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# GEOLOGY OF WEST-CENTRAL ALASKA

By

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T.P. Miller

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## INTRODUCTION

West-central Alaska includes a broad area that stretches from the Bering and Chukchi seacoasts on the west to the upper Yukon-Tanana Rivers region on the east, and from the Brooks Range on the north to the Yukon-Kuskokwim delta on the south. It covers 275,000 km$^2$, nearly one-fifth of the entire state, and all or parts of 29 1:250,000 scale quadrangles (Fig. 1).

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Fig 1 near here

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Rolling hills with summit altitudes between 300 and 1,000 m and isolated mountain ranges that rise to a maximum altitude of 1,500 m characterize the area (Wahrhaftig, 1965). The uplands are separated by broad alluviated coastal and interior lowlands that stand less than 200 m above sea level. Bedrock exposures are generally limited to elevations above 500 m and to cutbanks along the streams.

The bedrock underlying this huge area consists of six pre-mid-Cretaceous lithotectonic terranes which were assembled by Early Cretaceous time and were subsequently overlapped by mid- and Upper Cretaceous terrigenous sediments (Figs. 2, 3) (Jones and others, 1987; Silberling and others, in press). The bedrock in the east-central part is composed of lower Paleozoic sedimentary rocks and Precambrian metamorphic rocks that belong to the Nixon Fork and Minchumina terranes. A broad mid-Cretaceous uplift--the Ruby geanticline (Fig. 4)--borders the Nixon Fork terrane on the northwest and extends diagonally across the area from the eastern Brooks Range to the lower Yukon River valley. The core of the geanticline consists of the Ruby terrane, an assemblage of Precambrian(?) and Paleozoic continental rocks that was metamorphosed to greenschist, blueschist, and amphibolite facies in late Mesozoic time. Structurally overlying the Ruby terrane are allochthonous masses of upper Paleozoic and lower Mesozoic oceanic rocks variously assigned to the Angayucham, Tozitna, and Innoko terranes. The Yukon-Koyukuk basin is a large wedge-shaped depression filled with mid- and Upper Cretaceous terrigenous sedimentary rocks that extends from the Ruby geanticline westward to the Seward Peninsula and Bering and Chukchi seacoasts (Fig. 4). Lower Cretaceous island arc-type volcanic rocks of the Koyukuk terrane are exposed on structural highs within the basin. Large mid- and Late Cretaceous granitoid bodies intrude the northern part of the Yukon-Koyukuk basin and the Ruby geanticline; Upper Cretaceous and lower Tertiary calc-alkalic volcanic rocks are widely distributed over all but the northwestern part of the area. Continental flood basalts of late Cenozoic age overlap the west edge of the Yukon-Koyukuk basin along the boundary with the Seward Peninsula and the Bering and Chukchi seacoasts.

All pre-uppermost Cretaceous rocks in the area are tightly folded and broken by high-angle faults (Fig. 5). Uppermost Cretaceous and lowermost Tertiary rocks are broadly folded and cut by high-angle faults; those of Eocene and younger age are virtually undisturbed. The area is transected by three major east- and northeast-trending fault systems: the Kobuk, Kaltag, and Nixon Fork-Iditarod (Fig. 4). All three systems are believed to have had large-scale strike-slip movement in Late Cretaceous and early Tertiary time but the amount and direction of movement is well-documented only for the Kaltag fault (Patton and Tailleur, 1977; Patton and others, 1984).

Geographic localities mentioned in this report are referred to the U.S. Geological Survey Alaska Topographic Series 1:250,000 scale maps shown in Fig. 1. The reader will need to consult these topographic maps in order to locate specific geographic features.

## PRE-MID-CRETACEOUS LITHOTECTONIC TERRANES

### Minchumina terrane

**Definition and distribution**

The Minchumina terrane (Jones and others, 1987; Silberling and others, in press) consists of a northeast-trending belt of thin-bedded limestone, chert, argillite, and quartzite of Precambrian(?) and early Paleozoic age that extends for a distance of nearly 300 km from the southern part of the Medfra quadrangle to the northeastern part of the Kantishna River quadrangle (Figs. 1, 2 and 3). This belt of sparsely exposed bedrock underlies the Tanana-Kuskokwim lowland and

Figs. 2 & 3 near here

adjoining parts of the Kuskokwim Mountains (Wahrhaftig, 1965). Within the belt we recognize two subterranes--the Telida subterrane, which extends the entire length of the belt, and the East Fork subterrane, which is confined to the south-central part of the Medfra quadrangle (Patton and others, 1980; Fig. 3).

**Description**

*Telida subterrane* - The stratigraphic sequence that makes up the Telida subterrane has been pieced together from a study of widely scattered exposures in the Medfra quadrangle (Patton and others, 1980), the Kantishna River quadrangle (Chapman and Yeend, 1981; Chapman and others, 1975) and the northwestern part of the Mt. McKinley quadrangle (Chapman and others, 1981). Four separate lithologic units are recognized, but owing to lack of continuous exposures, their stratigraphic relations are uncertain. The following sequence, in ascending stratigraphic order, is based on regional structural relations and a few fossil collections:

1) The limestone and phyllite unit consists of impure limestone and dolomite, green-gray phyllite, and argillite. Probably pre-Ordovician in age.

2) The argillite and quartzite unit consists of slaty argillite, quartzite, quartz and quartz-feldspar grit, calcareous argillite, and chert. Contains Ordovician corals and graptolites and may include pre-Ordovician rocks in lower part.

3) The chert and argillite unit consists of dark gray to black chert, argillite, shaly limestone, and siliceous siltstone. It contains Ordovician graptolites and early Paleozoic radiolarians.

4) The limestone unit consists of reefal and algal limestone bodies containing Middle to Late Devonian corals.

*East Fork subterrane* - The East Fork subterrane (Fig. 3) occupies a small wedge-shaped area in the Tanana-Kuskokwim lowland between the Telida subterrane and the Nixon Fork terrane in the south-central part of the Medfra quadrangle. This subterrane consists entirely of the East Fork Hills Formation (Dutro and Patton, 1982)--a succession of alternating thin beds of limestone and orange-weathering dolomite that is locally sheared and foliated. Laminated dolomite, dark chert, and siliceous siltstone occur in subordinate amounts. Owing to the lack of good exposures and to the structural complexity of this formation, no estimate of total thickness is possible. The formation has been assigned an Early Ordovician to Middle Devonian age based on scattered conodont collections (Dutro and Patton, 1982).

The East Fork subterrane is juxtaposed with the Nixon Fork terrane along a northeast-trending fault that appears to be a strand of the Nixon Fork-Iditarod fault system (Dutro and Patton, 1982) (Fig. 5, D-D'). The East Fork subterrane is cut off on the southeast by the more north trending Telida subterrane. The contact between the two subterranes is not exposed, but the divergence in their regional trends suggests that the contact is faulted

**Interpretation and correlation** -

The Minchumina terrane is composed chiefly of deep-water deposits, which we interpret to be a continental-margin facies that is coeval, at least in part, with the lower Paleozoic platform carbonate rocks of the Nixon Fork terrane. The reefy algal limestones of Middle and Late Devonian age (unit 4) that cap the Telida subterrane represent a southeastward progradation (relative to their present orientation) of the shallow-water beds across the older deep-water deposits.

The Minchumina terrane appears to be part of an extensive, but discontinuous belt of deep-water Precambrian(?) and lower Paleozoic deposits that can be traced northeastward from the western part of the Alaska Range in the McGrath quadrangle, through the Tanana-Kuskokwim lowland at least as far as the Livengood quadrangle. This belt includes such deep-water assemblages as the Dillinger assemblage in the Alaska Range (Bundtzen and others, 1985), the Nilkoka Group along the lower Tanana River (Pe'we' and others, 1966), and the Livengood Dome Chert (Chapman and others, 1980) in the Livengood quadrangle. In southwestern Alaska, Decker and others (in press) include the Minchumina terrane in the White Mountain sequence of the Farewell terrane.

## Nixon Fork terrane

**Definition and distribution**

The Nixon Fork terrane (Jones and others, 1987; Silberling and others, in press) is composed of three stratigraphic packages separated by major unconformities: 1) a Precambrian metamorphic basement, 2) a thick lower Paleozoic platform carbonate sequence, and 3) a thin upper Paleozoic and

Mesozoic terrigenous clastic sequence (Fig. 2; Patton and others, 1980). The terrane extends for 500 km from the Holitna lowland in the Lime Hills quadrangle of southwest Alaska to the Nowitna lowland in the Ruby and Kantishna River quadrangles of west-central Alaska. It is bounded on the northwest by the Innoko terrane along the Susulatna lineament--a conspicuous topographic alignment of stream valleys interpreted to be a major fault zone (Patton, 1978) (Fig. 5, D-D'). On the southeast it adjoins the Minchumina terrane along a strand of the Nixon Fork-Iditarod fault system.The area described in this report (Fig. 3) covers the northern 300 km of the terrane and includes the best exposures of the three packages. The southwestern part of this terrane is described by Decker and others (in press).

**Description**

*Precambrian metamorphic rocks* - The lowest stratigraphic package consists of a greenschist metamorphic facies assemblage of pelitic and calc schists, greenstone and minor felsic metaplutonic rocks locally capped by felsic metavolcanic rocks (Patton and others, 1980). This assemblage is poorly exposed along the northwest side of the Nixon Fork terrane and dips southeastward beneath the lower Paleozoic carbonate rocks (Fig. 5, D-D'). Potassium-argon mineral-separate ages from this assemblage range from 921 to 296 Ma (Silberman and others, 1979; Dillon and others, 1985). Metaplutonic rocks from the lower part yielded a U-Pb zircon age of 1,265±50 Ma and metavolcanic rocks from the top yielded a U-Pb zircon age of 850±30 Ma (Dillon and others, 1985).

*Lower Paleozoic carbonate rocks* - The middle stratigraphic package is composed of four platform carbonate formations that have an aggregate thickness of more than 5,000 m and an age range of Early Ordovician to Late Devonian (Dutro and Patton, 1982). The Novi Mountain Formation--the oldest of the four--consists of about 900 m of cyclically interbedded shallow-water to supratidal silty to micritic limestone and calcareous siltstone of Early Ordovician age. This sequence is overlain by the Telsitna Formation, a 2,000 m-thick sequence of abundantly fossiliferous, shallow-water, limestone and dolomite of Middle and Late Ordovician age. Unconformably(?) above the Telsitna Formation is the Paradise Fork Formation, a 1,000 m-thick deeper-water assemblage of graptolite-bearing, dark, thin-bedded limestone and shale of Early to Late Silurian age (Dutro and Patton, 1982). At the top is the Whirlwind Creek Formation, a Late Silurian to Late Devonian sequence of shallow-water limestone and dolomite, 1,000 to 1,500 m thick.

*Upper Paleozoic and Mesozoic clastic rocks* - The highest stratigraphic package consists of Permian to Lower Cretaceous terrigenous, shallow-marine sedimentary rocks, which unconformably overlie both the lower Paleozoic platform carbonate rocks and the Precambrian basement rocks. These beds are composed largely of quartz and carbonate debris eroded from the underlying carbonate and metamorphic assemblages. The total thickness of this succession probably does not exceed 1,000 m. The lowest strata are composed of quartz-carbonate sandstone and siltstone of early Late Permian age. Locally, where these strata rest directly on the metamorphic basement, they contain a coarse basal conglomerate consisting of large angular blocks of pelitic schist and greenstone set in a quartz-carbonate sandstone matrix (Patton and Dutro, 1979). The Permian strata are disconformably overlain by an Upper Triassic sequence composed of quartz-carbonate sandstone and conglomerate in the lower part, and dark spiculitic chert in the upper part. The Triassic beds in turn are disconformably overlain by Lower Cretaceous quartz-carbonate clastic rocks and pebbly mudstones that range in age from Valanginian at the base to Aptian at the top. No strata of Jurassic age have been identified in the Nixon Fork terrane.

**Interpretation and correlation**

The tectonic affinities and paleogeography of the Nixon Fork terrane are not clear. Most workers agree that the Minchumina terrane and other lower Paleozoic deep-water assemblages, such as the Dillinger and Livengood terranes, represent a seaward "shale-out" of the platform carbonate rocks of the Nixon Fork terrane similar to that found along the early Paleozoic continental margin in the Canadian Cordillera (Churkin and Carter, 1979). However, the Nixon Fork terrane is not flanked on the opposite side by cratonic assemblages similar to those that lie along the inner margin of the Canadian Cordillera.

The paleontologic and paleomagnetic evidence bearing upon the biostratigraphic and tectonic affinities of the lower Paleozoic platform carbonate rocks of the Nixon Fork terrane is conflicting and controversial. Blodgett (1983) and Potter and others (1980), for example, argue that the Nixon Fork terrane has North American affinities, as indicated by the Devonian ostracod, brachiopod, gastropod, and trilobite fauna and the Middle and Late Ordovician brachiopod fauna. Palmer and others (1985), on the other hand, contend that the Nixon Fork terrane has Siberian platform affinities based on Middle Cambrian trilobites recently found in the Nixon Fork terrane southwest of the area covered by this chapter. Paleomagnetic studies by Plumley and others (1981) indicate that the Ordovician carbonate rocks of the Nixon Fork terrane have been displaced no more than 10° northward relative to the Ordovician pole position of the North American craton, but have been rotated clockwise about 70° prior to late Mesozoic time. Plumley and Coe (1982) proposed that the Nixon Fork terrane is "a section of the Canadian Cordillera" that rotated clockwise to its present position. A difficulty with this model, however, is that the present southeastward direction of shale-out of the Nixon Fork platform carbonate deposits is opposite that which would be expected if the west-facing early Paleozoic continental margin of the Canadian Cordillera were rotated 70° clockwise. Churkin and others (1984) suggested the poss ibility that the Nixon Fork terrane represents a fragment of the Cassiar platform--an outboard ridge of lower Paleozoic platform carbonate rocks in the central Canadian Cordillera that shales out eastward into deeper water deposits of the Selwyn basin.

Decker and others (in press) favor a stablistic model for the origin of the Precambrian and lower Paleozoic part of the Nixon Fork and Minchumina terranes (which they lump together in the White Mountain sequence of the Farewell Terrane). They argue that these terranes were "part of a coherent Paleozoic passive continental margin which lay upon a Precambrian continental crystalline basement to form a southwesterly-directed peninsular extension of the Paleozoic North America continent". In support of this model, they point out similarities between the major lithostratigraphic units of the Nixon Fork and Minchumina terranes with coeval rocks in northwestern Canada. A problem with this model, however, is that, although there are many similarities between the lower Paleozoic platform carbonate rocks in the two areas, the underlying Precambrian rocks are quite different. Unlike the Nixon Fork terrane, the Canadian succession does not record a major regional metamorphic event in Late Proterozoic or earliest Paleozoic time. Furthermore, the absence of a transitional facies between the fault-bounded blocks of the Nixon Fork terrane and the Telida and East Fork subterranes is an argument against their being a single coherent terrane.

We suggest that these terranes and subterranes represent an assemblage of small fault slices transported to their present positions from the North American (or Siberian?) continental margin along transform strike-slip faults. The paleomagnetic evidence for 70° of clockwise rotation of the Nixon Fork terrane may be the result of local rotation during tectonic transport of the fault slice that was sampled, rather than rotation of the entire continental margin.

## Innoko terrane

### Definition and distribution

The Innoko terrane (Jones and others, 1987; Silberling and others, in press) consists of a poorly exposed sequence of radiolarian chert and andesitic volcaniclastic rocks ranging in age from Late Devonian to Early Cretaceous (Fig. 2). This assemblage of oceanic and volcanic-arc rocks extends from near Poorman in the Ruby quadrangle, 250 km southwestward, to near Flat in the Iditarod quadrangle (Fig. 3). The best exposures are in the northwestern part of the Medfra quadrangle (Patton and others, 1980) and in the eastern part of the Ophir quadrangle (Chapman and others, 1985), but even in those areas outcrops are limited to scattered small knobs and pinnacles along ridgetops and to a few stream banks. On the southeast side, the Innoko terrane is faulted against the Nixon Fork terrane and against the mid-Cretaceous sedimentary rocks of the Kuskokwim basin along the Susulatna lineament (Patton, 1978). On the northwest side, the contact with the Ruby and Tozitna terranes is generally covered by Quaternary alluvial deposits and Late Cretaceous to early Tertiary volcanic fields, but regional relationships suggest that it is faulted. In the Iditarod quadrangle the Innoko terrane narrows to less than 15 km in width, and, at the southwest end near Flat, it appears to be overlapped by Upper Cretaceous and lower Tertiary volcanic rocks (M. L. Miller, oral commun, 1986).

Precambrian(?) and Paleozoic rocks, consisting chiefly of pelitic schist, carbonate rocks, and greenstone of greenschist metamorphic facies, are exposed in several structural windows beneath the Innoko terrane (Chapman and others, 1985). They are believed to be part of the Ruby terrane, which has been overridden by the Innoko along a low-angle thrust (Patton and Moll, 1982) (Fig. 5, D-D').

Large mafic-ultramafic complexes overlie the Innoko terrane at Mount Hurst in the southern Ophir quadrangle and on strike to the southwest along the upper Dishna River in the Iditarod quadrangle (Patton and others, in press; Miller and Angeloni, 1985). These ophiolite assemblages appear to be allochthonous with respect to the Innoko terrane and locally overlap onto the structural windows of the Ruby terrane. The origin of these bodies is uncertain--possibly they represent remnants of the mafic-ultramafic complex that makes up the Kanuti thrust panel of the composite Angayucham-Tozitna terrane (Fig. 2).

### Description

Two different rock assemblages (not shown separately on Fig. 3) are recognizable in the Innoko terrane: 1) an oceanic assemblage of radiolarian chert with minor carbonate rocks, basalt, and gabbro; and 2) a volcanic arc-like assemblage of volcaniclastic rocks, cherty tuff, volcanic graywacke, argillite, and diabase and gabbro intrusive rocks. Cherts in the oceanic assemblage yield radiolarians of Late Devonian(?), Mississippian, Pennsylvanian, Permian, and Triassic age. The carbonate rocks, which occur as turbidites intercalated with the chert, contain reworked foraminifers and conodonts ranging in age from Late Devonian to Late Mississippian. The cherty tuff in the arc assemblage has yielded Triassic and Early Jurassic(?) radiolarians and Triassic conodonts, and the volcanic graywacke in the upper part of the arc assemblage contains fragments of Inoceramus of Early Cretaceous(?) age. Field relations suggest that the arc assemblage overlies the oceanic assemblage, but the possibility that the two have been juxtaposed by thrust faulting cannot be ruled out.

**Interpretation and correlation**

The Innoko terrane is treated here as a single coherent sequence but may, in fact, represent two unrelated assemblages that have been juxtaposed by thrust faulting. The lower radiolarian chert oceanic assemblage correlates closely in age and lithology with chert assemblages in the Narvak thrust panel of the Angayucham-Tozitna terrane and may be an eastward extension of a part of that terrane. The thick volcanic arc-like assemblage in the upper part of the Innoko terrane has no counterpart in the Angayucham-Tozitna terrane, but a similar Triassic to Lower Cretaceous arc assemblage has been described in the Togiak terrane, which lies roughly on strike to the southwest in the lower Kuskokwim River region (Jones and others, 1987; Silberling and others, in press; Decker and others, in press). It is possible that the Innoko and Togiak terranes are coextensive, and lie beneath a cover of overlapping Upper Cretaceous and Tertiary sedimentary and volcanic rocks in the southern Iditarod and northern Sleetmute quadrangles (Fig. 1).

## Ruby terrane

**Definition and distribution**

The Ruby terrane (Jones and others, 1987; Silberling and others, in press) consists of a Precambrian(?) and Paleozoic assemblage of pelitic schist, quartzite, greenschist, orthogneiss, and marble (Fig. 2). It forms the metamorphic core of the Ruby geanticline--a pre-mid-Cretaceous uplift that trends diagonally across central Alaska along the southeast side of the Yukon-Koyukuk basin (Figs. 3 and 4). At its northeast end, the Ruby terrane is cut off by the Kobuk fault--a probable strike-slip fault that bounds the south edge of the Brooks Range.

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Fig. 4 near here

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The Ruby terrane extends southwestward from the Brooks Range to the Yukon River where it is offset right laterally about 160 km by the Kaltag fault (Patton and others, 1984). South of the fault, it continues through the Kaiyuh Mountains in the Nulato quadrangle and at least as far south as the Innoko River in the Ophir quadrangle (Figs. 1 and 3). The extent of the Ruby terrane south of the Innoko River is uncertain because of the lack of bedrock exposures in the Innoko Lowlands. Recent mapping (Angeloni and Miller, 1985) shows that similar rocks of greenschist metamorphic facies extend at least as far south as the north-central part of the Iditarod quadrangle. However, an assemblage of amphibolite-grade augen gneiss, amphibolite, and pelitic schist (assigned to the Idono sequence) is also found along the same structural trend but does not have a counterpart in the Ruby terrane (Miller and Bundtzen, 1985; Angeloni and Miller, 1985). These higher grade rocks may correlate with the Kilbuck terrane of southwestern Alaska, which is described by Decker and others (in press). A small area of metamorphic rocks on the lower Yukon River in the Russian Mission quadrangle, shown as Ruby terrane on the lithotectonic terrane map by Jones and others (1987), appears to be composed chiefly of metabasites and is interpreted by us to be Angayucham-Tozitna or possibly Innoko terrane (Fig. 3).

The Ruby terrane is bordered along the northwest side by a narrow band of rocks belonging to the Angayucham-Tozitna terrane, which rests in thrust contact on the Ruby terrane and dips northwestward beneath the mid-Cretaceous sedimentary rocks of the Yukon-Koyukuk basin (Fig. 5, B-B', C-C'). On the southeast side, it is bordered by several large allochthonous masses of Angayucham-Tozitna and Innoko terranes and by the Quaternary deposits of the Yukon Flats and Nowitna Lowland (Fig. 3; Wahrhaftig, 1965).

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Fig. 5 near here

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**Description**

The Ruby terrane is characterized by regionally metamorphosed greenschist facies metasedimentary rocks and metabasites of Precambrian(?) and Paleozoic age. Locally it also includes high-pressure greenschist facies assemblages, which are distinguished by the presence of glaucophane; and amphibolite facies assemblages, which are distinguished by the presence of sillimanite and kyanite. Typical rock types include quartz-mica schist, quartzite, calcareous schist, mafic greenschist, quartzofeldspathic schist and gneiss, metabasite, and marble. Potassium-argon dating and geological relations indicate that regional metamorphism occurred in Late Jurassic to Early Cretaceous time, probably during tectonic emplacement of the allochthonous oceanic rocks of the Angayucham-Tozitna terrane (Turner, 1984; Patton and others, 1984). Subsequently, both the metamorphic rocks of the Ruby terrane and the Angayucham-Tozitna terrane were widely intruded by mid-Cretaceous granitic plutons and extensively altered to andalusite-cordierite hornfels, hornblende hornfels, and contact marbles.

Dusel-Bacon and others (written commun., 1987) have summarized common mineral assemblages for the intermediate and high pressure greenschist facies and for the amphibolite facies in the Ruby terrane as follows:

Intermediate pressure greenschist facies:

Pelitic schists: quartz+white mica+chloritoid+chlorite±epidote, calcite, and sphene. Quartz+white mica±epidote, calcite, and biotite.

Metabasites: Epidote+actinolite+chlorite±zoisite, biotite, sphene, and quartz.

High pressure greenschist facies:

Pelitic schists: Glaucophane+white mica+garnet+chlorite+ chloritoid+ quartz. Glaucophane+white mica+calcite+

Metabasites: Albite+chlorite+actinolite+epidote group minerals±calcite and sphene. Chlorite+epidote+ sphene+plagioclase±white mica and glaucophane

Amphibolite facies:

Pelitic schists: Quartz+muscovite+biotite+staurolite+garnet. Quartz+muscovite+biotite+garnet. Kyanite+sillimanite+biotite+ quartz+potash feldspar.

In the Tanana quadrangle Dover and Miyaoka (1985) recognized polymetamorphism in which "low P/T amphibolite facies assemblages ($M_1$) formed during main-phase isoclinal folding ($F_1$); $M_1$ minerals occur as relics in rocks later subjected to a cataclastic ($F_2$), low-grade, retrogressive event ($M_2$)". Polymetamorphism has not been documented elsewhere, however, and as pointed out by Dusel-Bacon and others (written commun., 1987) it is uncertain if it has affected all parts of the Ruby terrane. High-pressure assemblages, indicated by the presence of glaucophane, have been identified in the Kaiyuh Mountains of the Nulato quadrangle (Patton and others, 1984; Forbes and others, 1971; Mertie, 1937), in the Kokrines Hills of the Melozitna and Tanana quadrangles (Patton and others, 1978; Chapman and others, 1982), and at a single locality on the north side of the Ray Mountains in the Tanana quadrangle (Dover and Miyaoka, 1985). Amphibolite facies assemblages have been reported in the Melozitna and Ruby quadrangles (Patton and others, 1978; Smith and Puchner, 1985), in the Tanana quadrangle (Dover and Miyaoka, 1985), and in the Beaver quadrangle (Brosge' and others, 1973).

**Protolith age**

The metamorphic rocks of the Ruby terrane are tentatively assigned an early and middle Paleozoic protolith age, as indicated by scattered fossil and radiometric ages and upon the gross lithologic similarities of these rocks to the better dated metamorphic assemblages in the southern Brooks Range (Arctic Alaska terrane). Fossils have been found in carbonate layers at three widely scattered localities: 1) early Middle Ordovician conodonts from near Illinois Creek in the Nulato quadrangle (A.G. Harris, written commun., 1984), 2) Middle Devonian conodonts from near Wolf Creek in the Melozitna quadrangle (A.G. Harris, written commun., 1983), and 3), a Devonian coral from near Yuki Mountain in the Ruby quadrangle (Mertie and Harrington, 1924). A Devonian U/Pb zircon age was obtained from a granite gneiss in the Ray Mountains of the Tanana quadrangle (Patton and others, 1987).

Precambrian rocks have not been identified in the Ruby terrane, but the possibility that they are present cannot be ruled out, particularly among the vast tracts of poorly exposed pelitic schists and quartzites. Precambrian rocks have been reported in similar assemblages in the southern Brooks Range (Mayfield and others, 1983; Dillon and others, 1980).

**Age of metamorphism**

Regional metamorphism both in the Ruby terrane and in the southern Brooks Range (Arctic Alaska terrane) is thought to be related to arc collision and overthrusting or "obduction" of the Angayucham-Tozitna and Innoko terranes in latest Jurassic to Early Cretaceous time (Turner, 1984; Patton, 1984). Dover and Miyaoka (1985) point out evidence for polymetamorphism in the Ray Mountains, and it is possible that part or all of the Ruby terrane also underwent an earlier metamorphic event. The regional metamorphism clearly pre-dates the widespread intrusion of Early Cretaceous ( 110 Ma) granitic plutons and the deposition of upper Lower Cretaceous (Albian) marginal conglomerates of the Yukon-Koyukuk basin, which locally contain a significant component of metamorphic debris. Two metamorphic mineral K-Ar ages of 136 and 134 Ma from the Ruby terrane (Patton and others, 1984) and a large number of K-Ar ages ranging from 130 to 85 Ma from similar metamorphic rocks in the southern Brooks Range (Turner, 1984) probably represent cooling ages set during unroofing of the isostatically rebounding metamorphic terranes following overthrusting of the Angayucham-Tozitna terrane.

**Interpretations and correlations**

Early workers (Cady and others, 1955; Payne, 1955; Miller and others, 1959) viewed the Ruby terrane as a narrow mid-Cretaceous structural high or "geanticline" bordering the southeast flank of the Yukon-Koyukuk basin. The metamorphosed Precambrian(?) and Paleozoic rocks of the Ruby terrane were presumed to extend beneath the basin and to connect with rocks of similar age and metamorphic grade exposed in the southern Brooks Range and on the Seward Peninsula. However, subsequent investigations around the margins of the Yukon-Koyukuk basin showed that the relations between the metamorphic borderlands and the basin were much more complex than previously supposed. Recognition of inward-dipping ophiolite assemblages along the margins of the basin, and the presence of a voluminous island-arc volcanic assemblage (Koyukuk terrane) within the basin, led to the suspicion that the basin has an ensimatic basement (Patton, 1970). Recent isotopic and petrologic studies of mid- and Upper Cretaceous granitic plutons and of Upper Cretaceous and lower Tertiary volcanic rocks in the Ruby terrane and adjacent parts of the basin (Arth, 1985, and in press; Miller, 1985; Moll and Arth, 1985), and geophysical investigations along the margin of the Ruby terrane (Cady, 1985) suggest that the Precambrian(?) and Paleozoic ensialic rocks of the Ruby terrane do not extend beneath the basin.

The metamorphic assemblages of the Ruby terrane and the southern Brooks Range (Arctic Alaska terrane) are grossly similar and may be correlative. Protoliths of both terranes appear to have general lithologic similarities including early to middle Paleozoic carbonate rocks dated by fossils and Devonian granitic rocks dated by zircons. The metamorphic grade, the K-Ar ages of the metamorphic minerals, and the general structural setting (i.e., overthrusting by the Angayucham-Tozitna terrane) are also similar. Both terranes contain abundant metabasalt and metadiabase, but felsic metavolcanic rocks of middle Paleozoic age, which locally are abundant in the southern Brooks Range, have not been identified in the Ruby terrane and mid-Cretaceous granitic plutons, which are widespread in the Ruby terrane, are absent from the southern Brooks Range. The two terranes are juxtaposed at the northeast apex of the Yukon-Koyukuk basin along the Kobuk fault zone--an east-trending belt of strike-slip(?) faulting of post-mid-Cretaceous age that extends along the south margin of the Brooks Range from Kotzebue Sound to the Yukon Flats (Patton, 1973) (Fig. 4). The faults cut off the northeast trends of the Ruby terrane, and north of the fault zone there are no indications that regional trends in the Brooks Range bend around the apex of the Yukon-Koyukuk basin to conform to the northeast strike of the Ruby geanticline (Patton and Miller, 1973; Decker and Dillon, 1984).

The gross similarities between the Ruby terrane and southern Brooks Range have prompted workers to infer that both terranes were once parts of a single continuous belt. Several tectonic models have been offered to explain their present configuration and relation:

1) Tailleur (1973, 1980) proposed that the Ruby terrane is an eastward

extension of the southern Brooks Range (Arctic Alaska terrane) and owes its present southwest trend to oroclinal bending related to east-west convergence between North America and Eurasia in Late Cretaceous and early Tertiary time.

2) Patton (1970) suggested that the Ruby terrane is a fragment of the southern Brooks Range which was rifted away in late Paleozoic time and subsequently rotated counterclockwise to leave behind the V-shaped Yukon-Koyukuk basin. Subsequent Early Cretaceous collision of an oceanic island arc (Koyukuk terrane) with this v-shaped continental margin resulted in overprinting of the metamorphic fabric in roughly its present orientation (Patton, 1984; Box, 1985).

3) Churkin and Carter (1979) argued that the Ruby terrane represents an eastward extension of the southern Brooks Range that has been displaced right laterally (in Cretaceous? time) to its present position by a major southwest-trending strike-slip fault, which they labelled the "Porcupine lineament".

All three of these models are based on the assumption that the Ruby terrane and the southern Brooks Range (Arctic Alaska terrane) once formed a continuous belt. However, much additional study and detailed mapping of the Ruby terrane are needed in order to critically evaluate this assumption. At present we cannot rule out the possibility that the Ruby terrane is an exotic fragment unrelated to the southern Brooks Range that was plucked from some distant part of the Cordilleran or Siberian continental margin and rafted to its present position before the overthrusting of the Angayucham-Tozitna terrane.

## Angayucham-Tozitna terrane

### Definition and distribution

The (composite) Angayucham-Tozitna terrane, as defined in this chapter, is composed of an imbricated thrust assemblage of oceanic rocks that ranges in age from Devonian to Jurassic and occurs as allochthonous remnants of huge thrust sheets that overrode the Ruby geanticline and southern Brooks Range in Late Jurassic to Early Cretaceous time (Figs. 2, 3, 5). Jones and others (1987); Silberling and others (in press) divide these oceanic assemblages into two separate terranes: the Angayucham and the Tozitna. However, our investigations show that these two terranes are composed of nearly identical thrust sequences which have been assembled in the same stacking order and show similar age ranges. In this chapter we therefore treat the Angayucham and Tozitna terranes as separate belts of the same terrane. In addition, we include in our Angayucham-Tozitna terrane an assemblage of phyllite and metagraywacke which underlies the oceanic rocks of both the Angayucham and Tozitna belts and was mapped separately by Jones and others as the Coldfoot and Venetie terranes. In our view, this assemblage has close tectonic affinities to the oceanic rocks of the Angayucham-Tozitna terrane, and we describe it in this report as the lowest of three thrust panels comprising the Angayucham-Tozitna terrane. We informally designate the three thrust panels, from lowest to highest, as: Slate Creek, Narvak, and Kanuti (Fig. 2).

The Angayucham belt of the Angayucham-Tozitna terrane forms a narrow but nearly continuous band for 500 km along the south edge of the Brooks Range from the lower Kobuk River to the northeast apex of the Yukon-Koyukuk basin, and along the northwest boundary of the Ruby terrane from the northeast apex of the basin to the Kaltag fault (Fig. 3). South of the fault the offset extension of the Angayucham belt can be traced, by scattered outcrops and aeromagnetic data, for an additional 50 km from near the village of Kaltag to the Innoko Lowland (Fig. 3).

The Tozitna belt of the Angayucham-Tozitna terrane consists of four large and several small allochthonous synformal masses that rest on Ruby terrane along the axis and southeast flank of the Ruby geanticline. Two large masses lie south of the Kaltag fault, in the Ruby and Nulato quadrangles, and two lie north of the fault, in the Tanana and Beaver quadrangles (Figs. 1, 3). The belt continues northeastward beyond the area covered by this chapter and includes a large synformal mass in the Christian quadrangle (Brosge' and Reiser, 1962; Patton and others, 1977; Jones and others, 1987; Silberling and others, in press).

A small area on the lower Yukon River in the Russian Mission quadrangle, shown as Ruby terrane on the lithotectonic terrane map of Jones and others (1987), tentatively is assigned by us to the Angayucham-Tozitna terrane (Fig. 3). Sparse reconnaissance field data suggest that most of the rocks in this area are upper Paleozoic and lower Mesozoic metabasites, more like rocks of the Angayucham-Tozitna terrane or possibly Innoko terrane than those of the Ruby terrane. The structural relation of the rocks in this area to the adjoining Middle Jurassic to Lower Cretaceous rocks of the Koyukuk terrane is uncertain.

**Description**

The Slate Creek, Narvak, and Kanuti thrust panels that make up the Angayucham-Tozitna terrane appear to represent a reversely stacked sequence that progresses from continental slope deposits in the Slate Creek or lowest panel, through oceanic rocks in the Narvak or middle panel, to cumulus and mantle peridotites and layered gabbro in the Kanuti or highest panel (Figs. 2, 5 A-A', B-B',C-C', D-D'). The contact between the Slate Creek and the Narvak thrust panels is generally blurred by tectonic shuffling, whereas the contact between the Narvak and Kanuti thrust panels is sharply defined and commonly marked by a thin layer of garnet amphibolite tectonite. A detailed description of each thrust panel follows:

*The Slate Creek thrust panel* is composed chiefly of phyllite and metagraywacke and minor amounts of carbonate rocks, basalt flows, and basalt breccias. This assemblage is easily eroded and typically forms a lowland between the more resistant basalt and chert of the Narvak thrust panel and the pelitic schist of the structurally underlying Ruby and Arctic Alaska terranes. The phyllite and metagraywacke are overprinted by a low-grade penetrative metamorphic fabric, but turbidite features, such as graded bedding and sole marks, are locally discernible. The metagraywacke is composed chiefly of quartz and chert clasts but, in places, contains a significant component of volcanic rock and feldspar clasts. Of particular interest is the presence in the upper part of the thrust panel of: 1) slices of exotic shallow-water Devonian carbonate rocks that commonly are covered or enveloped by basalt flows, and 2) debris-flow(?) breccias composed of angular blocks of vesicular basalt as much as 50 cm across set in a matrix of volcanic and carbonate rock debris. The possible tectonic significance of these will be discussed below.

The age of the phyllite and metagraywacke is controversial. Palynoflora recovered from the phyllite and metagraywacke in the Wiseman quadrangle (Gottschalk, 1987) and in the Christian quadrangle of the eastern Brooks Range (W.P. Brosge', unpublished data, 1987) suggest a Devonian age. Dillon and others

(1986), however, assign a Mississippian to Triassic age to this thrust panel on the basis of radiolarians from intercalated chert layers. We favor the Devonian age because, in our experience, the relation of the intercalated chert layers to the phyllite and metagraywacke is seldom clear and the possibility that they are fault slices cannot be ruled out.

*The Narvak thrust panel*, the most widely exposed of the three panels, consists of multiple thrust slices of pillow basalt, chert, gabbro, and diabase and minor amounts of basaltic tuffs, volcanic breccias, and carbonate rocks. In the Angayucham Mountains (Hughes quadrangle), where best exposed, the Narvak panel has an aggregate structural thickness of nearly 10 km (Pallister and Carlson, in press). All of the rocks in the Narvak panel are weakly metamorphosed to prehnite-pumpellyite facies and show an overall increase in metamorphic grade downward in the panel. Greenschist facies metamorphism and local high-pressure metamorphism, as indicated by the presence of glaucophane, occur at the base of the panel. Igneous textures are generally well preserved except in mylonite zones bordering thrust faults. The chert, which includes both interpillow and bedded types, ranges from pure radiolarite and spiculite to cherty tuffs. Sills and dikes of gabbro and diabase are common in both the Angayucham and Tozitna belts, but are especially abundant in the Tozitna.

Systematic detailed sampling for radiolaria from cherts in the well-studied section of the Narvak thrust panel in the Angayucham Mountains (Hughes quadrangle) gives a range in age from Devonian at the base to Jurassic at the top (Murchey and Harris, 1985). A similar range of radiolarian ages has been reported from widely scattered localities elsewhere in this panel (Dillon and others, 1986; Patton and others, 1984; Jones and others, 1984). Carbonate rocks, which appear to be confined to the lower part of the Narvak panel, yield mixed conodont faunas ranging from Ordovician to Late Mississippian in age (A.G. Harris, written commun., 1985) and a few megafossils of Devonian, Mississippian(?), and Permian age. Some of the conodont collections clearly have been reworked from shallow-water sources.

*The Kanuti thrust panel* is composed of mafic-ultramafic complexes consisting of a tectonite mantle suite in the lower part and a cumulus plutonic suite in the upper part (Loney and Himmelberg, 1985). The composition and structural setting of these complexes are described in detail by Patton and others (in press) and will only be summarized here.

The mantle suite is composed of partly serpentinized harzburgite and dunite but it also contains minor clinopyroxenite and the cumulus suite of wehrlite, clinopyroxenite, and gabbro (Loney and Himmelberg, 1985). The base of the thrust panel commonly consists of a layer of amphibolite as much as 25 m thick composed of a highly tectonized aggregate of amphibole, plagioclase and garnet. Amphibole dikes and gabbro in the cumulate plutonic suite yield K-Ar ages of 172 to 138 Ma, and metamorphic amphibole from amphibolite at the base of the panel yields K-Ar ages of 172 to 155 Ma (Patton and others, 1977; Patton and others, in press). These are interpreted as cooling ages related to tectonic emplacement of the thrust panel.

**Interpretation and correlation**

The Angayucham-Tozitna terrane represents allochthonous remnants of huge thrust sheets of oceanic rocks that overrode the Precambrian lower Paleozoic and continental margin deposits of the Arctic Alaska and Ruby terranes in Late Jurassic to Early Cretaceous time. The Angayucham belt forms a narrow band of slab-like bodies that rim the north and southeast sides of the mid-Cretaceous Yukon-Koyukuk basin and dip inward beneath the basin. The Tozitna belt forms allochthonous synformal masses aligned along the axis and southeast flank of the Ruby geanticline (Ruby terrane). The two belts are closely correlative in age and lithology, and we consider them to be remnants of the same overthrust sheets. Similar upper Paleozoic and lower Mesozoic oceanic assemblages appear to have overridden the early Paleozoic continental margin in Mesozoic time throughout the length of the North American Cordillera (Harms and others, 1984; Struik and Orchard, 1985). The Innoko terrane, which in its lower part is composed predominantly of radiolarian cherts that correlate in age with cherts in the Narvak thrust panel of the Angayucham-Tozitna terrane, may be an eastward extension of a part of the Angayucham-Tozitna terrane.

Several lines of evidence support a Late Jurassic to Early Cretaceous age of emplacement of the Angayucham-Tozitna terrane on the continental margin. Emplacement could not have begun earlier than Late Jurassic since K-Ar cooling ages of mafic rocks in the Kanuti thrust panel are Late Jurassic. The oldest flyschoid deposits derived from the Angayucham-Tozitna terrane in the western Brooks Range are Late Jurassic (Tithonian) in age (Mayfield and others, 1983). The emplacement must have been completed by late Early Cretaceous (Albian) time because at that time large volumes of flyschoid sediments containing debris from both Angayucham-Tozitna terrane and from the metamorphic rocks of the Ruby and Arctic Alaska terranes were being deposited in the Yukon-Koyukuk basin. Furthermore, on the Ruby geanticline, the Ruby terrane and the Angayucham-Tozitna terranes are stitched together by granitic plutons that yield U/Pb and K-Ar ages of about 110 Ma (Patton and others, 1987).

We interpret the Slate Creek thrust panel to represent an assemblage of continental slope-and-rise deposits that accumulated along a middle Paleozoic rifted continental margin. The bulk of the assemblage is composed of fine-grained siliciclastic turbidites, but the presence of coarse volcanic-rich breccias and of exotic blocks of shallow-water carbonate rocks, which locally are enveloped in basalt flows, leads us to believe that the assemblage was deposited in an extensional environment. Bimodal volcanism along the south edge of the Brooks Range (Arctic Alaska terrane) provides additional evidence of extension in middle Paleozoic time (Hitzman, 1984).

The Narvak thrust panel is an imbricated assemblage of oceanic basalt and chert, which we suggest was accreted to the continental margin when an intraoceanic volcanic arc (Koyukuk terrane) collided with the margin in latest Jurassic to Early Cretaceous time. The lower (upper Paleozoic) part of this assemblage appears to have formed near the continental margin, probably in the continent-ocean transition zone. Intercalated carbonate rocks in the lower part of the panel contain redeposited shallow-water conodont faunas of Ordovician to Late Mississippian age. The wide age range and diversity of these faunas suggest that they were derived from platform carbonate rocks belonging to the continental margin rather than to a carbonate buildup in an intraoceanic setting. By contrast, the upper (lower Mesozoic) part of the Narvak thrust panel has no carbonate rocks and shows no evidence of having formed near a continental margin.

Geochemical data from basaltic rocks of the Narvak thrust panel are characteristic of intraplate volcanism (Barker, in press; Pallister and Budahn, in press). Compositions of the major elements indicate that the basalts fall within the tholeiitic to alkalic rock series. Chondrite-normalized rare-earth element (REE) plots range from flat to strongly enriched in light rare-earth elements (Fig. 6A). These basalts lack the strongly depleted concentrations of Nb, Ta, and Ti

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Figure 6 near here

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that are characteristic of subduction-related arc volcanism. Instead they resemble basalts from intraplate seamounts (such as Hawaii) or plume-influenced spreading ridge islands (such as Iceland) (Thompson and others, 1984).

The Kanuti thrust panel is typical of the lower part of an ophiolite succession (Patton and others, in press). However, its geologic setting and geochemistry indicate that the ophiolites may have formed as the roots of a volcanic arc rather than as the lower part of a crustal section generated along a mid-ocean ridge. No high-level oceanic crustal rocks have been found in this thrust panel, and structurally the next higher sequence exposed within the Yukon-Koyukuk basin is the Jurassic and Lower Cretaceous andesitic volcanic arc assemblage belonging to the Koyukuk terrane (Fig. 5, A-A', B-B', C-C'). The chemistry of chromian spinels, which Dick and Bullen (1984) believe is an indicator of the petrogenesis of the peridotites, suggests that the ultramafic cumulates in this thrust panel are not typical of peridotites dredged from modern mid-ocean ridges (Loney and Himmelberg, oral commun., 1985).

Metamorphic amphibole from amphibolite at the sole of the Kanuti thrust panel yields Middle and Late Jurassic K-Ar ages (Patton and others, in press). These ages suggest that the Kanuti panel was thrust onto the Narvak panel before it collided with the continental margin in Late Jurassic to Early Cretaceous time (Patton and Box, 1985). A small tonalite-trondhjemite pluton of Middle and Late Jurassic age, exposed in the south-central part of the Yukon-Koyukuk basin (Fig. 5, E-E'), may represent an earlier phase of arc volcanism--a phase synchronous with emplacement of the Kanuti thrust panel onto the Narvak thrust panel (Patton, 1984).

We propose the following tectonic model to explain the evolution of the Angayucham-Tozitna terrane (Fig. 7):

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Fig. 7 near here

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1. <u>Middle and Late Jurassic</u> - an intraoceanic arc-trench system formed at some unknown distance from the continental margin. The trench lay between the arc and the continent, the arc migrating toward the continent. The Kanuti thrust panel was generated within the arc-trench system and was underplated by oceanic seamounts, now constituting the upper part of the Narvak thrust panel, during underthrusting of the oceanic plate.

2. <u>Late Jurassic and Early Cretaceous</u> - oceanic crust between the arc and continent was consumed, and continental underthrusting began. The lower part of the Narvak thrust panel, at the continent-ocean boundary, was underplated beneath the upper part of the Narvak panel. This event was followed successively by underthrusting of sediments from the continental slope and rise constituting the Slate Creek thrust panel, and finally by the underthrusting of the continental margin constituting the Arctic Alaska and Ruby terranes.

Although most workers agree that the oceanic rocks of the Angayucham-Tozitna terrane are allochthonous with respect to the metamorphic assemblages of the Ruby and Arctic Alaska terranes, not all agree that their emplacement was a product of subduction and terrane accretion. Gemuts and others (1983) argue that the mafic-ultramafic rocks of the Angayucham-Tozitna terrane were generated in local rift basins along the margin of the Yukon-Koyukuk basin and were emplaced on the metamorphic rocks during a later compressional event. Similarly, Dover (in press) suggests that the mafic-ultramafic rocks were generated within the continental rocks of the Ruby geanticline and southern Brooks Range and were tectonically emplaced by "classical nonaccretionary deformational processes." In our view, however, the models of Gemuts and others and of Dover are untenable, because they fail to account for: 1) the wide age range (Devonian to Jurassic) of the mafic-ultramafic rocks, 2) the characteristic reverse stacking order in which mantle and lower crustal mafic-ultramafic rocks overlie higher level crustal mafic rocks, and 3) the presence of high-pressure blueschist mineral assemblages in the underlying metamorphic rocks of the Ruby and Arctic Alaska terranes.

## Koyukuk terrane

### Definition and Distribution

The Koyukuk terrane, as defined by Jones and others (1987) and Silberling and others (in press), lies wholly within the Yukon-Koyukuk basin. It is composed dominantly of Upper Jurassic(?) and Lower Cretaceous andesitic volcanic rocks, but south of the Kaltag fault it also includes Middle and Late Jurassic tonalite-trondhjemite plutonic rocks which intrude an altered complex of mafic and ultramafic rocks of uncertain age and tectonic affinities (Figs. 2, 3). The Koyukuk terrane is exposed on a broad arch that extends across the north-central part of the Yukon-Koyukuk basin from the Seward Peninsula to the Koyukuk River, and on smaller structural highs within the basin. The best outcrops are in cutbanks along the Koyukuk River in the Hughes and Melozitna quadrangles and along the lower Yukon River in the Russian Mission quadrangle (Fig. 1). In the interstream areas exposures are confined largely to broad thermally altered zones surrounding mid- and Late Cretaceous granitoid plutons. The Koyukuk terrane is presumed to underlie much of the basin, but the nature and geometry of the contacts with older rocks that rim the basin are generally obscured by overlapping mid-Cretaceous terrigenous sedimentary rocks and younger volcanic rocks (see, for example, Fig. 5, sections A-A', B-B', C-C'. It is possible that the Koyukuk terrane stratigraphically overlies the Angayucham-Tozitna terrane and therefore does not, in reality, constitute a separate terrane.

### Description

The Koyukuk terrane is composed of two distinctly different assemblages: 1) Middle and Late Jurassic tonalite-trondhjemite plutonic rocks and a complex of altered mafic volcanic rocks and mafic and ultramafic plutonic rocks of uncertain but probable late Paleozoic or early Mesozoic age; and 2) Upper Jurassic(?) and Lower Cretaceous andesitic volcaniclastic rocks and flows (Fig. 2). The andesitic volcanic and volcaniclastic rocks unconformably overlie the tonalite-trondhjemite plutonic rocks and mafic-ultramafic complex in the Unalakleet and Holy Cross quadrangles and compose all of the exposed Koyukuk terrane elsewhere in the Yukon-Koyukuk basin.

The Middle and Late Jurassic tonalite-trondhjemite plutons occur in a linear fault-bounded complex extending along the Chiroskey fault from the Kaltag fault in the northern Unalakleet quadrangle southward to the central part of the Holy Cross quadrangle (Fig. 3; Fig. 5, section E-E'). These plutonic rocks are extensively sheared and fractured and are locally altered to pink granite by potassic metasomatism. K-Ar mineral ages range from 173±9 to 154±6 Ma. A representative spidergram of Middle Jurassic tonalite (Fig. 6B, sample 5) exhibits the characteristic signature of subduction-related magmatism, that is, enrichment of LIL (large ion lithophile) elements and depletion of Nb-Ta relative to the light rare-earth elements (REE). Clasts from this plutonic suite occur in overlying Lower Cretaceous volcaniclastic rocks in the Unalakleet quadrangle (Patton and Moll, 1985). In the Unalakleet quadrangle these plutonic rocks are faulted against, and locally appear to intrude, a poorly exposed assemblage of pillow basalt, diabase, gabbro, and serpentinized ultramafic rocks of uncertain tectonic affinities (Patton and Moll, 1985; unpublished data, 1986). Basalt from this assemblage shows a trace-element signature that is similar to that of basalts from the Angayucham-Tozitna terrane and is unlike that of basalts from the Upper Jurassic(?) and Lower Cretaceous part of the Koyukuk terrane. The trace-element characteristics of these pre-Middle Jurassic basalts are similar to "enriched" or "transitional" mid-ocean ridge basalts (E-MORB or T-MORB), to tholeiitic basalts from some ocean islands (tholeiitic OIB), and to some back-arc basalts (BABB) (Thompson and others, 1984; Saunders and Tarney, 1984). These basalts lack depletion of Nb and Ta relative to the light REE (such as La)--the primary diagnostic characteristic of volcanic-arc magmas.

The Upper Jurassic(?) and Lower Cretaceous volcaniclastic rocks and flows, which make up the bulk of the exposed Koyukuk terrane, can be divided into a lower unit of Late Jurassic(?) and early Neocomian age, and an upper unit of late Neocomian and Aptian age. The lower unit is the most extensive regionally and records an episode of voluminous andesitic magmatism. All known fossils are early Neocomian (Berriasian and Valanginian) in age, but the lower part of the unit may be as old as Late Jurassic. Lava flows range from basalt to dacite and are characterized by abundant plagioclase and subordinate amounts of pyroxene and/or hornblende phenocrysts. Pyroclastic and epiclastic volcanic rocks are predominant. They include angular tuff breccias, pillow breccias, lapilli tuffs, crystal tuffs, lithic tuffs, hyaloclastites, and shallow to deep marine conglomerates, sandstones, shales, and tuffaceous cherts. Regional stratigraphic correlation is difficult because of the lack of distinct marker horizons. Widely scattered, fossiliferous coquinoid limestones of Valanginian age indicate widespread shallow-marine deposition at that time.

The geochemistry of the volcanic rocks of the lower unit is extremely variable (Fig. 6B, samples 2 to 4), and ranges from arc tholeiite to shoshonite. All rocks of this unit exhibit the chemical characteristics of subduction-related magmatism (such as enriched LIL elements and depleted Nb-Ta relative to the light REE). Chondrite-normalized REE patterns vary from flat (Fig. 6B, sample 4) to extremely enriched in light REE (Fig. 6B, sample 2). Although relative age control for samples within this unit is generally poor, samples of known Valanginian age are all extremely light REE-enriched (that is, La content is more than 300 times the chondritic value). This suggests that the youngest samples of the lower unit of the Upper Jurassic(?) and Lower Cretaceous assemblage are the most enriched in LIL elements and in the light REE. However, neither the phenocryst mineralogy (plag±cpx±hbl) nor incompatible element ratios (such as La/Th, K/Rb, Zr/Sm) vary significantly within this unit, which suggests that the late trace-element enrichment is due to decreasing degrees of partial melting of the same mantle source (Box and Patton, in press).

The upper unit of the Upper Jurassic(?) and Lower Cretaceous assemblage is late Neocomian and Aptian in age and is gradational with the lower unit. It has been identified in the Hughes (Patton and Miller, 1966; Box and others, 1985), Unalakleet (Patton and Moll, 1985), Norton Bay (Patton and Bickel, 1956B) and Candle (Patton, 1967) quadrangles. In the Hughes quadrangle, where best studied (Box and others, 1985), the age ranges from Hauterivian to Aptian, based on mega- and microfossil identifications (J.W. Miller, written commun., 1983; N. Albert, written commun., 1985). K-Ar ages from the upper unit in the Unalakleet and Candle quadrangles are 118±3.5 Ma and 124±3 Ma, respectively (Patton and Moll, 1985; Patton, 1967). The upper unit has distinct sedimentologic, petrologic, and geochemical features that distinguish it from the lower unit. In each area the upper unit was deposited in a subsiding sedimentary environment. In the Norton Bay quadrangle this volcanic and volcaniclastic unit was deposited in the transition between nonmarine and shallow-marine environments. In the Hughes and Unalakleet quadrangles, the upper unit was deposited in a sub wave-base (slope?) setting in the vertical transition between shallow-marine and basinal deep-marine environments. Lava flows are typically andesites but differ from the lower unit in containing sanidine, biotite, and/or melanite garnet phenocrysts. Geochemically, they are similar to the Valanginian part of the lower unit in being extremely enriched in light REE (Fig. 6B, sample 2). However, they differ from flows of the lower unit in certain incompatible-element ratios (such as La/Th, K/Rb, Zr/Sm), which implies that they could not have been derived from the same source as the earlier flows (Box and Patton, in press).

**Interpretation**

The Koyukuk terrane is believed to be a Mesozoic intraoceanic volcanic-arc complex that collided with continental North America in Late Jurassic to Early Cretaceous time (Roeder and Mull, 1978; Gealey, 1980; Box, 1985; Fig. 7). Both the Jurassic plutonic rocks and the Upper Jurassic(?) and Lower Cretaceous volcanic rocks of the Koyukuk terrane have the geochemical signature of subduction-related magmatism. Arc magmatic activity extended from 173 to 115 Ma, with a possible hiatus in the Late Jurassic.

Three lines of evidence suggest that the Koyukuk terrane developed in an intraoceanic setting. First, the lack of exposures of older continental basement rock within the terrane, or of continental detritus in clastic sections within the terrane, suggests the lack of continental basement. Second, the lower crustal and upper mantle part of an ophiolite sequence (namely, the Kanuti thrust panel of the Angayucham-Tozitna terrane) dips beneath the northern and southeastern flanks of the Koyukuk terrane. This sequence may constitute the basement for part or all of the Koyukuk terrane. And third, Sr, Nd, Pb, and O isotopic data from Upper Cretaceous plutons in the northeastern part of the terrane and from lower Tertiary volcanic rocks in the eastern part of the terrane indicate the lack of Paleozoic or older continental crustal contamination (Arth and others, 1984; Moll and Arth, 1985).

The position of the surface trace of the subduction zone (that is, the trench) relative to the arc is suggested by several regional geologic features. The

Angayucham-Tozitna terrane dips beneath the northern and southeastern flanks of the Koyukuk terrane and includes garnet amphibolites that record Middle to Late Jurassic oceanic thrusting. This suggests that the Middle to Late Jurassic intraoceanic subduction zone lay to the north and southeast of contemporaneous arc magmatism in the Koyukuk terrane, as related to present coordinates and to the present configuration of the Yukon-Koyukuk basin. Likewise, Early Cretaceous structural and metamorphic features of the Arctic Alaska and Ruby terranes (that is, the outward-directed thrust belt and retrograded blueschist facies metamorphism) imply partial underthrusting of the North American margin beneath the Koyukuk terrane from the north and southeast. Stratigraphic evidence from the western Brooks Range (Mayfield and others, 1983) suggests that continental underthrusting beneath the Koyukuk terrane began at the end of the Jurassic or the beginning of the Cretaceous ( 144 Ma).

Continental underthrusting of the arc is apparently reflected in the Early Cretaceous volcanic geochemistry of the Koyukuk terrane. The flows of probable pre-Valanginian (that is, pre-138 Ma) age are arc tholeiitic and calc-alkaline rocks having moderate LIL and light REE enrichment typical of an intraoceanic volcanic arc. The flows of Valanginian (138-131 Ma) age are highly enriched in LIL and in light REE, and apparently were derived from the same source as the older flows but at sharply decreased degrees of partial melting. Presumably, this reflects decreasing convergence rates due to the difficulties of subducting continental crust. The Hauterivian to Aptian flows (130-115 Ma) are also highly enriched, but their different incompatible-element ratios suggest a change in the composition of the mantle source.

## OVERLAP ASSEMBLAGES

Major convergent motion between the lithotectonic terranes of western Alaska ceased in Early Cretaceous time. In mid- and Late Cretaceous time these terranes were eroded and partly covered by terrigenous clastic rocks (see Decker and others, in press, for a discussion of a similar relation in southwestern Alaska). Subsequently these mid- and Upper Cretaceous clastic rocks were themselves strongly deformed and displaced by large-scale strike-slip faulting. Both the lithotectonic terranes and the overlapping clastic rocks were subjected to several widespread magmatic events between mid-Cretaceous and Quaternary time.

The following section describes these overlap assemblages, which include: mid- and Upper Cretaceous terrigenous sedimentary rocks, mid- and Late Cretaceous plutonic rocks, Upper Cretaceous and lower Tertiary volcanic and plutonic rocks, and upper Tertiary and Quaternary flood basalts (Fig. 2).

### Mid- and Upper Cretaceous terrigenous sedimentary rocks

#### Distribution

Mid- and Upper Cretaceous terrigenous clastic rocks underlie a large part of the Yukon-Koyukuk basin in stratigraphic sections as much as 5 to 8 km thick. They may be grossly subdivided into a lower flyschoid assemblage composed of graywacke and mudstone turbidites, and an upper molassoid assemblage of fluvial and shallow-marine conglomerate, sandstone, and shale.

**Graywacke and mudstone turbidites**

The turbidite flyschoid assemblage was deposited in two vaguely defined subbasins: the Lower Yukon, which extends in a broad band along the west edge of the basin from the latitude of Kotzebue Sound southward to the Yukon delta, and the Kobuk-Koyukuk, which occupies a V-shaped area along the north and southeast margins of the basin (Figs. 8, 9). The two subbasins are separated by the Koyukuk terrane, a remnant volcanic arc that trends eastward from Kotzebue

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Figs. 8 and 9 near here

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Sound to the Koyukuk River and then southward beneath the Koyukuk Flats (Wahrhaftig, 1965). Near the Kaltag fault the Koyukuk terrane narrows, and the two subbasins converge. South of the fault, the subbasins are offset 100 to 160 km to the southwest and are separated by only a narrow fault-bounded slice of the Koyukuk terrane (Fig. 3, section E-E'). We believe that the Yukon-Koyukuk basin and the two subbasins owe their present configuration in large measure to a strong east-west compressional event that occurred in western Alaska and the Bering Strait region in Late Cretaceous and early Tertiary time (Fig. 9) (Patton and Tailleur, 1977; Tailleur, 1980).

The turbidite assemblage is sparsely exposed over about 60 percent of the Kobuk-Koyukuk subbasin and over about 50 percent of the Lower Yukon subbasin (Fig. 8). It includes midfan channel, midfan lobe, and outer fan to basin plain facies associations (Mutti and Ricci Lucchi, 1972), but lack of biostratigraphic control and poor exposures preclude delineation of these facies through time. Graywacke compositions are dominated by volcanic lithic fragments derived from the Angayucham-Tozitna (oceanic) terrane that rims the basin and from the Koyukuk volcanic arc terrane within the basin. Metamorphic debris from the Arctic Alaska, Seward, and Ruby terranes is present in variable but subordinate amounts.

In the Kobuk-Koyukuk subbasin widely dispersed fossils in the turbidite assemblage all appear to be Albian in age. However, in the western Bettles quadrangle, about 4 km of stratigraphic section are exposed beneath an early(?) Albian fossil occurrence (Box and others, 1985). The lower kilometer of this section has interbedded potassium-feldspar-bearing tuffs that are lithologically identical to, and presumably correlative with, tuffs of Barremian to Aptian age 70 km to the southwest in the Hughes quadrangle. There, the possibly correlative Barremian to Aptian tuffaceous section is overlain by turbidites of early Albian age. This variation in the age of the base of the turbidites and the lack of conglomeratic facies bordering the Koyukuk terrane suggest that the Koyukuk terrane was progressively onlapped by turbiditic basin-fill sediments derived primarily from the north and southeast subbasin margins. The age of these turbidites is confined to the Barremian to Albian interval, although the age of the base of the turbidite assemblage in the central part of the Kobuk-Koyukuk subbasin is not known.

The turbidite assemblage in the Lower Yukon subbasin consists of a central belt of noncalcareous turbidites flanked both east and west by belts of calcareous turbidites. Field and aeromagnetic data suggest that these graywacke and mudstone beds have an aggregate thickness of more than 6,500 m along the

Yukon River-Norton Sound divide (Gates and others, 1968). The central belt is composed of volcanic lithic graywackes with a very minor component of metamorphic detritus. It is divided by a fault into a western half of fine-grained turbidites with abundant carbonaceous material, and an eastern half of medium- to coarse-grained turbidites that have been partially replaced by secondary laumontite (Hoare and others, 1964). Paleocurrent directions are consistently to the northeast (Fig. 8). The flanking calcareous belts are significantly richer in metamorphic rock detritus and have a carbonate cement. They are typically fine-grained, and locally show reworking above storm base. Paleocurrent directions in these calcareous belts are scattered around the compass. Fossils in this Lower Yukon subbasin turbidite assemblage are confined to a few scattered ammonites of probable Albian age in the eastern calcareous belt.

**Fluvial and shallow-marine conglomerate, sandstone, and shale**

The molassoid assemblage of shallow-marine and non-marine sedimentary rocks is composed of: 1) marginal conglomerates that rim the basin, and 2) deltaic deposits that extend from the southeast margin across the southeast limb of the Kobuk-Koyukuk subbasin and the east half of the Lower Yukon subbasin (Fig. 8).

*Marginal conglomerates* - Polymictic conglomerate and sandstone eroded from the borderlands rim the basin on all three sides in sections estimated to be locally as much as 2,500 m thick. On the borderland side they unconformably overlie the Angayucham-Tozitna and Koyukuk terranes, and on the basinward side they rest on, and in part may be laterally gradational with the graywacke and mudstone turbidites. Along the north and southeast margins of the basin, the conglomerates are composed in the lower part of mafic rocks and chert derived from the Narvak and Kanuti thrust panels of the Angayucham-Tozitna terrane, and in the upper part of quartz and metamorphic rock clasts derived from the Arctic Alaska and Ruby terranes. Locally, an intermediate sequence consisting largely of metagraywacke clasts derived from the Slate Creek thrust panel of the Angayucham-Tozitna terrane occurs between the mafic-rich and quartz-rich conglomerates (Dillon and Smiley, 1984). This compositional progression in vertical section is thought to reflect erosional unroofing of the Arctic Alaska and Ruby terranes following overthrusting of the Angayucham-Tozitna terrane.

The mafic-rich conglomerates are restricted in outcrop to within 10-20 km of the north and southeast margins of the Kobuk-Koyukuk subbasin. They rest depositionally on Angayucham-Tozitna terrane and grade upward into the quartz-rich conglomerates. The mafic-rich conglomerates, which have an aggregate thickness of as much as 1,500 m, appear to have been deposited primarily in nonmarine alluvial fan and braided-stream environments. However, marine fossils recovered from these conglomerates in the Selawik quadrangle suggest that some of these strata were deposited in a nearshore marine environment (Patton and Miller, 1968). Paleocurrents are generally directed either away from or parallel to the subbasin margins (Fig. 8). Sparse fossils indicate that these conglomerates are late Early Cretaceous (Albian) in age.

The quartz-rich conglomerates form a nearly continuous band along the north and southeast margins of the basin, where they rest depositionally on the mafic-rich conglomerates and overlap onto the Angayucham-Tozitna terrane. The quartz-rich conglomerates, which also include varying amounts of quartz sandstone, shale, and thin bituminous coal beds, have an aggregate thickness of as much as 1,000 m. They range in age from earliest Late Cretaceous (Cenomanian) to middle Late Cretaceous (Santonian) (Patton, 1973).

Marginal conglomerates also crop out along the western edge of the Yukon-Koyukuk basin (Fig. 8), where they are divisible into two stratigraphic units: a lower nonmarine unit composed of andesitic volcanic rocks derived primarily from the Koyukuk terrane, and an upper shallow-marine unit composed of carbonate-cemented volcanic and metamorphic rock clasts derived from both the Koyukuk and the Seward terranes. The lower unit, which is in depositional contact with the Koyukuk terrane, consists of poorly sorted conglomeratic strata deposited on eastward-prograding alluvial fans. In the Candle quadrangle these conglomerates contain granitic boulders petrographically similar to nearby granitic plutons dated at about 105 Ma (Patton, 1967; Miller and others, 1966), indicating that the conglomerates are no older than middle Albian. The upper unit was deposited in a nearshore environment, the currents being directed away from and parallel to the west subbasin margin (Nilsen and Patton, 1984). Sparse palynomorphs and foraminifers suggest that this unit is also Albian in age.

*Fluvial and shallow-marine sandstone and shale* - A westward-prograding assemblage of deltaic deposits, which includes quartzose sandstone, shale, and thin seams of bituminous coal, forms a broad belt along the southeast side of the Yukon-Koyukuk basin from the Melozitna quadrangle southward to the Yukon delta (Fig. 8). This belt extends westward from the basin margin across the southeast arm of the Kobuk-Koyukuk subbasin and the east third of the Lower Yukon subbasin. At the Kaltag fault the belt is offset from 100 to 160 km right laterally. The deltaic deposits rest on graywacke-mudstone turbidites in the subbasins and grade laterally into the upper quartz-rich marginal conglomerates along the southeast edge of the Yukon-Koyukuk basin. Along the narrow belt of Koyukuk terrane that separates the two subbasins, the graywacke-mudstone turbidite section thins or is missing, and locally the deltaic deposits rest directly on volcanic rocks of the Koyukuk terrane. The deltaic deposits grade from nonmarine debris-flow and braided-stream deposits on the east, through delta-plain meandering-stream deposits, to delta-front deposits on the west (Nilsen and Patton, 1984). The delta-front deposits are faulted against the graywacke-mudstone turbidites along their west edge. The deltaic deposits had their source in the Ruby terrane and are distinguished from the underlying graywacke-mudstone turbidites by better sorting and by the predominance of clasts of quartz and metamorphic rock over volcanic rock. Paleocurrent indicators show a wide array of sediment-transport directions from northwestward to southeastward.

The fluvial and shallow-marine deltaic deposits have been studied in greatest detail along the Yukon and lower Koyukuk River in the Nulato, Kateel River, and Ruby quadrangles (Martin, 1926; Hollick, 1930; Patton and Bickel, 1956A; Patton, 1966; Nilsen and Patton, 1984; Harris, 1985). In this area they have an estimated thickness of 3,000 to 3,500 m and grade upward from shallow-marine beds with abundant mollusks of Albian age into nonmarine beds with plant fossils of Cenomanian and Turonian(?) age (R.A. Spicer, oral commun., 1987). To the south, in the Unalakleet quadrangle, mollusks as young as Cenomanian have been found in the marine strata, suggesting that the contact with the overlying nonmarine beds is diachronous (Patton and Moll, 1985).

**Interpretation**

We believe that the Yukon-Koyukuk basin originated in early Albian or possibly Aptian time as two subbasins separated by a remnant volcanic arc (Koyukuk terrane), possibly in the configuration shown in Figure 9A. During early and middle Albian the subbasins were filled with voluminous flyschoid deposits derived from the continental margin and from the remnant arc. In late Albian and early Late Cretaceous time, a broad prograding-delta complex composed of sediments derived from the continental margin was built out across the southeast limb of the Kobuk-Koyukuk subbasin, the adjoining part of the remnant arc, and the eastern part of the Lower Yukon subbasin. At approximately the same time, alluvial fans and narrow marine shelves composed of coarse detritus from the borderlands were built along the north and west sides of the basin. In Late Cretaceous to early Tertiary time, an east-west compressional event in western Alaska, probably related to convergence between the North American and Eurasian lithospheric plates, sharply constricted the central and southern parts of the Yukon-Koyukuk basin and offset the basin 100-160 km along the Kaltag fault (Fig. 9B) (Patton and Tailleur, 1977). The foreshortening in the basin is reflected in the isoclinal folding of the graywacke-mudstone turbidites in the central part of the Lower Yukon subbasin (Fig. 5, C-C') and in the juxtaposition of dissimilar sedimentary facies, probably by large-scale thrust faulting (Nilsen and Patton, 1984). Juxtaposition of divergent regional trends along the western margin of the basin suggests that large-scale thrusting also may have occurred there. The present structure of the basin and its margins is dominated by high-angle normal faults of late Cenozoic age which tend to obscure the earlier pattern of low-angle thrust faults.

## Mid- and Late Cretaceous plutonic rocks

Major plutonism in west-central Alaska took place from 113 to 99 Ma (late Early Cretaceous) with a volumetrically lesser episode from 79 to 89 Ma (Late Cretaceous). These plutonic rocks underlie about 5 percent of the region and can be grouped into three distinct suites on the basis of their composition, age, and distribution (Fig. 2); each suite apparently was derived from source material of different composition. Most of the variation within suites can be explained by fractional crystallization, variation in crustal melting, or local crustal contamination.

The largest of these suites intrudes the Ruby and Angayucham-Tozitna terranes along the Ruby geanticline. The remaining two suites occur entirely within the Yukon-Koyukuk basin and intrude both the Koyukuk terrane and the overlapping assemblage of mid- and Upper Cretaceous terrigenous sedimentary rocks. All three suites lack a metamorphic fabric and major deformation.

### Ruby geanticline plutons

*Distribution and age* - A large suite of plutonic rocks in west-central Alaska forms a major part of the northeast-trending Ruby geanticline (Fig. 4) and is exposed over 8,000 km$^2$, primarily in the Ruby terrane. The plutonic rocks in this region are concentrated in the 400 km-long segment of the Ruby terrane north of the Kaltag fault (Figs. 3; 4), where they are exposed over 40 percent of the terrane as opposed to less than 1 percent south of the fault (150 km$^2$). North of the Kaltag fault, they are probably the single most voluminous rock type and constitute one of the major Mesozoic batholithic complexes of interior Alaska--second only in area to the plutons of the Yukon-Tanana Upland. The batholith, which consists of individual plutons surrounded by narrow thermal aureoles developed in regionally metamorphosed pelitic country rocks, covers about twice as much area as the other two suites of Cretaceous plutons in west-central Alaska. The plutons are somewhat elongated in an east-west direction, oblique to the northeast-striking trend of the Ruby geanticline.

The plutonic rocks intrude Precambrian(?) and Paleozoic crystalline rocks of the Ruby terrane and the Devonian to Jurassic rocks of the Angayucham-Tozitna terrane, and are therefore no older than Jurassic. Radiometric age data constrain the age of the Ruby geanticline plutons to the mid-Cretaceous. K-Ar ages, chiefly on biotite, range from 112-99 Ma (Miller, 1985; Miller, in press). A mid-Cretaceous age for these plutonic rocks is corroborated by U/Pb zircon ages of 112-109 Ma from the Ray Mountains pluton in the Tanana quadrangle (Patton and others, 1987) and a Rb-Sr age of 112 Ma (Blum and others, 1987) from the Jim River pluton in the Bettles quadrangle.

*Description* - The Ruby geanticline plutons are composed chiefly ( 80 percent) of leucocratic biotite granite and have lesser amounts of granodiorite and muscovite-biotite granite (Fig. 10); syenite and monzonite are rare but do occur at the extreme north end of the Ruby geanticline (Blum and others, 1987).

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Fig. 10 near here

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The granites are typically coarse-grained, strongly porphyritic, and nonfoliated and form large plutons up to 800 $km^2$ in area. Mineralogically, they are characterized by an abundance of quartz and K-feldspar and lesser amounts of albite and biotite; hornblende is rare. Primary muscovite occurs in some phases of the large southern plutons but modal cordierite is lacking. Zircon, apatite, ilmenite, allanite, fluorite, and tourmaline are common accessory minerals. Some, and possibly all, of these plutons are composite bodies but only the Ray Mountains pluton in the Tanana quadrangle has been mapped in sufficient detail to document the separate phases (Puchner, 1984).

The plutons are highly evolved and are restricted in composition; the $SiO_2$ content generally ranges from 68 to 76 percent. They are K-rich, Na-depleted, and weakly to moderately peraluminous; normative corundum is usually greater than 0.8 percent (Miller, in press). They appear to belong to the ilmenite (magnetite-free) series of granitic rocks (Ishihara, 1981) and show low $Fe_2O_3/FeO$ and reduced magnetic susceptibility. Rb/Sr ratios are high. Initial $Sr^{87/86}$ ratios range from .7056 to .7294, show large internal variations, and have average values that decrease from southwest to northeast (Arth, 1985; Arth, in press). Nd initial ratios (NIR) show a reverse relationship to the $Sr^{87/86}$ ratios and increase to the northeast from .51158 to .51240 (Arth, 1985; Arth, in press). Representative chondrite-normalized, extended rare-earth element diagrams from two Ruby geanticline plutons are shown in Fig. 6C, samples 3 and 4.

Mineral deposits of tin, tungsten, and uranium are associated with these highly evolved plutonic rocks (Nokleberg and others, in press a and b). Such incompatible elements are characteristically associated with these types of granitic rocks.

*Interpretation* - The Ruby geanticline plutons comprise a high-silica, K-rich, weakly to moderately peraluminous, Fe-reduced, compositionally restricted suite of granitoid rocks. Such modal and major-element characteristics are typical of granitic rocks thought to have been generated by melting of continental crust, and typify the S-type granites of Chappel and White (1974).

Their high strontium initial ratios (SIR's>.7056) also indicate that significant amounts of Paleozoic or older continental crust were involved in the origin of the plutonic magmas (Arth, 1985). These characteristics are in direct contrast to those of neighboring granitic rocks of the eastern Yukon-Koyukuk basin.

**Eastern Yukon-Koyukuk basin plutons**

*Distribution and age* - Plutons in the eastern Yukon-Koyukuk basin consist of several large bodies in the Hughes and Shungnak quadrangles, and numerous small stocks in the eastern Melozitna quadrangle. They intrude both the Lower Cretaceous volcanic rocks of the Koyukuk terrane and the overlap assemblage of mid- and Upper Cretaceous terrigenous sedimentary rocks (for example, the Indian Mountain pluton shown in Fig. 5, B-B'). They yield Late Cretaceous K-Ar ages of 89 to 79 Ma, about 10 to 20 m.y. younger than the plutons in the adjoining Ruby geanticline and in the western Yukon-Koyukuk basin. Plutons belonging to this suite occur within 15 km of the plutons in the Ruby geanticline.

*Description* - The plutons in the eastern part of the basin consist of a compositionally expanded suite of tonalite to high-silica granite, the most typical rock type being a granodiorite (Fig. 10); gabbros and quartz diorites are lacking. Individual plutons commonly are compositionally zoned and show gradational internal contacts. The rocks are generally massive, leucocratic, medium-grained, hypidiomorphic, and equigranular, but locally are porphyritic. They are hornblende- and biotite-bearing, and contain abundant sphene, magnetite, apatite, zircon, and allanite. These eastern Yukon-Koyukuk basin rocks generally have $SiO_2$ contents of 62 to 73 percent, not including a 100 $km^2$ area of high-silica (76-78 percent) granite. They are relatively enriched in $Na_2O$ (>3.2 percent)($Na_2O/K_2O$>1) and CaO and have the high $Fe_2O_3$/FeO ratios of the magnetite series of Ishihara (1981). SIR's for this eastern suite of plutonic rocks range from .7038-.7056 and show little internal variation (Arth, 1985; in press); Rb/Sr ratios are low (Arth and others, 1984). Three representative diagrams of chondrite-normalized, extended rare-earth elements for this eastern suite are shown in Fig. 6D, samples 1-3.

*Coeval volcanic rocks* - We believe that silicic volcanic rocks near the Shinilikrok River in the Shungnak quadrangle (Patton and others, 1984) are coeval with the Late Cretaceous plutons of the eastern Yukon-Koyukuk basin. The volcanic complex, which underlies an area of about 170 $km^2$, consists of rhyolitic welded tuffs and dacitic flows, tuffs, and hypabyssal intrusive rocks and has yielded a K-Ar biotite age of 87 Ma (Patton and others, 1968). It rests unconformably on two western basin mid-Cretaceous plutons and has been intruded and thermally metamorphosed by the Wheeler Creek pluton of the Late Cretaceous eastern-basin suite. The spatial distribution, field relations, tightly constrained age, and chemical trends of the volcanic rocks strongly suggest that they are comagmatic with the compositionally similar Late Cretaceous plutons and that the latter intruded their own ejecta.

*Interpretation* - The plutons of the eastern Yukon-Koyukuk basin constitute a compositionally expanded calc-alkaline magmatic suite ranging from tonalite to granite. This compositional trend, together with the relatively high $Na_2O$ content, the high $Na_2O/K_2O$ ratio, the oxidized state of Fe, the abundance of hornblende in addition to biotite, and the presence of mafic xenoliths are all characteristics similar to those proposed by Chappel and White (1974) for I-type granites, which are granites generated with no continental crustal component.

SIR's and NIR's also suggest no involvement of Paleozoic or older crust in the generation of the plutonic magmas (Arth, 1985), but they are compatible with source areas that would include oceanic mantle and Mesozoic supracrustal rocks.

**Western Yukon-Koyukuk basin plutons**

*Distribution and age* - An east-west belt of 10 plutons and several small stocks, covering an area of about 1600 $km^2$, extends from the Shungnak quadrangle in the Yukon-Koyukuk basin to the margin of the Seward Peninsula in the Candle quadrangle. The belt continues onto the southeastern Seward Peninsula and St. Lawrence Island (Miller and Bunker, 1976). These plutons intruded the Upper Jurassic(?) and Lower Cretaceous volcanic rocks of the Koyukuk terrane and contributed debris to the mid- and Upper Cretaceous terrigenous sedimentary rocks, suggesting an Albian age that is confirmed by numerous K-Ar ages ranging from 113 to 99 Ma (Miller, 1971; 1972).

*Description* - This suite (Fig. 10) can be subdivided into two distinct but related series: a potassic series (KS) and a ultra-potassic series (UKS). The KS series is represented by $SiO_2$-saturated to slightly oversaturated rocks, such as monzonite, syenite, and quartz syenite, that are characterized by low quartz and abundant K-feldspar contents. Hornblende and clinopyroxene are the principal varietal mafic minerals. The KS series rocks average 4.5 percent $K_2O$; $SiO_2$ content ranges from 53.8 to 66.1 percent with a compositional gap to 73.9 percent. They have a lower abundance of incompatible elements and less radiogenic Sr than rocks of the UKS series. Representative chondrite-normalized, extended rare-earth element diagrams for the KS and for UKS series are shown in Fig. 6C, sample 2 and in Fig. 6C, sample 1 respectively.

The UKS series, which constitutes about 5 percent of the western Yukon-Koyukuk basin plutonic rocks, consists of single-feldspar, hypersolvus nepheline-bearing rock types including malignite, foyaite, ijolite, biotite pyroxenite, and pseudoleucite porphyry. $SiO_2$ ranges from 44.5 to 58.4 percent, $K_2O$ is as high as 16.6 percent, and the rocks are nepheline- and commonly leucite-normative (Miller, 1972). The UKS-series rocks define an ultrapotassic rock province consisting of at least 12 intrusive complexes and dike swarms that form a sinuous belt extending some 1300 km from the western Yukon-Koyukuk basin westward through the southeastern Seward Peninsula and St. Lawrence Island (Csejtey and Patton, 1974) to the east tip of the Chukotsk Peninsula, USSR (Miller, 1972).

*Interpretation* - The identifying characteristics of the KS and UKS series of the western Yukon-Koyukuk basin plutonic rocks are strong enrichment in $K_2O$ and depletion in $SiO_2$. Any model used to explain their petrogenesis must account for these features. The occurrence of the granitic plutons along a narrow linear belt in the Koyukuk terrane, despite marked differences in their composition, petrography, and age, suggests that the plutons are petrogenetically related. If, as we believe, the origin of the eastern Yukon-Koyukuk basin plutonic rocks is related to the melting of oceanic mantle and Mesozoic supracrustal rocks, possibly above a subduction zone, then the western Yukon-Koyukuk plutonic rocks may likewise have originated by melting of mantle material. This interpretation is supported by studies suggesting that ultrapotassic magmatic rocks generally originate in the mantle (Miller, 1972; 1985; in press). The gradual but strong increase in $K_2O$ from east to west in the Yukon-Koyukuk basin, however, and the corresponding increase in SIR's (Arth, in press), suggest that continental material also was involved in the generation of the plutonic magmas. Such an origin remains compatible with our interpretation that the Koyukuk terrane developed in an intraoceanic setting having no continental basement, providing that the mantle beneath the western Koyukuk terrrane is K-enriched subcontinental mantle, as has been suggested for the generation of K-rich magmas elsewhere (Varne, 1985).

**Summary**

The petrogenesis of the eastern Yukon-Koyukuk basin and the Ruby geanticline plutonic rocks appears relatively straight forward on the basis of mineralogical, chemical, and isotopic characteristics. The eastern Yukon-Koyukuk granitoids are confined to the basin and are typical of plutons derived from oceanic mantle or perhaps from Mesozoic supracrustal volcanic rocks. The Ruby geanticline granites are confined to the Ruby and overthrust Angayucham-Tozitna terranes and are typical of plutons generated in an anatectic continental environment. The boundary between these compositionally distinct granitic rocks is sharp--plutons of each suite are only about 15 km apart in the eastern Melozitna quadrangle--and it almost certainly coincides with the tectonic boundary that separates the basin from the geanticline.

The western Yukon-Koyukuk basin plutonic rocks are more enigmatic in origin than the other two suites. The boundary between the plutonic rock suites of the western and eastern parts of the basin, for example, is more gradational, particularly in isotopic systematics; and whereas the western Yukon-Koyukuk granitoids also appear to have been derived, at least in part, from the mantle, their mantle source could have been continental rather than oceanic.

## Late Cretaceous (Maastrichtian) and Early Tertiary (early Eocene) volcanic and plutonic rocks

**Distribution**

Late Cretaceous and early Tertiary magmatic activity occurred in a vast region of western Alaska, extending from the Arctic Circle to Bristol Bay. Rocks of this age that occur within the area described in this report include parts of two northeast-trending belts: the Kuskokwim Mountains belt (Wallace and Engebretson, 1984), which is located in the northern Kuskokwim Mountains and extends from the south side of the Kaltag fault to beyond the south edge of the area covered in this report; and the Yukon-Kanuti belt (Fig. 1 in Moll-Stalcup, in press), which lies northwest of the Kuskokwim Mountains belt and extends from the Arctic Circle southwest to the Kaltag fault and continues south of the fault on the west side of the Yukon River. There is no clear boundary between the Kuskokwim Mountains and the Yukon-Kanuti belts in the region south of the Kaltag fault. We divide the Upper Cretaceous and lower Tertiary volcanic rocks into two belts because the rocks from the Yukon-Kanuti belt are younger (65 to 47 Ma) than those in the Kuskokwim Mountains belt (72 to 60 Ma), and because the Yukon-Kanuti belt lies within the Yukon-Koyukuk basin, whereas the Kuskokwim Mountains belt overlies Precambrian(?) and Paleozoic continental rocks of the Ruby, Nixon Fork, and Minchumina terranes. The volcanic fields in both belts are commonly preserved in broad open synclines with dips generally less than 30°. Most of the synclines are fault-bounded on at least one flank.

**Description**

*Kuskokwim Mountains belt* -The Kuskokwim Mountains belt consists of volcanic fields, volcanoplutonic complexes and small plutons, dikes, and sills, all of which have K-Ar ages between 72 and 60 Ma. The belt occurs south and east of the Yukon River within this report area (Fig. 1 in Moll-Stalcup, in press) and extends into southwest Alaska beyond the area covered by this report. The volcanic fields consist chiefly of andesite (Nowitna), dacite, and rhyolite (Dishna and Sischu) or of basalt, andesite, dacite, and rhyolite (Yetna). The Sischu volcanic field also includes at its base a 25-m-thick section of nonmarine conglomerate, sandstone, and lignite containing palynomorphs of latest Cretaceous (Campanian to Maastrichtian) age (Patton and others, 1980). We interpret the volcanoplutonic complexes as eroded volcanic centers which now consist of circular outcrop areas of andesite flows and shallow hypabyssal rocks, intruded by small granitic stocks. Most of the volcanic rocks in the complexes are highly altered by the intrusions. Small dikes, sills, and stocks--many too small to be shown on published maps--occur throughout the Kuskokwim Mountains belt. These dikes, sills, and plugs are compositionally similar to the volcanic rocks, and range from monzodiorite to granite.

Present exposures in the Kuskokwim Mountains belt suggest that andesite, followed by rhyolite, are the overwhelmingly dominant volcanic rock types. Basalt is relatively uncommon and rocks having less than 52 percent $SiO_2$ are rare. Most of the intrusive rocks are intermediate to felsic in composition. Major element data on volcanic and plutonic rocks show trends typical of calc-alkalic suites: MgO, FeO*, $TiO_2$, $Al_2O_3$, and CaO decrease, and $K_2O$ and $Na_2O$ increase, with increasing $SiO_2$. $TiO_2$ is low (1.75 percent) and $Al_2O_3$ is relatively high (12 to 17 percent). None of the suites shows Fe-enrichment. $K_2O$ varies considerably from moderate (1.3 percent at 56 percent $SiO_2$) to very high values (4 percent at 56 percent $SiO_2$). Moderate to high-K suites plot in the subalkaline field on a total alkali vs. $SiO_2$ diagram. Very high K suites plot in the alkalic field and are classified as shoshonitic (Morrison, 1980). In the northern Kuskokwim Mountains the high-K calc-alkalic and shoshonitic suites tend to be older (71 to 65 Ma) than the moderate-K suites (68 to 62 Ma), although there is considerable overlap.

Igneous rocks of the Kuskokwim Mountains belt are characterized by a high incompatible-element content. In general, K correlates with other incompatible elements (Rb, Ba, Th, Nb, Ra, U, Sr, and LREE), such that the shoshonitic suites are most enriched in incompatible elements and the moderate-K suites are the least enriched. Furthermore, the major- and trace-element data indicate that all of the volcanic and plutonic rocks are highly enriched in K, Rb, Ba, Th, U, and Sr, and depleted in Nb-Ta relative to La--chemical characteristics typical of subduction-related volcanic arc rocks (Fig. 6E; Perfit and others, 1980; Thompson and others, 1984). Trace element ratios (Ba/Ta, Ba/La, La/Nb) of andesites in the northern Kuskokwim Mountains thus are similar to those in arc andesites (Gill, 1981), although these elements are somewhat more abundant in the high-K calc-alkalic and shoshonitic suites than in typical arc andesites.

Volcanic and plutonic rocks in the Kuskokwim Mountains belt have compositions that suggest they have undergone a significant amount of fractionation and many show isotopic and geochemical evidence of having interacted with continental crust. In the northern Kuskokwim Mountains--where the basement is Precambrian and Paleozoic carbonate rocks and schist of the Nixon Fork, Minchumina, and Ruby terranes--andesites in the Nowitna volcanic field have initial Sr isotope ratios (SIR) of 0.7045 to 0.7053 and trace-element abundances that suggest that the magmas have assimilated small amounts of continental crust during crystal fractionation (Moll and Arth, 1985). Rhyolites in the Sischu volcanic field have a high Sn, Be, U, W, and F content and SIR greater than 0.7080 (Moll and Arth, 1985; Moll and Patton, 1983), which suggest that they either were contaminated by large amounts of continental crust or were partial melts of the crust.

*Yukon-Kanuti belt* -Only three areas in the Yukon-Kanuti belt have been studied in detail (Moll-Stalcup, in press; Moll-Stalcup and others, in press): the Kanuti volcanic field in the Bettles quadrangle, the Yukon River area in the Ophir and Unalakleet quadrangles, and the Blackburn Hills field in the Unalakleet quadrangle. Extensive volcanic rocks of probable Tertiary age also occur farther south in the Holy Cross quadrangle but no age, petrologic, or geochemical data are available for those rocks.

Available data indicate that the Yukon-Kanuti belt consists chiefly of volcanic rocks varying from basalt to rhyolite, and minor intrusive rocks. The Kanuti field is composed predominantly of dacite, ranging in age from 59 to 56 Ma; the Yukon River rocks consist of basalt, andesite, dacite, and rhyolite, ranging in age from 54 to 48 Ma; and the Blackburn Hills volcanic field consists of basalt, andesite, rhyolite, and granodiorite, ranging in age from 65 to 56 Ma.

Data on the Yukon-Kanuti belt also show that a transition in chemistry and mineralogy occurred at about 56 Ma. Rocks older than 56 Ma are calc-alkalic and show the characteristic geochemical enrichments and depletions of arc rocks. Rocks 56 Ma or younger occur in the Yukon River area and the Blackburn Hills and are a mixed assemblage of calc-alkalic and mildly alkalic suites. The calc-alkalic rocks in the younger suite are chemically and mineralogically similar to those in the older suite. The alkalic rocks have less Nb-Ta depletion, less alkali enrichment, and mildly alkalic mineral assemblages (rhyolites: anorthoclase+hedenbergite; latites: anorthoclase+plagioclase+ biotite; and basalts: olivine+ plagioclase+clinopyroxene+ biotite). This chemical and mineralogical transition is not strongly reflected in the major-element data, which show a typical calc-alkaline affinity for all the rocks. Basalt, however, is restricted to the post-56-Ma assemblage, and three analyzed basalts have less Nb-Ta depletion and lower alkali/LREE ratios than basalts in typical arcs (Fig. 6E, sample 4) (Moll-Stalcup, in press).

Comparison of the pre-56 Ma rocks in the Yukon-Kanuti belt with those in the Kuskokwim Mountains belt shows that the two belts are compositionally similar in most respects. Rocks in the Yukon-Kanuti belt are moderate-to high-K calc-alkalic and range in composition from basalt to rhyolite. Major and trace element trends for the Yukon-Kanuti belt are similar to the Kuskokwim Mountains belt. However, the Yukon-Kanuti belt has lower $K_2O$ and incompatible element content than the Kuskokwim Mountains belt. Some of the variation in K and in incompatible element content may be due to the interaction of the Kuskokwim Mountains magmas with old continental crust of the Ruby, Nixon Fork, and Minchumina terranes. Basalts, andesites, dacites, and rhyolites in the Yukon-Kanuti belt have low SIR (0.7033-0.7053) and high NIR (0.51248-0.51290), which preclude significant interaction with old continental crust (Moll-Stalcup and Arth, in press). Some of the variation in $K_2O$ may be tectonically controlled, however, as suggested by the correlation of the $K_2O$ content with age, and by the occurrence of moderate-K, high-K, and shoshonitic rocks in the northern Kuskokwim Mountains overlying old continental crust.

**Interpretation and correlation**

The widespread calc-alkalic magmatism in western and southern Alaska between 75 and 65 Ma has been interpreted by Moll-Stalcup (in press) as representing a wide continental arc related to subduction of the Kula or Pacific plate beneath southern Alaska. She further interprets the transition to a mixed assemblage of mildly alkalic and calc-alkalic rocks at 56 Ma as marking the end of subduction-related magmatism in interior Alaska, and the transition to intraplate magmatism. The convergence angle (30°) between the present position of the Late Cretaceous and early Tertiary magmatic province and the plate-motion vector is close to the minimum required for arc magmatism (Wallace and Engebretson, 1984; Gill, 1981). Paleomagnetic data on a number of Late Cretaceous and early Tertiary volcanic fields, including the Nowitna and Blackburn Hills, indicate about 30° to 55° of counterclockwise rotation, but no major latitudinal displacement relative to North America since their formation (Hillhouse and Coe, in press; Thrupp and Coe, 1986). These data indicate that the magmatic belt may have had a convergence angle of 55° to 80° before the rotation of western Alaska in the Eocene. The age and $K_2O$ data also indicate that the magmatic arc was narrower and the K gradient across the arc steeper between 75 and 65 Ma, and that between 65 and 56 Ma, the arc broadened and the K-gradient was more gradual.

## Upper Eocene volcanic rocks

**Distribution**

Small volumes of volcanic rocks were erupted in western Alaska at about 40 Ma. Occurrences of these volcanic rocks within the area described in this report include three volcanic bodies in the Melozitna quadrangle: 1) a rhyolite field near the Indian River (41.6 and 39.9 Ma; Miller and Lanphere, 1981), 2) a basalt-rhyolite field in the Takhakhdona Hills (43.0 Ma; Harris, 1985), and 3) a rhyolite field near Dulbi Hot Springs (43.0 Ma; Patton and Moll, unpub. data, 1986). A fourth, little-known basalt field occurs at the boundary of the Unalakleet and Holy Cross quadrangles along the Yukon River (42.7 Ma; Harris, 1985). All of these volcanic fields are situated along the southeast margin of the Yukon-Koyukuk basin where the basin is relatively shallow.

**Description**

The upper Eocene volcanic rocks in western Alaska have not been well studied. The Indian River, Takhakhdona Hills, and Dulbi Hot Springs areas are described by Patton and others (1978) as consisting of rhyolite tuff, flows, and breccia and basalt flows. Obsidian occurs at the Indian Mountain locality. Four chemical analyses of basalt, andesite, dacite, and rhyolite obtained from the Takhakhdona Hills (Patton and Moll-Stalcup, unpub. data, 1987) suggest that the basalt is anorogenic and mildly alkalic. The andesite and dacite show "arc-like" enrichments and depletions similar to those in the nearby Late Cretaceous and early Tertiary Yukon-Kanuti belt. The other areas consist of basalt and rhyolite of uncertain affinity and may represent a bimodal suite related to movement along the many faults in western interior Alaska. The upper Eocene volcanic rocks are flat lying or only broadly folded, with dips generally less than 5°.

## Tertiary nonmarine coal-bearing deposits

Small deposits of poorly consolidated nonmarine clay shale, sandstone, conglomerate, and lignite that contain palynomorphs ranging in age from Oligocene to Pliocene are scattered along or near the Kaltag fault in the Unalakleet (Patton and Moll, 1985), Norton Bay (Patton, unpub. map, 1987), Melozitna (Patton and others, 1978), and Tanana (J.P. Bradbury, written commun., 1979) quadrangles. Float of lignite containing spores and pollen of Tertiary age has also been reported along the Tozitna river in the Tanana quadrangle (Chapman and others, 1982) and on the Mangoak River and near Elephant Point in the Selawik quadrangle (Patton, 1973). All the deposits appear to be of limited extent and confined to small structural or topographic basins.

## Upper Cenozoic basalt

### Distribution

Late Cenozoic volcanism was widespread along the westernmost margin of Alaska and on the adjacent Bering Sea shelf. Two large volcanic fields occur within the area covered by this report: one along the south shore of Norton Sound in the St. Michael and Unalakleet quadrangles, and the other a less well-studied field southeast of Kotzebue Sound in the Candle, Selawik, and Kateel River quadrangles (Figs. 1, 3). Two small fields of olivine basalt of uncertain, but probable late Tertiary or Quaternary age, also have been mapped on the Ruby geanticline in the southeastern part of the Bettles quadrangle (Patton and Miller, 1973).

### Description

The St. Michael volcanic field, covering about 2000 km$^2$, is located along the south shore of Norton Sound and consists of tholeiite and alkali olivine basalt flows, basanite tuffs, cones, and maar craters. A young cone at Crater Mountain is composed of basanite, which contains lherzolite nodules. The base of the volcanic field gives K-Ar ages of 3.25 and 2.80 Ma (D.L. Turner, written comm., 1987). Several steep-sided cones, which lack frost brecciation and lichen cover, are probably Holocene or Pleistocene in age.

The large field southeast of Kotzebue Sound covers about 4,500 km$^2$ and consists of vesicular olivine basalt flows and cones. Some of the cones contain peridotite nodules. None of the flows is dated, but they are presumed to be late Tertiary or Pleistocene in age and are correlative with the Imuruk Volcanics on the adjacent Seward Peninsula (Patton, 1967).

Chemical data on the St. Michael field and on a number of the volcanic fields located outside this report area (St. Lawrence Island, Nunivak Island, and the Seward Peninsula) indicate that all of the volcanic fields are compositionally similar, ranging from nephelinite through basanite through alkali olivine basalt to olivine tholeiite (Hoare, unpub. data, 1980; Swanson and Turner, unpub. data, 1987; Moll-Stalcup, in press). The St. Michael field also has quartz tholeiite and hawaiite. Most of the volcanic rocks have Mg numbers (100 Mg/Mg + $Fe^{2+}$) greater than 65, which implies they are primary or near-primary melts of mantle peridotite. Alkali olivine basalt and tholeiite represent at least 95 percent of the volcanic rocks present in all the volcanic fields, and they form broad shield volcanoes. Basanite and nephelinite compose 2-3 percent of the rocks, and eruptions of those magmas both precede and postdate eruptions of the more voluminous, less alkalic basalts (Hoare, unpub. data, 1980). Basanite and nephelinite occur in steep cones, short viscous flows, and tephra deposits emanating from the maar crater. They commonly contain xenoliths of lherzolite, pyroxene granulite, dunite, harzburgite, chromite, gabbro, or Cretaceous sedimentary bedrock, and megacrysts of anorthoclase, clinopyroxene, and kaersutite.

Trace-element data from the St. Michael field (Fig. 6F) indicate that the rocks are LREE-enriched, and that the LREE content increases with alkalinity. All the rocks have positive Nb-Ta anomalies similar to oceanic island basalts (OIB). SIR on the St. Michael field is 0.7027 (Mark, 1971)--similar to values for Nunivak Island and the Pribilof Islands, both of which plot in the field where OIB and MORB overlap on $^{143}Nd/^{144}Nd$-$^{87}Sr/^{86}Sr$ diagrams (Von Drach and others, 1986; Roden and others, 1984).

**Interpretation and correlation**

Bering Sea basalts are strikingly similar to Hawaiian lavas in composition, despite having formed in a different tectonic environment. The widespread Bering Sea basalts are not aligned along a hot-spot trace; rather they seem to be associated with extensional faulting. Young cones are aligned east-west defining a fracture or fault in the St. Michael field, as well as on Nunivak and St. Lawrence Island. The volcanic fields south of the Selawik Hills are bounded on the north by several east-west trending faults and the basalts on the Seward Peninsula are associated with east-west trending faults. Moll-Stalcup, (in press) believes that the Bering Sea basalts represent intraplate volcanism associated with regional north-south extension in the Bering Sea region in late Cenozoic time.

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## FIGURE CAPTIONS

1. Index map of west-central Alaska showing location of quadrangles (1:250,000) and outline of area described in this report.

2. Correlation of pre-mid-Cretaceous lithotectonic terranes and mid-Cretaceous and younger overlap assemblages.

3. Pre-mid-Cretaceous lithotectonic terranes and mid-Cretaceous and younger overlap assemblages (modified from Jones and others, 1987; Silberling and others, in press). Schematic cross sections along lines A-A' to E-E' shown in Figure 5.

4. Index map showing location of major tectonic elements in west-central Alaska.

5. Schematic cross-sections A-A' to E-E' illustrating gross structural features of west-central Alaska. Location of sections shown in Figure 3.

6. Chondrite-normalized extended rare-earth element diagrams (spidergrams using normalization factor from Thompson and others, 1984) for igneous rocks in western Alaska. A, Angayucham-Tozitna (composite) terrane (Box and Patton, unpublished data, 1987; B, Koyukuk terrane (Box and Patton, in press); C, Ruby geanticline and western Yukon-Koyukuk basin (T.P. Miller and J.G. Arth, written commun., 1987); D, Eastern Yukon-Koyukuk basin (Miller and J.G. Arth, written commun., 1987); E, Late Cretaceous-early Tertiary volcanic fields (Moll-Stalcup, in press); F, Upper Cenozoic Bering Sea basalts. Pribilof Island basalts from Lee-Wong and others (1979) and F. Lee-Wong (written commun., 1987); St. Michael basalts from E.J. Moll-Stalcup (unpubl. data, 1987); G, Examples of chondrite-normalized diagrams from modern tectonic settings (Thompson and others, 1984).

7. Tectonic model for evolution of the (composite) Angayucham-Tozitna terrane. A, In Middle and Late Jurassic time the upper part of the Narvak thrust panel of the Angayucham-Tozitna terrane is subducted beneath the Kanuti thrust panel at an intraoceanic arc-trench system an unknown distance from the continental margin. B, By latest Jurassic and Early Cretaceous time the continental margin becomes involved in the arc-trench system with successive subduction of the lower part of the Narvak panel, the Slate Creek thrust panel, and finally the continental rocks of the Arctic Alaska and Ruby terranes.

8. Map of Yukon-Koyukuk basin showing distribution of mid- and Upper Cretaceous terrigenous sedimentary rocks and of Middle Jurassic to Early Cretaceous Koyukuk terrane. Paleocurrent arrows indicate principal direction of sediment transport.

9. Diagrammatic sketches showing possible evolution of Kobuk-Koyukuk and Lower Yukon subbasins. A, Hypothetical configuration of subbasins during deposition of graywacke and mudstone turbidites in Early Cretaceous (Albian) time. B, Central and southern part of Yukon-Koyukuk basin strongly compressed (heavy arrows) and offset by Kaltag fault during Late Cretaceous and early Tertiary time.

10. Modal plots of plutonic suites in the Ruby terrane, eastern Yukon-Koyukuk basin, and western Yukon-Koyukuk basin.

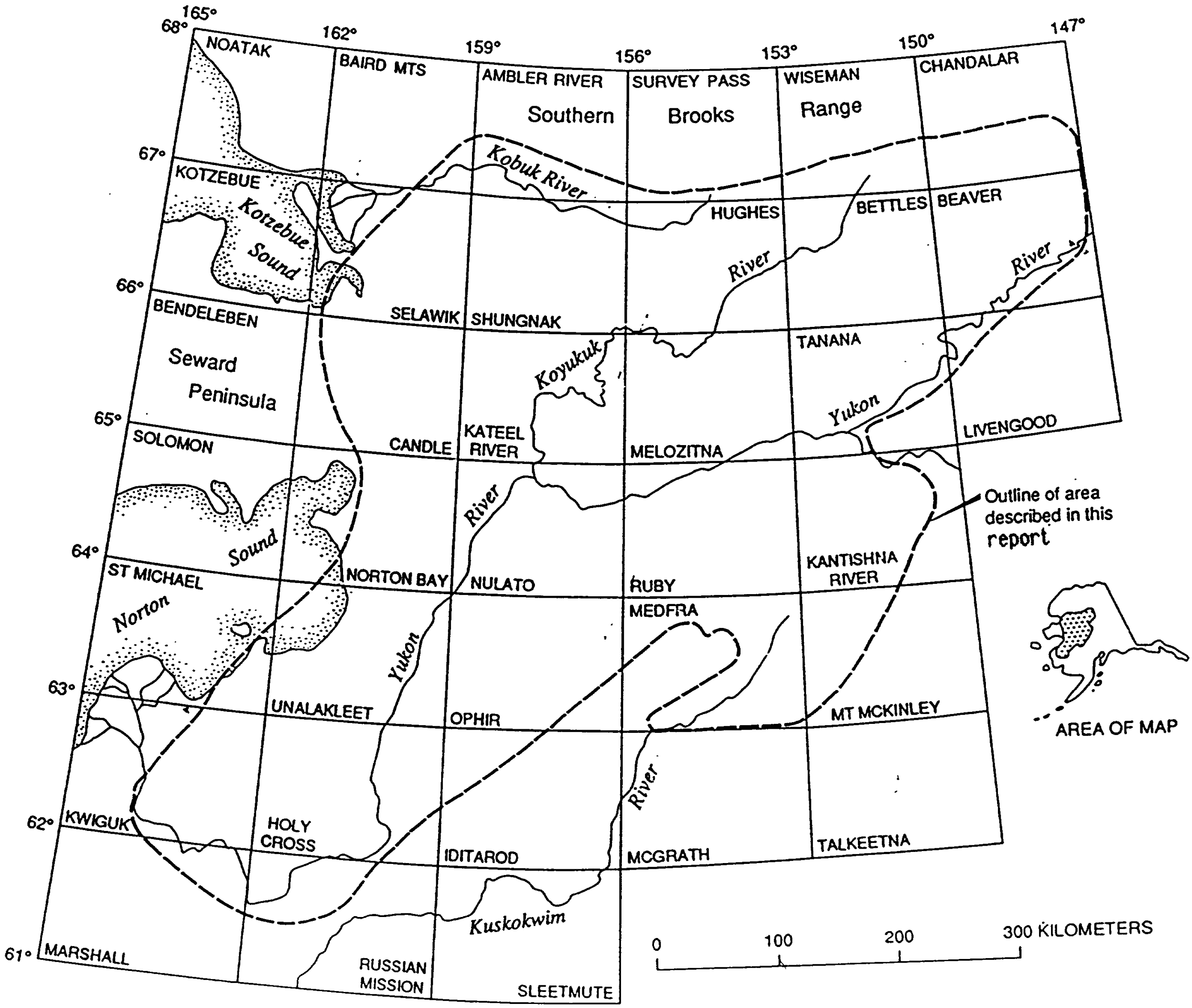
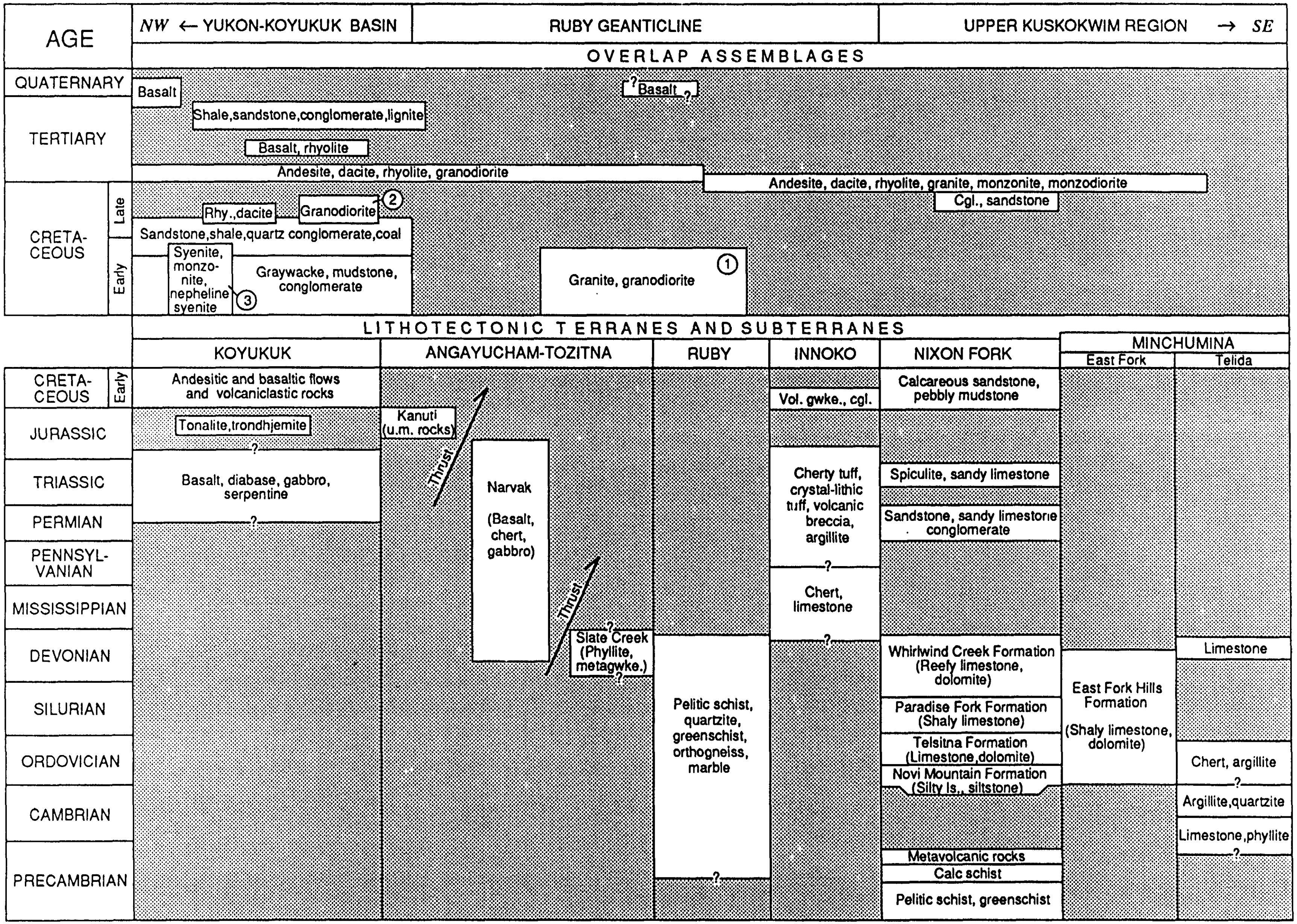
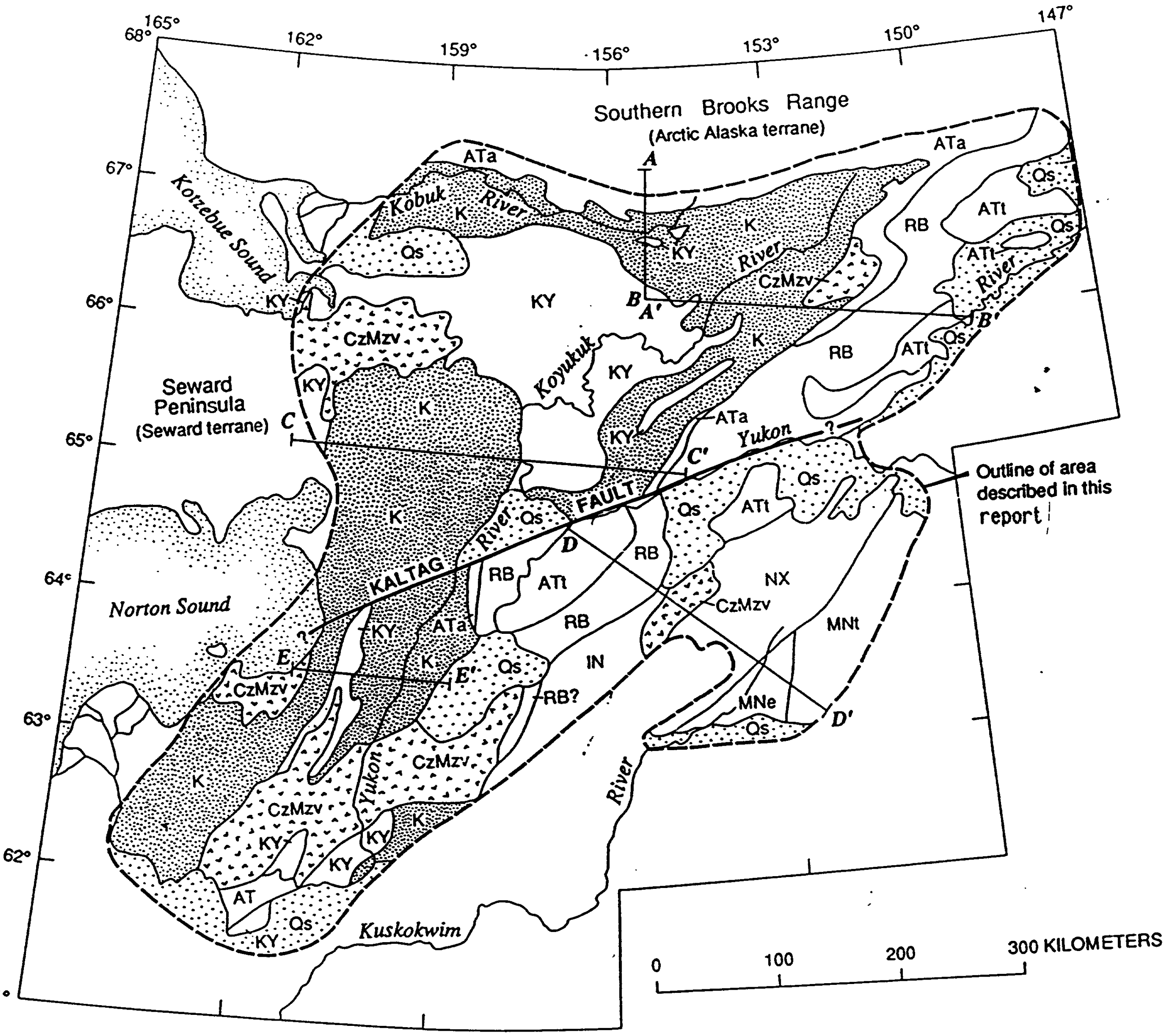

165°
68°
162°
159°
156°
153°
150°
147°
NOATAK
BAIRD MTS
AMBLER RIVER
SURVEY PASS
WISEMAN
CHANDALAR
Southern
Brooks
Range
67°
KOTZEBUE
Kotzebue
Sound
Kobuk River
HUGHES
BETTLES
BEAVER
River
River
66°
BENDELEBEN
SELAWIK
SHUNGNAK
TANANA
Seward
Peninsula
Koyukuk
Yukon
65°
SOLOMON
CANDLE
KATEEL RIVER
MELOZITNA
LIVENGOOD
River
Outline of area described in this report
Sound
64°
ST MICHAEL
Norton
NORTON BAY
NULATO
RUBY
KANTISHNA RIVER
MEDFRA
Yukon
63°
UNALAKLEET
OPHIR
MT MCKINLEY
AREA OF MAP
River
62°
KWIGUK
HOLY CROSS
IDITAROD
MCGRATH
TALKEETNA
Kuskokwim
61°
MARSHALL
RUSSIAN MISSION
SLEETMUTE
0
100
200
300 KILOMETERS

Figure 1




① Ruby geanticline plutons ② Eastern Yukon-Koyukuk basin plutons ③ Western Yukon-Koyukuk basin plutons

Figure 2




## EXPLANATION

### Overlap assemblages

| | |
|---|---|
| Qs | Surficial deposits (Quaternary) |
| CzMzv | Volcanic rocks (Cenozoic and upper Mesozoic) |
| K | Terrigenous sedimentary rocks (mid and Upper Cretaceous) |

### Lithotectonic terranes

Minchumina terrane

| | |
|---|---|
| MNt | Telida subterrane |
| MNe | East Fork subterrane |
| NX | Nixon Fork terrane |
| IN | Innoko terrane |
| RB | Ruby terrane |
| AT | Angayucham-Tozitna (composite) terrane |
| ATa | Angayucham belt |
| ATt | Tozitna belt |
| KY | Koyukuk terrane |
| —— | Contact |

Figure 3

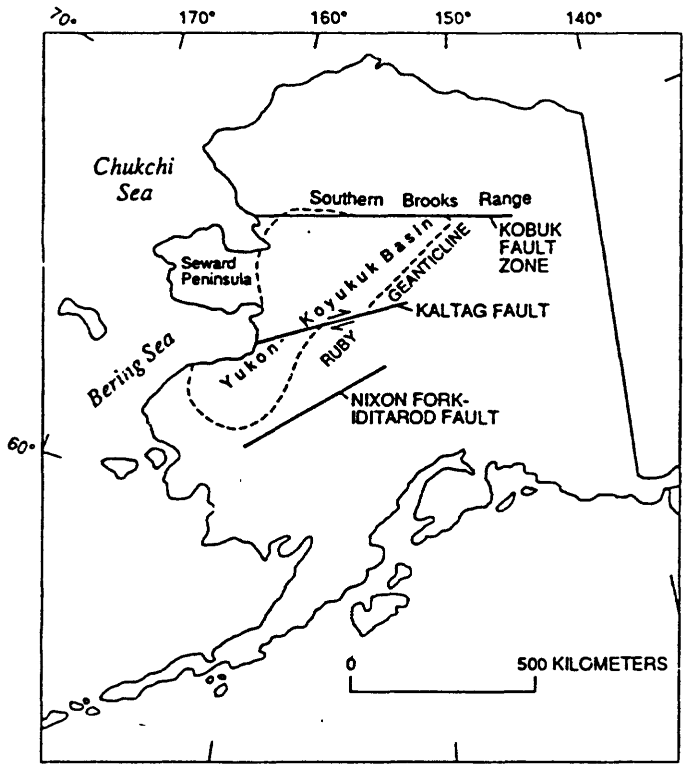

70°
170°
160°
150°
140°
60°
Chukchi Sea
Southern Brooks Range
KOBUK FAULT ZONE
Seward Peninsula
Koyukuk Basin
GEANTICLINE
KALTAG FAULT
Bering Sea
Yukon
RUBY
NIXON FORK-IDITAROD FAULT
0
500 KILOMETERS

Figure 4

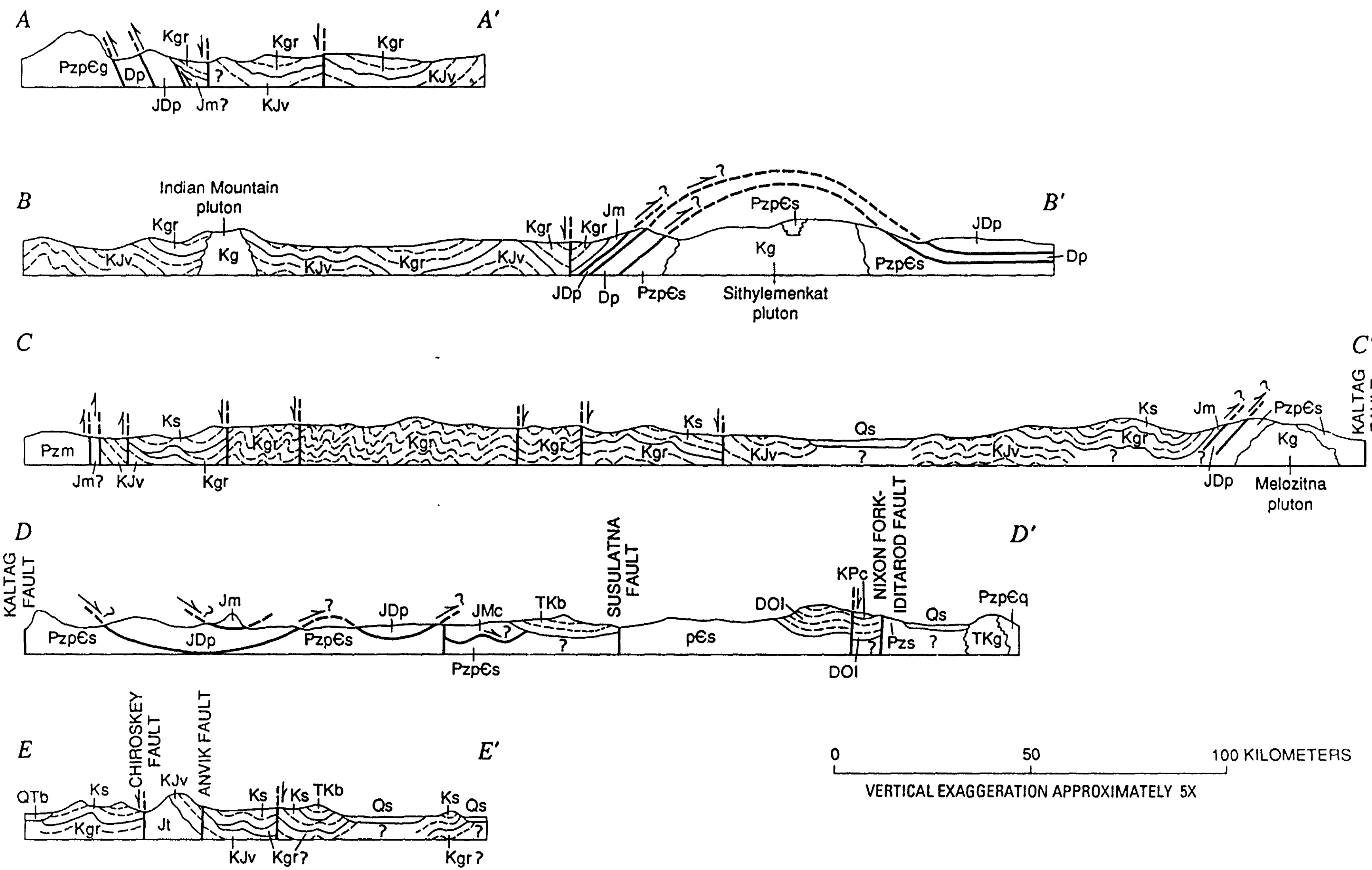

A
A'
PzpЄg
Dp
JDp
Jm?
Kgr
KJv
B
B'
Indian Mountain pluton
Kg
Jm
JDp
PzpЄs
Sithylemenkat pluton
Dp
C
C'
Pzm
Ks
Kgn
Qs
KALTAG FAULT
Melozitna pluton
D
D'
SUSULATNA FAULT
NIXON FORK-IDITAROD FAULT
JMc
TKb
pЄs
DOI
KPc
Pzs
TKg
PzpЄq
E
E'
QTb
CHIROSKEY FAULT
ANVIK FAULT
Jt
Kgr?
0
50
100 KILOMETERS
VERTICAL EXAGGERATION APPROXIMATELY 5X

Figure 5

# EXPLANATION

## Overlap assemblages

- **Qs** — Surficial deposits (Quaternary)
- **QTb** — Basalt (Quaternary to late Tertiary)
- **TKg** — Granitic rocks (early Tertiary and Late Cretaceous)
- **TKb** — Basalt, andesite rhyolite (early Tertiary and Late Cretaceous)
- **Kg** — Granitic rocks (Cretaceous)
- **Ks** — Sandstone, shale, conglomerate (Late and mid-Cretaceous)—Fluvial and deltaic deposits
- **Kgr** — Graywacke, mudstone, conglomerate (mid-Cretaceous)—Turbiditic deposits

## Pre- mid-Cretaceous terranes

Koyukuk terrane
- **KJv** — Andesite flows and volcaniclastic rocks (Early Cretaceous and Jurassic ?)
- **Jt** — Tonalite and trondhjemite (Jurassic)—Locally includes undated but probably older small bodies of basalt, diabase, gabbro, serpentine

Angayucham-Tozitna terrane
- Kanuti thrust panel: **Jm** — Mafic and ultramafic rocks (Jurassic)
- Narvak thrust panel: **JDp** — Pillow basalt, chert, gabbro (Jurassic to Devonian)
- Slate Creek thrust panel: **Dp** — Phyllite, metagraywacke (Devonian)

Ruby terrane
- **Pzp€s** — Schist, greenstone (Paleozoic and Precambrian ?)

Seward terrane
- **Pzm** — Marble, schist (early Paleozoic)

Innoko terrane
- **JMc** — Chert, volcaniclastic rocks (Jurasssic to Mississippian)

Nixon Fork terrane
- **KPc** — Quartz-carbonate clastic rocks, spiculite (Early Cretaceous to Permian)
- **DOl** — Limestone, dolomite (Devonian to Ordovician)
- **p€s** — Schist, metavolcanic rocks (Precambrian)

Minchumina terrane
- East Fork subterrane: **Pzs** — Shaly limestone and dolomite (early Paleozoic)
- Telida subterrane: **Pzp€q** — Quartzite, chert, phyllite, limestone (early Paleozoic and Precambrian ?)

Arctic Alaska terrane
- **Pzp€g** — Schist, quartzite, greenstone (early Paleozoic and Precambrian ?)

——— Contact

- - - - - Bedding or flow layering

⇀ Fault—Arrow shows direction of relative movement

Figure 5 explanation

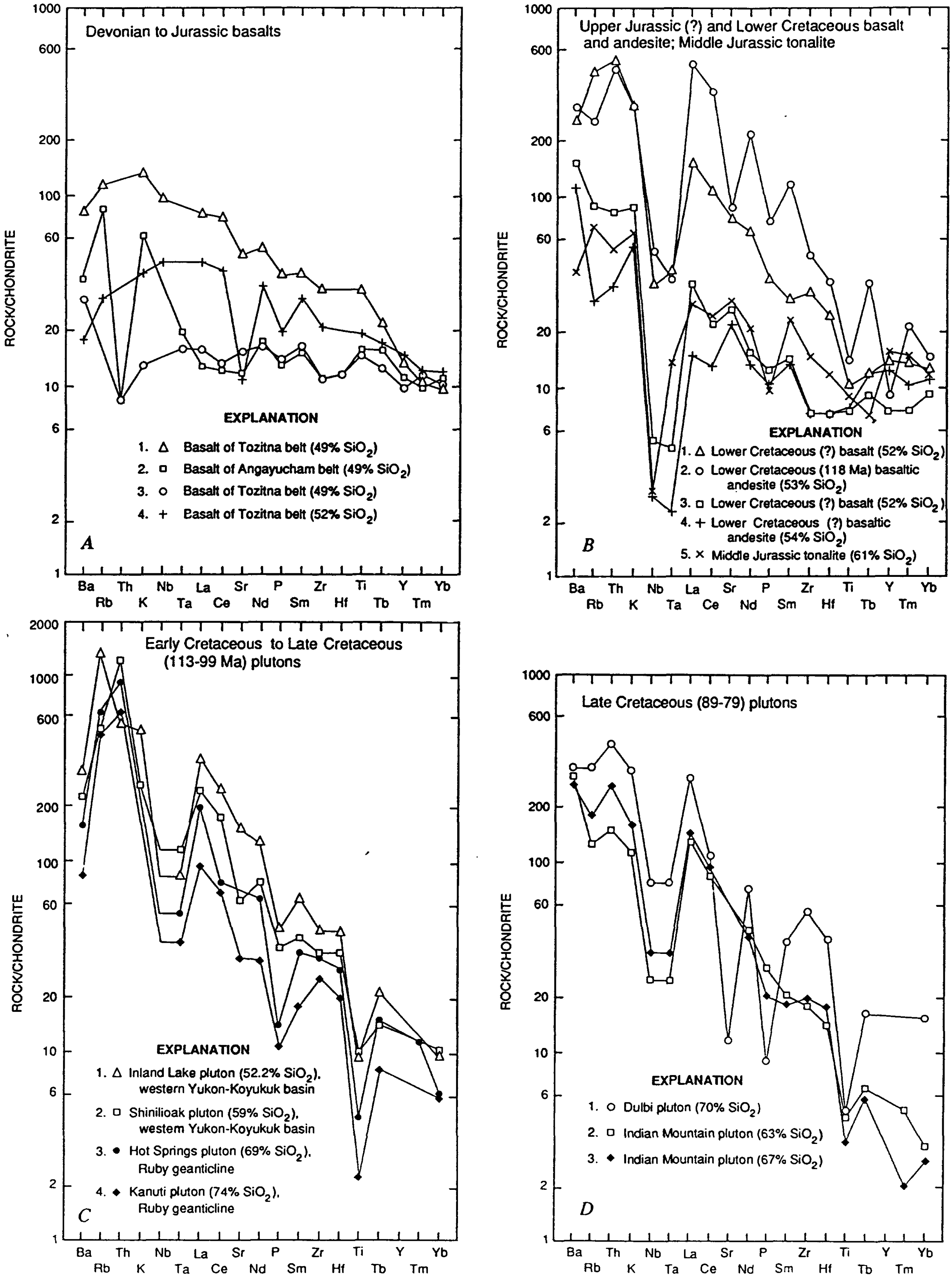
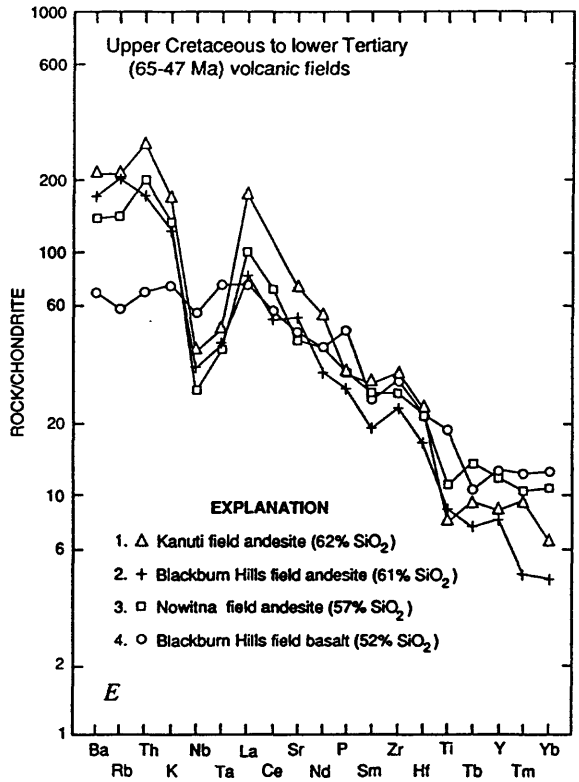
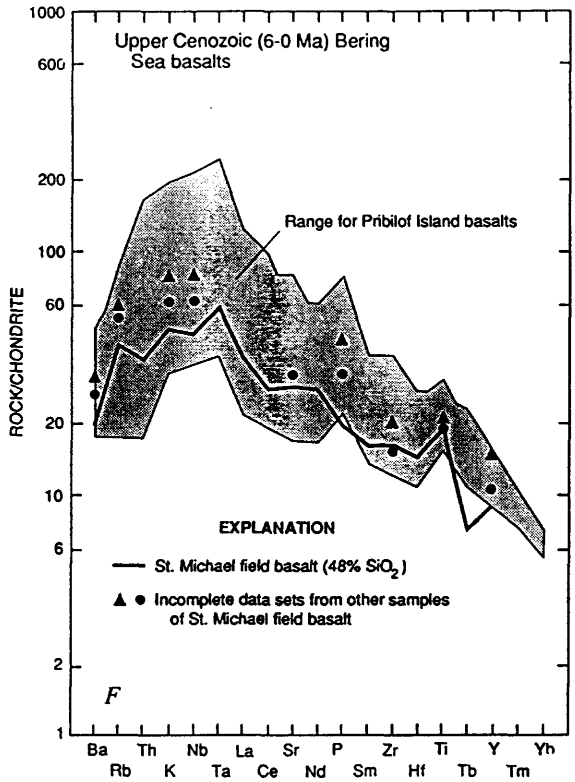

Devonian to Jurassic basalts
ROCK/CHONDRITE
EXPLANATION
1. △ Basalt of Tozitna belt (49% SiO2)
2. □ Basalt of Angayucham belt (49% SiO2)
3. ○ Basalt of Tozitna belt (49% SiO2)
4. + Basalt of Tozitna belt (52% SiO2)
A
Ba Rb Th K Nb Ta La Ce Sr Nd P Sm Zr Hf Ti Tb Y Tm Yb
Upper Jurassic (?) and Lower Cretaceous basalt and andesite; Middle Jurassic tonalite
EXPLANATION
1. △ Lower Cretaceous (?) basalt (52% SiO2)
2. ○ Lower Cretaceous (118 Ma) basaltic andesite (53% SiO2)
3. □ Lower Cretaceous (?) basalt (52% SiO2)
4. + Lower Cretaceous (?) basaltic andesite (54% SiO2)
5. × Middle Jurassic tonalite (61% SiO2)
B
Early Cretaceous to Late Cretaceous (113-99 Ma) plutons
EXPLANATION
1. △ Inland Lake pluton (52.2% SiO2), western Yukon-Koyukuk basin
2. □ Shinilioak pluton (59% SiO2), western Yukon-Koyukuk basin
3. ● Hot Springs pluton (69% SiO2), Ruby geanticline
4. ◆ Kanuti pluton (74% SiO2), Ruby geanticline
C
Late Cretaceous (89-79) plutons
EXPLANATION
1. ○ Dulbi pluton (70% SiO2)
2. □ Indian Mountain pluton (63% SiO2)
3. ◆ Indian Mountain pluton (67% SiO2)
D

Figure 6A-D


Upper Cretaceous to lower Tertiary (65-47 Ma) volcanic fields
ROCK/CHONDRITE
EXPLANATION
1. Δ Kanuti field andesite (62% $SiO_2$)
2. + Blackburn Hills field andesite (61% $SiO_2$)
3. □ Nowitna field andesite (57% $SiO_2$)
4. ○ Blackburn Hills field basalt (52% $SiO_2$)
E
Ba Th Nb La Sr P Zr Ti Y Yb
Rb K Ta Ce Nd Sm Hf Tb Tm


Upper Cenozoic (6-0 Ma) Bering Sea basalts
Range for Pribilof Island basalts
ROCK/CHONDRITE
EXPLANATION
St. Michael field basalt (48% $SiO_2$)
▲ ● Incomplete data sets from other samples of St. Michael field basalt
F
Ba Th Nb La Sr P Zr Ti Y Yb
Rb K Ta Ce Nd Sm Hf Tb Tm

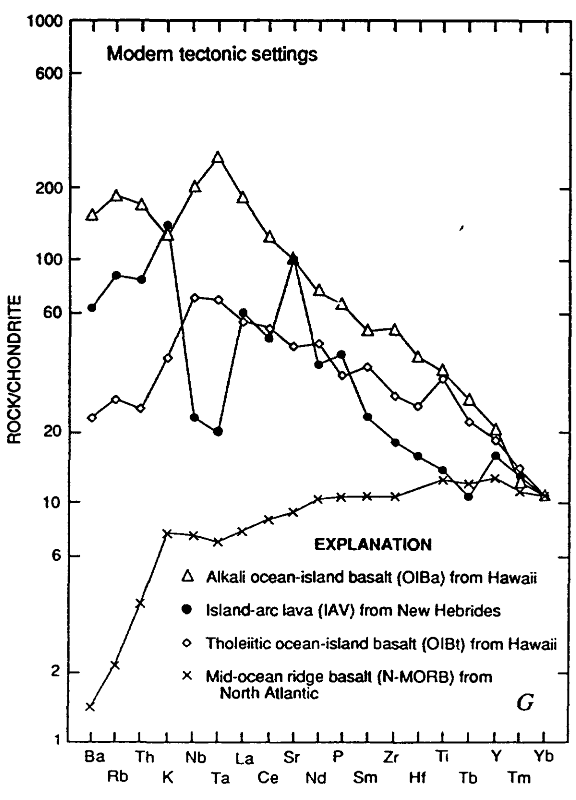

Modern tectonic settings
ROCK/CHONDRITE
EXPLANATION
Δ Alkali ocean-island basalt (OIBa) from Hawaii
● Island-arc lava (IAV) from New Hebrides
◇ Tholeiitic ocean-island basalt (OIBt) from Hawaii
× Mid-ocean ridge basalt (N-MORB) from North Atlantic
G
Ba Th Nb La Sr P Zr Ti Y Yb
Rb K Ta Ce Nd Sm Hf Tb Tm

Figure 6E-G

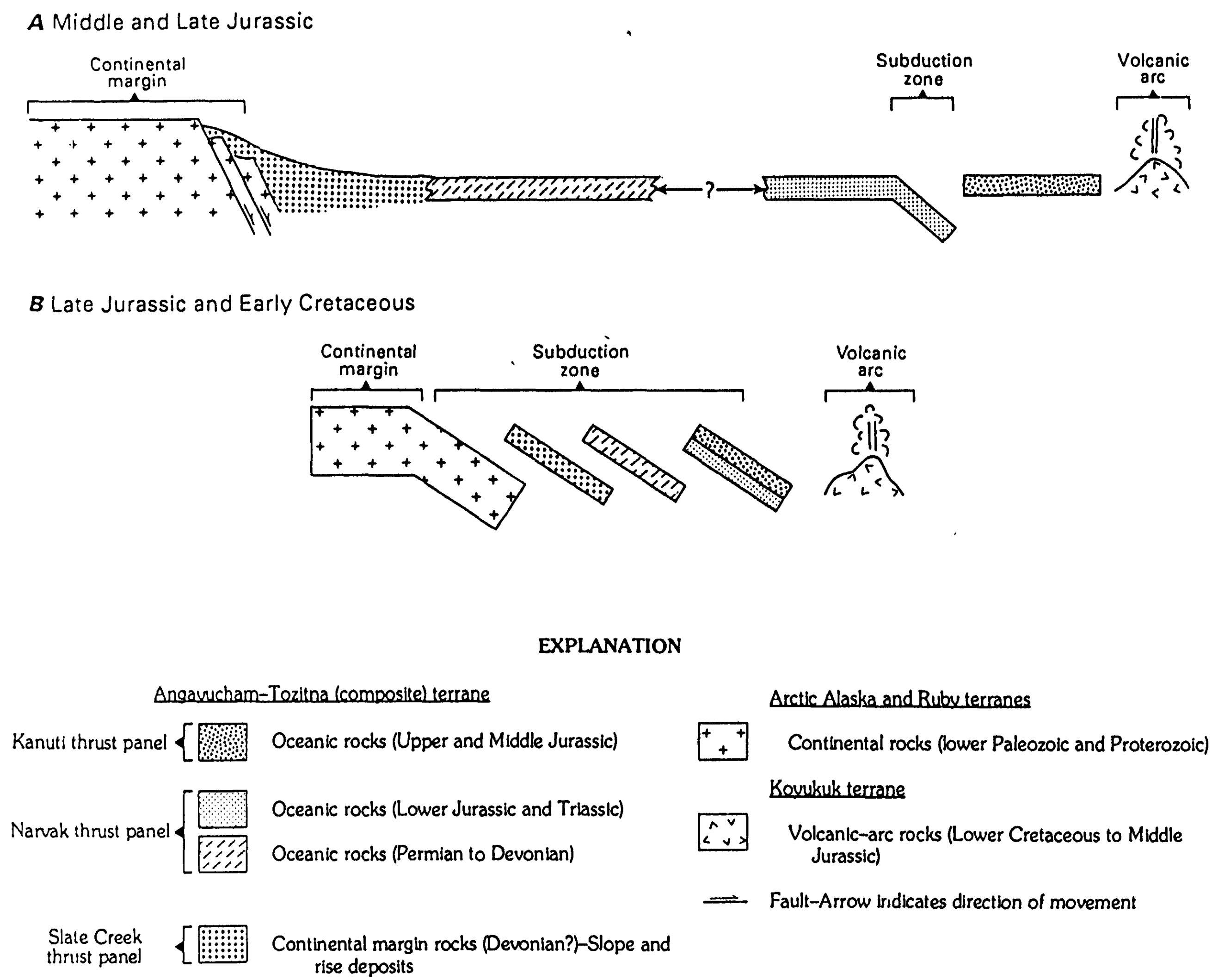
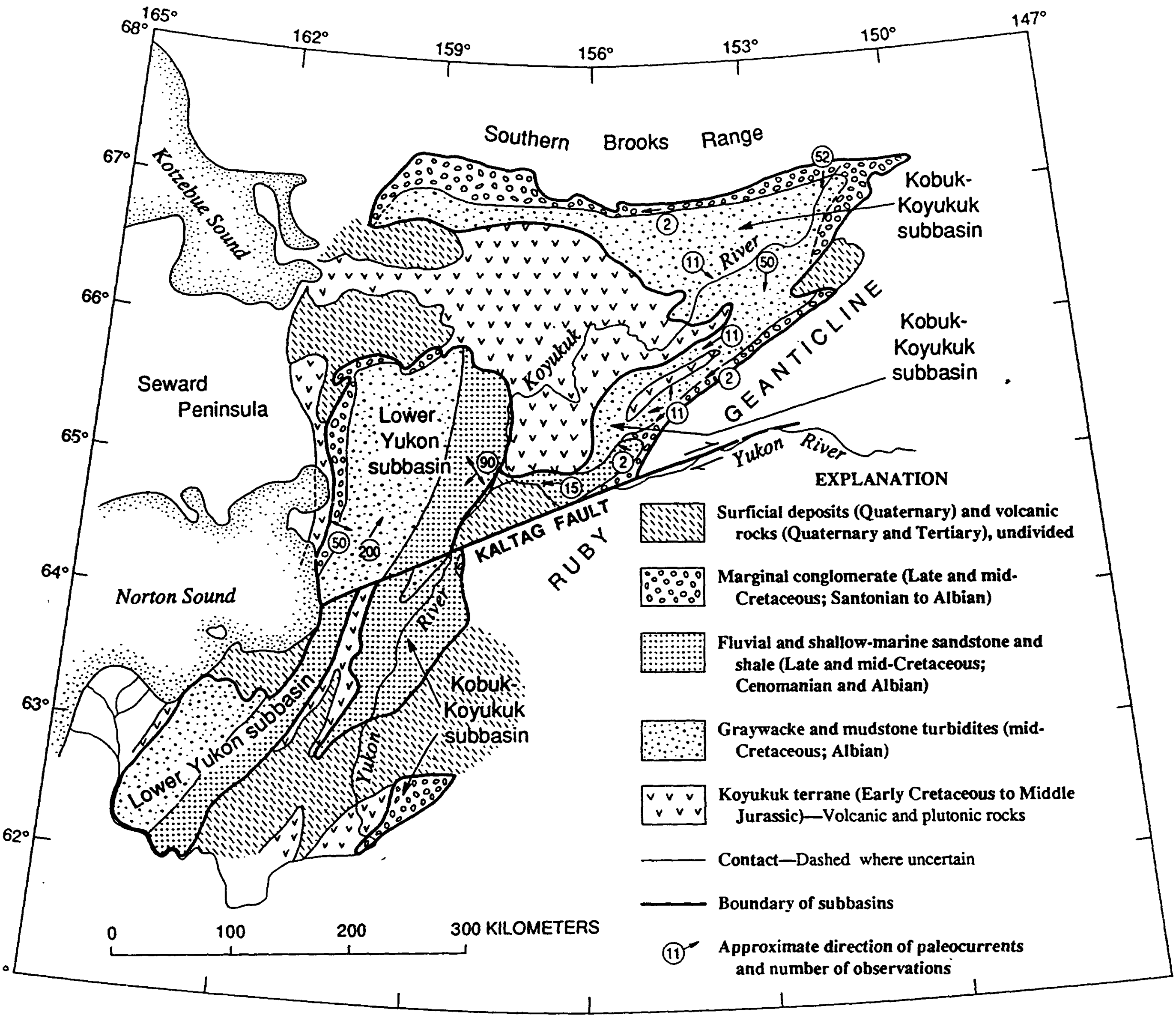

A Middle and Late Jurassic
Continental margin
Subduction zone
Volcanic arc
?
B Late Jurassic and Early Cretaceous
Continental margin
Subduction zone
Volcanic arc
EXPLANATION
Angayucham–Tozitna (composite) terrane
Kanuti thrust panel
Oceanic rocks (Upper and Middle Jurassic)
Narvak thrust panel
Oceanic rocks (Lower Jurassic and Triassic)
Oceanic rocks (Permian to Devonian)
Slate Creek thrust panel
Continental margin rocks (Devonian?)–Slope and rise deposits
Arctic Alaska and Ruby terranes
Continental rocks (lower Paleozoic and Proterozoic)
Koyukuk terrane
Volcanic-arc rocks (Lower Cretaceous to Middle Jurassic)
Fault–Arrow indicates direction of movement

Figure 7



165°
68°
162°
159°
156°
153°
150°
147°
67°
66°
65°
64°
63°
62°
61°
Southern Brooks Range
Kotzebue Sound
Seward Peninsula
Norton Sound
Kobuk-Koyukuk subbasin
Kobuk-Koyukuk subbasin
Kobuk-Koyukuk subbasin
Lower Yukon subbasin
Lower Yukon subbasin
Koyukuk River
Yukon River
Yukon River
RUBY GEANTICLINE
KALTAG FAULT
0 100 200 300 KILOMETERS
EXPLANATION
Surficial deposits (Quaternary) and volcanic rocks (Quaternary and Tertiary), undivided
Marginal conglomerate (Late and mid-Cretaceous; Santonian to Albian)
Fluvial and shallow-marine sandstone and shale (Late and mid-Cretaceous; Cenomanian and Albian)
Graywacke and mudstone turbidites (mid-Cretaceous; Albian)
Koyukuk terrane (Early Cretaceous to Middle Jurassic)—Volcanic and plutonic rocks
Contact—Dashed where uncertain
Boundary of subbasins
Approximate direction of paleocurrents and number of observations


Figure 8

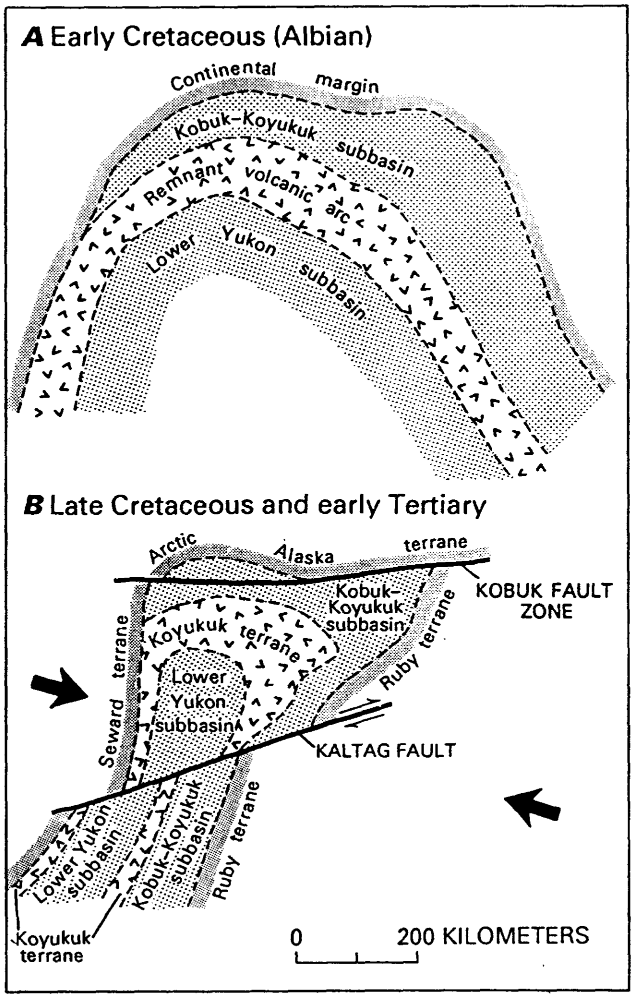

A Early Cretaceous (Albian)
Continental margin
Kobuk-Koyukuk subbasin
Remnant volcanic arc
Lower Yukon subbasin
B Late Cretaceous and early Tertiary
Arctic Alaska terrane
KOBUK FAULT ZONE
Kobuk-Koyukuk subbasin
Koyukuk terrane
Lower Yukon subbasin
Seward terrane
Ruby terrane
KALTAG FAULT
Lower Yukon subbasin
Kobuk-Koyukuk subbasin
Ruby terrane
Koyukuk terrane
0 200 KILOMETERS

Figure 9

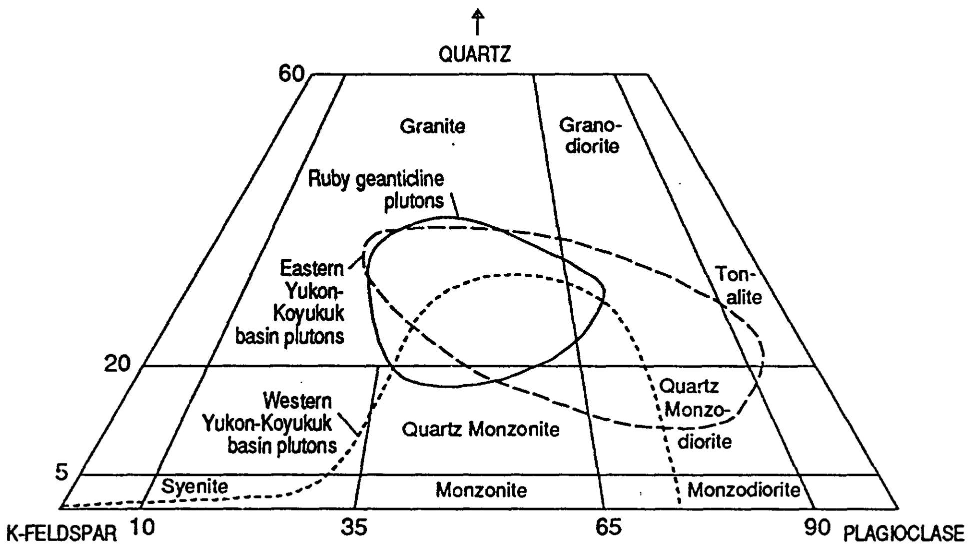

QUARTZ
60
Granite
Grano-
diorite
Ruby geanticline
plutons
Eastern
Yukon-
Koyukuk
basin plutons
Ton-
alite
20
Western
Yukon-Koyukuk
basin plutons
Quartz Monzonite
Quartz
Monzo-
diorite
5
Syenite
Monzonite
Monzodiorite
K-FELDSPAR
10
35
65
90
PLAGIOCLASE

Figure 10