

Crustal structure across the Bering Strait, Alaska: Onshore recordings of a marine seismic survey

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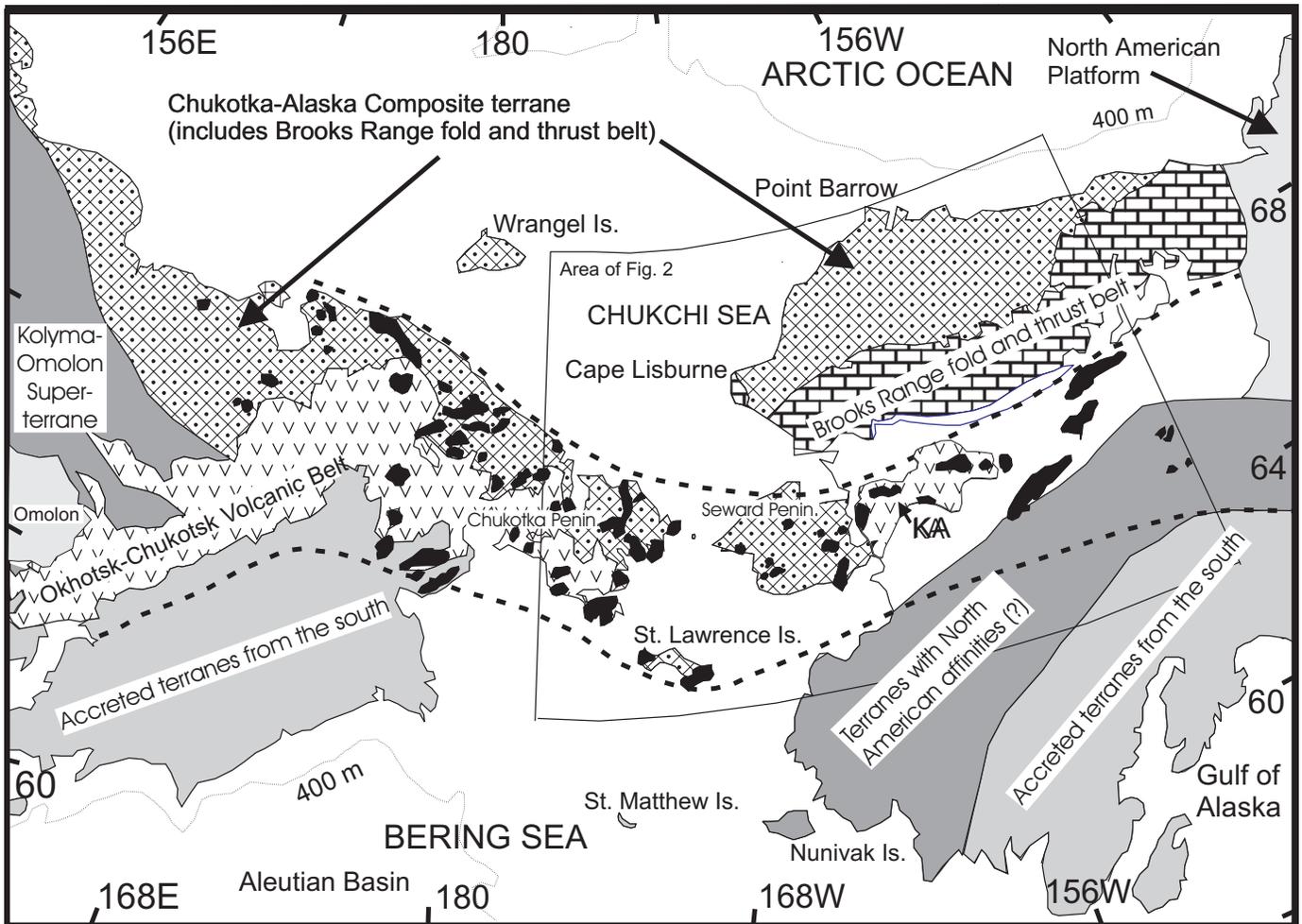
ABSTRACT

As part of an experiment to study crustal structure in Bering Strait–Chukchi Sea, we collected wide-angle seismic refraction data at onshore stations on the coasts of western Alaska and eastern Russia. Receiver gathers made from the onshore recordings of air-gun shots from two deep-crustal marine seismic profiles were used to construct seismic velocity models for the region. Results of the seismic analysis, combined with analysis of gravity data, indicate that crustal thickness ranges from 32 to 35 km along the profiles, the thinner crust occurring beneath a middle Cretaceous magmatic belt that includes the Okhotsk–Chukotsk volcanic belt and plutonic rocks on both the Chukotka and Seward Peninsulas. These results are consistent with models supporting widespread crustal extension in the Bering Strait region. In addition, there is no indication in the seismic or gravity data that a crustal root associated with a westward continuation of the Brooks Range currently exists to the west of the Lisburne Peninsula.

INTRODUCTION

The Bering Strait region links the Chukchi Shelf to the north and the Bering Shelf to the south, which together form an area of shallowly submerged continental crust (Figs. 1 and 2). Although on strike with the trend of the Brooks Range, the Bering Strait and adjacent parts of the Chukchi Sea appear to have a tectonic history distinct from that of the range in northern central Alaska, where a thick crust and elevated topography currently exist (Barnes, 1977; Fuis et al., 1997; Wissinger et al.,

1997). A complex history of contraction, extension, and transtension in the Bering Strait region has produced the structural features that characterize this bridge between the Asian and North American continents (Miller and Hudson, 1991; Dumitru et al., 1995). In 1994, two deep-crustal marine seismic profiles and accompanying wide-angle refraction data, constituting the Bering–Chukchi Crustal Transect, were acquired in the Bering Strait region (Fig. 2) (Klemperer et al., 1995; Brocher et al., 1995; Klemperer et al., this volume, Chapter 1). The combination of multichannel and wide-angle coverage provides detailed



Okhotsk-Chukotsk Volcanic Belt (OCVB), dominantly Upper Cretaceous in age, and the Koyukuk arc (KA), Lower Cretaceous.



North and south boundaries of the Cretaceous magmatic belt (dashed lines) and intrusive rocks, (black pattern)(from Bering Strait Field Party, 1



Chukotka-Alaska composite terrane. (Includes Brooks Range fold and thrust belt). Parts of the southern boundary are obscured by the OCVB and the terranes east of Seward Peninsula.



The Brooks Range fold and thrust belt.



Area east of Seward peninsula consisting of accreted terranes, volcanic and plutonic complexes and overlap deposits .



Terranes with North American affinities that have moved northwards along the North American margin.



Accreted terranes that have been transported northwards on the plates of the Pacific.



Omolon Massif containing Precambrian crystalline basement and considered to be a continental fragment transported to its present location.



The Kolyma-Omolon Superterrane (includes Omolon terrane), a complex assemblage of terranes accreted to the Siberian platform.

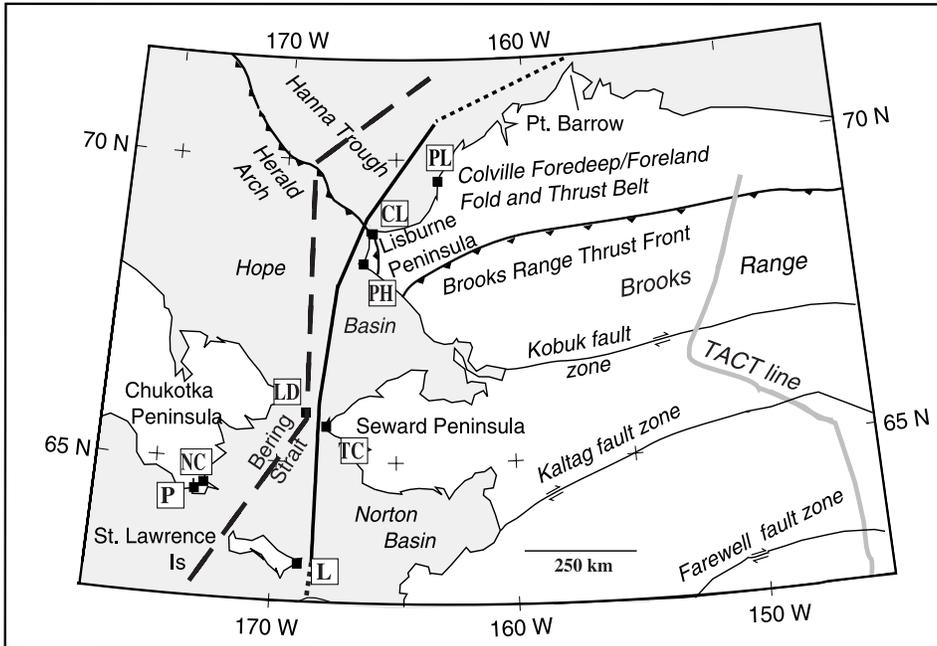


Figure 2. Tectonic map of Bering Strait region showing ship track (solid and dotted are northbound lines 1 and 2; dashed line is southbound line 3) and locations (solid squares) of onshore seismic stations used in refraction-wide-angle reflection analysis (modified from Brocher et al., 1995). CL is Cape Lisburne, L is Leitnik, LD is Little Diomedede, NC is New Chaplino, PH is Point Hope, PL is Point Lay, P is Provideniya, TC is Tin City. Also shown is location of Trans-Alaska Crustal Transect (TACT) through northern central Alaska. For complete description of Bering Strait seismic experiment, operating parameters, and collected data, see Brocher et al. (1995).

images of the crust and its general attributes, such as reflectivity, crustal thickness, possible rock composition, and the deep subsurface expression of structural boundaries. Raypaths from the ship to onshore receivers crossed several geologically significant features, including the Herald Arch, the Hanna Trough, and a region of crustal extension and orogenic collapse in the northern Bering Shelf (Miller and Hudson, 1991; Dumitru et al., 1995). Of particular interest in the refraction experiment were (1) the deep structure of Cape Lisburne, the Hope Basin, and the Herald Arch; (2) the crustal thickness and seismic velocity structure between Chukotka and Alaska; (3) the deep structure beneath the Cretaceous magmatic belt that crosses Bering Strait; and (4) the location of the western extension of the northern Brooks Range, if it exists beyond the Lisburne Peninsula. Each of these has important implications for reconstructing the structural evolution of northwestern Alaska.

GEOLOGIC BACKGROUND

Precambrian, Paleozoic, and lower Mesozoic rocks of the eastern Chukotka Peninsula and western Seward Peninsula are part of the continental crust of the Chukotka-Alaska composite terrane (Fig. 1). This terrane contrasts with a variety of accreted terranes to the south that include island arc, continental margin, oceanic sediment, and continental fragments (McGeary and Ben-Avraham, 1981; Fisher et al., 1982; Howell et al., 1987; Stavsky et al., 1990). An extensive and complex magmatic belt of Cretaceous age that extends from China to the Canadian Cordillera (Rubin et al., 1995; Bering Strait Geologic Field Party, 1997) includes extrusive rocks of the Okhotsk-Chukotsk volcanic belt and plutonic rocks on both the Chukotka and Seward Peninsulas. In the vicinity of the Bering Strait, the plutonic complexes show evidence of extension (Rubin et al., 1995; Amato and Wright, 1997; Bering Strait Geologic Field Party, 1997). In general, the Okhotsk-Chukotsk volcanic belt rocks are slightly younger (<90 Ma, P. Layer, 2000, personal commun.) than the cooling ages of the plutons in the Bering Strait area (ca. 90 Ma, Amato and Wright, 1997; Bering Strait Geologic Field Party, 1997). The lower parts of the Okhotsk-Chukotsk volcanic belt show evidence of being produced by Andean-style subduction; however, this convergent regime was followed later by extension ca. 86 Ma (Newberry et al., 1997). A curious feature of the Okhotsk-Chukotsk volcanic belt is that it ends abruptly at the eastern edge of Chukotka. The recognition of caldera structures within the Okhotsk-Chukotsk volcanic belt (Belyi, 1994) indicates minimal erosion, in stark contrast to the eastern side of the

Figure 1. Location map showing tectonic setting of Bering-Chukchi region. Accreted terranes from south have moved northward on plates of Pacific, arriving in late Mesozoic and Tertiary time. Terranes with North American affinities have moved northward along North American margin, but may have had earlier, more exotic affinities. Chukotka-Alaska composite terrane includes Brooks Range fold and thrust belt, northern Alaska, and northeastern Russia, together with their continental shelves. Okhotsk-Chukotsk volcanic belt (OCVB) overlaps terranes from south, edges of Kolyma-Omolon superterrane, and Chukotka-Alaska composite terrane, showing that these tectonic provinces were amalgamated by latest Cretaceous–earliest Tertiary time.

Bering Strait, where uplift has exposed the roots of plutons of similar age.

Between the Hanna Trough on the north and the Hope Basin on the south, the Herald Arch is a prominent fold-thrust system that contrasts with the less disturbed basins to the north and south (Grantz and May, 1987). The structural relationship of the Herald Arch to the extensive east-west-trending Brooks Range fold and thrust belt has been the focus of considerable debate. Some models link development of the Herald Arch to the formation of the Brooks Range (Middle Jurassic to middle Cretaceous), but the northwest-southeast orientation of the arch has led to speculation that it postdates the orogenic events of the western Brooks Range (Late Cretaceous to Tertiary). In addition, indications are that the Herald Arch predates the Hope Basin, which contains Eocene and younger sediments, thus further defining the age of formation (e.g., Patton and Tailleur, 1977; Grantz et al., 1970, 1981; Tolson, 1987). Moore et al. (1994) proposed two orogenic events in the Brooks Range, one Jurassic and/or Early Cretaceous age and the other Late Cretaceous age. The younger of these events is associated with west-trending folds that extend smoothly across northern Alaska and continue northwesterly along the Herald Arch (Moore et al., 1994).

Structural, petrologic, geochronologic, and seismological data suggest that episodes of generally north-south extension have affected the crust of the northern Bering Sea since middle to Late Cretaceous time and appear to be continuing today (e.g., Miller and Hudson, 1991; Dumitru et al., 1995; Page et al., 1991; Turner and Swanson, 1981; Mackey et al., 1997). Exposures of metamorphic rocks in the Seward Peninsula reveal deformational histories at several crustal levels and have led to a tectonic model involving regional denudation, tilting, and normal faulting related to these extensional events (Hannula and McWilliams, 1995; Dumitru et al., 1995). Blueschist facies metamorphic rocks exposed on the peninsula are believed to have originated at mid-crustal depths and provide evidence of postmetamorphic uplift and cooling in Cretaceous time (Hannula and McWilliams, 1995; Bering Strait Geologic Field Party, 1997). Today the Bering Strait region is seismically active. Earthquake focal mechanisms indicate that north-south-directed extension is occurring from eastern Chukotka through the Seward Peninsula to the Yukon Delta (Mackey et al., 1997; Mackey, 1999).

PREVIOUS WORK

Although there have been extensive multichannel seismic reflection investigations (many related to petroleum exploration) and a few sonobuoy refraction studies of the upper crust, there has only been limited previous work to determine the deep crustal structure of the Bering Strait region. In addition, the International Boundary between the United States and the former Soviet Union has precluded joint experiments or even the routine exchange of data. Thus, combined with the logistical difficulties inherent in the region, very few studies have exam-

ined the deep structure and continuity of structure along both sides of the Bering Strait.

Prior Russian studies of crustal structure were based on the analysis of converted waves (Mishin and Dareshkina, 1966), usually P_s , recorded predominantly at temporary stations deployed in the 1960s (see Fujita et al., this volume). Because these analyses were based on a small number of events and unsubstantiated assumptions about intracrustal seismic velocities (Belyaevsky and Borisov, 1974; Vashchilov, 1979; Bulin, 1989), they vary somewhat in their estimates of crustal thickness (usually $\sim\pm 5$ km) and their reliability is probably poor. These studies indicate crustal thicknesses of 37–39 km throughout Chukotka, with slightly thinner crust at Provideniya (32–37 km), and thicker crust in the vicinity of the Omolon massif to the west (40–41 km). The only other published Russian work is a profile along 173°E meridian based on magnetic data that indicate a crustal thickness of 30 km (Demenitskaya et al., 1973).

Prior published American studies of crustal thickness in the Chukchi Sea and Bering Strait region are also lacking. Ostensio (1968) used gravity measurements to suggest that the thick crust associated with the north-central Brooks Range (e.g., Barnes, 1977; Fuis et al., 1997) thins considerably into the south Chukchi Sea; he also referred to an unreversed refraction line on the continental shelf edge that yielded a Moho depth of 30 km. A refraction line between Point Barrow and ice station Arlis II, then at $\sim 74^\circ\text{N}$, 165°W , yielded a 32 km crustal thickness at Barrow (Hunkins, 1966) at the northern end of the present transect, and surface-wave dispersion studies of the Bering Shelf yielded a Moho depth of 27.6 km (Jin and Herrin, 1980) at the southern end.

SEISMIC DATA ACQUISITION AND ANALYSIS

The seismic refraction–wide-angle reflection data analyzed in this study are of a reconnaissance nature and were collected at accessible onshore sites on the eastern and western sides of the Bering Strait during both the northbound and southbound legs of the Bering-Chukchi Crustal Transect (Fig. 2). On the eastern side of the strait, the ship track provided approximately in-line raypaths for offsets beyond ~ 40 km for most of the Alaskan stations. On the western side of the strait, the ship was restricted to U.S. waters, and the resulting greater distance between the ship track and recording stations led to a fan recording geometry for stations in Russia.

Receiver gathers for each station were made from the recordings of air-gun shots fired every ~ 50 m and analyzed using a combination of one- and two-dimensional forward-modeling techniques (Luetgert, 1992). For receivers that lacked a significant degree of raypath reversal, only one-dimensional modeling of data from each station was performed. These one-dimensional velocity-depth functions were organized by distance into a two-dimensional pseudosection. The oblique recording geometry for all onshore stations at close range meant that no arrivals occur in the receiver gathers at offsets $< \sim 20$ km,

thus introducing uncertainty into estimates of the upper-crustal velocities. In many cases, estimates for near-surface velocities were obtained from the literature (e.g., Houtz et al., 1981) or inferred from published geologic maps. Although none of the receiver gathers represents completely reversed ray coverage, the section of the eastern transect between Lietnik on Saint Lawrence Island and Point Lay, Alaska, provides enough common subsurface sampling to justify a two-dimensional modeling technique for determining thickness and average velocities of the crust. Higher-order models (e.g., 2.5 dimensional or 3 dimensional) were not attempted because ray coverage was too sparse and the quality of some records too low.

Wide-angle data collected in the study range in signal-to-noise ratio from excellent to poor. For a complete discussion of all receiver gathers and processing parameters, see Brocher et al. (1995). In general, upper-crustal refracted phases (Pg) and prominent upper mantle reflections (PmP) can be traced in most gathers to offsets beyond 100 km (e.g., Fig. 3). Upper mantle refracted phases (Pn) were observed in only five gathers.

VELOCITY MODELS AND INTERPRETATION

Figures 4 and 5 contain crustal compressional-wave velocity models based on receiver gathers from the multichannel ex-

periment. Figure 4 is a composite of one-dimensional velocity-depth functions from Provideniya to Tin City. Figure 5 shows a crustal velocity model for Lietnik to Point Lay based on the two-dimensional ray-tracing analysis. To derive the models, we used traveltimes of Pg , PmP , and, where observed, PiP and Pn phases, from 16 receiver gathers. Picks were made of first arrivals and high-amplitude secondary arrivals, only some of which are attributable to coherent phases. Observed and calculated traveltime curves for the receiver gathers used in the two-dimensional model, along with ray diagrams showing the area of subsurface sampling, are shown in Figures 6 and 7. Calculated traveltimes were generally fit to within 0.15 s of observed times of identifiable phases. Errors associated with this level of agreement, assuming that the phases were correctly identified, are $\sim 2\%$ – 3% in velocity and 10% in depth. (For a more complete discussion of uncertainties and error estimates in forward modeling, see Ansorge et al., 1982.) Occasional outliers to 0.4 s are seen; however, these arrivals are attributed to (1) scattered or diffracted energy because they either could not be traced over significant distances and/or they exhibit phase velocities that are unrealistic, or (2) structural complexities that could not be represented effectively in the model. Due to the large number of traces in each gather, far fewer observed traveltimes for each phase are shown in the figures than were picked from the

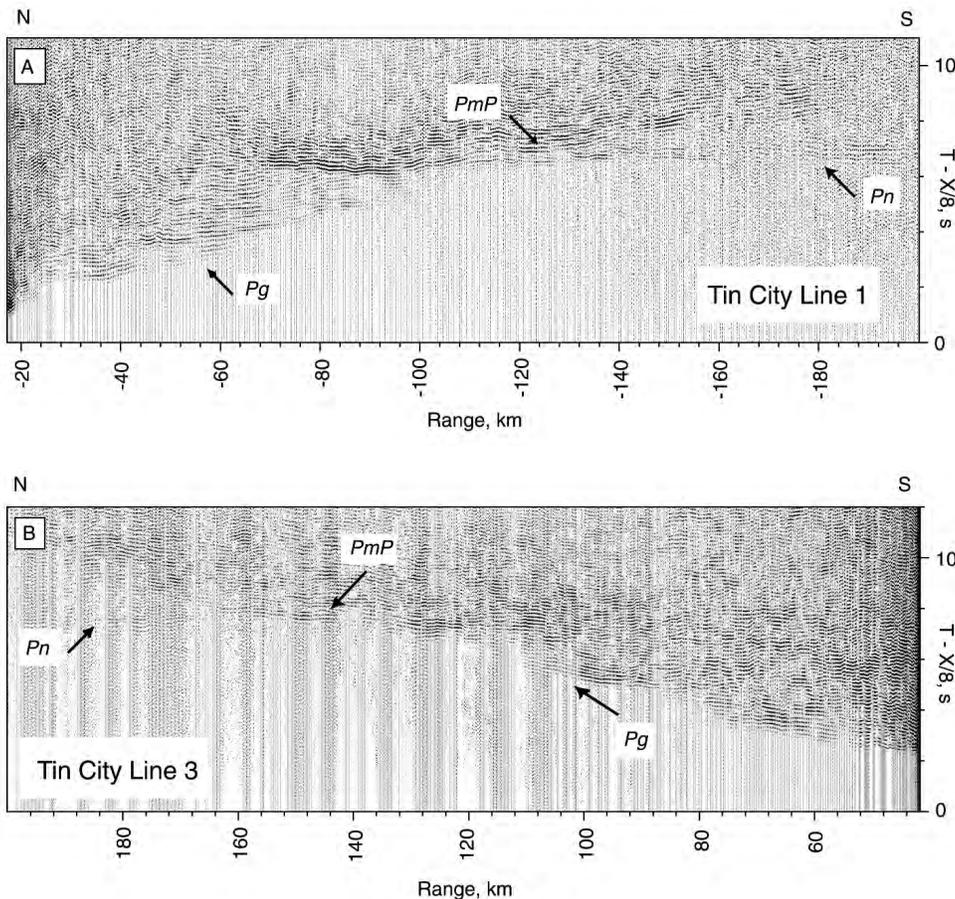


Figure 3. Wide-angle refraction receiver gathers from Tin City line 1 (A) and Tin City line 3 (B) (plotted with reduction velocity of 8 km/s, where T is traveltime and X is offset distance). Data have been bandpass filtered (6–13 Hz) and mixed over five traces. Offsets from recording station are given as positive for shots fired north of receiver and negative for shots fired south of receiver. In each gather, Pg (crustal phase), PmP (upper mantle reflection), and Pn (upper mantle refracted phase) are clearly apparent. Crossover of Pn phase with Pg crustal phase in each gather occurs at ~ 140 km offset and 7 s, indicating crustal thickness of ~ 32 km in this area.

Figure 4. Pseudo two-dimensional crustal velocity model constructed from one-dimensional velocity-depth functions between Provideniya and Tin City (see Fig. 2 for transect route). Because these data lack reversed raypath coverage, two-dimensional analysis was not warranted. One-dimensional analysis suggests that crust is ~32–33 km thick along western side of Bering Strait, similar to estimates for eastern side (see Fig. 5).

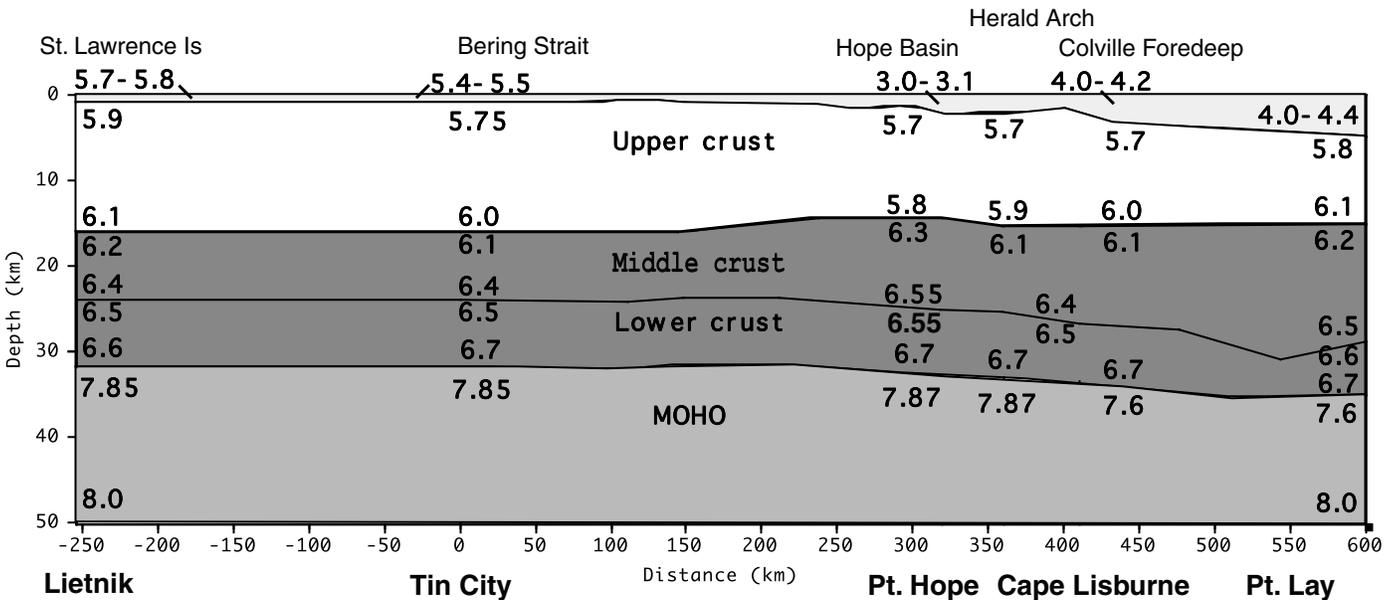
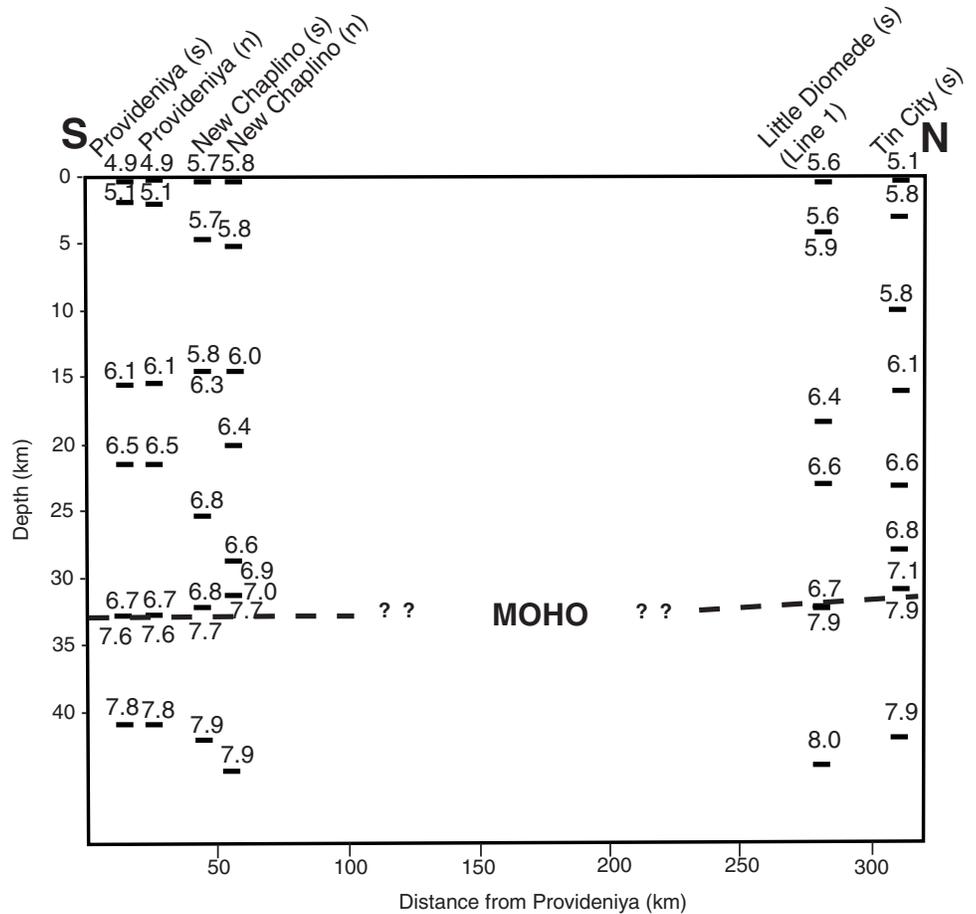


Figure 5. Crustal velocity model from Lietnik to Point Lay, Alaska, based on two-dimensional ray tracing. Variations in upper crustal rocks and sediment thickness along transect were accommodated by first model layer and based on results of reflection data along Bering-Chukchi Crustal Transect (Klemperer et al., Chapter 1) and on published geologic information for onshore station locations. Crustal thickness along profile ranges from ~32 to 35 km; thicker crust occurs to north of Cape Lisburne. See text for discussion.

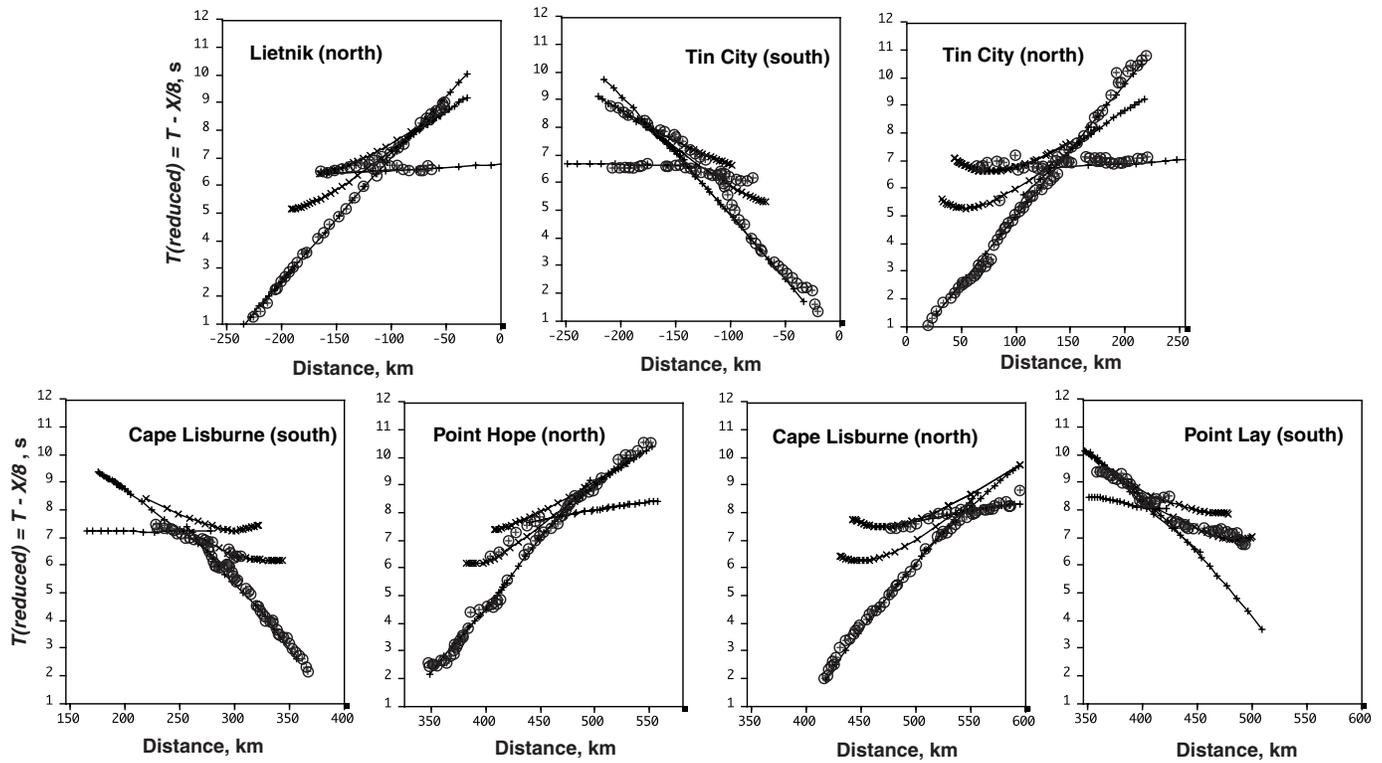


Figure 6. Observed (circles) versus calculated (pluses connected by solid line) traveltimes for stations used in two-dimensional model shown in Figure 5. Traveltimes, T , shown are reduced at 8 km/s with respect to offset distance, X . Offsets are given in model coordinates. North and south refer to raypaths arriving from air-gun shots fired to north or south of each onshore recording station. Observed traveltimes consist of first arrivals and high-amplitude secondary arrivals, but only some of latter are attributable to coherent phases. Due to large number of traces, far fewer observed traveltimes are shown than were picked from records. Generally, calculated times are fit to within 0.15 s of observed times of coherent phases (e.g., Pg and PmP phases, and where observed, PiP and Pn phases; see text). Occasional outliers, e.g., Tin City (south) at -100 km and 5 s, were not modeled and are mostly attributed to scattered or diffracted energy or to structural complexities that could not be effectively represented in model. Picks from three receiver gathers—Leitnik (south), Point Hope (south), and Point Lay (north)—are not shown but were considered in modeling.

records. In developing both models (Figs. 4 and 5), more weight was subjectively given to traveltime picks from those record sections in which all phases were clearly observed and the signal-to-noise ratio was high.

The two-dimensional modeling between Lietnik and Point Lay (Fig. 5) allowed us to include detail in the upper crust that correlates with near-surface geology, as described in published literature, and with interpretations of the reflection data (see Klemperer et al., this volume, Chapter 1). Such features as the Hope Basin and the Herald Arch fold and thrust belt significantly influence the arrival times of phases at the onshore stations and are thus considered in the model. Variable near-surface velocities representing laterally juxtaposed rocks are shown in the model's first layer. Compressional wave velocities for this layer in the region between Lietnik and Tin City are high (>5.4 km/s) relative to those at Point Hope (~ 3.0 km/s). Farther to the north, in the fold and thrust belt off Cape Lisburne, velocities are ~ 4.2 km/s.

Average velocities of the upper to middle crust in both the one- and two-dimensional models (Figs. 4 and 5) are ~ 5.8 km/s (excluding near-surface variations in the first model layer) and

~ 6.4 km/s in the middle to lower crust. These velocities are consistent with those of average continental crust (Christensen and Mooney, 1995; Rudnick and Fountain, 1995). At the base of the crust, velocities are ~ 6.7 km/s. Inclusion of a separate lower-crustal layer in the model was based on gathers having PiP intracrustal phases. Upper mantle Pn phases, where observed, had crossover distances with Pg crustal phases of ~ 140 – 160 km and estimated velocities of 7.6 – 7.9 km/s (Figs. 3 and 6), indicating crustal thicknesses ranging from 32 to 35 km. Our results indicate that the crustal velocity structure varies little from the eastern to the western shores of the Bering Strait between the Seward and Chukotka Peninsulas.

A combination of a late-arriving PmP upper mantle reflection and the lack of a clearly defined Pn crossover in the Point Hope record raises the possibility that the crustal structure beneath Cape Lisburne and the Herald Arch differs from that inferred for the rest of the transect (Fig. 8). Furthermore, the Pg phase in this receiver gather represents the first-arriving energy well beyond offsets observed in other gathers. These record attributes might be interpreted to indicate that this area has a lower

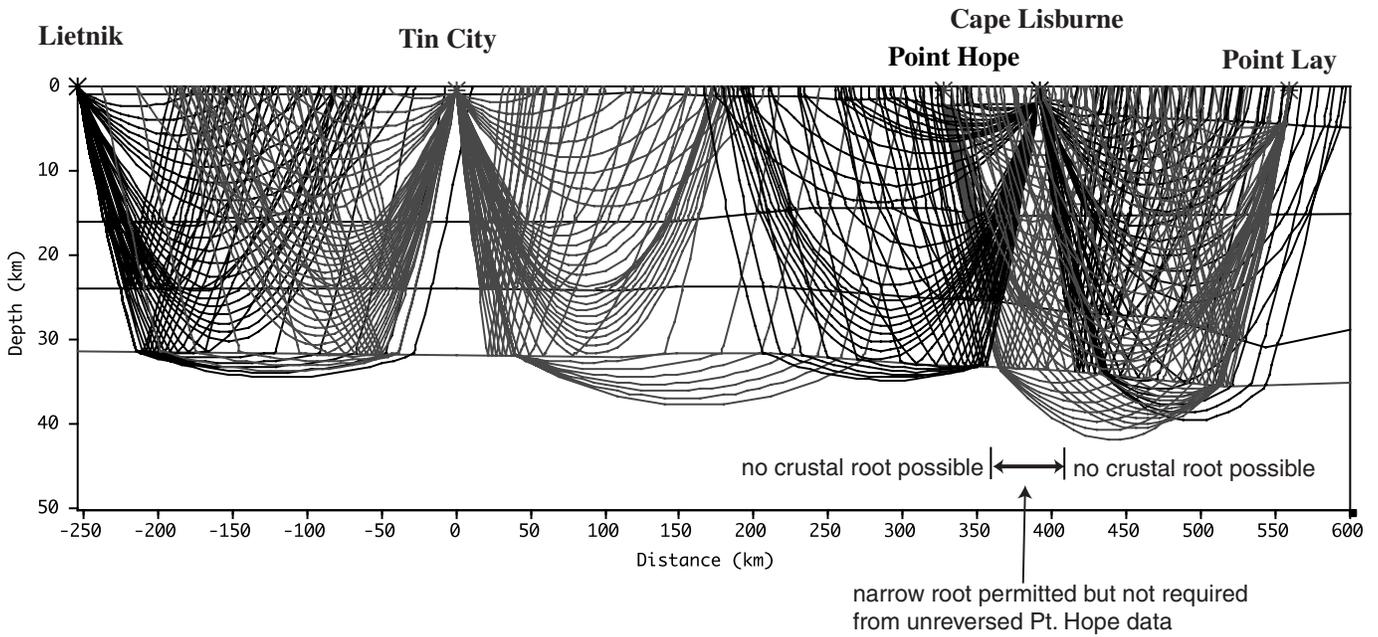
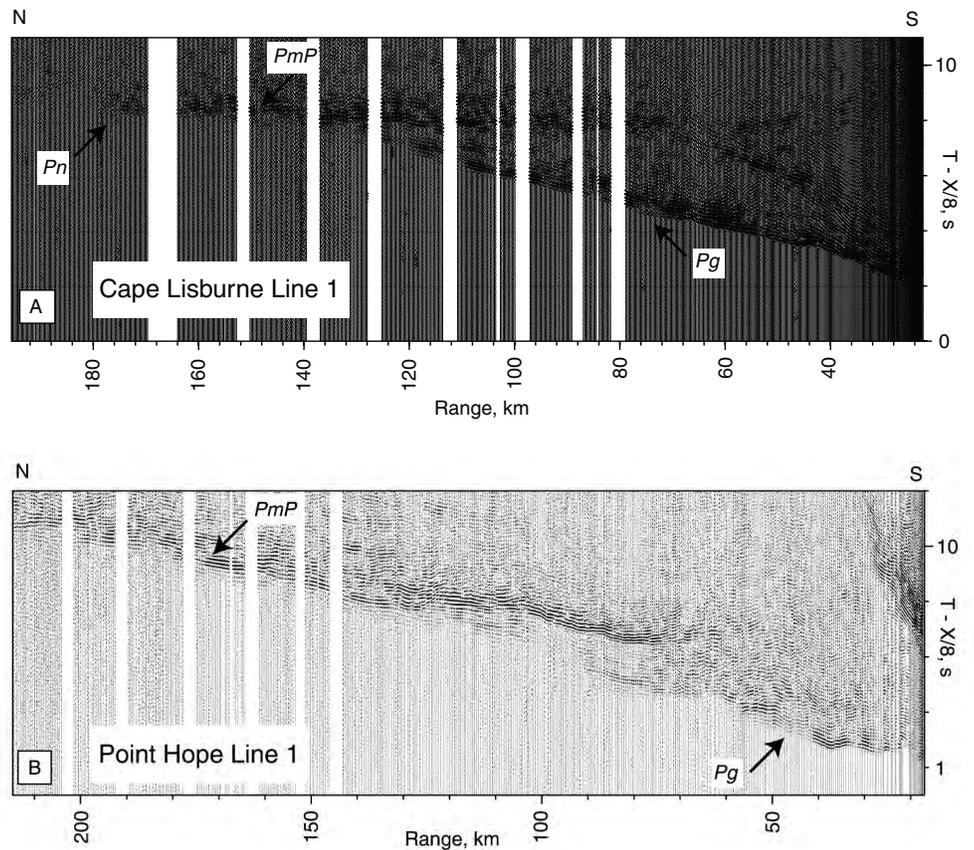


Figure 7. Ray diagrams corresponding to calculated traveltimes shown in Figure 6 and overlain on two-dimensional model shown in Figure 5. Note that raypath reversals are only partial and that at close offsets they represent oblique recording geometries. Two-headed arrow shows region of possible crustal root. However, preferred seismic and gravity models successfully match observed data without root (see text for discussion).

Figure 8. Wide-angle receiver gathers from Cape Lisburne line 1 (A) and Point Hope line 1 (B). Data have been band-pass filtered (6–13 Hz) and mixed over five traces. Positive offsets indicate data from shots fired north of receiver. Crossover of P_n upper mantle phase with P_g crustal phase appears at ~ 150 km offset in record from Cape Lisburne. No P_n phase is observed, however, in record from Point Hope. See text for discussion.



average crustal velocity and possibly a thick crustal root, which would be on trend with the westward extension of the northern Brooks Range. As an alternative to the model shown in Figure 5, a crustal model with a thickened root (~ 40 km crustal thickness) was tested against the data observations. Although the calculated traveltimes from the model could be made to match the data, the root could not extend northward of km +425 in the model (Figs. 5 and 6). The reason for this is that raypaths from the Point Hope gather have common sampling points in the lower crust and upper mantle with raypaths from the Cape Lisburne gather (Fig. 7), and the latter contains a clearly defined upper mantle P_n phase that indicates a crustal thickness of ~ 35 km near Cape Lisburne (Fig. 8). We argue that the data do not require the presence of the root in the vicinity of Point Hope to Cape Lisburne, and the lack of a clear upper mantle P_n phase in the Point Hope receiver gather can be attributed to a low signal-to-noise ratio or to a low or negative velocity gradient in the upper mantle.

GRAVITY MODELS

To examine independently the presence of a crustal root beneath Cape Lisburne, we compared satellite-derived gravity measurements (Sandwell and Smith, 1997) with values calculated using models without and with a thickened root (Figs. 9 and 10). Profiles for the models were extracted from gridded data from along five longitude lines between 168° and 170° W. The initial gravity model was based on a simplified version of

the refraction models, in which an average bulk density for the crust was assumed to be 3.0 g/cm^3 . The sedimentary basin depth for the Aleutian Basin and Bering Shelf was obtained from Worral (1991). Water depths (20–200 m) do not vary significantly throughout the region encompassed by the model. Sediment thickness for the Chukchi Sea was obtained from Grantz et al. (1994) and supplemented from Shipilov et al. (1989). The density assigned to sedimentary basins was 2.6 g/cm^3 , and was based on measured densities of clastic and carbonate rocks in test wells (Collins, 1958, 1961). The density used for mantle rocks was 3.3 g/cm^3 . Results of the analysis indicate that the presence of a crustal root of the maximum thickness and extent that the suite of tested seismic models could allow would result in a gravity anomaly three times larger than that observed (Fig. 10). Instead, the gravity models indicate that the observed anomalies can be sufficiently accounted for by a slight northward thickening of the crust and the presence of thick sediments in the basins in the Point Hope–Cape Lisburne area, in keeping with the preferred and more plausible seismic model (Fig. 5).

DISCUSSION

Of significant interest is the question of whether the Brooks Range orogen continues westward from the Lisburne Peninsula and merges with the Herald Arch or if the Herald Arch thrust zone crosscuts the Brooks Range. The absence of strong evidence for a crustal root or greatly thickened crust in the seismic and gravity data supports earlier interpretations that the crust of

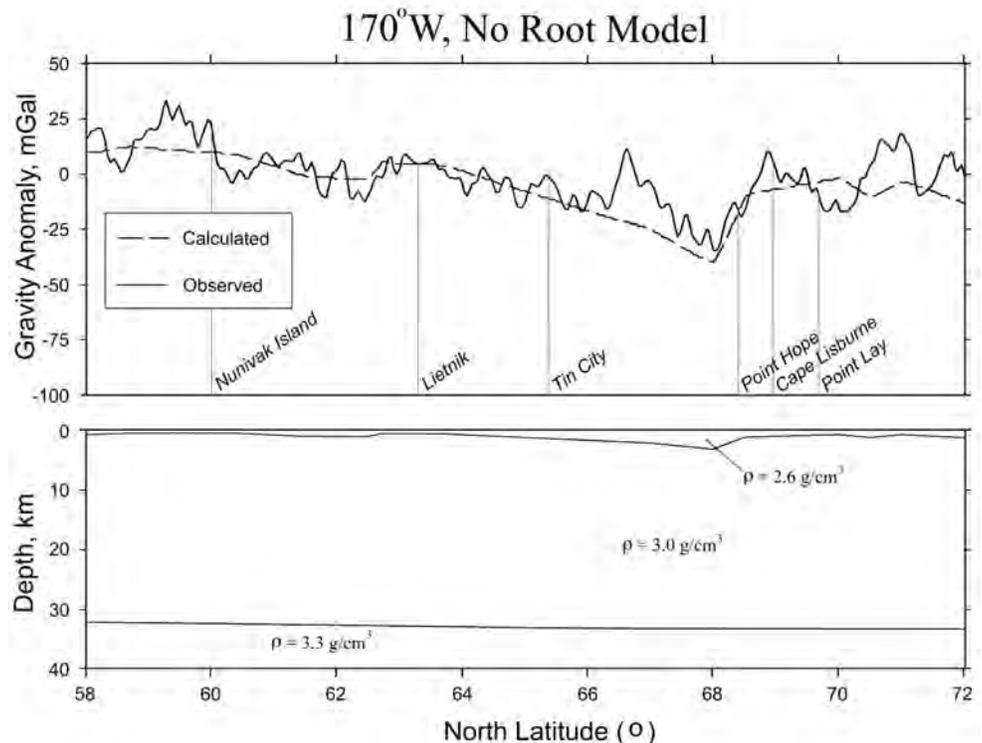
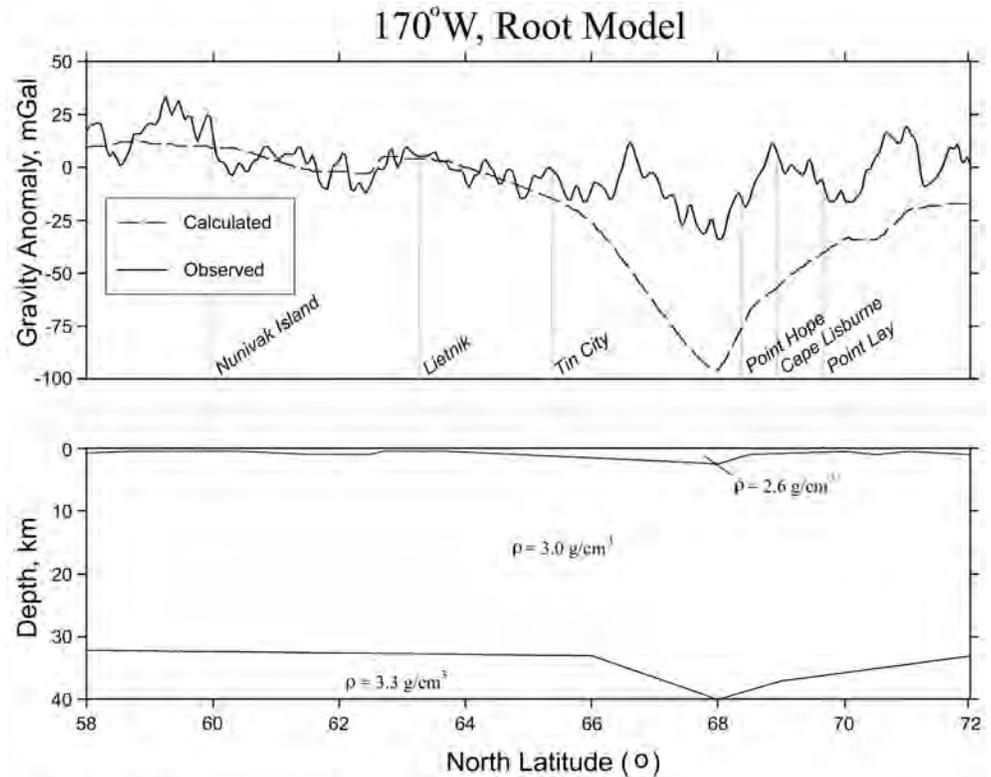


Figure 9. Gravity model of profile along 170° W meridian from 58° N to 72° N. Density, ρ , in g/cm^3 for sedimentary basins from Collins (1958, 1961). Gravity data were derived from gridded satellite altimetry data (Sandwell and Smith, 1997). Model indicates that gravity anomalies can be accounted for by configuration of near-surface sediments and gradual northward thickening of crust. Crustal root is not required.

Figure 10. Gravity model (as in Fig. 9) assuming crustal root to 40 km beneath Herald Arch (~68°N). Density, ρ , in g/cm^3 . Addition of root produces gravity low approximately three times that seen in gridded data. These results support no-root seismic model shown in Figure 5.



the Bering Strait and areas to the north near Point Hope and Cape Lisburne are thin relative to the thickened crust (~49 km) observed in the central Brooks Range (Fuis et al., 1997; Wissinger et al., 1997). Thus our results suggest that if the Brooks Range orogen formerly extended west of Lisburne Peninsula, its topographically high elevations and corresponding thickened crustal root have been removed by subsequent extension. This interpretation is corroborated by the multichannel seismic data, which lack any indication of a thick crustal root west of the Lisburne Peninsula (Fig. 11).

Although the seismic and gravity data provide no compelling evidence for continuity of the Herald Arch with the Brooks Range, the refraction data indicate a slight change in upper-crustal velocity from 5.7 km/s south of the Herald Arch to 5.8–6.1 km/s north of the Herald Arch. The slightly higher (<0.9–1.4 km/s) upper-crustal velocity observed in this area most likely reflects a change in petrology or depth to basement. In addition, a prominent northward dip to the middle-lower crustal interface (Fig. 5), accompanied by a drop in the reflectivity of the lower crust (Fig. 11) (Klemperer et al., this volume, Chapter 1) and a slight increase in crustal thickness north of Point Hope, are consistent with interpretations that the widespread north-south extension proposed for the area beneath the magmatic belt did not affect the crust north of the Herald Arch.

Results of the refraction analysis from the Bering Strait (e.g., crustal thickness of 32–35 km and average velocities of

6.4 km/s in the middle to lower crust) are consistent with geologic interpretations of extended continental crust in this area (Miller and Hudson, 1991; Dumitru et al., 1995; Bering Strait Geologic Field Party, 1997). In addition, these findings are in agreement with interpretations of multichannel seismic data (Fig. 11), which show a highly reflective lower crust (6–12 s two-way traveltimes) underlying the Cretaceous magmatic belt (Bering Strait Geologic Field Party, 1997; Klemperer et al., this volume, Chapter 1). Similar patterns of reflectivity are observed in other regions that have undergone extension or in areas that have undergone magmatism (Mooney and Brocher, 1987; Beaudoin et al., 1992). The lack of a significant change in lower-crustal velocities throughout the region covered by the two-dimensional refraction model (Fig. 5) suggests that the reflectivity of the lower crust observed between Saint Lawrence Island and the Bering Strait (Fig. 11) is unlikely to be the result of a large volume of mafic to ultramafic intrusions into the lower crust; rather, the average seismic velocity of 6.6 km/s along the profile is more consistent with a composite of felsic to intermediate igneous and metamorphic rocks with gabbroic intrusions (Klemperer et al., this volume, Chapter 1). On the Seward Peninsula, Jurassic and/or Early Cretaceous blueschist facies metamorphic rocks that formed at high pressures at mid-crustal depths were exhumed and subsequently uplifted. In view of the seismically derived crustal thickness of ~32 km west of the Seward Peninsula and assuming these now-exposed metamorphic rocks were formed at ~15 km depth, we estimate that

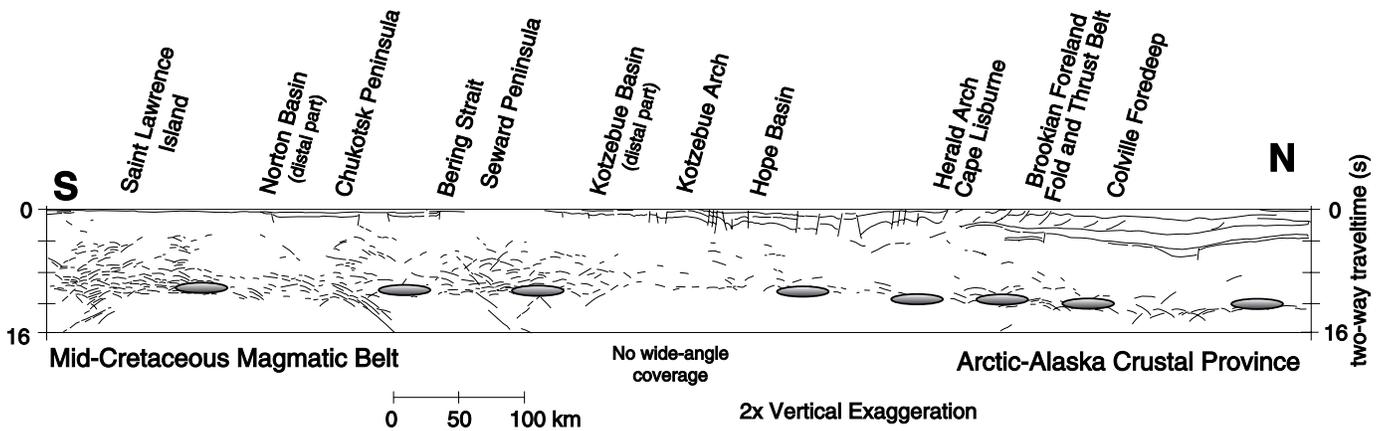


Figure 11. Line drawing of seismic reflection data interpretation (Klemperer et al., Chapter 1) along portion of transect corresponding to two-dimensional refraction model (Fig. 5). Ellipses indicate positions of wide-angle reflections that were used to define refraction Moho. In general, there is good agreement between locations of refraction and reflection Mohos. Note that reflection data lack indication of crustal root in area between Point Hope and Cape Lisburne, thus supporting no-root refraction model.

a thicker crust (>47 km) once existed in this area and at least 15 km of crust has been removed through the processes of extension and erosion.

CONCLUSIONS

Onshore refraction and wide-angle reflection data collected as part of the Bering-Chukchi Crustal Transect, in combination with gravity modeling of satellite data, have provided information on the general attributes of the crust in the Bering Strait region. Results yield present-day crustal thicknesses of 32–35 km, average velocities of 6.4 km/s in the middle to lower crust, and upper mantle velocities of 7.6–7.9 km/s. These observations are consistent with global averages for continental crust, although upper mantle velocities may be slightly low. Observations from the wide-angle data are consistent with models of widespread extension in the portion of the Bering Sea underlain by the Cretaceous magmatic belt and, when viewed in light of studies of blueschist facies rocks on the Seward Peninsula, suggest that the crust in this area may have been at least 47 km thick prior to extension. Crustal thickness and velocity estimates for the crust between the Seward and Chukotka Peninsulas support regional geologic, petrologic, geochronologic, and geochemical studies that indicate continuity of crustal structure from western Alaska to eastern Russia. The lack of compelling evidence in the seismic and gravity data for a crustal root west of the Lisburne Peninsula suggests that if the Brooks Range once continued beyond the peninsula, its root has been subsequently removed by extensional processes.

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REFERENCES CITED

- Amato, J.M., and Wright, J.E., 1997, Potassic mafic magmatism in the Kigluaiik gneiss dome, northern Alaska: A geochemical study of arc magmatism in an extensional setting: *Journal of Geophysical Research*, v. 102, p. 8065–8084.
- Anson, J., Prodehl, C., and Bamford, D., 1982, Comparative interpretation of explosion seismic data: *Journal of Geophysics*, v. 51, p. 69–84.

- Barnes, D.F., 1977, Bouguer gravity map of Alaska: U.S. Geological Survey Map GP-913, scale 1:2 500 000, 1 sheet.
- Beaudoin, B.C., Fuis, G.S., Mooney, W.D., Nokleberg, W.J., and Christensen, N.I., 1992, Thin, low-velocity crust beneath the southern Yukon-Tanana terrane, east central Alaska: Results from Trans-Alaska crustal transect refraction/wide-angle reflection data: *Journal of Geophysical Research*, v. 97, p. 1921–1942.
- Belyaevsky, N.A., and Borisov, A.A., 1974, Structure and thickness of the earth's crust of the USSR, *in* Dedeev, V.A., ed., *Structure of the basement of platformal regions of the USSR*: Leningrad, Nauka, p. 381–393 (in Russian).
- Belyi, V.F., 1994, *Geology of the Okhosk-Chukchi volcanogenic belt*: Magadan, Russia, Northeast Interdisciplinary Scientific Research Institute, 76 p. (in Russian).
- Bering Strait Geologic Field Party, 1997, Koolen metamorphic complex, N.E. Russia: Implications for the tectonic evolution of the Bering Strait region: *Tectonics*, v. 16, p. 713–729.
- Brocher, T.M., Allen, R.M., Stone, D.B., Wolf, L.W., and Galloway, B.K., 1995, Data report for onshore-offshore wide-angle seismic recordings in the Bering-Chukchi Sea, western Alaska and eastern Siberia: U.S. Geological Survey Open-File Report 95–650, 57 p.
- Bulin, N.K., 1989, Deep structure of the Verkhojansk-Chukotka fold belt according to seismic data: *Tikhookeanskaya Geologiya*, no. 1, p. 77–85 (in Russian).
- Christensen, N.I., and Mooney, W.D., 1995, Seismic velocity structure and composition of the continental crust: A global view: *Journal of Geophysical Research*, v. 100, p. 9761–9788.
- Collins, F.R., 1958, Test wells, Umiat area, Alaska, *in* *Exploration of Naval Petroleum Reserve No. 4, and adjacent areas, northern Alaska, 1944–53. 5. Subsurface geology and engineering data*: U.S. Geological Survey Professional Paper 305-B, p. 71–206.
- Collins, F.R., 1961, Core tests and test wells, Barrow area, Alaska, *in* *Exploration of Naval Petroleum Reserve No. 4, and adjacent areas, northern Alaska, 1944–53. 5. Subsurface geology and engineering data*: U.S. Geological Survey Professional Paper 305-K, p. 569–644.
- Demenistakaya, R.M., Ivanov, S.S., and Volk, V.E., 1973, Crust of the Arctic seas of Eurasia: *Tectonophysics*, v. 20, p. 97–104.
- Dumitru, T.A., Miller, E.L., O'Sullivan, P.B., Amato, J.M., Hannula, K.A., Calvert, A.T., and Gans, P.B., 1995, Cretaceous to recent extension in the Bering Strait region, Alaska: *Tectonics*, v. 14, p. 549–563.
- Fisher, M.A., Patton, W.W., and Holmes, M.L., 1982, Geology of Norton basin and continental shelf beneath northwestern Bering Sea, Alaska: *American Association of Petroleum Geologists Bulletin*, v. 66, p. 255–285.
- Fuis, G.S., Murphy, J.M., Lutter, W.J., Moore, T.E., and Bird, K.J., 1997, Deep seismic structure and tectonics of northern Alaska: Crustal-scale duplexing with deformation extending into the upper mantle: *Journal of Geophysical Research*, v. 102, p. 20873–20896.
- Grantz, A., and May, S.D., 1987, Regional geology and petroleum potential of the United States Chukchi Shelf north of Point Hope, *in* Scholl, D.W., Grantz, A., and Vedder, J.G., eds., *Geology and resource potential of the continental margin of western North America and adjacent ocean basins: Beaufort Sea to Baja California*: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 37–58.
- Grantz, A., Wolf, S.C., Breslau, L., Johnson, T.C., and Hanna, W.F., 1970, Reconnaissance geology of the Chukchi Sea as determined by acoustic and magnetic profiling, *in* Adkinson, W.L., and Brosge, M.M., eds., *Proceedings of the Geological Seminar on the North Slope of Alaska*: American Association of Petroleum Geologists, Pacific Section, Los Angeles, p. F1–F28.
- Grantz, A., Eittreim, S., and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada basin, *in* Nairn, A.E.M., Churkin, M., Jr., and Stehli, F.G., eds., *The Arctic Ocean*: New York, Plenum Press, The Ocean Basins and Margins, v. 5, p. 439–492.
- Grantz, A., May, S.D., and Hart, P.E., 1994, Geology of the Arctic continental margin, *in* Plafker, G., and Berg, H.C., eds., *The geology of Alaska*: Boulder, Colorado, Geological Society of America, *Geology of North America*, v. G-1, p. 17–48.
- Hannula, K.A., and McWilliams, M.O., 1995, Reconsideration of the age of blueschist facies metamorphism on the Seward Peninsula, Alaska, based on phengite $^{40}\text{Ar}/^{39}\text{Ar}$ results: *Journal of Metamorphic Geology*, v. 13, p. 125–139.
- Houtz, R.E., Eittreim, S., and Grantz, A., 1981, Acoustic properties of northern Alaska shelves in relation to the regional geology: *Journal of Geophysical Research*, v. 86, p. 3935–3943.
- Howell, D.G., Moore, G.W., and Wiley, T.J., 1987, Tectonics and basin evolution of western North America: An overview, *in* Scholl, D.W., Grantz, A., and Vedder, J.G., eds., *Geology and resource potential of the continental margin of western North America and adjacent ocean basins: Beaufort Sea to Baja California*: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 1–15.
- Hunkins, K., 1966, The Arctic continental shelf north of Alaska: Geological Survey of Canada, Paper 66–15, p. 197–205.
- Jin, D.J., and Herrin, E., 1980, Surface wave studies of the Bering Sea and Alaska area: *Bulletin of the Seismological Society of America*, v. 70, p. 2117–2144.
- Kirschner, C.E., 1998, Map showing sedimentary basins of onshore and continental shelf areas, Alaska: U.S. Geological Survey Miscellaneous Investigations Series, I-1873.
- Klemperer, S.L., Galloway, B.K., and Childs, J.R., 1995, Preliminary results of deep seismic profiling offshore Alaska from the Aleutian Basin to the Arctic Ocean: *Eos (Transactions, American Geophysical Union)*, v. 76, p. 590.
- Luetgert, J.H., 1992, MacRay: Interactive two-dimensional seismic raytracing for the Macintosh™: U.S. Geological Survey Open-File Report 92–356, 43 p.
- Mackey, K.G., 1999, *Seismological studies in northeast Russia [Ph.D. thesis]*: East Lansing, Michigan State University, 346 p.
- Mackey, K.G., Fujita, K., Gunbia, L.V., Kovalev, V.N., Imaev, V.S., Koz' min, B.M., and Imaeva, L.P., 1997, Seismicity of the Bering Strait region: Evidence for a Bering block: *Geology*, v. 25, p. 979–982.
- McGeary, S.E., and Ben-Avraham, Z., 1981, Allocthonous terranes in Alaska: Implications for the structure and evolution of the Bering Sea: *Geology*, v. 9, p. 608–613.
- Mishin, S.V., and Dashchikina, N.M., 1966, Isolation of converted waves on records of distant earthquakes: *Academy of Sciences of the USSR, Izvestiya Earth Physics*, v. 2, p. 598–601.
- Miller, E.L., and Hudson, T., 1991, Mid-Cretaceous extensional fragmentation of a Jurassic–Early Cretaceous compressional orogen: *Tectonics*, v. 10, p. 781–796.
- Mooney, W.D., and Brocher, T.M., 1987, Coincident seismic reflection/refraction studies of the continental lithosphere: A global review: *Reviews of Geophysics*, v. 25, p. 723–742.
- Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillion, J.T., 1994, Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., *The geology of Alaska*: Boulder, Colorado, Geological Society of America, *Geology of North America*, v. G-1, p. 49–140.
- Newberry, R.J., Allegro, G.L., Cutler, S.E., Hagen-Lavelle, J.H., Adams, D.D., Nicholson, L.C., Weglarz, T.B., Bakke, A.A., Clautice, K.H., Coulter, G.A., Ford, M.A., Myers, G.L., and Szumigala, D.J., 1997, Skarn deposits of Alaska: *Economic Geology Monograph* 9, p. 355–395.
- Ostenso, N.A., 1968, A gravity survey of the Chukchi Sea region, and its bearing on westward extension of structures in northern Alaska: *Geological Society of America Bulletin*, v. 79, p. 241–254.
- Page, R.A., Biswas, N.H., Lahr, J.C., and Pulpan, H., 1991, Seismicity of continental Alaska, *in* Slemmons, D.B., et al., eds., *Neotectonics of North America*: Boulder, Colorado, Geological Society of America, *Geology of North America, Decade Map Volume*, p. 47–68.

- Patton, W.W., Jr., and Tailleux, I.L., 1977, Evidence in the Bering Strait region for differential movements between North America and Eurasia: *Geological Society of America Bulletin*, v. 88, p. 1298–1304.
- Rubin, C.M., Miller, E.L., and Toro, J., 1995, Deformation of the northern circum-Pacific margin: Variations in tectonic style and plate-tectonic implications: *Geology*, v. 23, p. 897–900.
- Rudnick, R.L., and Fountain, D.M., 1995, Nature and composition of the continental crust: A lower crust perspective: *Reviews of Geophysics*, v. 33, p. 267–309.
- Sandwell, D.T., and Smith, W.H.F., 1997, Marine gravity anomaly from GEOSAT and ERS-1 satellite altimetry: *Journal of Geophysical Research*, v. 102, p. 10039–10054.
- Shipilov, E.V., Senin, B.V., and Yunov, A.Y., 1989, Sedimentary cover and basement of the Chukchi Sea from seismic data: *Geotectonics*, v. 23, p. 456–463.
- Stavsky, A.P., Checkhovitch, V.D., Kononov, M.V., and Zonenshain, L.P., 1990, Plate tectonics and palinspastic reconstructions of the Anadyr-Koryak region, northeast USSR: *Tectonics*, v. 9, p. 81–101.
- Tolson, R.B., 1987, Structure and stratigraphy of the Hope Basin, southern Chukchi Sea, Alaska, in Scholl, D.W., Grantz, A., and Vedder, J.G., eds., *Geology and resource potential of the continental margin of western North America and adjacent ocean basins: Beaufort Sea to Baja California*: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 59–71.
- Turner, D.L., and Swanson, S.E., 1981, Continental rifting—A new tectonic model for central Seward Peninsula, in Wescott, E., and Turner, D., eds., *Geothermal reconnaissance survey of the central Seward Peninsula, Alaska*: Fairbanks, University of Alaska Geophysical Institute Report UAG R-284, p. 7–36.
- Vashchilov, Y.Y., 1979, Seismicity and the problem of deep structure of the northeast USSR, in Lin'kova, T.I., ed., *Geophysical investigations of structure and geodynamics of the earth's crust and upper mantle of the northeast USSR*: Magadan, Russia, Northeast Interdisciplinary Scientific Research Institute, p. 138–157 (in Russian).
- Wissinger, E.S., Levander, A., and Christensen, N.I., 1997, Seismic images of crustal duplexing and continental subduction in the Brooks Range: *Journal of Geophysical Research*, v. 102, p. 20847–20871.
- Worrall, D.M., 1991, Tectonic history of the Bering Sea and the evolution of Tertiary strike-slip basins of the Bering Shelf: Boulder, Colorado, Geological Society of America Special Paper 257, 120 p.

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