# Seismic Reflection/Refraction Mapping of Faulting and Regional Dips in the Eastern Alaska Range

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We present the results of a Trans-Alaska Crustal Transect (TACT) investigation of the upper 2-5 km of the eastern Alaska Range in the vicinity of the Denali fault based on seismic reflection/refraction data, laboratory measurements of rock velocities, and structural mapping. The Denali fault is a major dextral slip structure mappable for more than 2000 km separating the Wrangellia and adjacent terranes to the south from the Yukon-Tanana and adjacent terranes to the north. Geologic mapping suggests over 400 km of dextral slip has occurred on the fault, yet within the upper 1.5 km of the crust along the TACT corridor, basement rocks juxtaposed along the Denali fault reveal no significant seismic velocity differences, although the fault zone itself is associated with a minor lowering of velocity. The lack of seismic velocity contrast adjacent to the fault is in agreement with laboratory measurements of elastic wave velocities of samples from terranes bordering the fault. Laboratory measurements of elastic wave velocities of the metasedimentary mica-quartz schists comprising the Yukon-Tanana basement are highly anisotropic because of preferred orientation of mica and predict significant variations in velocity accompanying variations in foliation dip. Although other interpretations are possible, the northward shallowing of foliation dip of basement rocks in the Yukon-Tanana terrane combined with the strong anisotropy associated with these highly foliated rocks can explain an observed northward increase in seismic velocity within this terrane. Seismic reflections from basement rocks within the Yukon-Tanana terrane may originate from variations in anisotropy with depth and/or changes in composition reflecting different proportions of sandstone and shale in the protolith.

#### INTRODUCTION

Deep seismic reflection profiling of the continents has provided many important insights into the nature and evolution of the continental crust. Seismic reflection profiles within crystalline terranes which produce few reflections or where there are difficulties in obtaining high-quality reflection data, however, may not provide significant guidance for mapping the crystalline bedrock into the subsurface. In such terranes, seismic refraction methods, which provide seismic velocities of the bedrock, often provide greater constraints on the subsurface configuration and properties of the basement rocks. When combined with laboratory measurements of the seismic velocities and densities of bedrock samples and detailed geological mapping, in situ measurements of seismic velocities provide constraints on the configuration and lithology of the bedrock which are unavailable from seismic reflection and other profiling methods. For instance, Brocher and Christensen [1990] showed that anisotropy in laboratory and in situ velocities can be used to constrain the average subsurface dip of foliation in highly foliated rocks in southern Alaska. By obtaining a greater understanding of the subsurface geometry and physical properties of the crystal-

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Paper number 91JB00905. 0148-0227/91/91JB-00905\$05.00 line basement, we ultimately seek to understand the origin of those reflections produced within these basement rocks.

We use these principles to map the subsurface geometry of crystalline terranes along a N-S trending seismic reflection profile following the Richardson Highway in eastern Alaska (Figure 1a). These data were acquired for the U.S. Geological Survey (USGS) in March 1986 as part of the Trans-Alaska Crustal Transect (TACT) Program, a comprehensive geological and geophysical study of the crust within a corridor across Alaska [Page, 1989]. In this paper we integrate seismic results from the Denali reflection line, which traversed northward obliquely across the Denali fault, a major terrane-bounding fault system and suture in the Alaska Range (Figure 1b), with laboratory measurements of rock velocities and detailed geological mapping. We present results from the direct inversion and forward modeling of both compressional and shear wave arrivals. In this complex area the Denali fault and nearby sutures, including the Broxson Gulch thrust, form the structural boundaries between the Wrangellia and the Maclaren terranes to the south and the Windy, Aurora Peak, and Yukon-Tanana terranes to the north [Jones et al., 1987; Nokleberg et al., 1985; W. J. Nokleberg et al., Bedrock geology and tectonic evolution of the northern Copper River Basin and eastern Alaska Range along the Trans-Alaskan Crustal Transect (TACT), Alaska, submitted to Journal of Geophysical Research, 1991] (hereinafter referred to as N91).





# SURFACE GEOLOGY

The Denali reflection line crosses, and was designed to image, from south to north, the Wrangellia, Maclaren, Aurora Peak, Windy, and southern Yukon-Tanana terranes [Jones et al., 1987; Nokleberg et al., 1982, 1985, 1986; N91] (Figure 1b). The north-south trend of the profile obliquely crosses the east-west to northwest striking tectonic grain defined by the sutures in the region (Figure 1b). The major sutures are the Broxson Gulch thrust which separates the Wrangellia and Maclaren terranes and the Denali fault which separates the Wrangellia and Maclaren terranes to the south from the Aurora Peak, Windy, and Yukon-Tanana terranes to the north. The following section briefly describes, from south to north, the major terranes and sutures traversed by the Denali line.

#### Wrangellia Terrane

The Wrangellia terrane extends discontinuously from southern Alaska into southeastern Alaska and southwestern Canada [Jones et al., 1987; Monger and Berg, 1987]. The oldest part of the Wrangellia terrane consists of upper Paleozoic volcanic and minor marine sedimentary rocks, comprising three major units: mainly andesite, dacite, and lesser basaltic flows of the Pennsylvanian Tetelna Volcanics; volcanic graywackes and breccias and intermediate tuffs and epiclastic rocks, argillites, and limestones of the Middle Pennsylvanian and Lower Permian Slana Spur Formation; and argillite and limestone of the Permian Eagle Creek Formation. The total estimated thickness of these formations is 2.5 km. These rocks are disconformably overlain by up to 5.4 km of submarine pillow basalt and subaerial basalt flows of the Triassic Nikolai Greenstone along with coeval mafic and ultramafic sills and plutons. Adjacent to the Richardson Highway the Wrangellia terrane is intruded by late Paleozoic metamorphosed intrusions and Late Jurassic and Cretaceous granitic plutonic rocks [Nokleberg et al. 1982; N91]. Lower to upper Tertiary continental deposits, up to several hundred meters thick, form the youngest part of the Wrangellia terrane.

The Wrangellia terrane is intensely faulted along the transect and exhibits prehnite-pumpellyite to lower greenschist facies metamorphism. A series of early to late Tertiary and Quaternary south verging thrust faults, such as the McCallum Creek–Slate Creek fault (Figure 1*b*), dip northward toward the Alaska Range and are interpreted as having formed during Cenozoic compression along the Denali fault.

The Wrangellia terrane is interpreted as a late Paleozoic

island arc which is overlain by an Upper Triassic rift sequence of basalt and related rocks, in turn overlain by Upper Jurassic and Lower Cretaceous island arc volcanic rocks and flysch [*Nokleberg et al.*, 1985; N91]. The terrane is bounded to the north by the Broxson Gulch thrust, which dips moderately north, and is interpreted by us as a part of the Talkeetna thrust (not shown in Figure 1), a Cretaceous suture reactivated in the Cenozoic [*Csejtey et al.*, 1982].

#### Maclaren Terrane

The Maclaren terrane, exposed south of the Denali fault in the eastern Alaska Range, consists of the Late Jurassic or older Maclaren Glacier metamorphic belt of schist, amphibolite, phyllite, argillite, and metagraywacke, and the regionally deformed and metamorphosed mid-Cretaceous to early Tertiary East Susitna batholith containing gabbro, quartz diorite, granodiorite, and lesser quartz monzonite plutons [Nokleberg et al., 1985; Jones et al., 1987; N91]. The Maclaren terrane is interpreted to have formed in a synorogenic Andean-type arc setting on the west margin of the Mesozoic North America. During the Cenozoic the Maclaren and Wrangellia terranes were tectonically transported about 400 km along the Denali fault from a location near the correlative Kluane Schist and Ruby Range batholiths in the southwestern Yukon Territory [Nokleberg et al., 1985; N91].

#### Denali Fault

The Denali fault is one of the major tectonic boundaries of North America, extending more than 2000 km from southeastern Alaska, through the Alaska Range, to the Bering Sea (Figure 1*a*). Detailed geological studies indicate 1–6.5 km of dextral slip since early Wisconsin or Illinoisan time [*Stout et al.*, 1973]. Regional correlations of the Maclaren terrane with the Kluane Schist and Ruby Range batholith in the southwestern Yukon Territory, and offset parts of Wrangellia from the central Alaska Range to the northern part of southeastern Alaska, indicate dextral motion along the Denali fault of about 400 km since the mid-Cretaceous [*Twenhofel and Sainsbury* 1957; *Grantz*, 1966; *Nokleberg et al.*, 1985; *Plafker et al.*, 1989]. Geologic mapping indicates that the Denali fault dips steeply or is vertical at the surface.

# Windy and Aurora Peak Terranes

The Windy terrane occurs locally along the Denali fault for several hundred kilometers and consists of narrow, faultbounded prisms of highly deformed and weakly metamorphosed Cretaceous flysch, lesser andesite flows and tuff, and middle Paleozoic calcareous shales and sandstone [*Jones et al.*, 1987; *Richter*, 1976; *Nokleberg et al.*, 1985; N91]. The Windy terrane is a tectonic melange of Mesozoic flysch and older Paleozoic sedimentary rocks (N91). Maximum structural thickness is a few kilometers.

The eastern apex of the Aurora Peak terrane lies west of the Richardson Highway, north of the Denali fault and Windy terrane, and south of the Yukon-Tanana terrane (Figure 1b). The Aurora Peak terrane consists of highly metamorphosed and deformed Paleozoic metasedimentary rocks and Cretaceous and lower Tertiary metagranitic rocks [Nokleberg et al., 1985; N91].





Fig. 1b. Lithotectonic terrane map of eastern Alaska along the Richardson Highway for the northern Wrangellia terrane and southern Yukon-Tanana terrane. Numbers along the Denali line indicate the distance along the line in kilometers. Strikes and dips are indicated in the Yukon-Tanana terrane only. A-A' indicates the location of the cross section shown in Figure 13b. Solid circles show source locations for refraction profiles shown in Figure 2.

# Southern Yukon-Tanana Terrane

The Yukon-Tanana terrane, which occurs in east central Alaska and the Yukon Territory of Canada [Jones et al., 1987; Monger and Berg, 1987], is divided into several subterranes. Along the Richardson Highway, Yukon-Tanana terrane rocks consist of Devonian and older metasedimentary schists and sparse Devonian metavolcanic and metagranitic rocks [Aleinikoff and Nokleberg, 1985; Nokleberg and Aleinikoff, 1985; Foster et al., 1987; Jones et al., 1987; N91]. These rocks are unconformably overlain by lower to middle Tertiary continental deposits that range up to several hundred meters thick.

In the study area the rocks of the Yukon-Tanana terrane are multiply deformed and metamorphosed. From north to



Fig. 1c. Map showing strikes and dips of the Jarvis Creek Formation within a part of the Yukon-Tanana terrane. The stippled region, showing the outcrop of Yukon-Tanana basement rocks, has been greatly simplified from the original 1:63,360 scale maps.

south along the Richardson Highway, and toward the Denali fault, lower amphibolite facies metamorphic minerals are systematically replaced by lower greenschist facies minerals. An intense penetrative mylonitic schistosity and parallel, sheared isoclinal folds form the major penetrative structures in the area.

To the south and southwest toward the Denali fault, schistosity and compositional layering are progressively tilted to steeper, south, and vertical dips near the Denali and Hines Creek faults (Figure 1c), forming a regional scale antiform of Cenozoic age. A series of early to late Tertiary and Quaternary north verging thrust faults, including the

Donnelly Dome-Granite Mountain fault, dip southward toward the Alaska Range (Figure 1b).

The southern Yukon-Tanana terrane is estimated from geological mapping, magnetotelluric soundings, and seismic refraction data to be about 8–12 km thick [Nokleberg and Aleinikoff, 1985; Foster et al., 1987; Luzitano et al., 1989; Stanley et al., 1990; N91]. The Yukon-Tanana terrane in east central Alaska is interpreted as a fragment of a highly metamorphosed and deformed arc of Devonian and Mississippian age [Nokleberg and Aleinikoff, 1985; Foster et al., 1987; N91].

# Quaternary Rocks

Quaternary deposits consist mainly of outwash plain and alluvial deposits from large glaciers, lateral and terminal moraines associated with valley glaciers that originated within the Alaska Range, and alluvial fans associated with streams and rivers emanating from the range and glaciers, *[Pewe and Reger, 1983].* Ice-rich silts or permafrost occur locally along the Richardson Highway [*Pewe and Reger,* 1983].

# Collection and Processing of the Seismic Reflection Data

The USGS contracted with Geophysical Systems Corporation to acquire 128-fold seismic reflection data along the Denali line (Figure 1) using sign bit recording and an array of four Vibroseis sources. Field parameters used to acquire the Denali line were identical to those used to obtain the Chugach line in southern Alaska as described by *Fisher et al.* [1989]. These parameters included a linear upsweep whose half-power points were 10 and 30 Hz and a symmetrical split spread of 1024 geophone arrays spaced at 30-m intervals. Nominal shot-to-group offsets exceeded 15 km. The clumping (potting) of geophone arrays into compact point arrays, rather than into distributed (linear) arrays, permitted the recording of low-velocity arrivals normally attenuated by linear geophone arrays.

Processing of the common shot gathers used for the refraction analysis was identical to that described by Brocher et al. [1989]. In brief, this processing consisted of the following procedure. Common shot gathers were first plotted as a function of source-receiver offset, using surveyed station locations accurate to within 1 m. For these plots, trace amplitudes were corrected for geometrical spreading by multiplying each trace by the square root of the range. Typical common shot gathers from along the Denali line shown in Figure 2 indicate that the data are generally of lower quality than those obtained for the Chugach line [Brocher et al., 1989], presumably because of higher noise levels along the Denali line. Data quality on the southern half of the Denali line is particularly poor owing to the proximity of the reflection line to the Alyeska oil pipeline within a narrow, alluvial valley. Data quality was further reduced by noise from high winds in the southern portion of the line. The difficulty in tracing refracted first arrivals more than 10 km from the source limited the depth to which reliable velocity models could be determined to less than 2 km.

Shear wave arrivals were also observed between kilometer 35 and kilometer 70 of the Denali line. Because of interference from the first arrivals and reflections from the



Fig. 2. Examples of common shot gathers used for travel time analysis. Source-receiver ranges were calculated using surveyor's locations for geophone stations. Travel times were linearly reduced using a velocity of 6 km/s, and amplitudes were corrected according to the square root of range. Locations of the shot gathers (kilometer 11.04, kilometer 41.76, and kilometer 71.52) are shown as solid circles in Figure 1b.

upper crust, and because they were recorded using vertical component seismometers, these secondary arrivals have lower signal-to-noise ratios than the P wave arrivals and can typically be traced only 4–5 km from the source, often only to the north of the source (Figure 3).

#### **TRAVEL TIME ANALYSIS**

We digitized over 5000 travel times from common shot gathers along the Denali line following procedures described by *Brocher et al.* [1989]. Compressional first arrivals and shear wave arrivals from gathers at intervals of 2–3 km along the line were digitized, which provided three to four reversed P wave travel times beneath every surface location (Figure 4). The more limited quality of the S wave data, however, reduced the number of fully reversed S wave branches by a factor of 8. Because the source signature consists of a zero-phase correlated Vibroseis (Klauder) wavelet, the time of the first amplitude maximum was selected as the first arrival time. The uncertainty of the digitized travel times is estimated as less than  $\pm 25$  ms for the *P* wave arrivals and as  $\pm 50$  ms for the *S* wave arrivals.

The assumptions and limitations of this type of refraction study are described in detail by *Brocher et al.* [1989]. We assumed that the surface recording geometry could be approximated by a straight line for each common shot gather. This approximation was in greatest error between kilometer 10 and kilometer 20 of the Denali line, where the Richardson Highway makes a series of sharp curves (Figure 1*b*).

# Forward Modeling

Because of the great flexibility with which velocity models may be parameterized using this method, we chose first to forward model the observed P and S wave travel times with a two-dimensional velocity-depth structure using computer algorithms described by *Červený et al.* [1977] and *Hill et al.* [1985]. The velocity model consists of layers containing



Fig. 3. Examples of common shot gathers used for travel time analysis of shear wave arrivals. The format of this figure is identical to that of Figure 2 except that a reduction velocity of 3 km/s was used to emphasize shear wave arrivals.

velocity gradients within layers and velocity discontinuities between layers.

Observed P wave travel times were generally matched to within 50 ms by the forward modeling (Figure 5), although



Fig. 4. Reduced (at 6 km/s) travel times showing travel time data used for the refraction analysis. Source locations are at apices of travel time V-shaped curves at reduced times equal to zero. Dramatic increases in the observed travel times on both ends of the line are caused by low-velocity sedimentary basins.

larger apparent misfits are present in the northernmost portion of the model. We believe that most of this apparent misfit is due to errors in picking phases due to the low S/Nof the data north of kilometer 78; larger explosions used for the reconnaissance refraction profiling yielded travel times closer to those modeled here than those shown in Figure 5. As discussed by many previous authors [e.g., *Hill et al.*, 1985], the uniqueness and resolution associated with the two-dimensional velocity-depth models resulting from this forward, nonlinear modeling procedure are difficult to quantify. This difficulty is even increased if the initial parameterization of the model is made too restrictive.

The initial shear wave velocity model used for forward modeling was derived from the P wave model by dividing the P wave velocity model (Figure 6) by 1.732 (assuming a Poisson's ratio of 0.25). In subsequent forward modeling, the thickness of the uppermost, Quaternary layer was not changed, although in order to match delays of the observed S wave arrivals it was necessary to alter the S wave velocities from the initial model. The forward modeling of the S wave arrivals was complicated by variations in the depth at which the S wave energy was converted from Pwave energy. In areas where a thick unit of Quaternary sediments covered the basement rocks, the conversion probably occurred at the base of these sediments. Where the



Fig. 5. Observed (circles) and calculated (crosses) travel times for the common shot gathers shown in Figure 2. Also shown, beneath each travel time plot, are ray paths through the appropriate portion of the velocity-depth model. Such plots provide an indication of the subsurface coverage and show that only the upper 1.5 km of the model is constrained by the first-arrival data.

Quaternary sediments were thin, the shear waves were generated directly at the source. Shear wave arrivals were generally matched within 50 ms and everywhere within 100 ms.

P wave velocities are resolved to within  $\pm 0.1$  km/s, particularly in the center of the velocity model, and the depths of interfaces are resolved to within 10% by this method on the basis of trial and error perturbations in model parameters. S wave velocities are resolved to within  $\pm 0.15$ km/s. The shortest observed P wave wavelengths ranged from 33 to 200 m, which, when considered with the average sensor spacing of 30 m, suggests that the spatial resolution in near-surface structure (a few hundred meters) is within several tens of meters. The spatial resolution at the base of the model (at 1.5 km depth) is probably a few hundred meters. Figure 5, which shows P wave ray paths through the model, indicates that the resolution of the procedure varies along the model depending on the density of ray paths along the profile. On average, only the uppermost 1.5 km of the structure is sampled by ray paths. Both ends of the profile lack reversed coverage, degrading the resolution of the procedure in these areas.

#### Inverse Modeling

For comparison we have also inverted both the P and the S wave travel times directly using an algorithm described by *Lutter et al.* [1990]. In this inversion algorithm, velocities are interpolated using bicubic splines between velocity nodes, so that no first-order velocity discontinuities are introduced into the model. In performing these inversions, we parameterized the model using nodes spaced every 0.25 km in depth and every 5.25 km (for P waves) and 3.5 km (for S waves) in distance. Since the parameterization of the velocity models used by *Lutter et al.* [1990] differs distinctly from that used for forward modeling, we interpret common features of both solutions as particularly well resolved elements of the velocity structure along the Denali line.

Both the forward and the inverse methods used to obtain velocity models rely on vertical velocity gradients to produce diving waves, rather than layers of constant velocity which produce head waves. Particularly within the shallow crust, where the dependence of seismic velocity on pressure is extreme, we believe the assumption of small vertical velocity gradients is valuable. We believe that pure head waves are rare in laterally inhomogeneous media and, if present, that they generally have very weak amplitudes [*Červený et al.*, 1977]. *Healy* [1963] has shown, however, that if the assumption of vertical velocity gradients is incorrect, the depth to higher-velocity basement rocks will be systematically overestimated.

The uniqueness of the final velocity-depth model depends most critically on shot-to-shot phase correlation 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 analyzed common shot gathers separated by small intervals, between 2 and 3 km, so that phase correlations could be interpolated from one source point to the next. The accuracy of our phase correlations is attested by the close reciprocity of the observed travel times between adjacent shots. Additionally, reflection two-way travel times predicted by the refraction model were required to correlate closely with the Denali seismic reflection section itself. Finally, we performed direct inversions of the travel times to determine whether features of interest were required by the observations.

#### THE REFRACTION MODEL

In the following discussion we describe the P and S wave velocity-depth models obtained through the forward modeling and inversion of observed travel times. These analyses indicate that there is no significant velocity contrast across the Denali fault, although there is a minor decrease in velocity within the fault zone itself, that there is a small but systematic northward increase in the velocity of the Yukon-Tanana basement rocks, and that Tertiary sedimentary rocks are faulted against higher-velocity basement rocks at both the northern and the southern ends of the model. A thin veneer of low-velocity Quaternary sediments blankets the entire model.

# Quaternary Deposits

The velocity-depth models derived from forward modeling include a layer, generally less than 100 m thick, and with P wave velocities between 1.1 and 2.1 km/s, at the surface



Fig. 6. (Top) Comparison of mapped Tertiary sedimentary rocks and Quaternary deposits along the Denali line with the uppermost portion of the velocity-depth model derived from the refracted first arrivals. Numbers in the model indicate compressional wave velocities in kilometers per second. A slash between velocities indicates a vertical velocity gradient between the numbers given. Vertical exaggeration is 20:1. The Denali line parallels the McCallum Creek–Slate Creek fault in the range shown. (Bottom) The velocity-depth model for the Denali line obtained from forward modeling of first arrival times is also shown. Patterns for Tertiary and Quaternary sedimentary rocks are identical to the top figure. Basement rocks, exceeding 4 km/s, are indicated by the darker pattern. Between kilometer 40 and kilometer 70, shear wave velocities are shown after the appropriate compressional wave velocities, with a comma separating the two velocities. Locations of rock samples used for laboratory measurements of velocity and density are indicated by large arrows with sample numbers (e.g., TA-22). Vertical exaggeration is 3.75:1.

along most of the Denali line (Figure 6). Because these velocities correspond to those expected for the Quaternary deposits described above [e.g., *Brocher et al.*, 1989], we infer that this layer correlates with the Quaternary sediments. A comparison of the distribution of mapped Quaternary deposits along the Denali reflection line and the velocity and thickness of the Quaternary units inferred from the refraction model is presented in Figure 6.

While the inferred Quaternary deposits are generally less than 100 m thick, their thickness exceeds 300 m in the location of a large terminal moraine between kilometer 76 and kilometer 80.6, near Donnelly Dome [*Pewe and Reger*, 1983]. The knob-and-kettle topography on the terminal moraine is matched by large relief at the base of the moraine deposits (Figure 6), suggesting that the latter relief may have resulted from glacial scouring. In addition, some of the relief at their base is probably tectonic in origin; at kilometer 80.3 the moraine is offset at the surface by a 3-m scarp, upthrown on the south, on the Donnelly Dome–Granite Mountain fault (Figure 6) [*Pewe and Holmes*, 1964] which may have experienced up to a few kilometers of north verging thrusting in the Cenozoic (N91).

The low velocities observed locally in the uppermost layer are well constrained by first arrivals recorded by the point geophone arrays used for the reflection profiling. Observed P wave velocities as low as 1.1 km/s are somewhat unusual in such studies. Along the Denali line the locations of these low-velocity arrivals coincide with extensive moraine deposits of Wisconsin and older age between kilometer 65 and kilometer 76 (Figure 6). Pewe and Reger [1983] noted that at kilometer 73.7 along the Richardson Highway, where low-velocity arrivals are recorded, the permafrost is more than 13 m thick. Most likely, this thick permafrost layer is impermeable, and the underlying sediments may be undersaturated or unsaturated. Thus we suggest that the low seismic P wave velocities (1.1 km/s) reflect undersaturated or unsaturated sediments beneath permafrost layers.

Along the Denali reflection line the highest-quality reflection data from the lower crust correspond to the area between kilometer 29 and kilometer 70 of the velocity-depth model. This interval corresponds to the portion of the model for which the Quaternary sediments are thinnest (generally less than 100 m thick) and for which these sediments are underlain by relatively high velocity basement rocks. In particular, rocks having P wave velocities between 2.5 and 4.0 km/s, and which are thought to degrade the seismic reflection data, are either absent or laterally restricted. In contrast, thick Tertiary sedimentary deposits, having Pwave velocities between 2.5 and 4.0 km/s (see below), are associated with lower-quality, deep crustal data along the seismic reflection profile. Thus for the Denali line, there is an inverse correlation between the thickness of the inferred Tertiary sedimentary deposits and the quality of the lower crustal portion of the seismic reflection line.

The Denali line results are consistent with those of Bro-



Fig. 7. Comparison of synthetic travel times (thin solid lines) superimposed on the uppermost portion of the unmigrated Denali seismic reflection line. The synthetic two-way travel times were calculated assuming normal incidence (not vertical propagation) from the velocity-depth model shown in Figure 6. The vertical exaggeration of this section is about 2:1. Symbols are defined as follows: Q, T, and b denote Quaternary deposits, Tertiary sedimentary rocks, and basement rocks, respectively.

*cher et al.* [1989] for the Chugach line, where thick Quaternary deposits are associated with low-quality data from the lower crust. Figure 6 (bottom) presents the entire near-surface velocity model obtained along the Denali line. In order to compare the velocity-depth model to the seismic reflection profile along the Denali line, the two-way travel times predicted by the refraction model are compared to the unmigrated Denali line (Figure 7). Two-way reflection travel times were calculated assuming normal incidence (not vertical propagation).

# Tertiary Sedimentary Rocks

Within the Wrangellia terrane between Isabel Pass and the McCallum Creek–Slate Creek fault (kilometer zero to kilometer 17), the location of a laterally continuous unit having P wave velocities between 2.5 and 4.0 km/s corresponds closely to the distribution of mapped Tertiary sedimentary rocks (N91). Coal-bearing Tertiary sedimentary rocks crop out at kilometer 10.1. The 350- to 900-m thickness for this unit as interpreted from the seismic refraction data is close to the estimated thickness of these Tertiary sedimentary rocks based on geologic mapping (N91). Reflection data from the Tertiary sedimentary rocks are characterized by discontinuous, disrupted reflections along much of the transect (Figure 7). Both the seismic reflection data and the refraction model suggest that the base of the Tertiary sedimentary rocks has been locally displaced by high-angle post-Tertiary faults. The McCallum Creek–Slate Creek fault, which is



Fig. 8. Velocity models along the Denali line derived from forward modeling and inversion of the P and S wave travel times: (a) compressional wave model (in kilometers per second) derived from forward modeling, showing velocity contours for velocities greater than 2.5 km/s. Thick dashed lines show the locations of velocity discontinuities. Thin dashed lines show velocity contours in 0.25-km/s intervals. (b) The compressional wave model derived from direct inversion of observed travel times is plotted at the same scale as Figure 8a. Note that an uneven contour interval was used and that the stippled region has a resolution in excess of 0.75. The inversion model used nodes every 0.25 km in depth down to 1.5 km and every 5.25 km in distance. The rms error in travel time produced by this model is 44 ms. (c) The shear wave velocity model (in kilometers per second) between kilometer 35 and kilometer 70 of the Denali line derived from forward modeling is also shown. Note that velocity contours are shown for velocities greater than 1.75 km/s. Thick dashed lines show the locations of velocity discontinuities. (d) The shear wave velocity model derived from direct inversion of observed travel times is plotted at the same scale as Figure 8c. The stippled region has a resolution in excess of 0.75. The inversion model used nodes every 3.5 km in distance. The rms error in travel time signal model is 30 ms.

interpreted as a high-angle fault with undetermined net thrust or strike-slip displacement, truncates the Tertiary sedimentary rocks on the seismic profile.

Inferred Tertiary sedimentary rocks overlie the Yukon-Tanana terrane to the north and also have P wave velocities between 2.5 and 4.0 km/s. These units thicken by nearly 1.7 km across the high-angle Donnelly Dome–Granite Mountain fault at kilometer 80.3 (Figure 6). The thickness and P wave velocity of the 3.6-km/s units of Figure 6 are consistent with their identification as Tertiary sedimentary rocks of the Tanana River basin. The reflection signature of the Tertiary sedimentary rocks changes dramatically north and south of Donnelly Dome and the Granite Mountain–Donnelly Dome fault (Figure 7). South of the dome and fault, the reflections are high amplitude, discontinuous, and disrupted, as seen also in the Wrangellia terrane. North of the dome and fault, within the Tanana River basin, the sedimentary rocks are subhorizontal and not strongly reflective.

Laterally restricted, triangular (in cross section) units

having P wave velocities between 2.5 and 4.0 km/s occur near the Denali fault and Ruby Creek, at kilometer 30 and kilometer 60, respectively, where they obtain thicknesses of up to several hundred meters (Figure 6). We interpret these smaller units as alluvial deposits because of their location at present-day stream channels. The alluvial fan located at Ruby Creek, near kilometer 60, contains a high percentage of clasts of Tertiary age derived from the Jarvis Creek coal field [*Pewe and Reger*, 1983].

# **Basement Structure**

In the following section, those parts of the velocity models shown in Figures 6 and 8 having compressional velocities in excess of 4 km/s are referred to as basement rocks. Figure 8 presents a comparison of forward and inverse velocity models for both compressional and shear wave arrivals. Laboratory-measured compressional wave velocities for rock samples collected along the Richardson Highway (Ta-

Pressure, MPa	Sample Orientation*	Wrangellia Terrane			Yukon-Tanana Terrane		
		TA-18, Greenstone†	TA-22, Andesite Breccia†	TA-28, Meta- Andesite†	TA-20, Mica-Quartz Schist†	TA-21, Mica-Quartz Schist†	TA-29, Mica-Quartz Schist†
10	Α	6.64	4.88	5.51	3.37	3.13	5.07
	B	6.46	4.89	5.65	5.23	4.85	6.11
	č	6.67	5.10	5.78	4.62	4.77	6.12
	Mean	6.59	4.96	5.65	4.41	4.25	5.77
20	A	6.67	5.06	5.69	3.89	3.64	5.34
	B	6.52	5.06	5.80	5.48	5.08	6.22
	č	6.71	5.24	5.89	5.02	5.06	6.22
	Mean	6.63	5.12	5.79	4.80	4.59	5.93
50	A	6.72	5.36	5.95	4.83	4.57	5.69
	B	6.60	5.34	6.01	5.86	5.50	6.38
	Č	6.76	5.46	6.05	5.65	5.56	6.39
	Mean	6.69	5.39	6.00	5.48	5.21	6.15
100	Å	6.77	5.62	6.11	5.47	5.30	5.84
	R	6.67	5 59	6.14	6.07	5.82	6.47
	č	6.80	5.65	6.16	6.00	5.91	6.49
	Mean	6.75	5.62	6.14	5.85	5.68	6.27
200	A	6.83	5.84	6.22	5.79	5.76	5.93
200	B	6.76	5.81	6.24	6.17	6.04	6.53
	Č	6.86	5.82	6.25	6.14	6.09	6.55
	Mean	6.82	5.83	6.24	6.04	5.96	6.34
500	A	6.92	6.03	6.35	5.96	6.05	6.05
500	B	6.87	6.01	6.36	6.27	6.18	6.61
	Č	6.96	5.98	6.37	6.25	6.21	6.62
	Mean	6.92	6.01	6 36	6.16	6.15	6.43
1000	A	6.96	6.16	6 44	6.07	6.25	6.14
	л D	6.03	6.12	6.45	6 34	6.27	6.67
	C C	7.05	6.09	6 46	6.33	6.30	6.68
	Mean	6.98	6.12	6.45	6.25	6.27	6.50

TABLE 1. Compressional Wave Velocity (Vp) and Density (p) of Selected Rocks as a Function of Pressure

Velocity is in kilometers per second.

\*Sample orientation is as follows: A, perpendicular to foliation; B, parallel to lineation and foliation; and C, parallel to foliation, perpendicular to lineation.

†Densities are as follows: TA-18,  $\rho$ =3011 kg/m<sup>3</sup>; TA-22,  $\rho$ =2587 kg/m<sup>3</sup>; TA-28,  $\rho$ =2771 kg/m<sup>3</sup>; TA-20,  $\rho$ =2645 kg/m<sup>3</sup>; TA-21,  $\rho$ =2633 kg/m<sup>3</sup>; and TA-29,  $\rho$ =2751 kg/m<sup>3</sup>.

ble 1) were measured as a function of hydrostatic pressure using a pulse transmission technique described in detail by *Christensen* [1985]. To investigate anisotropy, velocities were obtained in three mutually perpendicular directions for each sample. Locations of five of the samples are shown in Figure 6. A sixth rock sample, TA-18, from the Nikolai Greenstone, was collected from a quarry near the Richardson Highway, approximately 60 km south of the Denali fault.

A plot of P wave velocity at 20 MPa, corresponding to a depth of burial of about 0.7 km, versus density (Figure 9) illustrates three important lithological properties which are significant for interpretation of the velocity model. First, samples of mica-quartz schist from the Yukon-Tanana terrane (TA-20, TA-21, and TA-29) have anisotropies from 14 to 29% in P wave velocity (Table 1) and from 13 to 16% in S wave velocity (Table 2). Both P and S wave velocities are fast for propagation within the foliation and slow normal to foliation (Tables 1 and 2). Strong preferred orientation of highly anisotropic mica is primarily responsible for the anisotropy [Christensen, 1965]. The higher velocities and density of sample TA-29 are related to a greater abundance of mica and the presence of clinozoisite and calcite. Second, rock samples from the Wrangellia terrane (TA-18, TA-22, and TA-28) are relatively isotropic. Foliations are poorly developed in all three samples, and preferred mineral orientation is weak. Third, the Wrangellia terrane samples collected in close proximity to the Denali fault zone (TA-22 and TA-28) have velocities similar to the average velocities of the mica-quartz schists of the Yukon-Tanana terrane.

The basement structure of the models shown in Figures 6 and 8 has several important features. No significant P wave velocity contrast exists across the Denali fault. This observation is explained by the laboratory measurements which show that the rocks on the adjoining terranes have approximately the same seismic velocities (Figure 9). We believe these methods can resolve large velocity contrasts where they exist, because forward modeling did resolve a significant velocity contrast across the Border Ranges fault, in southern Alaska [Brocher et al., 1989]. While the absence of a velocity contrast across the shallow trace of the Denali fault implies that there will be difficulty in mapping this interface at depth using seismic refraction methods, preliminary interpretation of the deep crustal refraction data indicates that a substantial velocity contrast exists at depth [Luzitano et al., 1989]. Thus at depth the Denali fault does appear to juxtapose differing units with contrasting geophysical properties, suggesting a difference between midcrustal rocks of the Yukon-Tanana and Aurora Peak terranes.

The forward and inverse models are consistent with a minor P wave velocity anomaly within the Denali fault zone itself, indicated by the depression of the 5.0- to 5.75-km/s isolines (Figures 8a and 8b). We interpret this finding as indicating that the fault zone is associated with faulting and fractures and therefore has a higher crack density and lower



Fig. 9. Laboratory measurements of density and compressional wave velocity at 20 MPa, corresponding to a depth of 0.7 km, for rock samples from the Wrangellia and Yukon-Tanana terranes. Solid circles correspond to measurements taken perpendicular to foliation, whereas solid squares show measurements taken parallel to foliation (see Table 1). Locations of samples along the Denali line are provided in Figure 6. Samples from Wrangellia terrane (TA-18, TA-22, and TA-28) show much less anisotropy than those from the Yukon-Tanana terrane (TA-20, TA-21, and TA-29).

seismic velocity. Lowered velocities within strike-slip faults are commonly observed elsewhere [*Mooney and Ginzburg*, 1986]. Alternatively, rocks within the Maclaren, Aurora, and Windy terranes may have slightly lower velocities than those of the Wrangellia and Yukon-Tanana terranes.

Throughout the remainder of the text we lump together the Maclaren and Wrangellia terranes, as well as the Windy Aurora Peak terranes, with the Yukon-Tanana terrane. We choose to lump these smaller terranes with their larger neighboring terranes since they were extremely narrow (only a few kilometers wide) where they were crossed by the Denali line, and since there is little apparent difference in their seismic velocities from the adjacent terrane. We admit, however, that the velocity decrease in this area might be related to terrane differences rather than to the Denali fault zone itself. We have no independent means that would allow us to uniquely determine the origin of this anomaly.

A distinct P wave velocity contrast exists within the shallow basement rocks across the McCallum Creek–Slate Creek (Figures 6 and 8). South of this fault, between kilometer zero and kilometer 17, Wrangellia basement rocks with velocities of 5.4–5.7 km/s underlie the Tertiary sedimentary and volcanic rocks. North of the McCallum Creek–Slate Creek fault the Wrangellia basement is structurally higher than it is to the south and has appreciably lower P wave velocities of 4.9–5.2 km/s. The higher basement velocities south of the fault probably reflect the greater depth to basement; greater lithostatic pressures cause more microcracks to close, raising the velocity. Alternatively, part of the velocity difference may result from the compositionally

distinctive assemblages juxtaposed by the McCallum Creek– Slate Creek fault. The lower velocities of the Wrangellia basement to the north are from the Slana Spur Formation, whereas the higher velocities to the south may reflect basaltic rocks of the Nikolai Greenstone.

Within Yukon-Tanana basement rocks, from kilometer 40 to kilometer 65, a small yet significant northward increase in velocity, from 4.9 to 5.2 km/s, occurs at relatively shallow depths (Figures 6 and 8). While we recognize that this velocity increase is small, for several reasons we believe that it is required by the travel time data. First, the quality of the travel time observations along this segment of the model is high, because of large signal-to-noise ratios of the first arrivals (Figure 2). The quality of travel time observations can be evaluated by examining the reciprocity of travel times for the shots along this portion of the Denali line. Of the 48 reversed branches between kilometer 40 and kilometer 71, 86% of the reciprocal times agree within 30 ms, and the largest reciprocal error is only 41 ms. The reciprocal errors are small primarily because the observed travel time branches along this segment are simple and nearly linear (Figure 5). Second, as a result of the simplicity of the travel times, the agreement between the observed and the calculated travel times along this segment of the profile is generally within 25 ms, i.e., to within the accuracy of the observed travel time data. Third, despite our efforts to do so, it was not possible to match the observed travel time data using a constant velocity for the shallow basement rocks in this portion of the model. At a source-receiver range of 10 km the travel times for layers having velocities of 4.9 versus 5.2 km/s differ by 118 ms, although for smaller ranges the difference is proportionately less. As most of the observed

TABLE 2. Shear Wave Velocity (Vs) and Density  $(\rho)$  of Yukon-Tanana Mica-Quartz Schists

Pressure, MPa	Orientation*	TA-20†	TA-21†	TA-29†
10	Α	2.87	2.56	3.29
	В	3.22	2.46	3.41
	С	3.41	3.16	3,82
20	Α	3.07	2.79	3.35
	В	3.34	2.65	3.44
	С	3.52	3.32	3.86
50	Α	3.43	3.23	3.44
	В	3.58	3.05	3.48
	С	3.73	3.63	3.92
100	Α	3.71	3.58	3.50
	В	3.75	3.45	3.52
	С	3.87	3.86	3.97
200	Α	3.86	3.82	3.53
	В	3.86	3.79	3.56
	С	3.95	3.99	4.00
500	Α	3.93	3.94	3.57
	В	3.91	3.97	3.60
	С	3.99	4.04	4.03
1000	Α	3.97	4.01	3.60
	В	3.95	4.02	3.62
	С	4.02	4.06	4.06

Velocity is in kilometers per second.

\*Orientation is as follows: A, propagation perpendicular to foliation, displacement in foliation; B, propagation parallel to foliation, displacement perpendicular to foliation; and C, propagation parallel to foliation, displacement parallel to foliation.

†Densities are as follows: TA-20,  $\rho$ =2645 kg/m<sup>3</sup>; TA-21,  $\rho$ =2633 kg/m<sup>3</sup>; and TA-29,  $\rho$ =2751 kg/m<sup>3</sup>.



Fig. 10. Illustration of variations in shear wave velocity observed in laboratory measurements of shear wave arrivals that have propagated within the foliation plane of a sample of mica-quartz schist from the Yukon-Tanana terrane (sample TA-29). Only the direction of particle motion differs for the two curves shown here. The stippled curve is for particle motion perpendicular to the foliation plane, and the solid curve is for particle motion parallel to the foliation plane. The measurements were performed at 40 MPa confining pressure. The time difference between the two arrivals, approximately 1.4  $\mu$ s, corresponds to a difference in shear wave velocity of close to 0.45 km/s and suggests that shear wave splitting should be observed in these rocks.

travel times were modeled to within 25 ms, systematic shifts of more than 50 ms are resolvable by the data, as would be predicted at ranges greater than 4 km from replacing a velocity of 4.9 km/s by a velocity of 5.2 km/s. Fourth, this portion of the velocity model is well constrained because it lies within the center of the reflection profile, insuring densely reversed ray coverage of the subsurface. Fifth, the observation of this lateral velocity gradient in the inversion results (Figure 8*b*) indicates that the data do have the ability to resolve the velocity increase inferred from forward modeling.

On the basis of both forward modeling and direct inversion of the shear wave arrival times, observed S wave arrivals are consistent with a slight northward increase in shear wave velocity (Figures 8c and 8d). At the top of the pre-Tertiary basement the shear wave velocity increases from 2.0 km/s at kilometer 40 to 2.3 km/s at kilometer 50 and to 2.5 km/s at kilometer 60 (Figure 6). Below 1 km depth, shear wave velocities increase from 3.2 km/s at kilometer 40 to 3.4 km/s at kilometer 60 (Figure 8c), although these velocities are not as well constrained as those within the overlying weathered interval of the basement.

Laboratory measurements of shear wave velocities in mica-quartz schists from the Yukon-Tanana terrane at 20 MPa (Table 2) are consistent with the in situ shear wave velocities. The preferred orientation of mica in these rocks is also responsible for a strong anisotropy in shear wave velocities, which is clearly evident in Figure 10 and Table 2. Figure 10 shows a substantial difference in shear wave travel times for two signals propagating within the foliation direction but for which the particle motion is either parallel or perpendicular to the foliation. Thus the laboratory measurements of shear wave velocity are consistent with the sense of northward increase in seismic velocity (Table 2), although direct comparisons to the field data are complicated by the laboratory observations of shear wave splitting for propagation parallel to foliation.

The reflection data presented in Figure 7 show a number of intrabasement reflections within the mica- and quartz-rich Yukon-Tanana terrane. The reflections consist of homoclinal dips and local broad antiforms and synforms which we interpret as broad folds in planar surfaces. The planar surfaces are probably a combination of mylonitic schistosity, parallel compositional layering, and parallel isoclinal folds. We interpret these broad folds in the subsurface as part of the same generation of late Cenozoic folds that are exposed as a broad antiform and synform at the surface. The reflections could originate from variations in anisotropy with depth [*Christensen and Szymanski*, 1988] and/or changes in composition perhaps reflecting different proportions of sand-stone and shale in the protolith.

Donnelly Dome, between kilometer 78 and kilometer 80, is cored by high-velocity basement rocks (Figures 6 and 8). Both forward and inverse velocity models (Figures 8a and 8b) include a high-velocity block between kilometer 75 and kilometer 80, with P wave velocities as much as 0.8 km/s faster than the basement immediately to the south. The depth to the top of the high-velocity block differs significantly, however, being several hundred meters deeper in the inversion model. The location and high P wave velocity of the block under Donnelly Dome are consistent with an interpretation that the block is the subsurface continuation of Devonian metagranodioritic rocks of the Granite Mountain Pluton (Figure 1b) intruding the metasedimentary and metavolcanic rocks of the Yukon-Tanana terrane.

# DISCUSSION

We interpret the northward increase in P and S wave velocities observed in the basement rocks of the Yukon-Tanana terrane between kilometer 40 and kilometer 70 as the result of velocity anisotropy due to preferred mineral orientation within the foliated rocks of the terrane. This conclusion is based on field observations of a shallowing of dip of the mica-quartz schists foliation from south to north in the vicinity of the seismic line (Figure 1c) and the significant velocity anisotropy of Yukon-Tanana schists measured in the laboratory (Tables 1 and 2).

The shear wave velocities obtained within the Yukon-Tanana terrane provide significant constraints on our interpretation of the velocity increase to the north. The northward increase in compressional and shear wave velocities at a subsurface depth of 0.7 km between kilometer 40 and kilometer 70 (from 5.25 to 5.5 km/s and 2.5 to 2.75 km/s) corresponds to a poorly resolved decrease of Poisson's ratio from 0.35 to 0.33. Thus the field measurements show a minor decrease of Poisson's ratio with increasing compressional velocity. If the schists were isotropic, any compositional change producing a velocity increase would likely involve a decrease in guartz content and thus an increase in Poisson's ratio [Christensen and Fountain, 1975; Holbrook et al., 1988] from south to north, which is opposite to that observed. This observation, when coupled with the agreement between the field measured velocities (5.25 and 2.5 km/s) and those measured in the C direction (for P waves) and B direction (for S waves) at 20 MPa in the laboratory for sample TA-21, argues for anisotropy rather than bulk com-



Fig. 11. Plot of compressional wave velocity as functions of propagation azimuth and structural dip for samples of anisotropic mica-quartz schist from the Yukon-Tanana terrane assuming an average strike of N50°W and a confining pressure of 20 MPa, equivalent to a depth of 0.7 km. Field-measured velocities of 5.25 and 5.5 km/s, shown as squares with error bars, on the southern and northern portions of the schist belt, are consistent with a shallowing of dip from south to north which is consistent with field observations.

positional change. Because of the anisotropy inherent in these rocks, any discussion of Poisson's ratio is, of course, complicated by the existence of two shear or quasi-shear waves for propagation directions other than normal to foliation. As has been discussed earlier, compositional variability associated with Devonian metagranodiorite intrusive rocks may explain the observed high-velocity basement rocks near Donnelly Dome. The presence at depth of similar, yet unknown, intrusions to the south of Donnelly Dome could also increase upper crustal velocities.

Alternatively, the northward increase in compressional and shear wave velocities could also be related to the increase in metamorphic grade from south to north. Because the metasedimentary schists of the Yukon-Tanana terrane are quartz-rich, however, the transition from greenschist to lower amphibolite facies along this segment ought to produce insignificant changes in mineralogy and seismic velocity.

If we therefore interpret the small but significant northward velocity increase observed in the basement rocks of the Yukon-Tanana terrane as resulting solely from velocity anisotropy within the foliated rocks of the terrane, it is possible to estimate the average dip of the foliation in the subsurface. Laboratory-measured compressional wave velocities determined for samples of mica-quartz schist from the Yukon-Tanana terrane provide information about velocities within the terrane as functions of azimuth and dip of the foliation. Average P wave velocities at 20 MPa, equivalent to a depth of approximately 0.7 km, for directions within and normal to the foliations of samples TA-20, TA-21, and TA-29 (Table 1), allowed construction of P wave velocity versus azimuth curves for foliation dips of 0°, 30°, 60°, and 90° (Figure 11). In constructing this figure, compressional wave velocity (Vp) as a function of azimuth  $(\theta)$  is given by

 $Vp^{2}(\theta) = cp^{2} + A + C \cos 2\theta + D \sin 2\theta$ 

 $+ E \cos 4\theta + F \sin 4\theta$ 

where cp is the isotropic velocity and A, C, D, E, and F are constants given by Backus [1965, equation (22)]. We assume that the  $2\theta$  terms approximate the anisotropy of the region beneath the reflection line and that the average strike of the foliation is N50°W as measured in outcrops (Figure 1c). The  $0^{\circ}$  foliation dip line at the top of the diagram predicts high P wave velocities (5.51 km/s) which do not vary with azimuth. The 0° dip curve is in agreement with measurements in Table 1 and previous findings [e.g., Christensen, 1965] that micaquartz schists are often transversely isotropic. As the dip of the foliation increases, P wave velocity varies with azimuth, and anisotropy reaches a maximum when the foliation is vertical (90° dip). At maximum anisotropy, velocities remain 5.51 km/s for horizontal ray paths parallel to foliation at azimuths of 130° and 310°. Minimum velocities, however, of 4.29 km/s will be recorded at azimuths of 40° and 220°, where the ray paths are again horizontal but now normal to foliation.

The field-determined velocities within the Yukon-Tanana terrane obtained along the Richardson Highway between kilometer 30 and kilometer 70 are oriented at an average azimuth of 357°. These velocities are plotted in the velocity field predicted from the laboratory measurements assuming a strike and dip of the metamorphic foliation (Figure 11). If compositional and/or mineralogical changes are minimal between kilometer 30 and kilometer 70, the P wave velocity data predict a shallowing of dip from south to north. To better estimate this change in dip, we have plotted in Figure 12 the expected variation of velocity with foliation dip angle along the azimuth of the Richardson Highway (177° or 357°, Figure 11). The 5.25-km/s velocity observed within the southern part of the Yukon-Tanana terrane predicts a foliation dip of approximately 40° at 0.7 km depth, whereas to the north the dip shallows to approximately 0°-15° to produce the observed velocity of 5.5 km/s. A cross section illustrating



Fig. 12. Compressional wave velocity as a function of the foliation dip for mica-quartz schists of the Yukon-Tanana terrane. In preparing this plot, seismic wave propagation along the reflection line (357°), an average strike of N50°W, and a confining pressure of 20 MPa, corresponding to a depth of approximately 0.7 km, have been assumed. Solid circles with error bars show the field measurements of velocities within the upper basement rocks of the Yukon-Tanana terrane.



(a) Geological interpretation of the velocity model shown in Figure 6. The interpreted velocity model is Fig. 13. plotted with a vertical exaggeration of 2:1. Faults inferred in the uppermost part of the model are shown as dashed curves where they are projected to depth without an accompanying velocity contrast across the inferred fault. (b) The geological cross section A-A' along the Denali line (Figure 1) is shown at the same horizontal scale as for Figure 13a but without vertical exaggeration. Note that the distance between Isabel Pass and the Donnelly Dome-Granite Mountain fault is about 15% less for Figure 13a because of the fact that the seismic model in Figure 13a follows the crooked Richardson Highway whereas cross section A-A' is straight. Abbreviations for symbols used (in alphabetical order) are as follows: ap, Silurian to Cretaceous metasedimentary and metagranitic rocks of the Aurora Peak terrane; cu, cumulate mafic and ultramafic rocks of the Wrangellia terrane; jcs, Devonian and older metasedimentary rocks of the Jarvis Creek Glacier subterrane of the Yukon-Tanana terrane; jcg, Devonian metagranitic rocks of the Yukon-Tanana terrane; jcv, Devonian metavolcanic rocks of Jarvis Creek Glacier subterrane of the Yukon-Tanana terrane; Kg, Cretaceous granite and granodiorite; ¶Ps, Pennsylvania and Permian sedimentary and volcanic rocks of the Slana Spur Formation of the Wrangellia terrane; Pe, Permian sedimentary rocks of the Eagle Creek Formation of the Wrangellia terrane; Pi, Permian shallow intrusive rocks of the Wrangellia terrane; Ts, Tertiary sedimentary rocks; and Qs, Quaternary sediments. The geology is after Nokleberg et al. [1982, 1985, 1986] and N91.

our preferred structural interpretation based on the seismic velocity measurements is shown in Figure 13a. In this figure the southern sense of the dipping foliation of the Yukon-Tanana terrane between Ruby Creek and Donnelly Dome is not constrained by the seismic measurements, but rather is determined from the observed dips at the surface (Figure 1c). The magnitude of the dip is, however, constrained by the seismic velocities. These estimates of dip at depth are in close agreement with those extrapolated from surface measurements at numerous surface exposures (Figure 1c). Minor differences may be explained if the foliation dip increases with depth within the Yukon-Tanana terrane, by deviations from the assumptions used to predict velocities from the laboratory measurements or by additional and unknown factors. Three-component recordings of seismic arrivals (to detect shear wave splitting) from this part of the Yukon-Tanana terrane could serve to substantiate the presence of anisotropy.

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The interpretative cross section along the Denali line in Figure 13*a* summarizes the structural relationships we have investigated. Within the Wrangellia terrane the McCallum Creek–Slate Creek fault juxtaposes Tertiary sedimentary rocks against the Pennsylvanian and Permian Slana Spur Formation. The seismic data described here do not place additional constraints on the dip of this fault depth, nor do our data constrain the dip or sense of motion on the Denali fault zone, which, on the basis of geologic mapping, is shown schematically in Figure 13*a* with a vertical dip. The southern flank of the inferred Devonian metagranodiorite bodies projects

upward to the north at a dip of 15° to the surface exposure of the Donnelly Dome-Granite Mountain fault. However, this fault is not observed in the reflection data, and the projection of this trend is not constrained by the refraction model.

For comparison to the interpreted velocity model in Figure 13*a*, in Figure 13*b* we also show a geological cross section based on regional mapping (N91). Major similarities and differences between the two models are present. Both the seismic model and the cross section show that foliation dips within the Yukon-Tanana terrane are steep near the Denali fault zone and are shallow to the north. Both show thick Tertiary sedimentary rock units south of the McCallum Creek-Slate Creek fault and north of the Donnelly Dome-Granite Mountain fault. Both show granodiorite in the vicinity of Donnelly Dome. The structural complexity of basement structure within the Wrangellia terrane or in the Denali fault zone of Figure 13b, however, is not matched by the seismic model. No seismic reflection or refraction evidence constrains the vertical structure postulated for the Denali fault zone in Figure 13b. Figure 13b provides an explanation for the higher velocities of the basement rocks south of the McCallum Creek-Slate Creek fault: south of the fault the same lithologies are at deeper levels, and thus more fractures within them have been closed, raising the seismic velocities.

# REFLECTION COEFFICIENTS WITHIN THE YUKON-TANANA BASEMENT

Having determined that foliation within the Yukon-Tanana terrane rocks can reasonably explain small but

significant lateral variations in seismic velocities, we now investigate the possible role of this foliation in producing seismic reflections from within the Yukon-Tanana terrane. Calculations of reflection coefficients based on the velocity measurements provided in Table 1 indicate that variations in composition, anisotropy, or a combination of both could cause the large-amplitude reflections observed within the Yukon-Tanana terrane basement. A variety of reflection coefficients were calculated on the basis of the laboratory measurements at 100 MPa (corresponding to depths of 3-4 km), thought suitable, on the basis of the crustal velocities, for reflections between 1.5 and 2 s two-way travel time (TWTT). To test the effect of simply changing the composition, single interfaces juxtaposing velocities perpendicular to foliation for sample TA-29 against sample TA-20 or sample TA-21 were evaluated, yielding reflection coefficients of 0.05–0.07, classified by Sheriff [1975] as fair reflectors. With a given uniform composition, variations in anisotropy (direction A versus direction C in Table 1) predict a similar reflection coefficient of about 0.05. Pronounced changes in foliation direction would probably occur only at or near fault planes. The biggest single contrast would result from a combination of variation in anisotropy and composition, producing a reflection coefficient of 0.105 between sample TA-20 in the A direction and sample TA-29 in the C direction. Sheriff [1975] classifies reflection coefficients larger than 0.1 as characteristic of strong reflectors. Given the compositional layering of the rocks within the Yukon-Tanana terrane, even larger reflection amplitudes could result. The compositional layering of rocks within the Yukon-Tanana terrane is derived from bedded, fine-grained sedimentary rocks that were multiply, penetratively deformed into thinly layered mylonitic schists with an intense schistosity defined mainly by parallel white mica and crushed, granulated, and flattened quartz.

#### SUMMARY

We have used seismic reflection/refraction data, laboratory measurements of elastic wave velocities, and results from geologic mapping to study the structure of the uppermost crust along the TACT corridor across the eastern Alaska Range. The Denali fault represents the suture zone between the Wrangellia and adjacent terranes to the south and the Yukon-Tanana and adjacent terranes to the north. Although the Denali fault along the TACT corridor juxtaposes distinct lithologies at the surface, the laboratory and field measurements indicate that a significant velocity contrast is neither present nor expected across the fault at shallow levels (<1.5 km deep). Regional refraction data across the Denali fault system, however, suggest that within the middle crust, lithologies with more distinctive velocities are juxtaposed by the fault at greater depth [Luzitano et al., 1989], consistent with decoupling of the near-surface rocks from those of the middle crust. The Denali fault system itself is associated with a small low-velocity zone, which may be related to the increased shearing and fracturing expected there. Thrust faults mapped on the surface can be imaged in the subsurface by refraction methods as lower-velocity Tertiary sedimentary rocks are faulted against older, highervelocity metamorphic and igneous rocks. Rocks within the Yukon-Tanana terrane are more anisotropic than those in the Wrangellia terrane to the south. Variations in regional

dips of foliated rocks in the Yukon-Tanana terrane are apparently accompanied by variations in the seismic velocities of the first arrivals, although other explanations for this systematic variation cannot be ruled out. Either anisotropy or compositional changes may also cause reflections from broad folds within the Yukon-Tanana terrane basement, although the strongest reflections probably result from a combination of both.

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