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Introduction to special section: The Trans-Alaska Crustal Transect (TACT) across Arctic Alaska

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This special section of the *Journal of Geophysical Research* addresses the composition and structural evolution of the lithosphere in northern Alaska. Investigations reported in this section were mainly undertaken as part of the Trans-Alaska Crustal Transect (TACT), an integrated geological and geophysical transect of the entire Alaskan lithosphere along a north-south corridor undertaken from 1984 to 1992 (Figure 1). The onshore segment of the transect approximately follows along the route of the trans-Alaskan pipeline; the offshore segment extends across the continental margin in the Gulf of Alaska to the Pacific plate. The TACT line is unique in that it provides a coordinated onshore/offshore geological and geophysical traverse of the North American plate in Alaska from the active convergent Pacific margin to the passive Arctic margin of the continent.

The segment of TACT in northern Alaska traverses the low-lying Arctic coastal plain, the rugged east-west trending mountains of the Brooks Range, the eastern part of the Koyukuk basin, and the highlands southeast of the Koyukuk basin (Figure 2). In the Brooks Range, investigations under the TACT program included new geologic mapping at 1:63,360 scale in a 20- to 40-km-wide corridor along the Dalton Highway as well as studies of critical localities in areas adjacent to the mapped corridor (Figure 2). During 1990, coordinated seismic refraction and reflection investigations of the deep crust were carried out along the Dalton Highway by the U.S. Geological Survey and Rice University along a line that extends approximately 315 km from south of Prudhoe Bay across the Brooks Range and eastern apex of the Koyukuk basin into the northern Ruby terrane (Figure 2).

Setting

The Arctic Alaska segment of the transect includes a wide variety of geologic belts and addresses a broad range of important geological problems. On the basis of affinities in lithology, deformation, and their inferred tectonic evolution, geologic belts in Arctic Alaska have been variously referred to as belts, allochthons, terranes, subterranes, etc. In particular, a variety of terrane subdivision schemes have been applied to the combined continental subdivisions of the Brooks Range and the North Slope to simplify description of the major tectonostratigraphic units. The combined North Slope and Brooks Range units have been referred to as the Arctic Alaska terrane, the Arctic Alaska superterrane, or the Arctic composite terrane, and their constituent subdivisions are designated as subterranes or terranes [e.g., *Moore*, 1992; *Plafker and Berg*, 1994; *Silberling et al.*, 1994]. Terrane names shown on Figure 2 and discussed below follow usage of *Moore* [1992] and *Moore, Wallace, Mull, Adams, Plafker, and Nokleberg* [this issue (a)].

Tectonostratigraphic units examined by this part of the TACT investigation are, from north to south, the North Slope terrane, the De Long Mountains terrane, the Endicott Mountains terrane, the Hammond terrane, the Coldfoot terrane, the Slate Creek terrane, the Angayuchum terrane, and the Ruby terrane. We briefly describe each of these. (1) The North Slope terrane consists of a basement of variably metamorphosed Precambrian to lower Paleozoic rocks intruded by Devonian granite (Franklinian Sequence) overlain by autochthonous to parautochthonous Mississippian conglomerate, Carboniferous shelf carbonate rocks, and Permian to lower Mesozoic strata composed of nonmarine to deep shelf, partly calcareous, fine-grained, terrigenous clastic rocks derived from the north (Ellesmerian Sequence). Both the Franklinian and Ellesmerian sequences are unconformably to conformably overlain on the North Slope by an overlap assemblage of Lower Cretaceous to Cenozoic age strata (Brookian Sequence) that was derived from the Brooks Range to the south. (2) The De Long Mountains terrane (also referred to as the Picnic Creek or Ipnavik River allochthon), which is exposed discontinuously along the northern margin of the Brooks Range along and near the TACT corridor, is the youngest and highest of the allochthons in the northern Brooks Range. It consists of variable amounts of chert, cherty limestone, limestone, shale, and minor sandstone of Late Devonian through mid-Cretaceous age that were structurally telescoped during Early Cretaceous north vergent deformation. (3) The Endicott Mountains terrane (also referred to as the Endicott Mountains or Brooks Range allochthon) underlies the northern part of the Brooks Range and structurally underlies the De Long Mountains terrane. It consists of relatively unmetamorphosed rocks correlative with the Ellesmerian Sequence, including Devonian to lower Mesozoic terrigenous clastic rocks, shale, shelf carbonate rocks, and chert that was complexly deformed during and telescoped by Early Cretaceous thin-skinned north vergent deformation. (4) The Hammond terrane, exposed in the central Brooks Range, consists of structurally complex Late Proterozoic(?) to Devonian mixed clastic, volcanic, and carbonate rocks that lie structurally beneath the Endicott Mountains terrane. The rocks are ductilely deformed by complex north-vergent structures and are metamorphosed to low greenschist mineral assemblages. (5) The Coldfoot terrane (also referred to as the "schist belt") consists of Devonian and younger(?) polymetamorphosed and polydeformed quartz-mica schist, calc-schist, marble, and metavolcanic rocks that underwent blueschist facies metamorphism in Early Cretaceous time and, later, retrograde metamorphism to greenschist facies. The schistose rocks are intruded by Early Devonian granitic rocks that are metamorphosed to orthogneiss. (6) The Slate Creek

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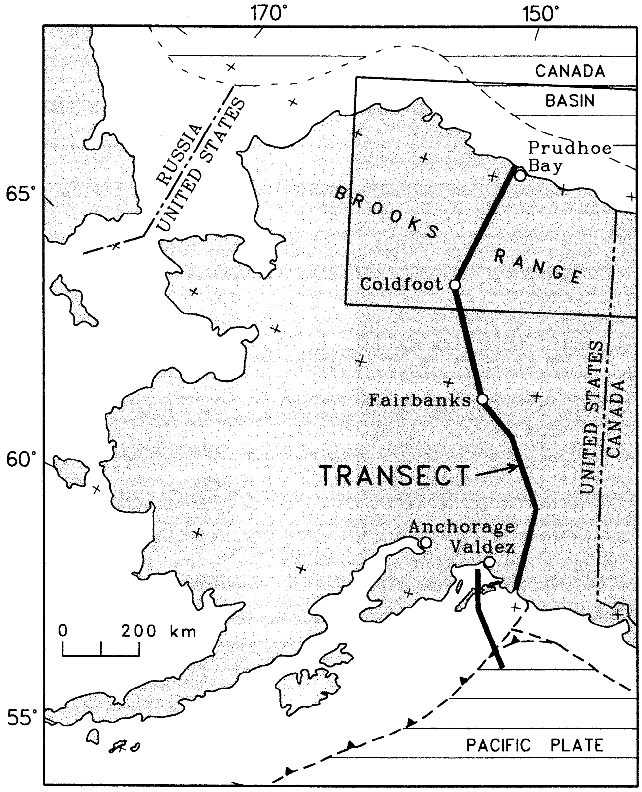

Figure 1. Route of the Trans-Alaska Crustal Transect (TACT) by the U.S. Geological Survey and collaborating institutions from 1984 to 1992. Rectangle shows location of Figure 2.

terrane is a tectonic unit of ductilely deformed Devonian (and possibly younger) phyllite and subordinate metasandstone that is displaced by major, south dipping normal faults of mid-Cretaceous age. (7) The Angayucham terrane at the southern margin of the Brooks Range is made up of a structurally and stratigraphically complex accretionary assemblage of low-greenschist-facies, oceanic island basalt and pelagic rocks of Mississippian to Jurassic age that were thrust onto the Arctic Alaska superterrane from the south during latest Jurassic and Early Cretaceous time. (8) The northern part of the Ruby terrane consists of metamorphosed and complexly deformed Proterozoic(?) through middle Paleozoic quartz-rich schist and metacarbonate that are locally intruded by Early Devonian metagranite and by mid-Cretaceous plutons. Between the Angayucham and Ruby terranes, the transect extends across the eastern apex of the Koyukuk basin, which consists of an overlap assemblage of synorogenic Lower to mid-Cretaceous marine flysch derived mainly from the Brooks Range.

TACT Contributions

This special section consists of 10 related papers on the geology and deformational history of Arctic Alaska along the TACT corridor (seven papers), the geologic and thermal evolution of the southern Colville basin and adjacent north front of the Brooks Range along a profile 250 km west of the TACT corridor (one paper), and the deep crustal structure of Arctic Alaska based on seismic reflection/refraction data (two papers). Geologic studies have succeeded in refining structural models of the upper crust of the Brooks Range and have provided constraints on the tectonic evolution of the orogen. Interpretations of the new seismic reflection/refraction data provide geophysical cross sections of the deep structure of the Brooks Range and adjacent regions to a depth of more than 50 km.

Geologic and Deformational History

A comprehensive overview of the new data acquired by the TACT project on the lithology, age, and structural relations across the Brooks Range orogen is given by *Moore et al.* [this issue (a)]. They provide new interpretations of the nature of the contact between allochthonous and parauthochthonous rocks in the northern part of the transect, the relation of the metamorphic core to the fold and thrust belt, the protolith ages and stratigraphy of metamorphic rocks in the southern part of the orogen, and the structures that characterize the boundary of the orogen with its hinterland and foreland. On the basis of these, and other new data presented in this issue, a significantly revised model [*Moore et al.*, this issue (a), Figure 21) for the evolution of the Brooks Range orogen is proposed in which deformation in the Brooks Range was characterized by thin-skinned, shallow level deformation during Early Cretaceous time and thick-skinned, basement-involved deformation during Late Cretaceous and Tertiary time. A zone of down-to-the-south ductile and brittle normal faulting along the southern margin of the Brooks Range is best explained by mid-Cretaceous extension following the Early Cretaceous contractional deformation.

New conodont and U-Pb ages from schistose metasedimentary rocks in the Coldfoot terrane of the southern Brooks Range suggest to *Moore, Aleinikoff, and Harris* [this issue (b)] an Early Devonian (and younger?) age for large parts of the schist, instead of the Precambrian and early Paleozoic ages inferred by previous workers. This age revision has major implications for tectonic restorations of the Coldfoot terrane, because rather than constituting the oldest rocks exposed in the Brooks Range as previously thought, the rocks of the terrane are partly or wholly coeval with rocks of the Hammond, Endicott Mountains, and De Long Mountains terranes to the north. These new data require significant revision in structural restorations of all the coeval terranes as shown by *Moore et al.* [this issue (b), Figure 8]. However, unresolved difficulties exist in restorations of the penetratively deformed high-grade metamorphic rocks of the Coldfoot terrane with respect to rocks in the partly coeval terranes to the north, which remained at structurally high levels and are relatively unmetamorphosed. The new data also highlight the problem of what constitutes basement to the southern Brooks Range terranes, an issue that is critical to constructing balanced structure sections across the Brooks Range.

Within the Endicott Mountains terrane (allochthon), detailed biostratigraphic and lithofacies reconstructions by *Dumoulin et al.* [this issue] for the Carboniferous sequence (Lisburne Group) and by *Adams et al.* [this issue] for the Permian sequence provide new data on the nature and amount of structural deformation within the terrane. The data indicate to Dumoulin et al. that considerable tectonic shortening has occurred both within the Endicott Mountains terrane and that structural deformation has caused abrupt shifts in age and lithofacies of Carboniferous strata between the TACT corridor and the part of the Brooks Range to the northeast (De Long Mountains). Adams et al. interpret juxtaposed Permian lithofacies to indicate at least 80 km of tectonic shortening between

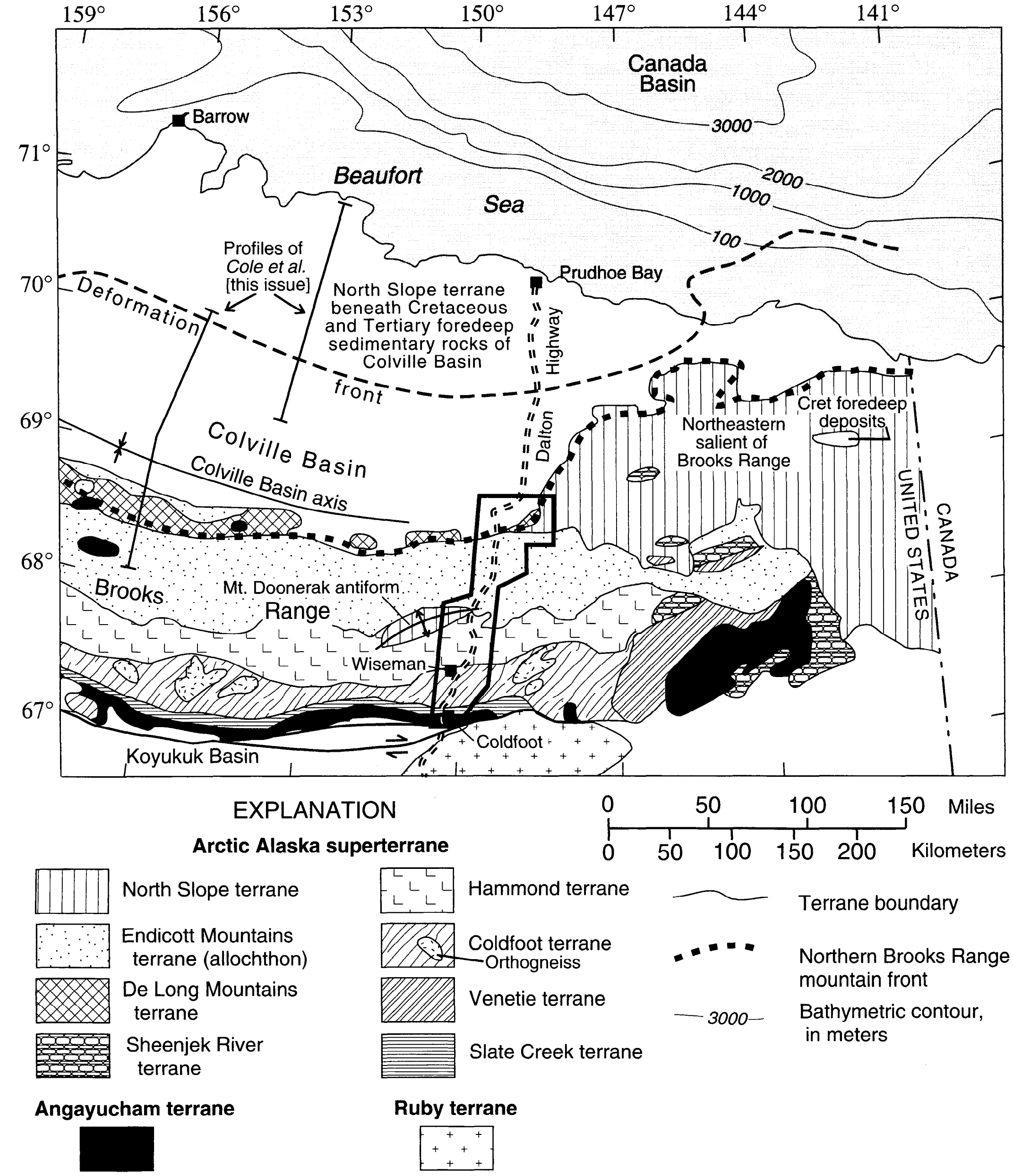

Figure 2. Part of Arctic Alaska showing TACT geologic mapping in the Brooks Range (outlined by heavy solid line) and the Dalton Highway (double dashed lines), which is the approximate route of the seismic reflection/refraction profile. This segment of the transect examined the evolution of the Brooks Range orogen and adjacent regions of the Koyukuk basin to the south and the North Slope terrane and Colville basin to the north. Figure modified from *Moore et al.* [this issue (a)].

the southern and northern margins of the Endicott Mountains terrane along the transect. Although Dumoulin et al. interpret Carboniferous facies relations of dominantly carbonate rocks to favor tectonic restoration of the allochthonous Endicott Mountains terrane north of coeval strata in the Mount Doonerak antiform, the Permian data of Adams et al., together with interpretations of facies relations in the Upper Devonian Kanayut clastic sequence [*Nilsen*, 1981] and Triassic strata [*Mull et al.*, 1989], are most compatible with restoration to a position south of the Mount Doonerak area.

Detailed studies of the complex structures and distribution of lithologic units within the Endicott Mountains terrane (allochthon) suggest to *Wallace et al.* [this issue] that (1) the Endicott Mountains terrane consists of a northward tapered wedge of multistoried duplexes in which the rocks young from south to north; (2) a basal detachment thrust fault separates the Endicott Mountains structural wedge from an underlying wedge of multistory duplex rocks of the parautochthonous North Slope terrane; and (3) Colville basin foredeep deposits have not been thrust significant distances beneath the mountain front. These interpretations provide critical constraints on the deep structure of the Brooks Range and on evaluation of the petroleum potential of the southern Colville basin and northern Brooks Range.

Stratigraphic, structural, seismic, drill hole, fission track, and thermal data were used to interpret the tectonic evolution of the northern Brooks Range front and adjacent Colville basin along the TACT corridor [*Mull et al.*, this issue] and along a traverse 250 km to the west [*Cole et al.*, this issue]. The data along the transect document three significant events: (1) major post-Valanginian to Aptian northward vergent deformation and >300 km of crustal shortening of the Endicott Mountains terrane; (2) onset of the main phase of clastic sedimentation in the Colville foredeep from Aptian through Late Cretaceous time; and (3) renewed uplift, folding, warping, and backthrusting in the northern Brooks Range and southern Colville basin in Late Cretaceous to early Tertiary time. Because range-front thrusting ended before the main phase of Cretaceous sedimentation in the foreland basin, Mull et al. suggest that previous interpretations of large-scale underthrusting of Albian and younger rocks of the Colville basin beneath the northern front of the Brooks Range along the transect or anywhere in the central Brooks Range are probably incorrect. Farther west, the data of Cole et al. suggest that initiation of deposition in the Colville basin may have been as early as Barremian and that multistory duplex stacks of Carboniferous to Neocomian strata (Endicott Mountains and De Long Mountains terranes) are located both along the mountain front and as a major northward tapering wedge in the subsurface north of the front. The structural model presented by *Cole et al.* [this issue, Plate 2] differs from the transect area in that seismic reflection data indicate that a thick Barremian to Albian basinal sequence has underthrust ~20 km southward beneath strata of the Endicott Mountains and De Long Mountains terranes. If correct, this interpretation suggests a change in the style of range-front deformation west of the TACT line, a change that could be explained by differences in the stratigraphy and/or the amount of Late Cretaceous and Tertiary contraction in the two areas.

Interpretations of fission track data on apatite from surface rocks in the Brooks Range and Colville basin along the transect and adjacent regions by *O'Sullivan et al.* [this issue] provide new constraints on the timing and amount of rapid episodic uplift resulting from tectonic deformation. At least three, and possibly five, such uplift events are inferred in the northern Brooks Range from middle Cretaceous to Miocene time (~100 ± 5 Ma, ~60 ± 4 Ma, ~24 ± 3 Ma), whereas in the southern half of the Colville basin there were at least four uplift events from early Paleocene to Miocene time (~60 ± 4 Ma, ~46 ± 3 Ma, ~35 ± 2 Ma, ~24 ± 3 Ma). The fission track analysis indicates that individual events probably result from erosion of the order of 2–5 km during 3–5 Myr intervals. These data are significant in that they indicate that episodic contraction persisted into the late Tertiary in the Brooks Range and North Slope.

Deep Crustal Structure

Seismic reflection/refraction data provide an image of the principal structures beneath Arctic Alaska to depths as great as 65 km. The data provide new evidence for southward wedging of the crust and uppermost mantle of the North Slope into the crust and uppermost mantle of the Brooks Range [*Wissinger et al.*, this issue; *Fuis et al.*, this issue] and also northward wedging of continental crust (Ruby terrane?) into the crust of the southern Brooks Range [*Fuis et al.*, this issue]. Structures imaged include (1) gently to moderately dipping detachment thrust faults in the upper crust within and between major allochthons, (2) northward tapering wedges of imbricated strata of the Endicott Mountains and De Long Mountains terranes overlying parauthochthonous strata of the North Slope terrane in the northern Brooks Range and southern Colville basin, (3) antiformal structures that extend to a depth of at least 10 km beneath the Mount Doonerak antiform (window), which in turn are underlain by duplex structures within a south dipping slab of imbricated Franklinian sequence (North Slope terrane) that extend down to a south dipping basal decollement in the midcrust, (4) a thick, southward tapering underthrust wedge consisting of North Slope crust and mantle beneath a basal decollement that dips gently southward from 10 km depth near the northern front of the Brooks Range to 30 km in the southern Brooks Range [*Wissinger et al.*, this issue; *Fuis et al.*, this issue] beneath the south front of the range, (5) a thick northward tapering structural wedge of probable continental crust (Ruby terrane?) that occurs beneath the Koyukuk basin and southern Brooks Range, (6) a Moho that is depressed to ~50 km depth beneath the highest part of the Brooks Range, and (7) prominant reflectors that occur locally beneath the Moho in the northern Brooks Range.

Overview of New Results

TACT-related studies reported in this special section have made important contributions to understanding of the tectonic evolution of rocks and structures now exposed at the surface in the Brooks Range and adjacent region. Two long-lived periods of contractional deformation are suggested by the data. The first resulted from collision between the southern margin of Arctic Alaska and an oceanic arc (Koyukuk arc) during latest Jurassic and Early Cretaceous time. The second was intracontinental deformation that was probably driven by plate subduction and terrane accretion along the south margin of Alaska during Paleocene through Miocene time.

The earlier deformation resulted in upper crustal thin-skinned deformation of the order of hundreds of kilometers across the Brooks Range and the southern part of the North Slope terrane. Coeval intense deformation and metamorphism also affected the leading, southern edge of Arctic Alaska (Slate Creek, Coldfoot, and southern Hammond terranes) due to partial subduction beneath the oceanic crust (Angayuchum terrane) that lay between the arc and the Arctic Alaska superterrane. An important finding is that although this collision caused large-scale north vergent thrusting along the northern front of the Brooks Range, it did not result in significant underthrusting of Cretaceous strata in the Colville basin in the vicinity of the transect. Thus the structural style and petroleum potential of the northern front of the Brooks Range differs fundamentally from that of the Rocky Mountains overthrust belt in Canada and the conterminous United States to which it has frequently been compared.

The later deformation, the main phase of which roughly coincides with the Laramide orogeny of the southern Rocky Mountains, was a thick-skinned shortening that is indicated by episodic uplift in Arctic Alaska [*O'Sullivan et al.*, this issue] and by folding and uplift of post-mid-Cretaceous strata in the Colville basin. Evidence that at least local contractional deformation continues to the present in parts of northern Alaska includes folding of Quaternary strata and low-level shallow seismicity [*Grantz et al.*, 1994]. The Cenozoic deformation undoubtedly is an indication of ongoing deeper level deformation within the crust of Arctic Alaska that is probably responsible for the present physiographic expression of the Brooks Range.

Two alternative interpretations for the deep crustal structure and tectonics of Arctic Alaska are presented here. *Fuis et* *al.* [this issue] suggest that a southward verging North Slope plate wedges between the crust and uppermost mantle (i.e., wedge tip at the Moho) in the southern Brooks Range as a rigid indentor. Crustal thickening and uplift of the Brooks Range is thus accomplished by whole-crustal wedge tectonics. In the model of *Wissinger et al.* [this issue] the tip of the wedge is localized between the middle and lower crust of the southern Brooks Range, implying that the lower crust of the Brooks Range is underthrust northward beneath the North Slope in a manner analogous to the European lower crust of the Alps [*Pfiffner et al.*, 1990; *Mooney et al.*, 1992].

Fuis et al. [this issue] compare late-stage wedge tectonics of the Brooks Range with the European Alps. In both cases a small wedge of continental crust (North Slope and Adriatic) splits the lithosphere of a larger continental mass (Arctic Alaska and European continent) into two pieces, an upper deforming crust and an underthrusting lower crust and mantle. In northern Alaska, only mantle is underthrust beneath the North Slope wedge; in the European Alps, both the lower crust and mantle extend beneath the Adriatic wedge.

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