s layer can be traced from Prince William Sound to the southeast almost as far as Middleton Island. As for the PWS and Kayak lines, *PiP* and faint *PiiP* reflections along the TACT line from the top and bottom of this layer define its thickness to be about 4 km.

Total crustal thicknesses in Prince William Sound along the TACT line are constrained by the strike lines PWS, Montague, and Kayak and by observations of faint *PmP* reflections at near-vertical incidence which can be traced with difficulty into larger-amplitude reflections at offsets of nearly 100 km. Discontinuous *PmP* reflections from the TACT line can be traced on data from eight recorders stationed within Prince William Sound and are reversely recorded by stations on opposite sides of Prince William Sound at Whittier and Signal Mountain. Forward modeling of these arrivals is consistent with a subhorizontal Moho at a depth of 34 km, in close agreement with the 33.5 km depth determined along the PWS line where it intersects the TACT line (Figure 10c). Similarly, forward modeling of *Pn* arrivals from the Kayak line provides a crustal thickness of 32 km in the same location.

The subducted oceanic crust of the Pacific plate can be traced up to 40 km beneath the slope on seismic reflection line 425 [*Plafker et al.*, 1982]. Additional information on the slab geometry is provided by the refractions recorded at Middleton Island from shots seaward of the island (Figure 2). These first arrivals are modeled as refractions from the subducted oceanic crust (Figure 14); they indicate that the top of the oceanic crust

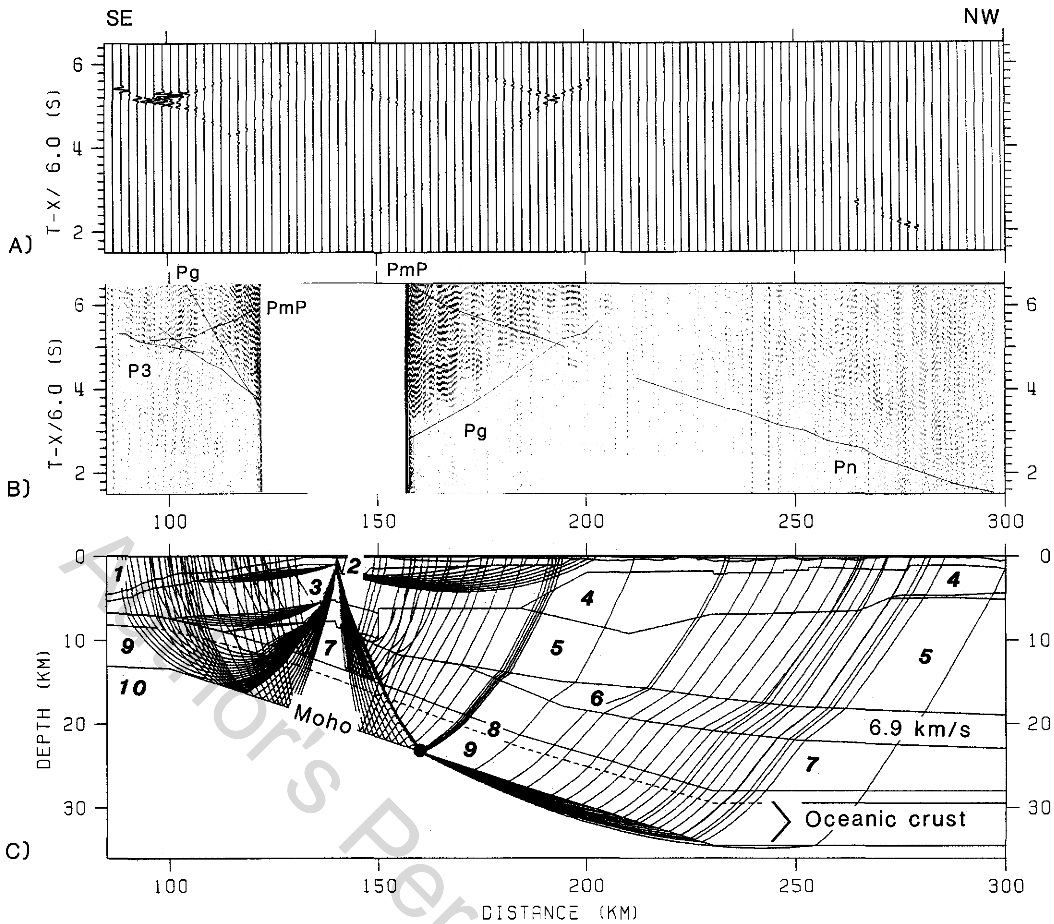


Figure 14. (a) Synthetic and (b) observed wide-angle records and (c) ray diagram for the recording of the TACT line obtained at Middleton Island. Format of this figure is the same as for Figure 11. Layer 1 is the Pacific Ocean, and layers 2 and 3 correspond to sedimentary units on the slope and shelf. Layers 4 and 5 have velocities from 5.0 to 6.1 km/s and are inferred to represent rocks of the Orca Group. Layer 6 is the 6.9-km/s refractor. Layer 7 is a low-velocity zone having assumed velocities from 5.8 to 6.4 km/s. Layers 8 and 9 model crust of the underthrust Pacific plate, with velocities of 5.0 to 6.2 km/s and 6.2 to 7.0 km/s, respectively. Layer 10 is the upper mantle, with a velocity of 7.7 km/s. Critical point is indicated by solid dot.

lies at a depth of about 7 km seaward of Middleton Island. First arrivals recorded on Middleton Island from shots landward of the island are modeled as *Pn* refractions from the subducted oceanic mantle beneath a landward thickening accretionary complex (Figure 14). Six stations from Signal Mountain to Culross Island (Figure 3) provide reversed ray paths to control the velocity of 7.7 km/s for the subducted upper mantle. Apparent *Pn* velocities of 8.9 km/s can be explained by a Moho dipping landward at about 9° seaward of Prince William Sound. *PmP* reflections provide evidence for the Moho at the base of the subducted Pacific plate at a depth of 34 km as far northwest as Whittier (Figure 3), but reflections from the top of the Pacific plate beneath Prince William Sound cannot be identified with confidence. An alternate model which fits the *PmP* and *Pn* data nearly as well as the one shown in Figure 10 has the oceanic crust maintaining a constant dip of 9° beneath Prince William Sound and a continental Moho under Prince William Sound at a depth of 34 km. This alternate model is not preferred for regional tectonic considerations discussed below.

The Suckling Line

Three stations recorded the 134-km-long Suckling reflection line (Figure 2), two recorders were deployed on Kayak Island and in the Suckling Hills, and one was located over the Pacific plate (sonobuoy). The offshore recording did not produce observable signals from the continental slope or shelf, and thus recordings of the Suckling line made in the Suckling Hills and on Kayak Island are unreversed. To partially compensate for unreversed records, we used velocity models from the Kayak line and refraction results from *Bayer et al.* [1978] to constrain the velocity structure of the upper 15 km of the crust at model km 105, 113, and 125 (Figure 15).

Unreversed *Pi* refractions are consistent with a landward dip for the 6.9-km/s layer beneath the Suckling reflection line (Figure 15). The *Pi* refractor lies at a depth of 12 km near the intersection of the Kayak and Suckling lines at km 105, slightly deeper than the 10- to 11-km depth reported by *Bayer et al.* [1978] for a 7-km/s refractor and the 9.7-km depth determined from the Kayak and Suckling seismic reflection

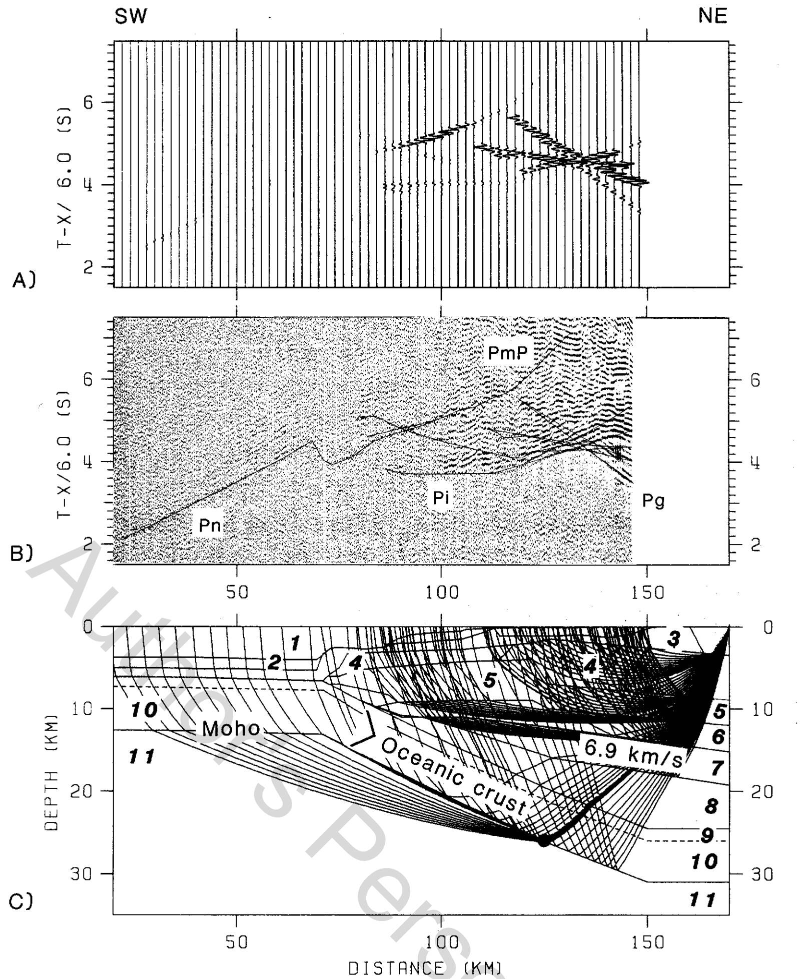


Figure 15. (a) Synthetic and (b) observed wide-angle records and (c) ray diagram for the recording of the Suckling line obtained in the Suckling Hills. Format of this figure is the same as for Figure 13. Layer 1 is the Pacific Ocean, and layers 2 and 3 correspond to sedimentary units on the Pacific plate and continental slope and shelf. Layers 4 to 6 have velocities from 4.0 to 5.9 km/s and represent sedimentary rocks of the Yakutat terrane. Layer 7 is the 6.9-km/s refractor. Layer 8 is a low-velocity zone having assumed velocities from 6.5 to 6.6 km/s. Layers 9 and 10 model crust of the underthrust Pacific plate, with velocities of 5.8 to 6.2 km/s and 6.2 to 7.2 km/s, respectively. Layer 11 is the upper mantle, with a velocity of 8.0 km/s. Critical points are indicated by solid dots.

lines. Faint but coherent unreversed *Pn* arrivals are consistent with a Moho dipping landward at about 10°, but there is no wide-angle seismic evidence for the existence and geometry of the oceanic crust underneath the margin as proposed by *Bruns* [1985]. Based on the assumed lower crustal velocities of 6.5 to 6.6 km/s underlain by subducted oceanic crust, the crustal thickness determined from unreversed *Pn* arrivals is about 27 km beneath model km 125, at the landward limit of subsurface coverage (Figure 10e).

Comparison between *Pi* refractions recorded at Kayak Island and Suckling Hills shows a delay of 0.9 s in *Pi* arrivals at Kayak Island relative to Suckling Hills. The relative delay indicates a rapid westerly depression of the 6.9-km/s layer across the Kayak Island zone, which is consistent with the magnetic model across the Kayak Island zone by *Griscom and Sauer* [1990]. The depth of the magnetic source used by *Griscom and Sauer* [1990] in this vicinity also closely matches the depth to the 6.9-km/s refractor determined by *Bayer et al.* [1978].

Laboratory Measurements

Samples of Prince William terrane rocks of the Orca Group collected on Montague and Hinchinbrook Islands and near Cordova (Figure 3 and Table 1) allow us to compare laboratory and field measurements of compressional wave velocities, as has been done previously for the TACT transect [*Brocher et al.*, 1989, 1991a; *Fuis et al.*, 1991; *Beaudoin et al.*, 1992]. Figure 16 shows the average and the range of compressional wave velocities measured in three samples from Montague Island (TA-35, TA-36, and TA-37; each sample measured in three perpendicular orientations). The average curve shows the typical rapid increase in velocity that is caused by crack closing to pressures of about 1.5 kbar (4 km); from 1.5 kbar to 6 kbar (16 km) the average seismic velocity increases from about 5.75 km/s to 6.0 km/s. The curves shown in Figure 16 are uncorrected for increasing temperature in the crust, which can significantly lower the velocities in the lower crust (corrections are approximately -0.02 to -0.06 km/s per 100°C increase in temperature [*Christensen*, 1979]).

Table 1. Compressional Wave Velocity *Vp* and Density ρ of Selected Rocks as a Function of Pressure

Pressure, MPa	Sample Orientation*	Velocity, km/s					
		TA-34†	TA-35†	TA-36†	TA-37†	TA-38†	TA-39†
10	A	4.31	4.42	5.06	5.54	5.47	5.40
	B	4.58	4.71	4.29	5.63	5.22	5.49
	C	4.57	4.16	5.28	5.85	5.38	5.04
	mean	4.49	4.43	4.88	5.67	5.36	5.31
20	A	4.50	4.67	5.22	5.64	5.59	5.52
	B	4.75	4.92	4.63	5.70	5.37	5.59
	C	4.72	4.43	5.39	5.91	5.50	5.21
	mean	4.65	4.67	5.08	5.75	5.49	5.44
50	A	4.78	5.10	5.47	5.79	5.77	5.68
	B	5.01	5.25	5.14	5.80	5.62	5.74
	C	4.95	4.92	5.55	5.98	5.70	5.47
	mean	4.92	5.09	5.39	5.86	5.70	5.63
100	A	5.08	5.45	5.63	5.89	5.93	5.80
	B	5.26	5.52	5.45	5.87	5.83	5.84
	C	5.16	5.35	5.67	6.04	5.88	5.66
	mean	5.17	5.44	5.58	5.93	5.88	5.77
200	A	5.37	5.70	5.75	5.96	6.07	5.91
	B	5.52	5.74	5.63	5.95	6.02	5.95
	C	5.41	5.69	5.78	6.10	6.05	5.81
	mean	5.43	5.71	5.72	6.00	6.05	5.89
500	A	5.69	5.92	5.87	6.07	6.22	6.06
	B	5.81	5.95	5.81	6.05	6.19	6.10
	C	5.71	5.95	5.91	6.18	6.20	5.99
	mean	5.74	5.94	5.87	6.10	6.21	6.05
1000	A	5.87	6.07	5.97	6.14	6.32	6.17
	B	5.97	6.10	5.96	6.13	6.31	6.22
	C	5.88	6.10	6.01	6.24	6.30	6.12
	mean	5.91	6.09	5.98	6.17	6.31	6.17

*The laboratory measurements were completed in three mutually orthogonal cores obtained from each sample, providing an estimate of the velocity anisotropy inherent to each rock type. Sample orientation is as follows: A, perpendicular to foliation; B, parallel to lineation and foliation; and C, parallel to foliation, perpendicular to lineation. Velocities were measured in a hydrostatic pressure apparatus at room temperature using a pulse transmission technique described by *Christensen* [1985].

†Lithologies and densities are as follows: TA-34, graywacke, ρ=2603 kg/m^3; TA-35, graywacke, ρ=2649 kg/m^3; TA-36, graywacke, ρ=2692 kg/m^3; TA-37, phyllite, ρ=2715 kg/m^3; TA-38, graywacke, ρ=2722 kg/m^3; and TA-39, graywacke, ρ=2684 kg/m^3. Sample locations are as follows: TA-34, 60°15'57"N, 146°36'03"W; TA-35, 59°48'57"N, 147°40'15"W; TA-36, 60°09'29"N, 147°21'26"W; TA-37, 60°08'11"N, 147°13'20"W; TA-38, 60°34'44"N, 146°43'22"W; and TA-39, 60°34'19"N, 146°42'48"W.

The average velocities of the upper crust (<18-km depth) determined from the seismic refraction profiling along the TACT, PWS, and Montague lines are compared with the laboratory data in Figure 16. Below the weathered zone, which extends to a depth of about 4 km (about 1.5 kbar), the comparisons show an excellent agreement between the laboratory and field data and suggest that the entire upper crust of Prince William Sound consists of Orca Group graywackes and phyllites and lesser amounts of intrusive rocks.

Laboratory measurements show relatively little (about 3-4%) seismic anisotropy at 2 kbar, in agreement with the similar velocity-depth curves for the orthogonal TACT and PWS lines (Figure 16) at their intersection near Smith Island. Phyllites and mica-quartz schists in the Chugach and Yukon-Tanana terranes have anisotropy of 14-29% [*Brocher et al.*, 1989, 1991a; *Fuis et al.*, 1991], which is much greater than the 3-4% anisotropy measured in metasedimentary samples from the Orca Group.

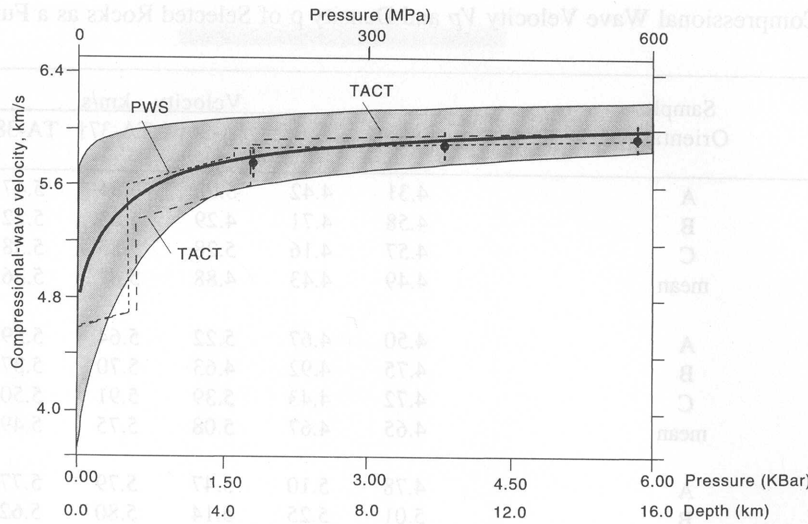


Figure 16. The range of laboratory measurements of compressional wave velocity versus confining pressure for three orthogonal directions in three different samples of graywackes and phyllites from Montague Island (shaded region; see Table 1 for sample locations). The averaged compressional wave velocity versus confining pressure for the nine velocity measurements (heavy solid line) are compared to seismic refraction velocities determined for the PWS (dotted line) and TACT (dashed) lines in the vicinity of Smith Island. Velocities determined from the Montague seismic line are shown as individual solid circles having vertical dashed lines to show the uncertainty of the refraction velocities. The close agreement between refraction velocities and laboratory measurements supports the interpretation that Orca Group rocks underlie Montague Island and Prince William Sound to a depth in excess of 16 km.

Discussion

As discussed in the introduction, the wide-angle seismic reflection/refraction profiles presented here were designed to address important questions related to the accretion of continental and oceanic terranes in southern Alaska. These questions include (1) what is the geometry of the Pacific plate beneath the Prince William and Yakutat terranes, (2) to what depths do terranes extend, (3) what is the nature and geometry of the interface between the Prince William and Yakutat terranes and its relationship to current seismicity, and (4) how are terranes metamorphosed and deformed by tectonic underplating?

The 6.9-km/s (*Pi*) Refractor

A widespread 6.9-km/s refractor mapped beneath the northern Gulf of Alaska beneath inferred Orca Group rocks of the Prince William terrane represents the most important and bestconstrained result from our wide-angle study. This 4-km-thick layer, which directly underlies the *PiP* reflection, can be mapped from a point beneath the western end of the Yakutat terrane beneath the Kayak Island zone to points beneath the northwestern end of the Prince William terrane (Figure 17). We believe that the 6.9-km/s refractor corresponds to a layer of Eocene oceanic crust, a piece of the Yakutat terrane. The oceanic crust was previously inferred to underlie the western two-thirds of the Yakutat terrane and the northern part of the Prince William terrane on the basis of seismic refraction, dredging, and magnetic anomaly data [*Bayer et al.*, 1978; *Schwab et al.*, 1980; *Bruns*, 1985; *Plafker*, 1987; *Griscom and Sauer*, 1990]. Compilations of marine refraction measurements indicate that a velocity of 6.9 km/s is consistent with seismic layer 3, usually interpreted as unaltered gabbro [*Christensen and Salisbury*, 1975]. Compilations of laboratory measurements of temperature corrected velocities at pressures between 4 and 10 kbar suitable for depths of 12 to 24 km indicate an average velocity for gabbro of 7.12 ± 0.22 km/s [*Holbrook et al.*, 1992]. Our confidence in this interpretation is strengthened by the observation that the depth to the source of the prominent Slope anomaly is, within the limits of our resolution, identical to the top of the 6.9-km/s refractor (Figure 17) [*Bruns*, 1985; *Griscom and Sauer*, 1990]. Eocene oceanic crust previously inferred to represent the top of the lower crust of the Yakutat terrane is compatible with our wide-angle data.

Because the 6.9-km/s refractor underlies both the Prince William and Yakutat terranes, it may represent an underthrust part of either terrane or perhaps a third terrane consisting of Eocene oceanic crust. Since this refractor underlies the Yakutat terrane and is currently moving landward beneath the Prince William terrane, the refractor is unlikely to represent a lower part of the Prince William terrane but is more likely to be part of the Yakutat terrane. *Fuis et al.* [1991] describe similar high-velocity refractors beneath the Chugach Mountains to the north that underlie the Chugach and Peninsular/Wrangellia terranes. These refractors to the north of our study area represent tectonically underplated oceanic crust.

In our view, a map of the depth to the top of the refractor is also a map of the thickness of the Prince William terrane west of the Kayak Island suture zone. Figure 17 reveals that the Prince William terrane thickens landward (northwestward) from 15 to 24 km, forming a very large accretionary prism.

Microseismicity and focal mechanism studies [*Brocher et al.*, 1991b] suggest that the 6.9-km/s refractor, which we interpret as underlying the Prince William and the Yakutat terranes, represents the interface of the Aleutian subduction zone. These investigators showed that microseismicity along

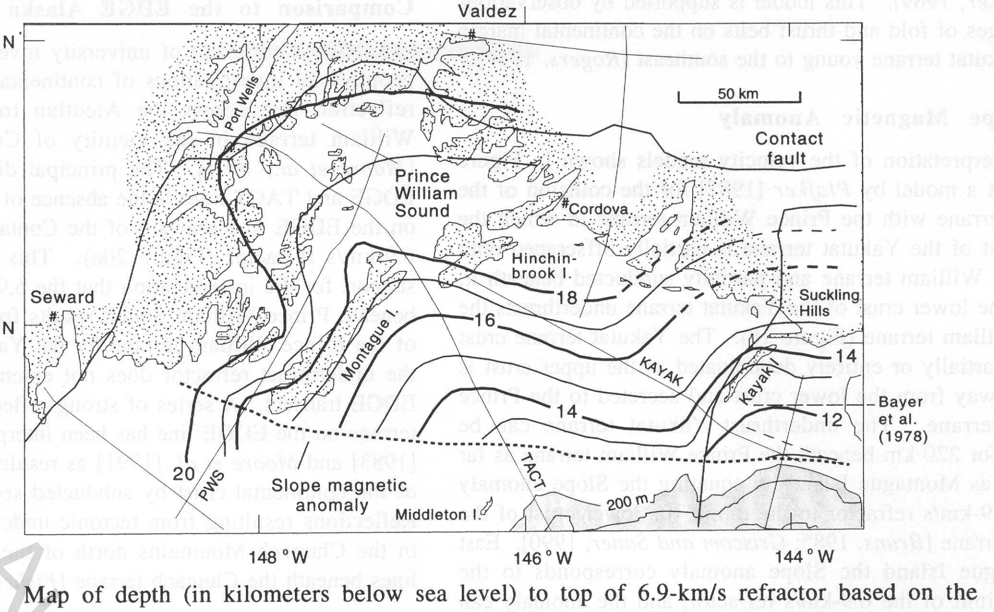


Figure 17. Map of depth (in kilometers below sea level) to top of 6.9-km/s refractor based on the velocity models presented in Figure 10 and *Bayer et al.* [1978]. The refractor east of Montague Island appears to be terminated to the south by the Slope anomaly. The depth contours indicate that the prominent refractor and seismic reflector dip to northwest subparallel to the Aleutian trench. The steep gradient in depth contours near Kayak Island is chosen to match magnetic models [*Griscom and Sauer*, 1990] and wide-angle data recorded during the acquisition of the Suckling line. Seismicity patterns suggest that, as discussed in the text, this map also represents a contour map on the top of the megathrust in the northern Gulf of Alaska.

the Wadati-Benioff zone lies within the 6.9-km/s refractor and argued that the shallow dip and depth inferred for the great 1964 Alaska earthquake is consistent with the top of the 6.9-km/s refractor. This inference agrees with previous interpretations showing the main zone of decoupling and shearing at the top of the Yakutat oceanic crust rather than at the top of the Pacific plate crust [*Plafker*, 1987, Figure 3A]. The depth to the top of the 6.9-km/s refractor (Figure 17) thus also represents depth to the Wadati-Benioff zone associated with the Aleutian megathrust.

The observation that the Kayak Island zone, a boundary between the Prince William and Yakutat terranes, is underlain by the 6.9-km/s refractor, supports previous inferences by *Plafker* [1987] and *Griscom and Sauer* [1990] that the Kayak Island zone is a relatively inactive terrane boundary compared to the Pamplona fold and thrust belt (Figure 18). We prefer models proposing the Pamplona fold and thrust belt to be the current location where strain is concentrated in the upper plate above the megathrust [*Griscom and Sauer*, 1990], and we agree with previous suggestions that this geometry is evolving

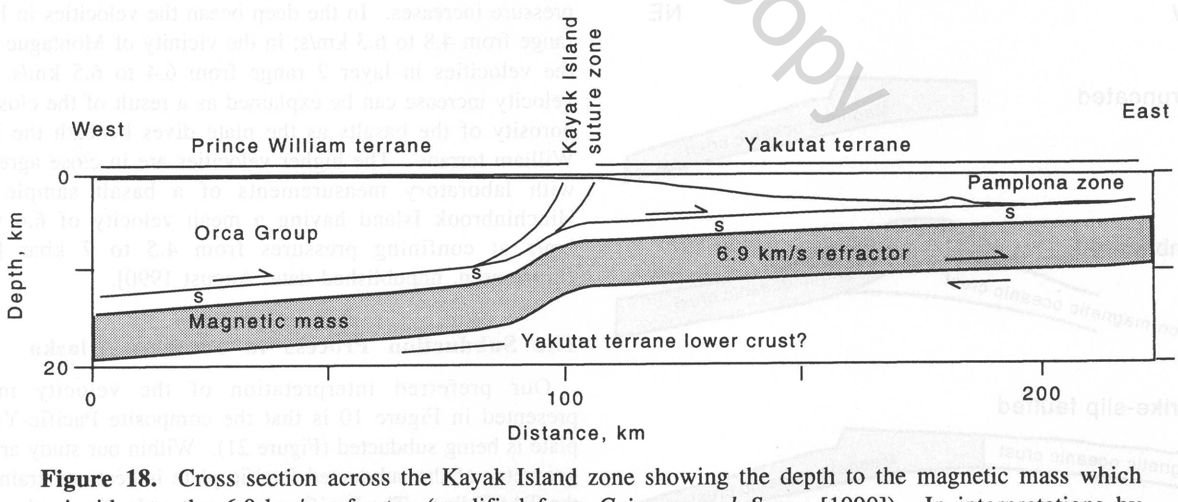


Figure 18. Cross section across the Kayak Island zone showing the depth to the magnetic mass which coincides to the 6.9-km/s refractor (modified from *Griscom and Sauer* [1990]). In interpretations by *Griscom and Sauer* [1990] and *Plafker* [1987], a 2-km-thick layer of subducted sediments (s) lies on top of the 6.9 km/s refractor and forms the base of the Orca Group. This thin layer of subducted sediments, presumably having seismic velocities similar to those of the overlying Orca Group, is required to account for all the missing sediment resulting from over 220 km of subduction but is not resolved by our wide-angle profiles.

[e.g. *Plafker*, 1969]. This model is supported by observations that the ages of fold and thrust belts on the continental margin of the Yakutat terrane young to the southeast [*Rogers,* 1977].

The Slope Magnetic Anomaly

Our interpretation of the velocity models shown in Figure 10 support a model by *Plafker* [1987] for the collision of the Yakutat terrane with the Prince William terrane in which the upper crust of the Yakutat terrane is partially offscraped onto the Prince William terrane and partially subducted beneath it, whereas the lower crust of the Yakutat terrane underthrusts the Prince William terrane (Figure 18). The Yakutat terrane crust is being partially or entirely delaminated as the upper crust is stripped away from the lower crust and accreted to the Prince William terrane. The underthrust Yakutat terrane can be extended for 220 km beneath the Prince William terrane as far westward as Montague Island by equating the Slope anomaly and the 6.9-km/s refractor to the top of the lower crust of the Yakutat terrane [*Bruns*, 1985; *Griscom and Sauer*, 1990]. East of Montague Island the Slope anomaly corresponds to the southern limit of the 6.9-km/s refractor, and the anomaly can be explained by the truncation of the gabbro layer, whereas west of Montague Island the refractor can be traced to the south of the Slope anomaly.

Models for the origin of the Slope anomaly along the PWS line show that magnetic Eocene oceanic crust is truncated by either strike-slip or thrust faulting along the NW projection of the Transition fault (Figure 19). The presence of strong reflections which splay upward in this location on the PWS seismic reflection line (not shown) provides the best support for the model shown in Figure 19b. At the convergence rate of 54 mm/yr in a N15°W direction [*DeMets et al.,* 1990], the Yakutat terrane must have underthrust the Prince William terrane for at least the past 7.1 m.y. [*Bruns,* 1985]. Tectonic reconstructions suggest that underthrusting of the Yakutat terrane beneath the Prince William terrane probably began about 30 Ma [*Plafker*, 1987], so that the Slope anomaly may represent only about 25% of the subducted Yakutat terrane crust.

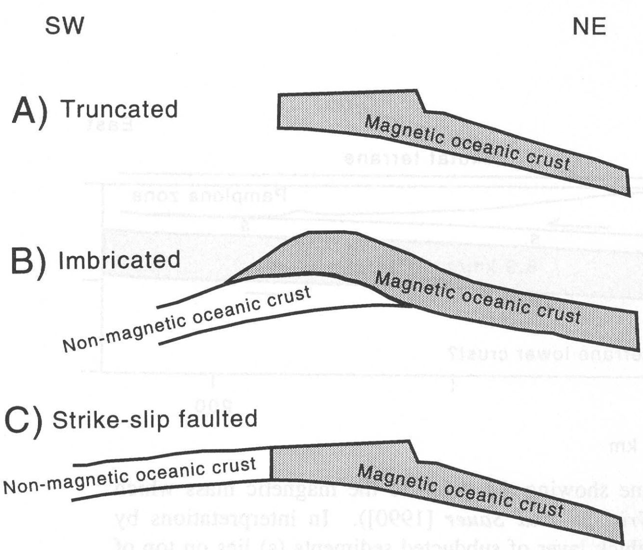


Figure 19. Models for the slope anomaly along the PWS line, showing (a) the magnetic model for this anomaly [*Bruns*, 1985; *Griscom and Sauer*, 1990], (b) geologic interpretation of magnetic model due to thrust faulting, and (c) geological interpretation of magnetic model due to strike-slip faulting.

Comparison to the EDGE Alaska Line

EDGE, a consortia of university investigators dedicated to geophysical investigations of continental margins, acquired a reflection line across the Aleutian trench and the Prince William terrane in the vicinity of Cook Inlet (Figure 1) [*Moore et al.,* 1991]. The principal difference between the EDGE and TACT lines is the absence of a midcrustal refractor on the EDGE line seaward of the Contact fault similar to the 6.9-km/s refractor (Figure 20a). This observation provides support for the interpretation that the 6.9-km/s refractor found beneath Prince William Sound results from the underthrusting of the Prince William terrane by the Yakutat terrane but that the underthrust refractor does not extend as far south as the EDGE transect. A series of strong reflections in the Chugach terrane on the EDGE line has been interpreted by *Fisher et al.* [1983] and *Moore et al.* [1991] as resulting from underplating of the continental crust by subducted sediments (Figure 20a). Reflections resulting from tectonic underplating are also seen in the Chugach Mountains north of the TACT and Suckling lines beneath the Chugach terrane [*Fisher et al.*, 1989a].

The Subducting Pacific Plate

Our analysis of the sonobuoy records along the TACT line indicate that the igneous oceanic crust is of normal thickness seaward of the trench (Figure 9). Velocities of the seismic layer 2 appear to be normal, although layer 2 has a velocity gradient slightly lower than those found elsewhere in the Pacific and Atlantic Oceans (Figure 9). The velocity gradient in seismic layer 3 is normal, although layer 3 velocities may be as much as 0.2 km/s lower than normal. These lower velocities might be related to extensional cracking associated with the flexure of the subducting Pacific plate at the Aleutian trench. Similar reductions in crustal velocity have been reported from other trenches [*Bodine et al.*, 1981] and near the Hawaiian Islands [*Brocher and ten Brink,* 1987].

In our interpretation, the upper oceanic crust becomes increasingly metamorphosed with increasing depth of burial. Our modeling is consistent with an increase in layer 2 velocities beneath the Prince William terrane as the overburden pressure increases. In the deep ocean the velocities in layer 2 range from 4.8 to 6.3 km/s; in the vicinity of Montague Island the velocities in layer 2 range from 6.4 to 6.5 km/s. This velocity increase can be explained as a result of the closing of porosity of the basalts as the plate dives beneath the Prince William terrane. The higher velocities are in close agreement with laboratory measurements of a basalt sample from Hinchinbrook Island having a mean velocity of 6.4 to 6.5 km/s at confining pressures from 4.5 to 7 kbar [N. I. Christensen, unpublished data, August 1990].

The Subduction Process in Southern Alaska

Our preferred interpretation of the velocity models presented in Figure 10 is that the composite Pacific-Yakutat plate is being subducted (Figure 21). Within our study area the geometry of the subducted Pacific plate is best constrained by the TACT line. The Pacific plate apparently dips to the northwest at about 9-10° to the seaward limit of Prince William Sound, and it flattens beneath the sound. The downgoing slab can be reliably traced as far landward as Smith Island in Prince William Sound, almost 200 km northwestward from the trench. The underthrust Yakutat terrane (the 6.9-km/s refractor) and low-velocity layer (underplated sediments?) beneath

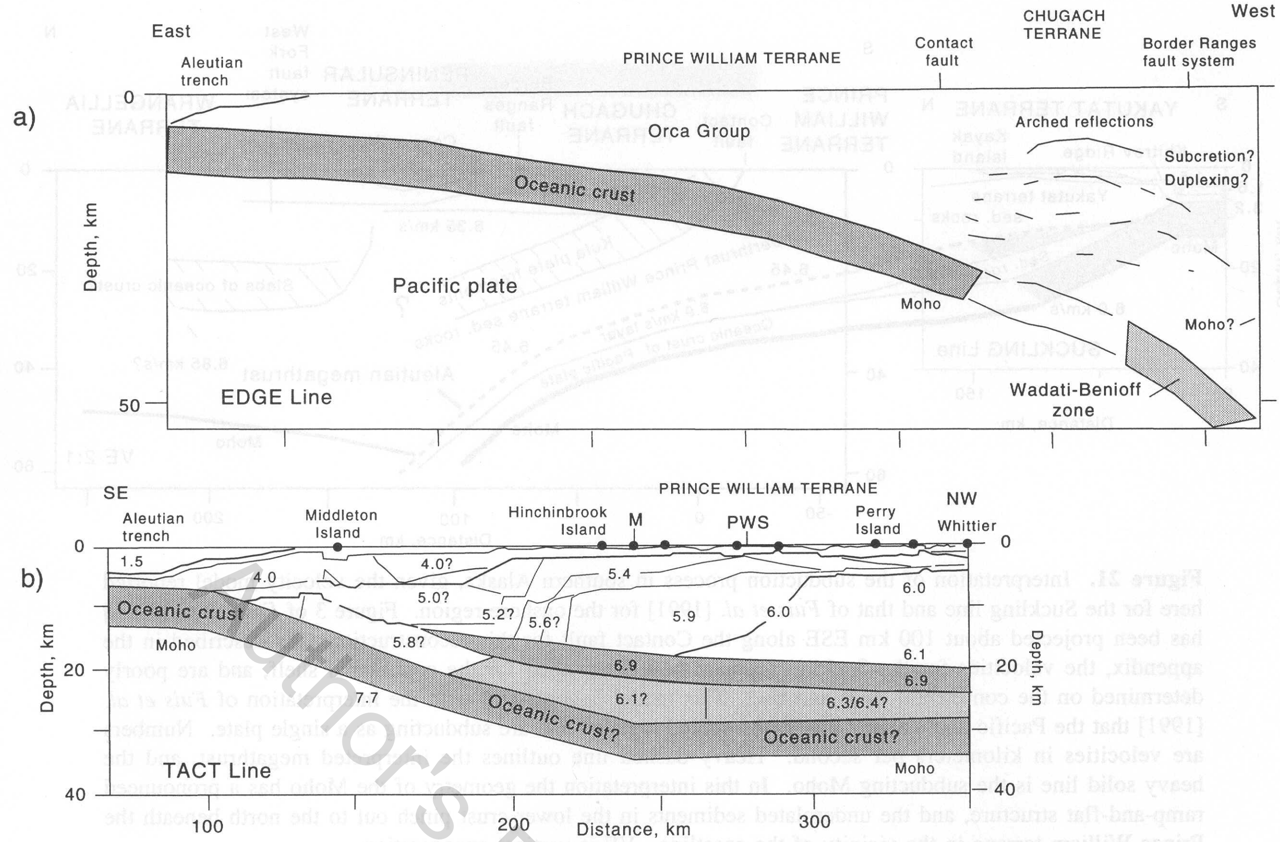


Figure 20. Comparison of the (a) EDGE and (b) TACT lines showing the geometry of the subducted Pacific plate in the northern end of the Aleutian trench. The interpretation of the EDGE reflection line was simplified from *Moore et al.* [1991]. Both sections are plotted with a vertical exaggeration of 2:1. As described in the appendix, the velocities for the TACT line are best determined for (1) the Prince William terrane between Hinchinbrook Island and Whittier, (2) the slope seaward of Middleton Island, and (3) the oceanic crust seaward of the Aleutian trench. The velocities of the crust on the continental shelf between Middleton and Hinchinbrook Islands is the least well determined part of the model.

the 6.9-km/s refractor wedge out to the north beneath the Prince William terrane in the vicinity of the coastline.

The subducting crust of the single subducting plate model of *Fuis et al.* [1991] has a thickness and velocity appropriate for a single thickness of oceanic crust beneath the Chugach Mountains, although it underlies an overriding plate that appears to be made up of several thicknesses of oceanic crust of late Mesozoic or early Cenozoic age that were tectonically underplated or added to the upper crust (Figure 21). The top of the subducting plate lies along the top of the Wrangell Wadati-Benioff zone [*Page et al.*, 1989]. In contrast, farther south along the Suckling line, the Yakutat terrane has 1-2 times the thickness of the igneous crust of the Pacific plate and has a quite different velocity structure with a high-velocity (6.9 km/s) layer at its top and a low-velocity layer (6.1-6.6 km/s) at its base (Figure 21).

Our interpretation of the wide-angle seismic data is also consistent with the possibility that the Pacific plate maintains a constant 9-10° dip beneath Prince William Sound. This alternate interpretation, however, would require that two plates subduct in the study area, each at different dip angles: the Pacific plate at 9-10° and the Yakutat terrane at about 3-4°. There is, however, no indication of a double Wadati-Benioff zone to indicate independent subduction of the Pacific and Yakutat plates [*Page et al.*, 1989]. Furthermore, this configuration would require material originally subducted along with the Pacific plate to be transferred northward to the subducting Yakutat plate. Thus we do not favor this alternate interpretation of the velocity structure.

Summary

Data from over 1100 km of wide-angle seismic reflection/refraction profiles along five transects in southern Alaska have been used to develop a structural and tectonic model for the Prince William and Yakutat terranes and the subducting Pacific plate. Interpretations of magnetic anomaly and hypocentral and focal mechanism data support the inference that the top of a widespread 6.9-km/s refractor represents the megathrust between the subducting lower crust of the Yakutat terrane (or a separate, related terrane) and the overriding upper crust of the Yakutat terrane and Prince William terrane. Our preferred interpretation is that there is one subducting plate representing a composite of the Pacific and Yakutat plates.

Our unreversed wide-angle reflection/refraction data from the Pacific plate seaward of the Aleutian trench indicate that the oceanic crust has a normal thickness and velocity. Forward modeling of *Pn* arrivals indicates that the Pacific plate dips northwestward at about 9-10° from the Aleutian trench, and seismicity data and our wide-angle data both indicate that the Wadati-Benioff zone and Moho flatten or dip very gently beneath Prince William Sound. We interpret these data to

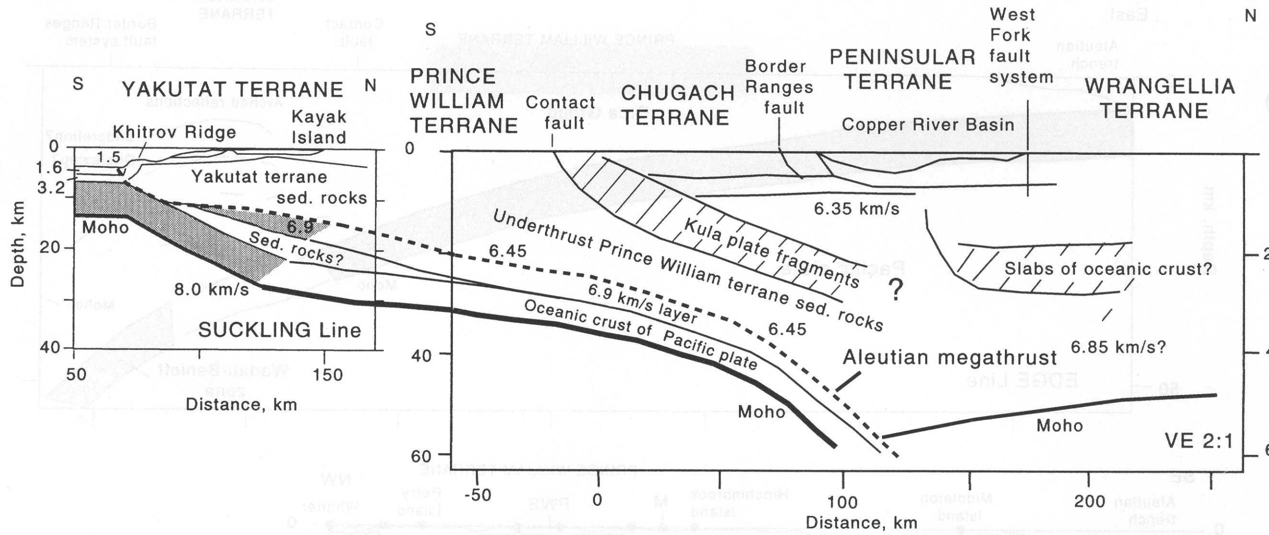


Figure 21. Interpretation of the subduction process in southern Alaska, given the velocity model reported here for the Suckling line and that of *Fuis et al.* [1991] for the onshore region. Figure 3 of *Fuis et al.* [1991] has been projected about 100 km ESE along the Contact fault for this reconstruction. As described in the appendix, the velocities for the Suckling line are best determined for the continental shelf, and are poorly determined on the continental shelf and rise. This model is consistent with the interpretation of *Fuis et al.* [1991] that the Pacific and Yakutat plates are welded together and are subducting as a single plate. Numbers are velocities in kilometers per second. Heavy dashed line outlines the interpreted megathrust, and the heavy solid line is the subducting Moho. In this interpretation the geometry of the Moho has a pronounced ramp-and-flat structure, and the underplated sediments in the lower crust pinch out to the north beneath the Prince William terrane in the vicinity of the coastline. VE is vertical exaggeration.

indicate that one composite plate (Pacific-Yakutat) is subducting beneath the northern Gulf of Alaska and that the Yakutat plate pinches out northward beneath the Prince William terrane in the vicinity of the coastline.

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