Seismic images of the Brooks Range, Arctic Alaska, reveal crustal-scale duplexing

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ABSTRACT

An integrated set of seismic reflection and refraction data collected across the Brooks Range, Arctic Alaska, in 1990, has yielded a composite image of this Mesozoic and Cenozoic fold-and-thrust belt that reveals duplexing to lower-crustal depths. Interpretations from this image are as follows. (1) Many terranes and subterranes that were amalgamated in the Late Jurassic to Early Cretaceous extend no deeper than the upper crust (3–10 km). (2) In contrast, crustal duplexing, extending to nearly 30 km depth above a south-dipping basal decollement, has produced latest Cretaceous to Cenozoic antiforms, including the Doonerak antiform in the central Brooks Range and anticlinoria near the northern range front. (3) The duplexing occurs in basement rocks of the North Slope subterrane, which core the antiforms. (4) North-dipping structures in the middle crust of the Yukon-Koyukuk basin and southern Brooks Range may postdate Mesozoic terrane amalgamation and predate or coincide with the duplexing. (5) The thickest crust, 50 km, occurs beneath the north-central Brooks Range, north of the root zone of the basal decollement. The position of the thickest crust may indicate that either the duplexed crust above the decollement was thrust onto and depressed the plate beneath the North Slope or the protracted tectonic history of the Brooks Range has left structures not simply explainable in terms of a single collisional event.

GEOLOGIC SETTING AND DEFINITION OF THE PROBLEM

The Brooks Range, Arctic Alaska, is a Mesozoic and Cenozoic fold-and-thrust belt that is an extension of the western North American Cordillera (Oldow et al., 1989; Grantz et al., 1991). In contrast to other parts of the Cordillera, the Brooks Range is a collisional orogen in which the passive margin of North America was telescoped in a south-dipping subduction zone (using present coordinates). Following the initial collision, an ocean basin, underlying the present Arctic Ocean, opened north of the orogen. The Brooks Range further differs from inboard parts of the Cordillera farther south in the excessive shortening postulated for it (more than 500 km [Mayfield et al., 1983; Oldow et al., 1987] vs. a few hundred kilometres for other parts of the Cordillera [Oldow et al., 1989]). In 1990, we conducted an integrated seismic reflection and refraction survey across this orogen (Fig. 1) in order to image its structure to upper-mantle depths and thereby test several hypotheses on its structure and evolution.

The Brooks Range began to form in the Late Jurassic and Cretaceous by southward subduction (using present coordinates) of a continental margin beneath an island-arc terrane (Roeder and Mull, 1978; Moore and Mull, 1989) that may be represented by rocks of the present Yukon-Koyukuk basin (Fig. 1). In the southern Brooks Range, normal faults and greenschist-facies overprints on high-pressure, subduction-zone metamorphic rocks indicate an episode of extension in mid-Cretaceous time (Gottschalk and Oldow, 1988; Miller and Hudson, 1991). A foreland basin (Colville basin) of Albian and younger age was formed north of the Brooks Range and underlies the North Slope (Fig. 1). The northern continental margin of Alaska is a passive margin formed by the opening of the Amerasian basin (beneath part of the present Arctic Ocean) in the Early to Late Cretaceous. Uplift and contraction continued into the Cenozoic in the northeastern Brooks Range and produced the northeastern salient of the Brooks Range and the Doonerak antiform in the interior of the range (Moore et al., 1992).

The Brooks Range and North Slope compose the Arctic Alaska terrane, which is divided into subterranes (Fig. 1). Of special interest are the Endicott Mountains subterrane, an allochthonous sequence of Paleozoic and Mesozoic sedimentary rocks, and the North Slope subterrane, a mostly intact fragment of North American continent. In the subsurface, the North Slope subterrane consists chiefly of metasedimentary and metavolcanic rocks (Proterozoic to Middle Devonian), overlain by Paleozoic and Mesozoic sedimentary rocks generally similar to those of the Endicott Mountains subterrane and by foreland deposits shed from the Brooks Range.

Geologic cross sections along our profile by Mull et al. (1987), Oldow et al. (1987), and Grantz et al. (1991) provide testable models of Brooks Range structure. Of spe-

Geology; January 1995; v. 23; no. 1; p. 65–68; 5 figures; 1 insert.

cial interest are (1) the great depth of duplexing depicted by Oldow et al. (1987), (2) the possibility of north-dipping panels of basement rocks in the southern Brooks Range depicted by Grantz et al. (1991), (3) the large amount of structural repetition in the northern Brooks Range (275 km of shortening estimated by Oldow et al., 1987), and (4) the thin-skinned nature of the Endicott Mountains subterrane depicted in all three cross sections.

SEISMIC PROFILING

In 1990, a seismic imaging survey was conducted across the Brooks Range and flanking geologic provinces (North Slope and Yukon-Koyukuk basin; Fig. 1) by the U.S. Geological Survey and Rice University (Murphy et al., 1993; Levander et al., 1994). The goal of the survey was to produce a detailed image of the crust and upper mantle by using integrated reflection and refraction techniques. In addition, laboratory seismic velocities for most major rock units of northern Alaska were obtained in order to better interpret seismic results.

A 700-channel seismograph system was used to record 65 shots at 44 separate shotpoints (Fig. 1; Murphy et al., 1993). All seismographs recorded vertical-component motion only. The instruments were deployed five times in abutting and overlapping arrays, producing a 315-km-long profile. Instrument spacing nominally was 100 m. Both small shots (45–275 kg) and large shots (680–1800 kg) were fired to produce a vertical-incidence to wide-angle refraction-reflection data set with continuous offset coverage from 0 to more than 200 km. In-line shot spacing averaged 8 km, and signal-to-noise ratios were excellent from most shots.

RESULTS

The seismic data were processed in several ways to produce different but complementary images of the crust of the Brooks Range. First, vertical-incidence reflection sections were prepared as described in Levander et al. (1994). Short-offset (0–10 km), common-midpoint (CMP), low-fold sections are shown in Figures 2A (whole crust) and 3 (middle and upper crust).[1] In addition, a single-fold section displaying energy (amplitude squared) was pieced together by using the best deep data, with offsets as large as 32 km (Fig. 2B). The low-fold section produces the clearest image of the upper crust; the single-fold energy display emphasizes a 2-s-thick band of reflections spanning the refraction–wide-angle-reflection Moho (Fig. 4A; see footnote 1). Second, wide-angle reflection data were processed as described in Fuis et al. (1992) to independently produce reflection sections comparable to the CMP sections (black lines in Fig. 3; red lines in Fig. 4A). Finally, traveltimes of first arrivals and wide-angle reflections were inverted by using the method of Lutter et al. (1990) to produce a seismic-velocity model of the profile (Figs. 4A, 4B). The seismic-velocity model is quite detailed in the upper 6 km or so of the crust and permits the downward projection of some features seen at the surface, including folds and faults. The following results were obtained from these multiple images.

1. The CMP data resolve fine-scale structure, whereas the wide-angle data resolve only structures larger than shotpoint spacing. The wide-angle image does indicate which CMP reflections connect with one another and thus gives a larger picture of the orogen (Figs. 3, 4A). In areas of poor CMP data, such as in the southern Brooks Range, the wide-angle image is the main source of information.

2. Reflections can be grouped into zones (Fig. 4B) that we have interpreted in terms of geologic units (Fig. 5) on the basis of surface geology, seismic velocity, and reflection character.

Zone A, in the northern Brooks Range, contains strong, parallel to en echelon reflections that are gently arched at the Doonerak antiformal axis and at the northern range front. This zone is interpreted chiefly as imbrications and internally folded layers of Carboniferous limestone (Lisburne Group) and other Carboniferous to Triassic rocks of the North Slope subterrane for the following reasons: (a) industry well and CMP data from the North Slope indicate that the Lisburne produces prominent reflections in the section (see Bird and Magoon, 1987; Oldow et al., 1987); (b) imbricated Lisburne layers that are exposed in the Doonerak window 5 km west of the seismic line (Seidensticker et al., 1987) project approximately into the southern arch in reflections (Figs. 1, 4A); (c) folded limestone layers in a west-plunging anticlinorium exposed 20 km east of the line (Brosgé et al., 1979) project approximately into the northern arch in reflections; (d) arches in seismic-velocity contours coincide with the arches in reflections (Fig. 4A) and are consistent with the fact that the Lisburne Group has slightly higher average velocities (5.8–6.2 km/s at 0.5–2 kbar) than do most overlying rocks, including most of the rocks of the Endicott Mountains subterrane.

Zone B, in the northern and central Brooks Range, contains strong, linear, south-dipping, en echelon reflections. This zone is interpreted as thrust horses of North Slope subterrane basement rocks because (a) surface mapping indicates that such rocks occupy the cores of the antiforms in the northeastern Brooks Range (Wallace and Hanks, 1990; T. E. Moore, unpublished map) and (b) its model velocity (6.2 ± 0.5 km/s) is consistent with a mixture of rocks similar to those exposed in the Doonerak Window (6.0 km/s, phyllite; 6.8 km/s, greenstone; both at 4 kbar), although this velocity is also consistent with many other rocks, including the Lisburne Group. The base of this zone, extending from 10 km depth beneath the North Slope to nearly 30 km depth in the central Brooks Range, is not everywhere a distinct reflection. It is interpreted as a decollement into which en echelon thrust faults (corresponding to the reflections) sole. Roof (or back) thrusts are inferred at the top of zone B, beneath the Lisburne, as depicted by Wallace and Hanks (1990).

Zone C, in the central Brooks Range, contains moderate to weak, flat to gently south- or north-dipping reflections. High near-surface seismic velocities in this region are consistent with laboratory velocities of rocks of the Coldfoot and Hammond subterranes (5.8–6.5 km/s at 0.5–2 kbar, with anisotropies as great as 30%). The configuration of seismic-velocity contours suggests northward vergence, but the shapes and thicknesses of interpreted rock bodies are poorly constrained.

Zone D, cresting beneath the axis of the Doonerak antiform, contains distinctive, strong reflections that have curved to ramp-and-flat geometries, with moderate south dips on the ramps. Zone D is interpreted as thrust horses of North Slope subterrane basement rocks, as was zone B. The higher velocity in the upper part of zone D, 6.6 ± 0.5 km/s, may indicate a larger component of metavolcanic rocks. The thrust horses of zones B and D are interpreted to be latest Cretaceous–Cenozoic in age, because cooling, interpreted as uplift, of the Doonerak antiform occurred at 65–70 Ma and at 24 ± 3 Ma (P. B. O'Sullivan et al., unpublished). However, the image, especially of zone D, may be complicated by older structures.

Zone E contains moderate to weak wide-angle reflections in the middle crust of the Yukon-Koyukuk basin and southern Brooks Range that dip gently northward. Multiple interpretations of zone E are possible, because it cannot be tied to outcrop. Grantz et al. (1991) proposed north-dipping panels of basement rocks in this region, from which the overlying Mesozoic terranes of the Brooks Range were stripped during north-

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[1] Loose insert: Figures 2, 3, and 4 are on a separate sheet accompanying this issue.

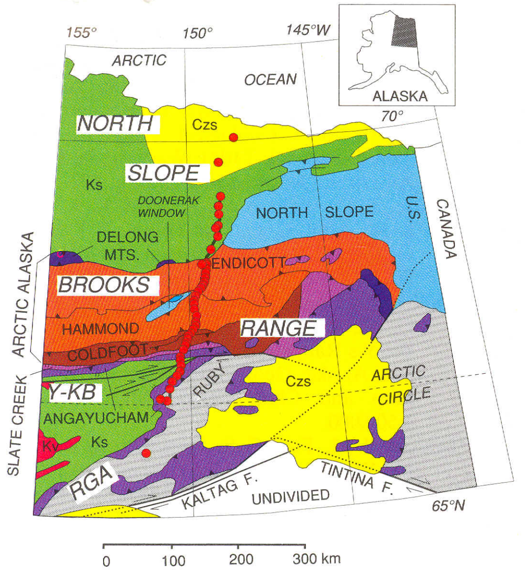

Figure 1. Terrane map of northern Alaska showing shotpoints (red dots) of 1990 seismic experiment; modified from Grantz et al. (1991). Terrane and subterrane names in nonitalicized print: Arctic Alaska terrane comprises Brooks Range and North Slope and is subdivided, from north to south, into sedimentary North Slope, DeLong Mountains, and Endicott Mountains subterranes and metasedimentary-metavolcanic Hammond and Coldfoot subterranes. Melange-phyllonite and ophiolitic terranes (Slate Creek and Angayucham terranes, respectively) separate Arctic Alaska terrane from island-arc Koyukuk terrane to south. Ks—Cretaceous sedimentary rocks, Kv—Cretaceous volcanic rocks, Czs—Cenozoic sedimentary rocks, Y-KB—Yukon-Koyukuk basin, RGA—Ruby geanticline. See Explanation for symbols and unit colors.

EXPLANATION

🟨 Cenozoic sedimentary rocks *

🟩 Cretaceous sedimentary rocks

Endicott Mountains subterrane

🟥 Clastic rocks

⬛ Lisburne Group limestone**

North Slope subterrane exclusive of Cretaceous and younger rocks

🟩 Displaced Mississipian to Triassic rocks--chiefly Lisburne Group limestone**

🟦 Displaced pre-Mississippian rocks--chiefly metasedimentary(?)

🟦 Displaced pre-Mississippian rocks--chiefly metavolcanic or plutonic(?); intermediate velocity

⬜ Autochthonous pre-Mississippian rocks**

🟧 Hammond subterrane

🟫 Coldfoot subterrane

🟪 Slate Creek and Prospect Creek terranes

🟪 Angayucham and Tozitna terranes

Ruby terrane

▨ Metasedimentary and metavolcanic rocks

🟫 Cretaceous pluton**

🟪 Delong Mountains subterrane*

* Map only
** Cross section only

Unknown terranes**

🟫 Intermediate velocity

🟫 Intermediate to high velocity

▨ With north-dipping reflections

Symbols

Major faults*; arrows strike-slip fault, tooth on upper plate of thrust fault, double line on downthrown plate of normal fault, dashed where buried

Wide-angle reflections**;
Prominent;
Moderate to weak;
Studied in preliminary fashion only

Major faults**, including basal decollement

Faults between thrust horses**

Contour of seismic P-wave velocity (km/s) interval, 0.25 km/s**

Figure 5. Geological interpretation of Figure 4. RGA—Ruby geanticline, SRF—southern range front, NRF—northern range front, S.L.—sea level. Symbols on faults at top: tooth—upper plate of thrust fault; double line—downthrown plate of normal fault; solid and open circles—motion away and toward, respectively, on strike-slip faults. See text for discussion. See Explanation for symbols and unit colors.

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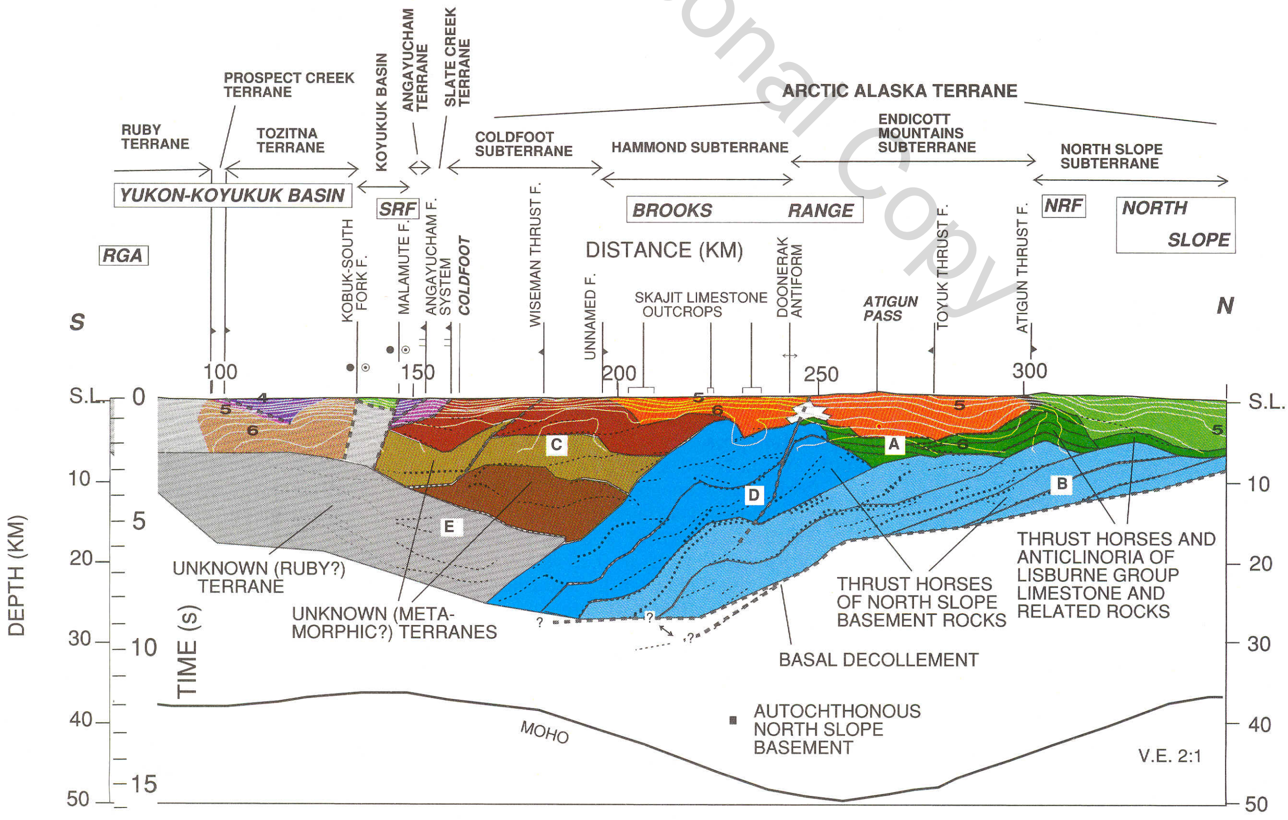

ward thrusting. Alternatively, the reflections of zone E may represent detachment faults that originated during extension in the southern Brooks Range. Finally, as interpreted in Figure 5, this zone might represent the top of a tectonic wedge of Ruby(?) terrane rocks. Although wide-angle reflections of zone E extend across the deep projections of the Cretaceous Kobuk–South Fork and Malamute faults, they cannot clearly resolve truncation of these faults, as interpreted in Figure 5.

The Moho is deepest, 50 km, beneath the zone of Cenozoic shortening in the northern Brooks Range. It shoals (by 13 km) beneath the North Slope and southern Brooks Range. It falls at or near the base of a prominent 5- to 10-km-thick zone of CMP reflections.

DISCUSSION AND CONCLUSIONS

The interpretation shown in Figure 5 is retrodeformable in the sense that area, but not necessarily line length, is conserved. Preliminary estimates of shortening made from this interpretation are considerably reduced over prior estimates of Oldow et al. (1987), primarily because North Slope subterrane basement is interpreted to be involved in thrusting near the northern range front. Minimum shortening in the Lisburne is of the order of 125 km compared to 275 km estimated by Oldow et al. (1987). A minimum latest Cretaceous–Cenozoic shortening of the order of 45 km is required to produce the Doonerak antiform and the anticlinoria on the North Slope and is of the same order (38–45 km) as that calculated from balancing of cross sections in the northeastern Brooks Range by Wallace (1993).

The opposing vergence represented by zones B and D and zone E is reminiscent of opposing vergence observed and modeled in many orogenic belts (e.g., Beaumont and Quinlan, 1994). The Moho depression, however, is located to one side rather than beneath the region of convergence of zones B and D and zone E and thus differs from most other orogenic belts. This geometry may be explained by (1) thrusting of a deformable plate onto a less deformable plate or (2) a complex history of orogeny that cannot be modeled as a single collisional event. In interpretation 1, the highly faulted part of the crust above and south of the basal decollement overrode and depressed the plate beneath the North Slope; the present crustal root is a bottom corner of this plate. In interpretation 2, a tectonic history that includes Late Jurassic–Early Cretaceous shortening, mid-Cretaceous extension, and renewed latest Cretaceous–Cenozoic shortening, with differing loci of maximum deformation, has created the crustal root where it exists at present. Future modeling of Brooks Range deformation may shed light on these and other possible interpretations.

ACKNOWLEDGMENTS

Funded in part by the National Science Foundation, geophysics program, grants EAR 8905222 and EAR 9105002 and by IRIS subagreement 0127 and 0140. Many people, acknowledged in Murphy et al. (1993), helped in the data acquisition and processing. Chief among these people are Ed Criley, supervisor of U.S. Geological Survey field operations, Isa Asudeh, supervisor of Canadian Geological Survey field operations, and Jim Fowler, manager of the IRIS/PASSCAL program. We also thank Tom Brocher, Gill Mull, Roy Johnson, and an anonymous reviewer for helpful manuscript reviews, and Wes Wallace and Nihal Okaya for discussions that influenced our interpretation.

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Manuscript received May 9, 1994
Revised manuscript received September 22, 1994
Manuscript accepted September 28, 1994