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Thematic Mapper Study of Alaskan Ophiolites

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Summary of Research: August, 1986 to January, 1987

Introduction

The major objectives of this project are to use Landsat Thematic Mapper (TM) images to produce improved geologic maps of the ophiolites of the Brooks Range, and to recognize regional-scale structures that might affect the spatial distribution of the ophiolites. From the Thematic Mapper data, we have obtained significant new information concerning the distribution of rock types and structures that could not easily be acquired with conventional geologic studies. The information obtained from the TM data, in combination with other geologic data, is being used to further our understanding of the tectonic evolution of the Brooks Range. An example of our results to date is described in this report. Results of our work in the Maiyumerak Mountains area of the western Brooks Range are used to illustrate the kind of information being obtained with the Landsat TM data, and the way that the information is being integrated with other geologic data.

The physiographic provinces of northern Alaska are shown in Figure 1. The Brooks Range is a fold-thrust belt of Late Jurassic and Early Cretaceous age, thought to have formed north of a southward-dipping subduction zone. The thrust sheets of the Brooks Range consist of oceanic crust and mantle (termed ophiolite), forming the structurally highest sheets, and platform sedimentary rocks. Sediments shed from the uplifted Brooks Range were deposited to the north in the Colville Basin and to the south in the Yukon-Koyukuk Basin during Cretaceous time. The distribution of ophiolite exposures in the western Brooks Range is shown in Figure 2, a TM Band 7 mosaic of two scenes (path 80, rows 12 and 13). The location of the mosaic is shown in Figure 1. The major ophiolite exposures are Asik Mountain, the Maiyumerak Mountains, Avan Hills, and Misheguk Mountain.

The Maiyumerak Mountains are exposures of mafic volcanic rock that were mapped as a single basalt unit during reconnaissance mapping by USGS workers; lithologic units were not differentiated nor were structures identified. During one week of reconnaissance mapping in the central Maiyumeraks in 1985, we recognized two distinct basalts separated by a north-south trending fault. The eastern basalt weathers reddish-brown and consists of two units, a sheeted dike unit (consisting entirely of parallel, planar dikes) that is overlain by a unit of massive and pillowed flows. The western basalt weathers grey and consists of flows intruded by randomly oriented dikes. The distribution of these rocks is shown in Figure 3. The extremely rugged terrain of the Maiyumeraks, and the short time available, limited our work to reconnaissance mapping in a small area. The basalts could not be differentiated on standard false-color infrared aerial photographs, so our reconnaissance work could not be extrapolated to larger areas using the photographs.

Correlations between reflectance, mineralogy, and geochemistry

The Thematic Mapper images have made it possible to extrapolate our field observations throughout the Maiyumerak Mountains. Figure 4 is a geologic map of the Maiyumeraks, interpeted from TM images and constrained by our field observations. Where the rocks are not covered by vegetation, four spectrally distinct basalts have been recognized using scaled false-color composites and an image produced by a principal components transformation. For visual identification of units, scaled composite images of Bands 3, 2, and 1 (a pseudo-natural color image) and 7, 3, and 1 have been most useful (with the bands displayed in red, green, and blue, respectively). The scaling of the composites is based on statistics for the exposed rocks of interest, rather than for the entire scene, in order to enhance subtle reflectance differences. The best principal component image for recognition of spectral differences is a combination of components 3, 4, and 5 (principal components 1 and 2 show reflectance differences that are primarily due to slope orientation and vegetation cover, respectively). The Maiyumeraks appear to be comprised of two thrust plates of basalt. The lower plate is comprised of basalt with relatively low reflectance in Bands 1, 2, 5, and 7 and high reflectance in Band 3, as compared to the basalt of the upper plate. Each thrust plate can be divided into two basalts, based on spectral differences, designated basalts A and B in the lower plate, and basalts C and D in the upper plate. Basalts A and C correspond to the reddish-brown weathering and grey weathering basalts observed in the field. The basalts of the lower thrust plate have apparently been exposed in the center of a north-trending antiform. Areas of especially high reflectance in Bands 5 and 7 occur in both thrust plates (outlined by dashed lines in Figure 4). These correspond to areas of weak hydrothermal sulfide mineralization.

The cause of the reflectance differences between the basalts of the two thrust plates has been studied by examining the mineralogy and chemistry of samples that were collected during our field work in 1985. The characteristics of the lower and upper basalts are summarized in Figure 5. The TM radiance measurements are presented as normalized digital numbers (DN), in which the DN values of the two basalts in each of the six reflectance bands have been divided by the DN values in the lower basalt (the DN values are averages of several hundred pixels from directly illuminated slopes). The reflectance differences between the upper and lower basalts are readily apparent in the normalized plot for the upper basalt. The DN values differ by less than 10%, corresponding to very small reflectance differences. The comparatively high Band 3 reflectance of the lower basalt is produced by greater amounts of iron hydroxides in the weathered surfaces on the basalts. X-ray diffraction measurements of powders from the weathered surfaces indicate that, except for iron hydroxide concentration, there are no significant mineralogic differences between the upper and lower basalts. The smaller concentration of iron hydroxides within weathered surfaces on the upper basalt accounts for its grey weathering color as compared to the reddish-brown weathering color of the lower basalt.

The differing weathered surfaces on the two basalts are apparently due to differences in metamorphic mineral assemblages. Both basalts have been metamorphosed at greenschist facies conditions, and both contain the iron-bearing metamorphic minerals chlorite and epidote. However, primary clinopyroxene is preserved in the lower basalt, whereas metamorphic actinolite is present in the upper basalt, indicating that the upper basalt was affected by more intense metamorphism (eg. slightly higher temperatures, greater fluid activity, and/or longer time). The actinolite apparently "binds" iron during weathering, suppressing the formation of iron hydroxides. The reflectance differences detected by the Thematic Mapper are, therefore, making it possible to map metamorphic-facies variations within basalts.

The metamorphic differences being mapped with the TM data provide information that can be used in paleogeographic reconstructions of northern Alaska because the metamorphic differences correlate with geochemical differences in the basalts that are indicative of tectonic setting. The concentrations of trace elements in basalts are diagnostic of origins in different tectonic settings. Figure 6, for example, illustrates the discrimination of basalt-types, using hafnium, thorium, and tantalum. The Maiyumerak upper-basalt samples are similar to calc-alklaline basalts formed in modern island arc or marginal basin settings, whereas the lower-basalt samples are similar to modern tholeiitic island arc or marginal basin basalts. The Maiyumerak basalts are unlike mid-ocean ridge basalts (MORB), which are typical of major ocean basins, as well as ocean island basalts and continental flood basalts. The tholeiitic and calc-alkaline affinities of the Maiyumerak basalts are corroborated by the rare-earth-element patterns of the samples (Figure 5).

Similar correlations between reflectance, metamorphic mineral abundances, and geochemistry have been identified in basalts of the Angayucham Terrain, along the southern margin of the Brooks Range, 300 km west of the Maiyumerak Mountains (Figure 5). Previous workers recognized two thrust sheets of basalt in the Ambler District of the Angayucham Terrain and, as in the Maiyumeraks, the basalts of the upper plate are actinolite-bearing whereas the lower-plate basalts lack actinolite. The differences in metamorphic mineral abundances produce reflectance differences like those of the Maiyumerak basalts, with the upper basalt having relatively low Band 3 reflectance. The mineralogies correlate with trace element and rare earth element variations that suggest that the lower basalt formed in an oceanic plateau setting, whereas the upper basalt might have formed in an ocean island setting.

Other ophiolite exposures of the Brooks Range are being examined in a similar manner in order to identify previously unrecognized lithologic variations. Gabbros and ultramafic rocks are being studied, in addition to basalts. The reflectance variations observed in the TM data are making it possible to produce significantly improved geologic maps of the ophiolites.

Recognition of large-scale structures

Previous mapping in the Brooks Range has emphasized the importance of low-angle thrust faults in the structural evolution of the range. High-angle faults (ie. strike-slip faults and normal faults) are reportedly less common. The improved spatial resolution of the TM data, as compared to Landsat multispectral scanner data, and the synoptic coverage, make the TM images especially useful for the identification of high-angle faults. High-angle faults are more readily recognized than thrust-faults on the TM images because the high-angle structures are commonly expressed as abrupt, linear topographic features or contacts between rock types. Numerous linear features, interpreted to be faults, have been recognized on the TM images during our mapping of the Brooks Range ophiolites. For example, the Maiyumeraks are cross-cut by many north-northeast trending, high-angle faults (Figure 4). Offsets of lithologic contacts suggest that motion on the faults was down-on-the-west and/or right-lateral.

The faults in the Maiyumeraks parallel a major topographic lineament that separates the basalts of the Maiyumeraks on the west from limestones on the east (Figure 2). The lineament is arcuate and extends approximately 100 km, from Asik Mountain to Misheguk Mountain (indicated by arrows in Figure 2). The lineament parallels the eastern margin of the Noatak basin. The Noatak Basin is characterized by large-amplitude gravity and aeromagnetic anomalies, suggesting that the basin is underlain by ophiolitic rocks. The ophiolites of the Brooks Range form the structurally highest thrust-sheets, occurring above the sedimentary rocks. The low elevation of the ophiolitic rocks in the basin, as compared to the sedimentary rocks to the east of the topographic lineament, suggests that the lineament is the trace of a high-angle fault with down-on-the-west displacement. Folding in the sediments indicates that there may also have been a component of right-lateral displacement on the fault. These displacements coincide with the motions inferred for the smaller faults mapped within the Maiyumerak basalts (Figure 4). The Noatak Basin might, therefore, be a graben-structure bounded by high-angle faults along the east margin of the basin. Less definitive linear structures paralleling the western margin of the basin suggest that the basin might also be bounded by faults on the west.

This previously unrecognized graben structure accounts for the spatial distribution of the ophiolites in the western Brooks Range. Figure 7 shows the distribution of both exposed and subsurface ophiolites in northern Alaska. It has been suggested that the entire Brooks Range was once covered by large ophiolite thrust sheets that were subsequently eroded, leaving exposures only at low elevations in the Angayucham Terrain and the western Brooks Range. The east-west trending line of isolated ophiolite exposures in the western Brooks Range are preserved along the axis of a major synclinorium. The large lobe of ophiolitic rocks extending south from the synclinorium are preserved in the graben structure that was identified on the TM images. The ophiolites have been dropped down with respect to the surrounding sedimentary rocks by normal faulting. The age of this faulting and its relationship to the tectonic evolution of the Brooks Range is not yet understood.

The results discussed above will be presented in two invited papers at a symposium on the tectonic evolution of the Brooks Range. The symposium is a part of the Geological Society of America annual Cordilleran Section meeting. Copies of the abstracts are included.

Geochronology of the western Brooks Range ophiolites

In order to better constrain events affecting the ophiolites of the Brooks Range, we have dated samples collected during 1985 using the $^{40}Ar/^{39}Ar$ radiometric age-dating technique. The samples are from the Asik Mountain and Avan Hills exposures. We have dated both igneous samples, yielding the age of formation of the ophiolites, and metamorphic samples, yielding the age of thrusting of the ophiolites. The $^{40}Ar/^{39}Ar$ technique yields the age at which a mineral cooled below the temperature at which Ar is retained within the mineral. We have analyzed hornblende, biotite, and K-feldspar. Our results are summarized and compared to previously published K-Ar dates, in Figure 8. The $^{40}Ar/^{39}Ar$ technique has several advantages as compared to the K-Ar technique; ages can be determined more precisely and thermal events that affected the retention of Ar can be recognized. Our $^{40}Ar/^{39}Ar$ ages for the igneous formation of the ophiolite are similar to the previous K-Ar ages, but the metamorphic ages, indicating the time of thrusting, are approximately 10 million years older than the published ages. Thrusting of the ophiolites was the earliest deformational event in the Brooks Range. The $^{40}Ar/^{39}Ar$ data, therefore, indicate that the Brooks Range deformation began 10 million years earlier than was previously realized. The data also indicate that the ophiolites were thrust soon after their formation, consistent with the geochemical data discussed above, which suggest that the ophiolites formed in an arc or marginal basin setting.

The $^{40}Ar/^{39}Ar$ data also provides information about the thermal evolution of the ophiolites. This information might help explain the metamorphic facies differences that have been recognized from the TM data in the basalts of the ophiolites. Because Ar is retained by different minerals at different temperatures (the "closure" temperature), a cooling history for the ophiolites can be constructed from the $^{40}Ar/^{39}Ar$ data (Figure 9). The closure temperatures of hornblende, bitotite, and K-feldspar are approximately 500°C, 350°C, and 150°C, respectively. The ophiolites appear to have cooled rapidly soon after thrusting, probably by conduction, followed by a long period of slow cooling, probably during uplift of the Brooks Range.

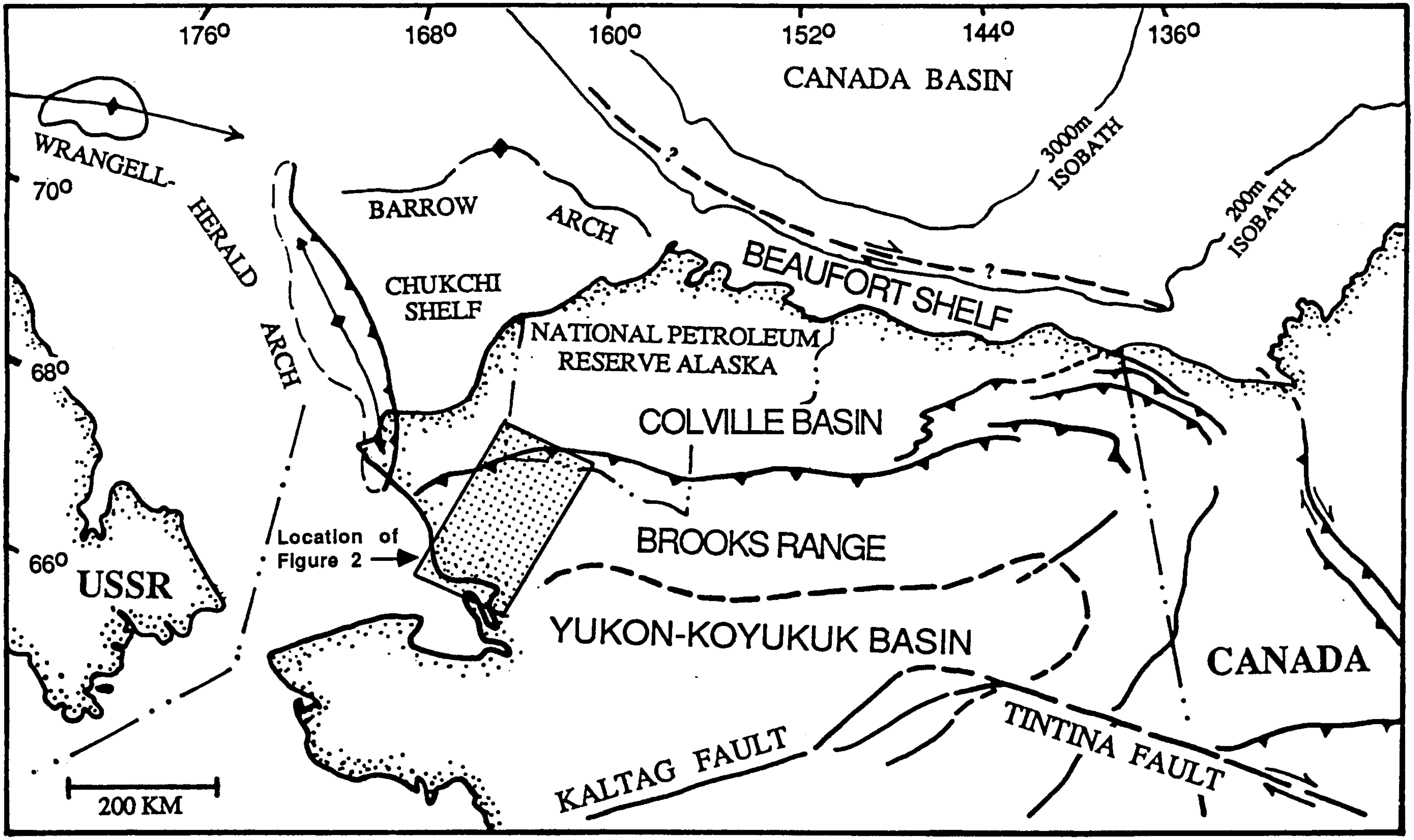
The $^{40}Ar/^{39}Ar$ ages are summarized in Figure 10 along with the ages of other events affecting northern Alaska. We are using this age data to constrain tectonic models for the evolution of the Brooks Range. It is generally thought that the Brooks Range formed by southward-directed subduction of a small continental block (Arctic Alaska) beneath oceanic lithosphere now preserved as the Yukon-Koyukuk Basin (Figure 1). It has been assumed by many workers that subduction of the Arctic Alaska block, and construction of the Brooks Range, was synchronous with the opening of the ocean basin north of Alaska (the Canada Basin). Our $^{40}Ar/^{39}Ar$ data and other published age data indicate that subduction commenced well before opening of the Canada Basin. The data also suggest that much, if not all, of the thrusting in the Brooks Range was completed before the opening of the Canada Basin. This information requires that tectonic models for the evolution of northern Alaska be re-evaluated. Models for the formation and accumulation of hydrocarbons in the Colville Basin north of the Brooks Range, (eg. at the Prudhoe Bay oil field), must also be reconsidered. We recently received Thematic Mapper data for the Colville Basin, as part of the additional allotment of scenes provided by NASA. Drainage patterns in the basin appear to record a history of recent uplift. Uplift patterns in the basin, determined from the TM images, might provide further information on the tectonic evolution of northern Alaska.

List of Figures

Abstracts

Invited papers to be presented at the Geological Society of America Cordilleran Section meeting in May, 1987, as part of symposium on Brooks Range tectonics:

1. Landsat TM studies, Brook Range, Alaska
2. Basalt Geochemistry, Brooks Range, Alaska



176°
168°
160°
152°
144°
136°
CANADA BASIN
3000m ISOBATH
200m ISOBATH
WRANGELL-HERALD ARCH
70°
68°
66°
BARROW ARCH
CHUKCHI SHELF
BEAUFORT SHELF
NATIONAL PETROLEUM RESERVE ALASKA
COLVILLE BASIN
BROOKS RANGE
YUKON-KOYUKUK BASIN
Location of Figure 2
USSR
CANADA
KALTAG FAULT
TINTINA FAULT
200 KM

Figure 1

Figure 2

MAIYUMERAK MOUNTAINS

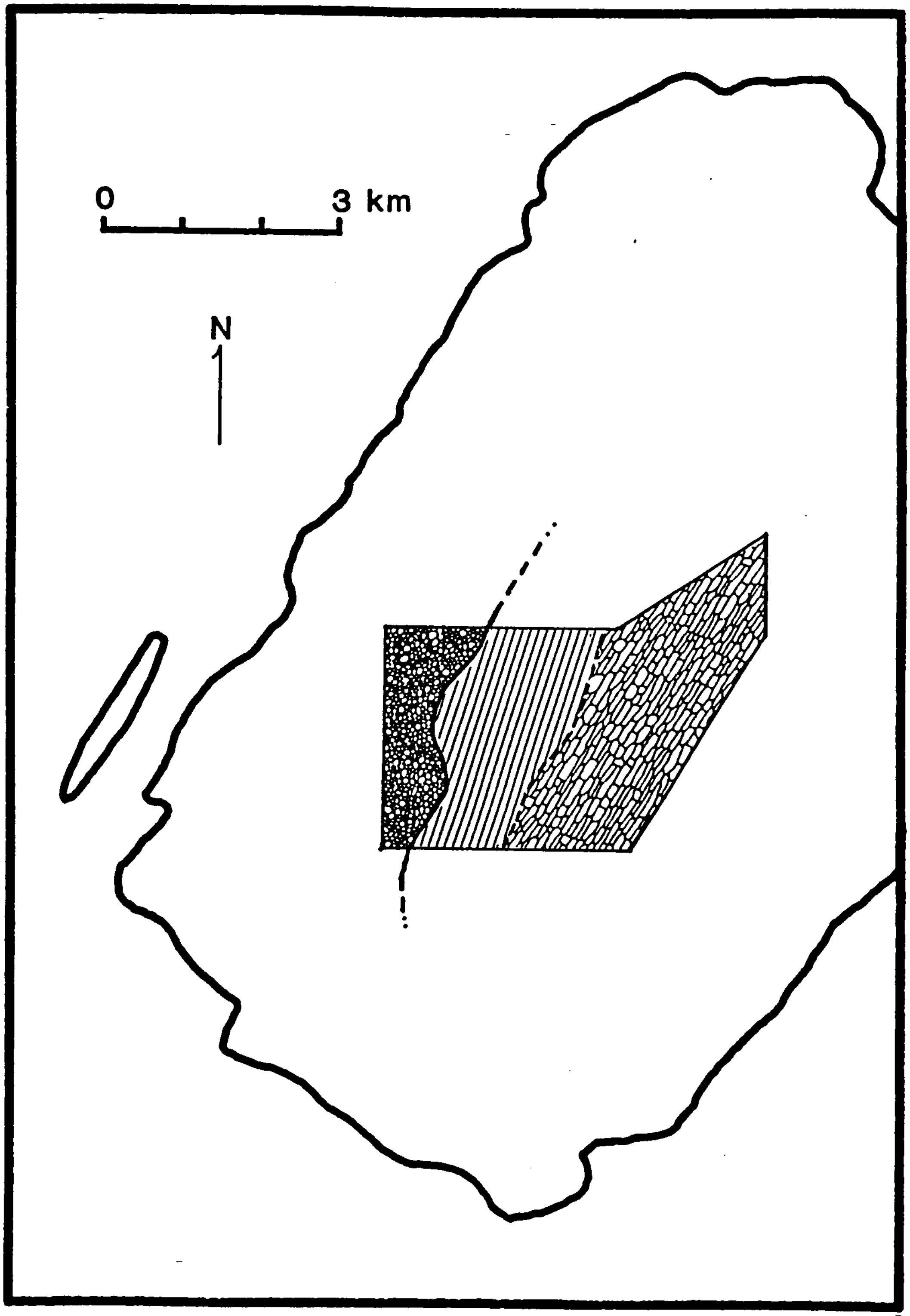


Figure 3

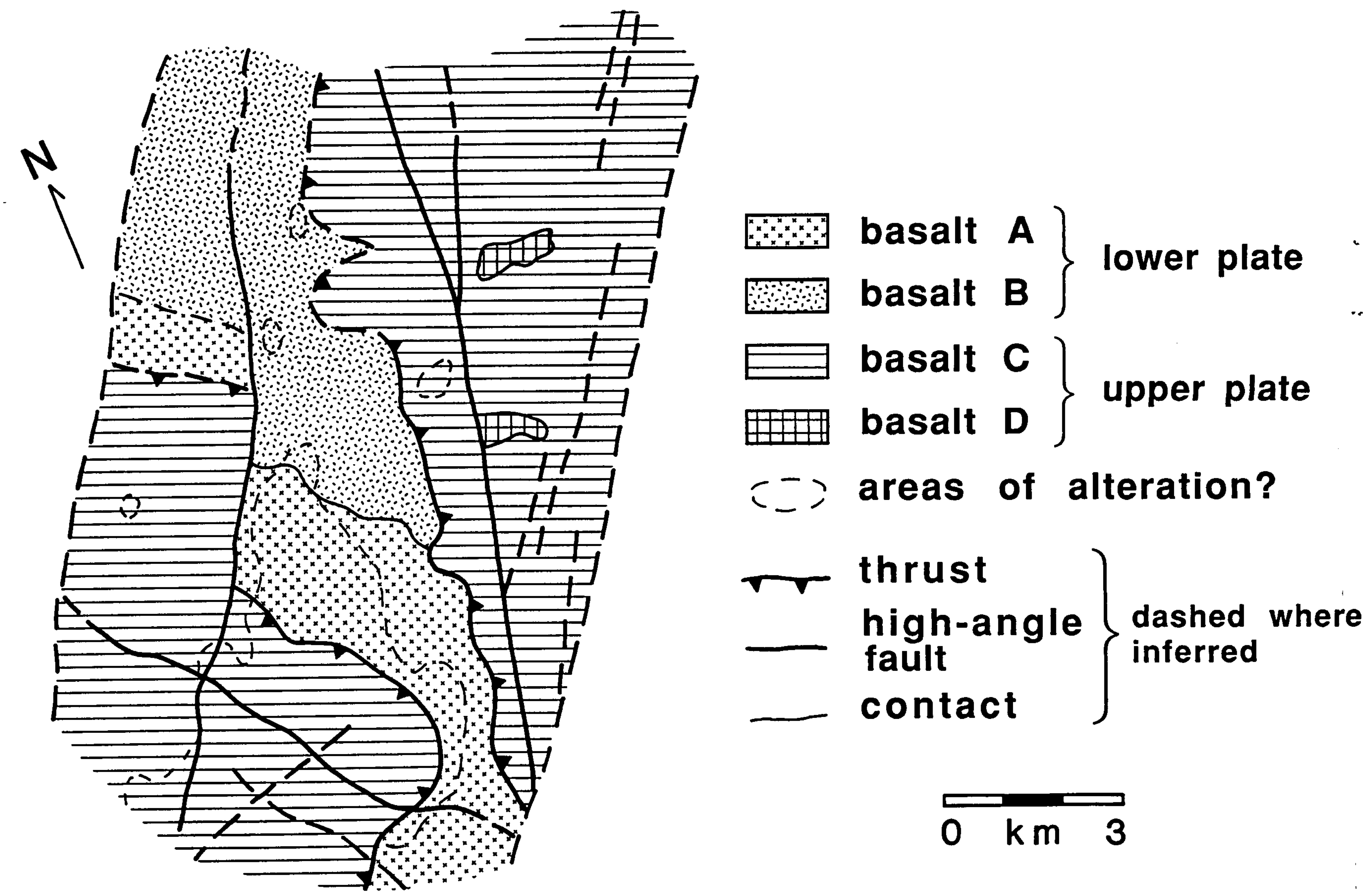
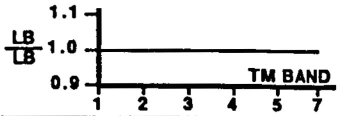
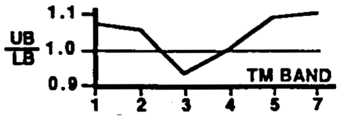
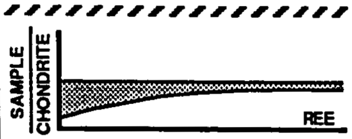
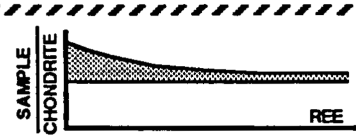

N
basalt A
basalt B
lower plate
basalt C
basalt D
upper plate
areas of alteration?
thrust
high-angle fault
contact
dashed where inferred
0 km 3

Figure 4

MAIYUMERAK MAFIC VOLCANIC ROCKS

	LOWER BASALT	UPPER BASALT
NORMALIZED TM DIGITIAL NUMBERS		
COLOR	REDDISH BROWN	DARK GREY
FE-BEARING MINERALS	CHLORITE ± EPIDOTE ± CLINOPYROXENE ± MAGNETITE	ACTINOLITE ± EPIDOTE ± CHLORITE ± MAGNETITE
RARE EARTH ELEMENT PATTERNS		
AGE	MIDDLE JURASSIC OR OLDER	MIDDLE JURASSIC OR OLDER
TECTONIC SETTING (Hf-Th-Ta)	ARC OR MARGINAL BASIN (THOLEIITIC?)	ARC OR MARGINAL BASIN (CALC-ALKALINE?)

ANGAYUCHAM MAFIC VOLCANIC ROCKS

(Hitzman et al., 1982; Pallister, 1985)

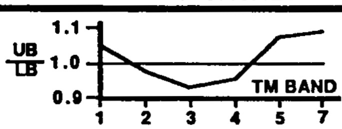
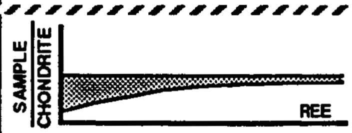
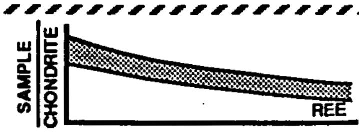
	LOWER BASALT	UPPER BASALT
NORMALIZED TM DIGITIAL NUMBERS		
COLOR	BROWN TO BRICK RED	DULL REDDISH BROWN
FE-BEARING MINERALS	CHLORITE ± EPIDOTE ± CLINOPYROXENE ± MAGNETITE	CHLORITE ± EPIDOTE ± ACTINOLITE ± CLINOPYROXENE ± MAGNETITE
RARE EARTH ELEMENT PATTERNS		
AGE	TRIASSIC	JURASSIC
TECTONIC SETTING (Hf-Th-Ta)	N-MORB AND E-MORB (OCEANIC PLATEAU?)	E-MORB (OCEAN ISLAND?)

Figure 5

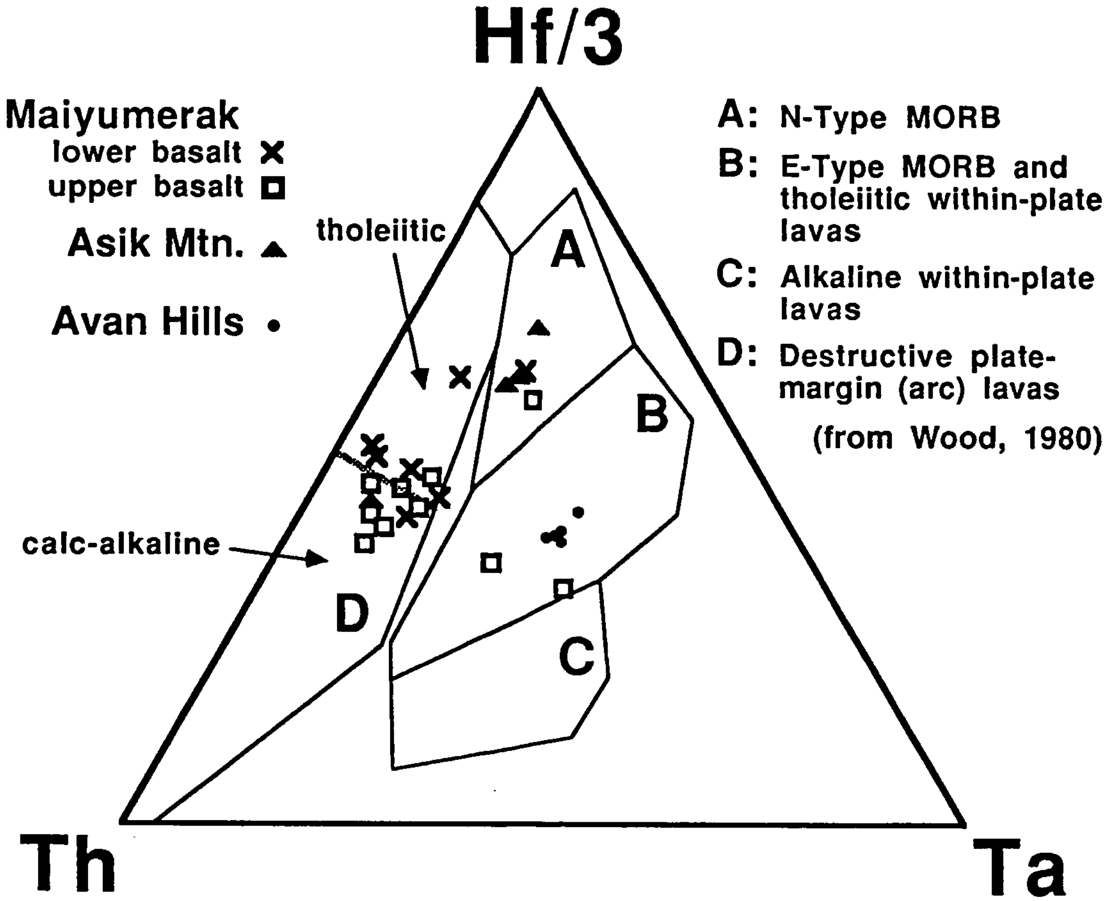

Hf/3
Maiyumerak
lower basalt
upper basalt
Asik Mtn.
Avan Hills
tholeiitic
calc-alkaline
A
B
C
D
Th
Ta
A: N-Type MORB
B: E-Type MORB and tholeiitic within-plate lavas
C: Alkaline within-plate lavas
D: Destructive plate-margin (arc) lavas
(from Wood, 1980)

Figure 6

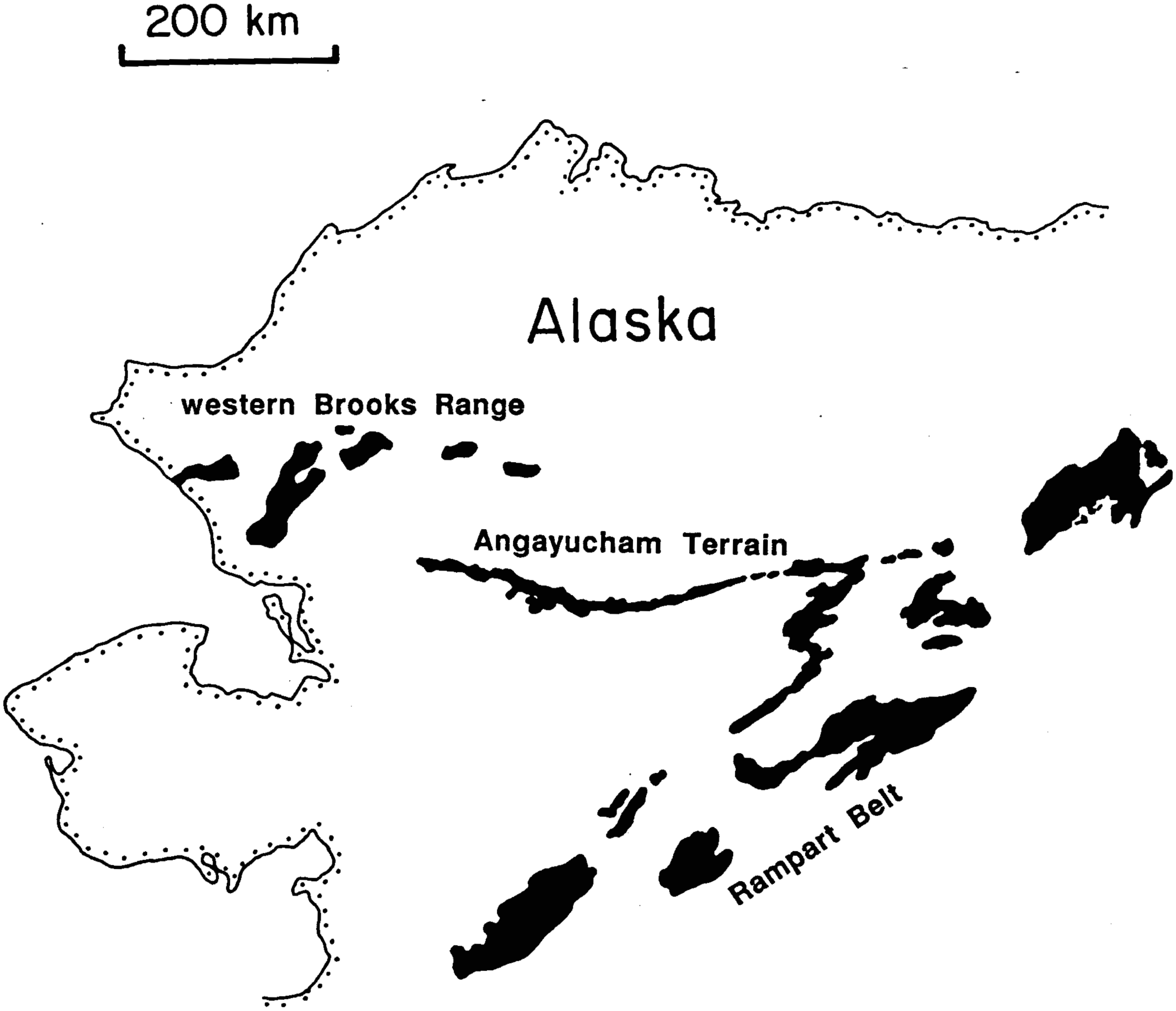
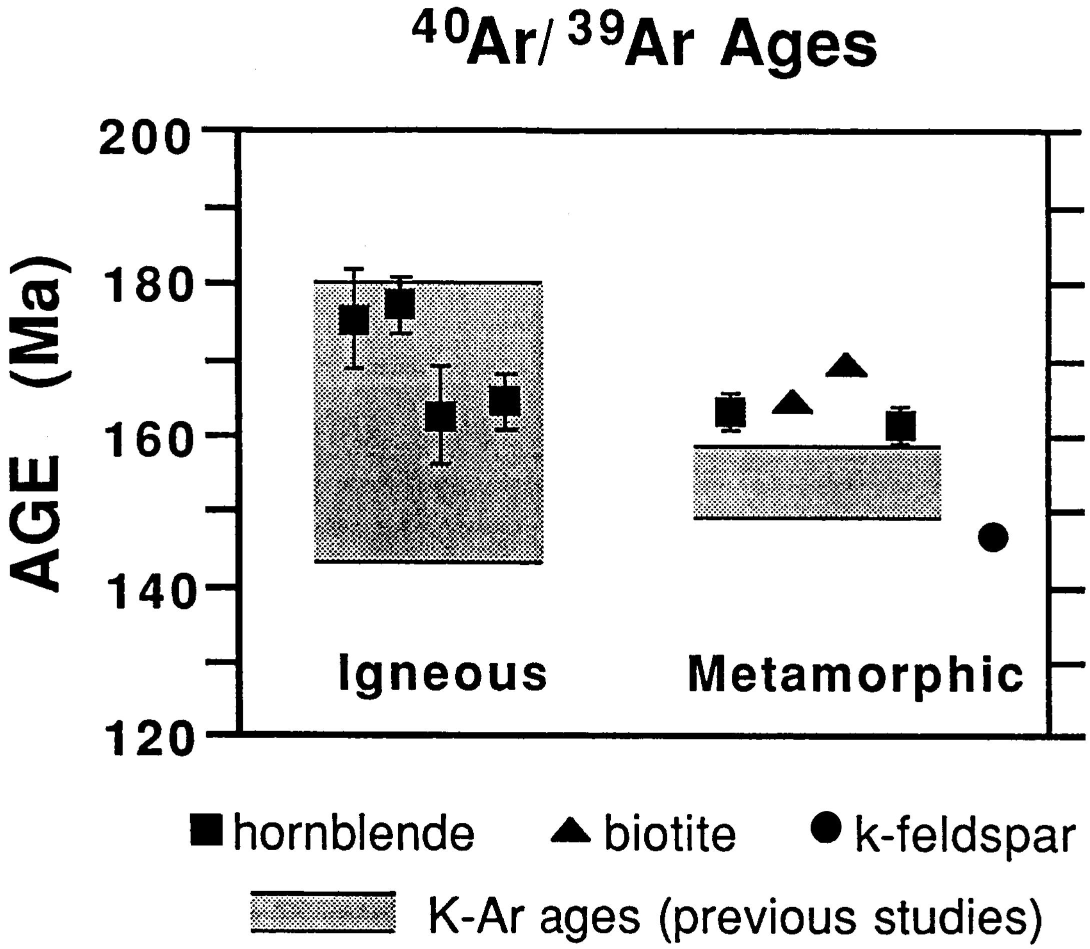

200 km
Alaska
western Brooks Range
Angayucham Terrain
Rampart Belt

Figure 7



40Ar/39Ar Ages
AGE (Ma)
200
180
160
140
120
Igneous
Metamorphic
hornblende
biotite
k-feldspar
K-Ar ages (previous studies)

Figure 8

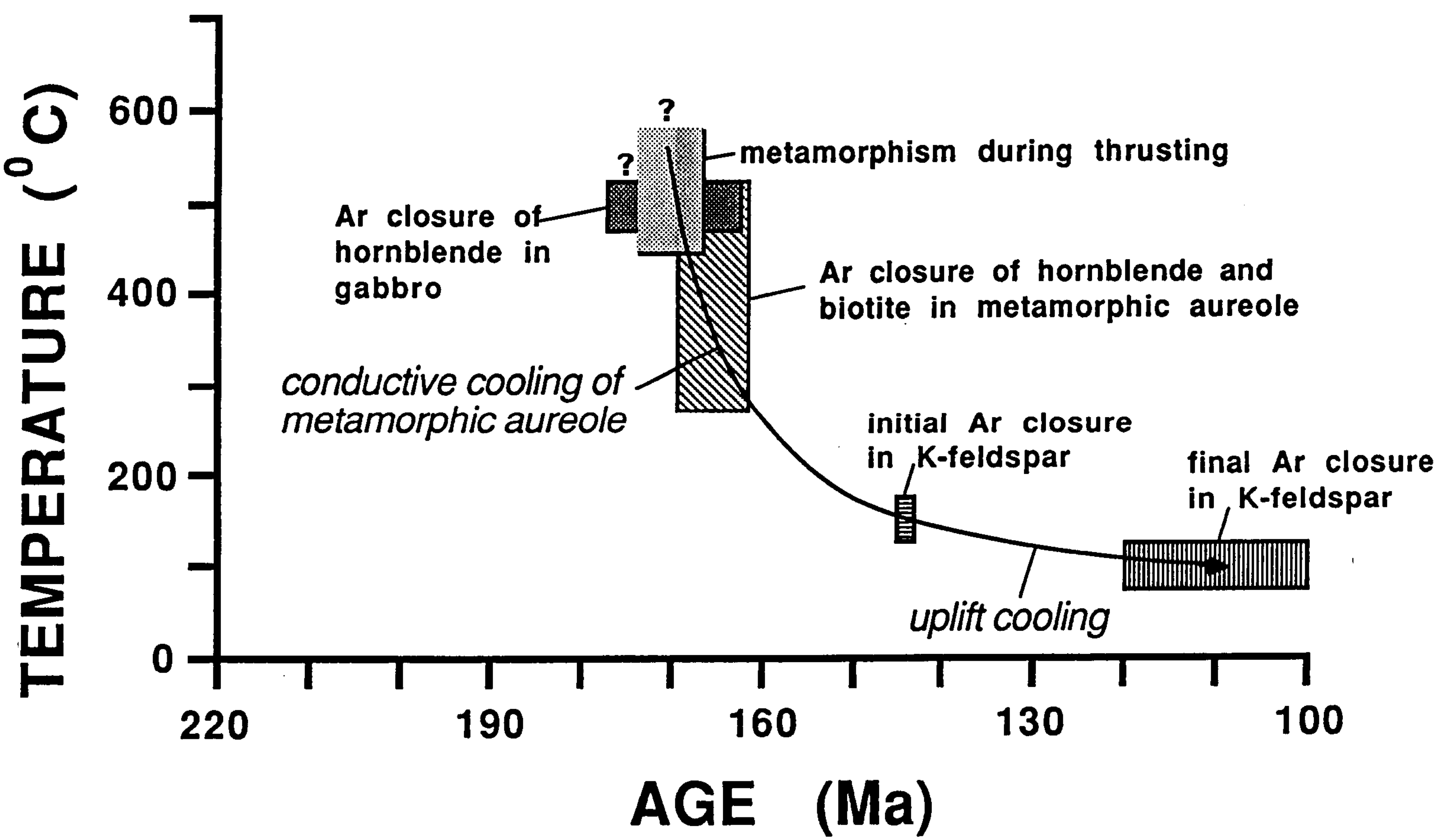

TEMPERATURE (°C)
600
400
200
0
220
190
160
130
100
AGE (Ma)
?
?
metamorphism during thrusting
Ar closure of hornblende in gabbro
Ar closure of hornblende and biotite in metamorphic aureole
conductive cooling of metamorphic aureole
initial Ar closure in K-feldspar
final Ar closure in K-feldspar
uplift cooling

Figure 9

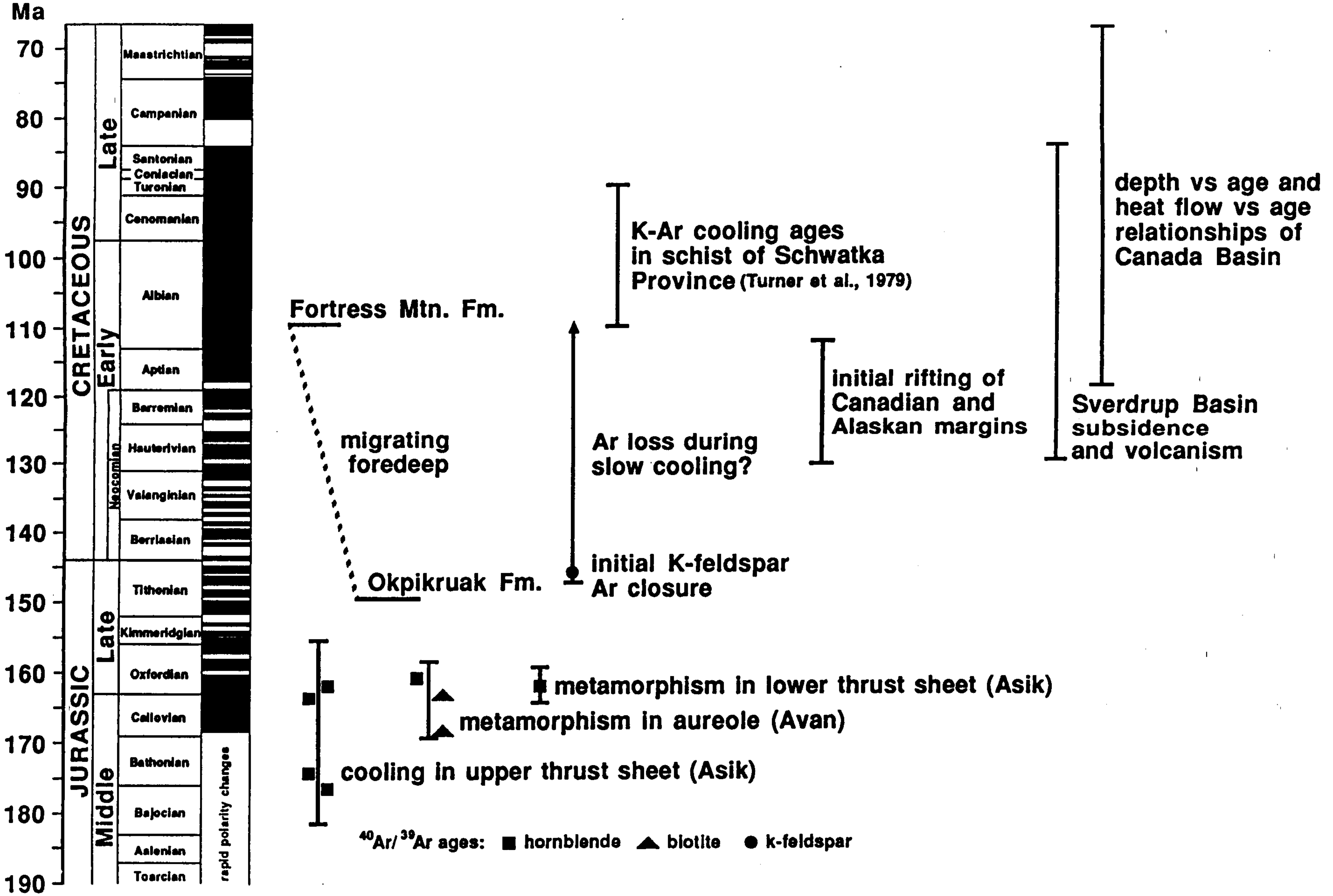

Ma
70
80
90
100
110
120
130
140
150
160
170
180
190
CRETACEOUS
JURASSIC
Late
Early
Neocomian
Late
Middle
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
rapid polarity changes
Fortress Mtn. Fm.
migrating foredeep
Okpikruak Fm.
K-Ar cooling ages in schist of Schwatka Province (Turner et al., 1979)
Ar loss during slow cooling?
initial K-feldspar Ar closure
initial rifting of Canadian and Alaskan margins
depth vs age and heat flow vs age relationships of Canada Basin
Sverdrup Basin subsidence and volcanism
metamorphism in lower thrust sheet (Asik)
metamorphism in aureole (Avan)
cooling in upper thrust sheet (Asik)
$^{40}Ar/^{39}Ar$ ages: hornblende biotite k-feldspar

Figure 10

LANDSAT TM STUDIES, BROOKS RANGE, ALASKA

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Landsat Thematic Mapper (TM) data of the western Brooks Range are being used to map subtle lithologic variations, and large-scale structures, that are not readily recognized in the field. Basalt of the Maiyumerak Mountains is separable into two spectrally distinct units that are interpreted to be thrust sheets; basalt of the upper thrust sheet is characterized by high reflectance in TM bands 1, 2, 5 and 7 and low reflectance in band 3, as compared to basalt of the lower thrust sheet. The reflectance differences are produced by differences in the weathered surfaces of the basalts. The surface differences are dependent on the basalts' metamorphic mineralogy; both basalts have greenschist-facies mineral assemblages, but actinolite is common in the upper thrust sheet and rare in the lower sheet. The weathered surfaces on the actinolite-bearing, upper basalt contain smaller amounts of hydrous iron-oxides. The spectral and mineralogic variations correlate with geochemical differences. The geochemical differences indicate that the basalts might have formed in different tectonic settings (Wirth et al., this volume).

The thrust sheets in the Maiyumerak Mountains are cut by several high-angle, northeast-trending faults. These faults parallel an arcuate topographic lineament, recognized on TM images, that bounds the Noatak Basin on the east and extends 100 km, from Asik Mountain to Misheguk Mountain. The lineament separates ophiolitic rocks on the west from allocthonous sedimentary rocks on the east. The lineament is interpreted to be the trace of a high-angle fault. Offsets of lithologic contacts, and folding in the sedimentary rocks, indicate that displacement on the inferred fault was down-on-the-west and/or right-lateral. The Noatak Basin is characterized by large amplitude gravity and aeromagnetic anomalies, suggesting that the basin is underlain by ophiolitic rocks (Barnes and Tailleur, 1970). Ophiolitic rocks in the western Brooks Range form the structurally highest thrust sheets, occurring above allocthonous sedimentary rocks. The low elevation of the ophiolitic rocks in the basin, as compared to the surrounding sedimentary rocks, has been attributed to a large synformal structure (I. Ellersieck, personal communication). Alternatively, the distribution of these ophiolitic rocks might be the result of down-on-the-west displacement on high-angle faults that bound the east side of the Noatak basin.

BASALT GEOCHEMISTRY, BROOKS RANGE, ALASKA

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Basaltic flows and dikes at Asik Mountain, Avan Hills, and in the Maiyumerak Mountains, western Brooks Range, have diverse geochemical characteristics.

Two basalts, in the western Maiyumerak Mountains, are interpreted to be from two different thrust sheets juxtaposed by north-south, high-angle faulting (Harding et al., this volume). East of the fault (lower thrust sheet), pillowed and massive basalt flows are cross-cut by north-south-trending, near vertical and subparallel mafic dikes. The flows and dikes have clinopyroxene and plagioclase, with variable amounts of secondary chlorite, epidote and calcite. Most basalts east of the fault plot in the tholeiite field of some trace element diagrams and have flat, or slightly depleted, light rare-earth element (LREE) patterns. West of the fault (upper thrust sheet), the basalts are more metamorphosed, and are mostly chlorite, actinolite, epidote and calcite. Mafic dikes here are less common, and are curved and have variable orientations, in contrast to those east of the fault. Basalts from west of the fault plot in the calc-alkaline field of some trace element diagrams, and typically have flat to LREE-enriched patterns. Both basalts are depleted in Ta relative to Th, and have trace element abundances similar to island-arc basalt on trace element diagrams, indicating the presence of a subduction- related geochemical component (Pearce et al., 1984).

Mafic flows at Asik Mountain and Avan Hills are structurally overlain by layered and crystalline mafic and ultramafic rocks and are more metamorphosed and deformed than those in the Maiyumerak Mountains. Asik Mountain basalts have flat REE patterns, while Avan Hills basalts have LREE-enriched patterns. Trace element abundances in the Asik and Avan basalts are similar to normal MORB, and enriched MORB or tholeiitic within-plate basalt, respectively.