New structural and stratigraphic insights for northwestern Pakistan from field and Landsat Thematic Mapper data

Joel Robinson* *Department of Geology, Miami University, Oxford, Ohio 45056*
Richard Beck *Department of Geography, University of Cincinnati, Cincinnati, Ohio 45221*
Edwin Gnos *Mineralogisch-Petrographisches Institut, Berne University, Baltzerstrasse 1, 3012 Bern, Switzerland*
Robert K. Vincent *Department of Geology, Bowling Green State University, Bowling Green, Ohio 43403*

ABSTRACT

The remote Waziristan region of northwestern Pakistan includes outcrops of the India-Asia suture zone. The excellent exposure of the Waziristan ophiolite and associated sedimentary lithosomes and their inaccessibility made the use of Landsat Thematic Mapper (TM) data desirable in this study. Landsat TM data were used to create a spectral ratio image of bands 3/4, 5/4, and 7/5, displayed as red, green, and blue, respectively, and a principal component analysis image of bands 4, 5, and 7 (RGB). These images were interpreted in the context of available geologic maps, limited field work, and biostratigraphic, lithostratigraphic, and radiometric data. They were used to create a coherent geologic map of Waziristan and cross section of the area that document five tectonic units in the region and provide a new and more detailed tectonic history for the region. The lowest unit is comprised of Indian shelf sediments that were thrust under the Waziristan ophiolite. The ophiolite has been tectonically shuffled and consists of two separate tectonic units. The top thrust sheet is a nappe comprised of distal Triassic to Lower Cretaceous Neotethyan sediments that were underthrust during the Late Cretaceous by the ophiolite riding on Indian shelf strata. The uppermost unit contains unconformable Tertiary and younger strata. The thrust sheets show that the Waziristan ophiolite was obducted during Late Cretaceous time and imply that the Paleocene and Eocene deformation represents collision of India with the Kabul block and/or Asia.

*Present address: Volcanic Hazard Team, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025; e-mail: jrobins@usgs.gov.

Keywords: geologic mapping, tectonics, remote sensing, Himalaya, Pakistan.

INTRODUCTION

Waziristan is located near the junction of the western terminus of the Himalayan orogen and western transpressional margin of the Indo-Pakistani craton (Fig. 1). The area includes exposures of Cretaceous and early Tertiary structures and stratigraphic relationships not evident in other areas of the India-Asia suture zone, particularly those areas north of the Himalayan mountain chain. To unravel the Late Cretaceous through early Tertiary geologic history of the suture zone, we obtained and processed Landsat Thematic Mapper (TM) data to identify areas most likely to contain key geologic relationships. These processed images were combined with recent lithostratigraphic, biostratigraphic, petrologic, and radiometric studies of the region to provide foci for our field work (Beck et al., 1995, 1996). Field checks of the merged satellite and geologic information allowed us to construct a new geologic map and cross section of the little-known Waziristan segment of the India-Asia suture zone. The new map expands limited mapping of the ophiolite, verifies and refines our previous general conclusions, and reveals several new copper prospects and a granitoid in the area (Robinson et al., 1997, Robinson, 1998).

The application of multispectral imaging to remote regions such as northwest Pakistan makes the construction of detailed geologic maps possible and economical. The Landsat TM satellite combines good spatial and spectral resolution and allows geologic mapping directly on an image with a spatial resolution of approximately 30 m. The application of band ratioing and principal component analysis allows structural and lithologic data to be extrapolated from limited ground truth. Landsat TM imagery was used to map the Waziristan ophiolite and environs of northwestern Pakistan (Fig. 1) and to create a detailed regional geologic map of the area.

The purpose of this study was to determine the tectonic history of the westernmost India-Asia suture zone by creating and using a new and more detailed geologic map. There have been many debates over the timing of the collision between the Indian subcontinent and the Eurasian continent as well as their precollisional history. To completely understand the collision, the whole India-Asia suture zone must be studied. Most of the work along the suture zone has been north of the Himalayas proper because of the relatively easy access. The westernmost collision zone has not been studied as extensively, but warrants study because a record of Late Cretaceous and early Tertiary deformation is preserved there.

The data analyzed in this study will be used to argue that the Waziristan Igneous Complex is an ophiolite rather than an island arc, that the Waziristan ophiolite was obducted during the Late Cretaceous rather than during the Paleocene, and that the Paleocene and Eocene deformation represents collision of India with the Kabul block and/or Asia (Beck et al., 1995, 1996).

Regional Geology

The suture zone is a montage of strongly deformed ophiolites and other tectonic blocks. The Waziristan ophiolite sits along the suture zone between the Afghanistan block and the India plate. The ophiolites include, from north to south; the Bela, Muslimbagh, Zhob, Waziristan, and Khost (Figs. 1 and 2). The related tectonic blocks include the Kabul block, with its associated ophiolite, and the Katawaz basin (Figs. 1 and 2). Latitude and longitude coordinates for locations cited in this study are listed in Table 1. We will briefly

GSA Bulletin; March 2000; v. 112; no. 3; p. 364–374; 5 figures; 2 tables.

TABLE 1. LOCATIONS DISCUSSED IN TEXT

Locality	Latitude	Longitude
Aziz Khel	33°5′N	70°10′E
Bannu	33°0′N	70°38′E
Bobai	32°18′N	69°39′E
Chale Talao	32°20′N	69°20′E
Chinarop Piquet	32°59′N	70°14′E
Chinike Zhawar	32°18′N	69°19′E
Datta Khel	32°54′N	69°0′E
Gaj River	26°54′N	67°5′E
Hangu	33°32′N	71°4′E
Jandola	32°20′N	70°7′E
Janjal	32°34′N	69°56′E
Khajuri Post	32°57′N	70°20′E
Khan Kot	32°3′N	69°20′E
Khirthar Hill	27°0′N	67°15′E
Khost	33°20′N	69°58′E
Kohat	33°36′N	71°29′E
Litra Nala	31°1′N	70°25′E
Mandanna Kach	32°22′N	70°4′E
Manzai Oba	32°20′N	69°18′E
Mir Ali	33°0′N	70°16′E
Miran Shah	32°55′N	70°4′E
Mughal Kot	31°26′N	70°5′E
Nikaband	32°23′N	70°3′E
Nili Kach	32°7′N	70°0′E
Parh Range	26°54′N	67°5′E
Quetta	30°12′N	67°0′E
Razmak	32°44′N	69°51′E
Shahur Tangi	32°19′N	70°2′E
Shinki Post	32°57′N	70°21′E
Tarka Purga	32°50′N	69°40′E
Thal	33°22′N	70°33′E
Wana	32°19′N	69°35′E
Zer Ghar	32°59′N	70°6′E
Zhob	31°15′N	67°45′E

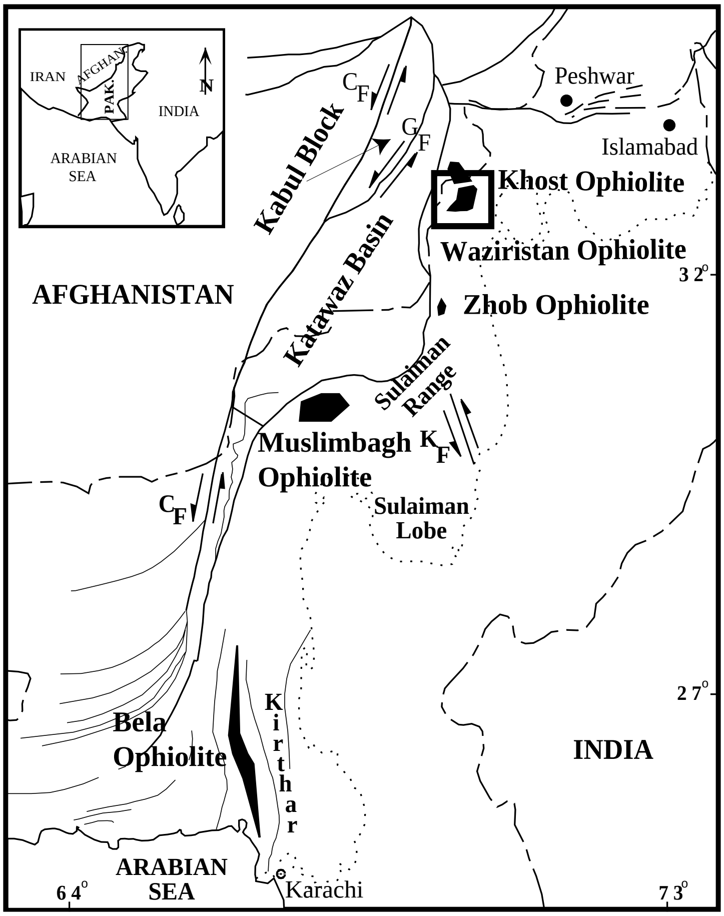

Figure 1. Regional map of Pakistan showing location of study area, the positions of the Pakistani ophiolites, regional faults, the Katawaz basin, the Kabul block, the Sulaiman Range, and the Sulaiman Lobe. CF—Chaman fault, GF—Gardez fault, KF—Kingri fault (after Haq and Davis, 1997).

review the regional geology of the Waziristan segment of the suture in order to provide a spatial context for our remote sensing results.

Waziristan Ophiolite. The Waziristan ophiolite is the largest ophiolite in Pakistan after the Bela (Fig. 1). The ophiolitic rocks are thrust slices that have been underthrust largely by Jurassic and Cretaceous calcareous rocks of the Indo-Pakistani plate. Rocks in the entire Waziristan ophiolite belt are intensely thrusted, folded, faulted, and in places fractured, brecciated, and granulated. The new geologic map indicates that the ophiolite has been tectonically shuffled such that the lowest parts of the sequence now overlie the upper parts (Fig. 3). A complete section in normal order has not been found; however, all the components of a typical ophiolite (ultramafic rocks, feldspathic plutonic rocks, sheeted dikes, volcanic rocks, and pelagic sediments) are present (Jan et al., 1985). Paleocene and Eocene sedimentary rocks, mostly limestone and shale with a red oxidized zone toward their base, unconformably overlie the ophiolitic rocks (Jan et al., 1985; Beck et al., 1996).

The Waziristan ophiolite lies in the middle of a tectonic stack consisting of thrust sheets from the Indo-Pakistani plate (Figs. 2 and 3). The lowest exposed thrust sheet consists of Indian outer and inner shelf limestone, calciturbidites, chert, and shale of Jurassic–Cretaceous age. The ophiolite lies in two separate thrust sheets. Ultramafic and intrusive mafic rocks have been thrust over extrusive mafic rocks. Preliminary $^{40}Ar/^{39}Ar$ dates from hornblende crystals in the metamorphic sole suggest that the Waziristan ophiolite formed ca. 96–90 Ma and was obducted prior to 80 Ma (E. Gnos, 1997, personal commun.). These dates are consistent with the timing of deformational events during the Late Cretaceous that were proposed by Beck et al. (1996). Beck's work is based on the biostratigraphy of strata in what is interpreted as a Late Cretaceous syn-obduction foredeep and shows that the ophiolite was obducted ca. 85 Ma. $^{40}Ar/^{39}Ar$ ages from alkaline igneous intrusions crosscutting tectonic contacts fix tectonic shuffling of the ophiolite to before 80 Ma (E. Gnos, 1997, personal commun.). The ophiolite was later thrust beneath a package of deep marine allochthonous sedimentary rocks of Triassic to Cretaceous age. A sequence of uppermost Cretaceous, Paleocene, and Eocene marine and terrestrial strata unconformably overlies the deep marine allochthon and ophiolite.

The northern continuation of the Waziristan ophiolite extends into easternmost Afghanistan and is referred to as the Khost ophiolite. The Khost ophiolite contains intermediate to ultramafic igneous rocks. Lower Paleozoic to Jurassic calcareous shelf sedimentary rocks were underthrust to the northwest below the Khost ophiolite. The ophiolite is tectonically overlain by a Triassic to Upper Jurassic sequence of pelagic sediments. Tuffs and exotic blocks of Cretaceous shallow water limestone have been found over the ophiolite (Krishnan, 1953a, 1953b; Cassaigneau, 1979; Tapponnier et al., 1981, Treloar and Izatt, 1993).

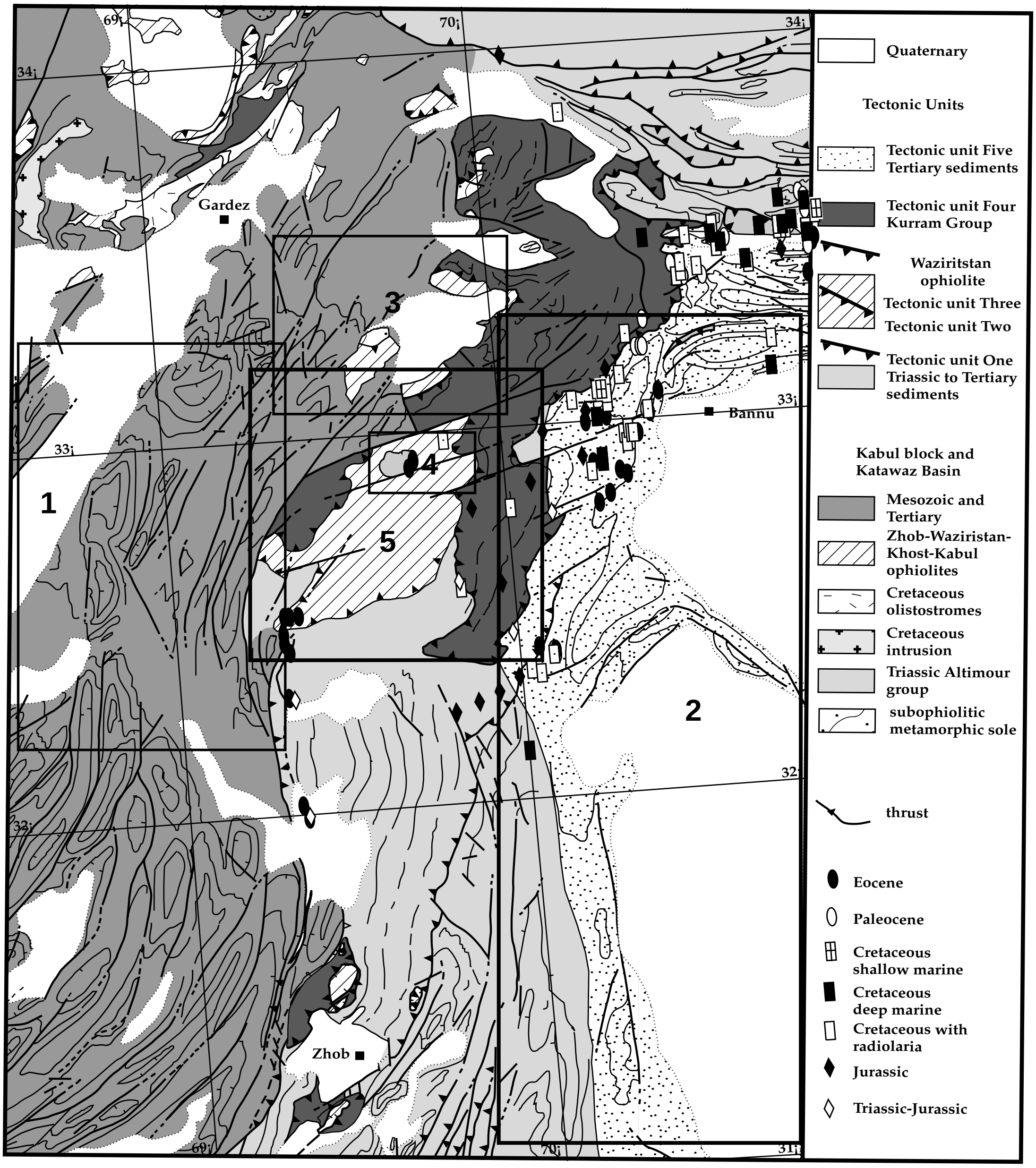

Figure 2. Regional geologic map of Waziristan showing locations of the major tectonic units and study area. The lowest tectonic unit consists of Triassic to Tertiary Indian shelf strata. The shelf strata underthrusted the next two units, the tectonically shuffled ophiolite. The ophiolite was then thrust beneath a Triassic to Tertiary bathyal sequence. The fifth unit consists of Tertiary sediments deposited unconformably over the thrust sheet stack. Approximate areas of mapping: 1—Ganss (1970); 2—Hemphill and Kidwai (1973); 3—Cassaigneau (1979); 4—Badshah (1985); 5—this study.

Katawaz Basin. The Katawaz basin borders the Khost-Waziristan ophiolite along its western margin and crops out in the westernmost part of the map area (Figs. 2 and 3). The Katawaz basin is interpreted as a large transtensional basin located west of the Indian plate (including Pakistan), which formed during the collision. Subsidence of the basin was synchronous with the deposition of upper Paleocene to middle Eocene shallow water limestone, clastic deposits, and pelagic sediments on the Indian shelf to the east (Cassaigneau, 1979). During the collision, the basin was shortened and inverted and is now dominated by southwest-trending tight folds with slaty cleavage (Hunting Survey Corporation, 1960; Qayyum et al., 1996).

Previous Mapping of Waziristan

Stratigraphy and Regional Mapping. *Stratigraphy.* Verchere (1867) described his work on what he called the Afghan Mountains, in his paper on the geology of Kashmir. He described in broad terms the rocks, mineral resources, and fossils of Waziristan. Smith (1895) entered Waziristan along the Tochi River and described the igneous complex and associated sedimentary rocks. He collected samples from the igneous complex and recognized abundant trachytes. Stuart (1922) also entered along the Tochi River in 1919 as part of the Waziristan Field Force. This expedition confirmed Smith's observations, and Stuart prepared a 1:500 000-scale geologic reconnaissance map. He recognized Jurassic sedimentary rocks in the area and identified Cretaceous strata. By 1922, a reconnaissance geologic map of the east-central Waziristan region was published with correctly identified rocks.

Kaever (1964) worked in the Khost region, just to the north of Waziristan. He used foraminifers to date limestone unconformably above the Kandahar Volcanics, located on what was the southern margin of Eurasia, as Paleocene? to early Eocene and locally as early late Eocene. Ganss (1970) studied a large part of eastern Afghanistan and mapped the flysch deposits along the Afghanistan-Pakistan border adjacent to the western edge of the Waziristan ophiolite. Hemphill and Kidwai (1973) mapped and described the stratigraphy to

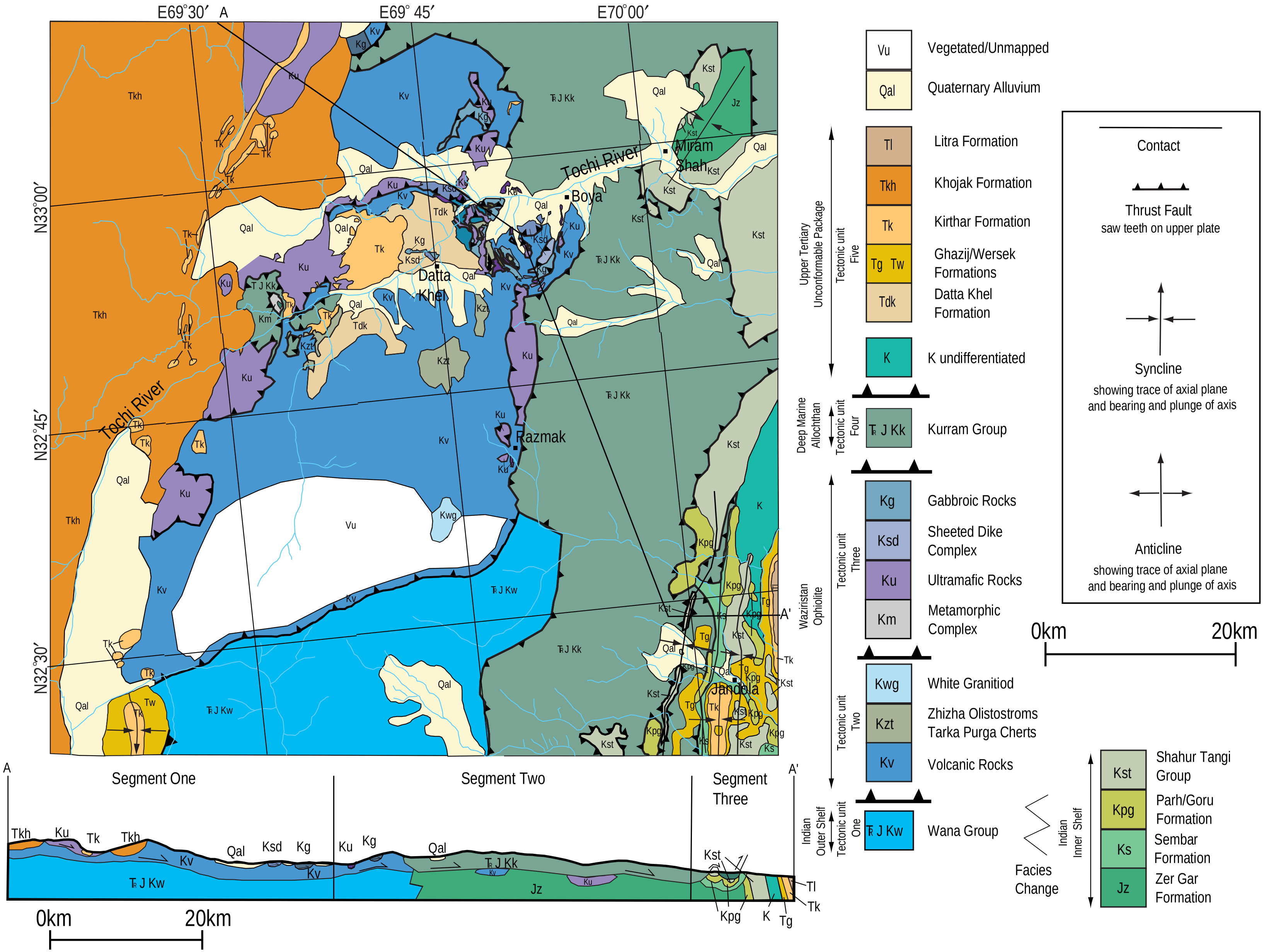

Figure 3. New geologic map, tectonostratigraphy, and cross section for the Waziristan region. The major tectonic units can be seen on this map. The lowest tectonic unit consists of the Wana Group and the Shahur Tangi Group through the Zer Gar Formation, a continental shelf sequence. This unit underthrusted the next two units, the tectonically shuffled ophiolite. The lower slice of the ophiolite, the second unit, consists of the white granitoid through the volcanic rocks. The upper slice of the ophiolite, the third unit, is the gabbroic rocks through the metamorphic complex. The ophiolite was then thrust beneath the fourth unit, the Kurram, a Triassic to Tertiary bathyal sequence. The fifth unit consists of Tertiary sediments, the Litra Formation through the K undifferentiated, deposited unconformably over the thrust sheet stack.

TABLE 2. TECTONOSTRATIGRAPHY OF WAZIRISTAN

Tectonic units	Group	Formation*	Member	Display color: Ratio (3/4, 5/4, 7/5)	Display color: Principal components (1, 2, 3)	Thickness (m)	Lithology†	Paleo-environment	Age§
		Litra Fm.				1649	Shl, snd, cong	Fluvial	
		Khojak Fm.	Shaigalu		Red	3950	Snd		Olig.–e. Mio.
Tectonic unit five			Murgha Faqirzal			1941	Shl, snd		M. Eoc.–m. Olig.
		Kirthar Fm.	Habib Rahi		Whitish pink	55	Lst	Shallow marine	
			Tabai			55	Lst	Shallow marine	
			Wersek			55	Lst	Shallow marine	Paleo.–m. Eoc.
		Ghazij/Wersek Fm.	Ghazij Shale		Pink	720	Shl	Open marine	E. Eoc.
			Wersek Shale			720	Shl	Open marine	M. Eoc.
		Datta Khel Fm.			Dark green to brown, red		Cong	Shoreline	
	unconformity								
		Cretaceous undiff.							Cret.
	thrust								
Tectonic unit four	Kurram Group				Variegated pinkish/red		Shl, lst, chert, snd, vol, mafic		L. Jur.–Cret.
	thrust								
		Feldspathic plutonic rocks					Gab, l. gab, anor		
Tectonic unit three		Sheeted Dike Complex		Yellow			Greenschist		
		Ultramafic rocks		Blue	Dark blue		Harz, dun, pyrn		
		Metamorphic Complex		Red			Amphibolite		
	thrust								
		White Granitoid			White		Gran, ton		
Tectonic unit two		Zhizha Olistrostrome/ Tarka Purga Cherts			Green		Shl, chert		
		Volcanic rocks		Purple			Basalt		
	thrust								
	Wana						Lst, shl, chert	Slope	L. Tri.–E. Jur.
	facies change								
	Shahur Tangi	Shinki Post Fm.			Red	700	Shl, lst, snd	Deep marine	L. Cret.
		Khajuri Post Fm.				>1200	Snd, lst, shl	Deep marine	L. Cret.
Tectonic unit one		Parh/Goru Fm.	Parh Limestone		Lime green		Lst	Deep marine	L. Cret.
			Goru Limestone			536	Lst	Deep marine	L Jur.–L. Cret.
		Sembar Fm.			Yellow/orange	284	Shl, lst, snd	Deep marine	E. Cret.
		Zer Gar Fm.			Light pink	~900	Lst	Middle–outer shelf	M.–L. Jur.

Note: Tectonostratigraphy of the Waziristan ophiolite and associated strata and their display colors. This table shows the five tectonic units and the units' lithology.
*Fm.—Formation; undiff.—undifferentiated.
†anor—anorthosite; cong—conglomerate; dun—dunite; gab—gabbro; l. gab—leucogabbro; harz—harzburgite; lst—limestone; shl—Shale; snd—sandstone; pyrn—pyroxinite; ton—tonolite; vol—volcanic rocks (after Robinson, 1998).
§E.—Early; e.—early; M.—Middle; m.—middle; L.—Late; Tri.—Triassic; Jur.—Jurassic; Cret.—Cretaceous; Paleo.—Paleocene; Eoc.—Eocene; Olig.—Oligocene; Mio.—Miocene.

the east of the Waziristan ophiolite. Meissner et al. (1974, 1975) mapped and compiled the stratigraphy south of the Waziristan ophiolite. Beck (1995) documented the sedimentary stratigraphy and compiled the biostratigraphy of the Waziristan region (Table 2).

Igneous Rocks. One year after Smith's fieldwork, Hayden (1896) analyzed the petrology of samples collected by Smith and recognized high-pressure and low-temperature minerals that geologists now associate with subduction zones. In 1940, A. L. Coulson investigated the mineral resources in the Northwest Frontier Province, including Waziristan. Coulson (1940) recognized that the relative percentage of ultramafic rocks was small when compared to the amount of mafic to intermediate igneous rocks in the Waziristan ophiolite. In addition to dating limestone, Kaever (1964) identified mafic-ultramafic rocks just to the north of the Waziristan ophiolite in Khost. Mattauer et al. (1978) approached the study of the Waziristan region through Kohistan. They studied the western end of the Kohistan island arc and identified the Jalalabad block as part of precollisional Indo-Pakistan. Cassaigneau (1979), who had previously worked with Mattauer, moved southeast into the Khost region where he also found mafic to ultramafic rocks. In 1985, Jan et al. documented the chromite chemistry of the samples collected by the Federally Administered Tribal Areas Development Corporation (FATADC) from the eastern edge of the Waziristan ophiolite. A 1:100 000 geologic map covering large parts of the Waziristan ophiolite was also published by the FATADC (Badshah, 1985). This research prompted Jan et al. (1985) to revise the petrology of the Waziristan ophiolite. They recognized a typical suite of ophiolite rocks, yet they were unable to find a complete and ordered ophiolite secession.

Ahmad and Hamidullah (1987) questioned the validity of the name "Waziristan Ophiolite." They revisited the igneous petrology and geochemistry of the Waziristan ophiolite and found ultramafic rocks with major and trace element compositions similar to the Chilas Mafic-Ultramafic Complex. Hence, they referred to the Waziristan ophiolite as the Waziristan Igneous Complex and interpreted it as an island arc.

Age of Obduction. While working in Khost, Cassaigneau (1979) speculated about a Triassic date for obduction, which he later revised to Paleocene. Extensive fieldwork and biostratigraphy allowed Beck (1995) to revise the timing of the ophiolite obduction and collision in this area to Late Cretaceous and late Paleocene, respectively. E. Gnos (1997, personal commun.) studied the igneous petrology of the ophiolite and collected samples for $^{40}Ar/^{39}Ar$ dating. The samples provided an age (ca. 85 Ma) for the obduction of the ophiolite. The radiometric ages he obtained were consistent with Beck's (1995) findings.

Image Processing

This study used six bands (1, 2, 3, 4, 5, and 7) in the visible and near-infrared parts of the electromagnetic spectrum collected by the Landsat TM sensor on the Landsat 5 satellite. The images were processed using ER Mapper image processing software. Spectral ratios and principal component analysis methods were applied to the data. A spectral ratio is the division of one spectral band by another (Vincent and Thomson, 1971). This process eliminates the atmospheric backscatter and the environmental portions of the reflected light, and the composition component of the reflectance can be viewed directly. The ratio technique is most useful when combined with laboratory spectra, which allows one to narrow the number of possible surface compositions (Grove et al., 1992; Vincent, 1997).

Digital multispectral data lend themselves to statistical analysis. The statistical technique known as principal component analysis resolves textural and compositional information (Hall, 1979). This enhancement effectively increases the contrast between bands. The investigator may choose which principal components to view as primary colors depending on the purpose of the study and the study area. The principal component analysis statistical treatment does not remove the atmospheric or the environmental components of the surface reflectance. This enhancement provides the greatest contrast between the rock types present, although the lithologic composition cannot be determined without ground truth (Vincent, 1997). Principal component analysis is most useful for geologic mapping in combination with compositional techniques such as the spectral ratio.

We applied the spectral ratio and principal component analysis methods to create a 3/4, 5/4, and 7/5 RGB ratio image and first, second, and third principal components of the TM bands 4, 5, and 7 image. We recognized the spectral signatures of specific materials by a combination of ground truthing (Badshah, 1985; Badshah et al., 1999) and a listing of TM brightness and ratio codes of minerals (Grove et al., 1992, Vincent, 1997).

INTERPRETATION

Remote sensing is efficient and effective, but must be verified by ground truth and previous research. E. Gnos performed most of the ground truthing for the igneous rocks. To place the new map in the proper context of previous research, we will briefly revisit the regional geology.

On the regional and local maps (Figs. 2 and 3), the five tectonic units are identified in the area. The lowest unit (unit one) consists of Triassic to Tertiary Indian shelf sediments. The middle two units are the ophiolite, which has been tectonically shuffled so that the lower ophiolitic rocks (unit three) were underthrust by the upper ophiolitic rocks (unit two). The ophiolite units were then thrust beneath unit four, an allochthon consisting of deep-water Triassic to upper Maastrichtian strata. Tertiary strata, unit five, were unconformably deposited over the whole tectonic stack.

Different igneous rock types (Table 2) contained within the ophiolite—ultramafic rocks, gabbroic rocks, and the sheeted dike complex (Fig. 3)—are distinguishable in the spectral ratio image (Fig. 4). The ultramafic rocks, primarily harzburgite, contain olivine, enstatite, and serpentine. The composition gives the ultramafic rocks a pinkish to orange color in the image. The gabbroic rocks are yellowish because their anorthite and augite content creates a high spectral characteristic in the 3/4 and 5/4 ratios, which are displayed as red and green, respectively. The sheeted dike complex appears bluish-purple because of its labradorite and augite content. Snow, clouds, and dark cloud shadows are an intense red in the image, and vegetation appears green-black to black. In the image, the ultramafic rocks, gabbroic rocks, and sheeted dike complex of the ophiolite appear as pink to orange, yellow, and bluish-purple, respectively.

The principal component analysis image used in this study consists of the first, second, and third principal components displayed as RGB of TM bands 4, 5, and 7 (Fig. 5). This image distinguishes between the ophiolite and the associated sedimentary strata and between individual sedimentary rocks (Table 2). As stated before, ground truthing is necessary to determine the spectral signature of specific materials. Through ground truthing (Badshah, 1985; Beck et al., 1996; Badshah et al., 1999) and the use of ratio images, the distributions of specific rock types were determined.

On the principal component analysis image (Fig. 5), vegetation is turquoise, and snow is green. Starting on the left side of the image, the first major unit is the Khojak Formation (Table 2), a syn-collisional flysch deposit. It appears red and has been intensely deformed. To the right of the Khojak Formation, toward the center of the image, is a large area that is pink to almost white. This is the Kirthar Limestone (Table 2), which unconformably overlies the ophiolite. Adjacent to the limestone, to the left, are some ultramafic rocks and the metamorphic sole of the ophiolite (Table 2). The ultramafic rocks appear as dark-blue and/or navy-blue, and the metamorphic sole appears brown. The white area, at approximately N32°37′ and E69°45′, is a white granitoid. With the exception of the ultramafic rocks, the other major ophiolitic rocks can be identified more easily in the ratio image.

Northwest of the Kirthar Limestone is the Datta Khel Formation (Table 2), a clastic series that ranges from dark green/brown to green with some red. The texture suggests long, continuous ridges. At the very bottom center of the image, partially obscured by vegetation, lies the Wana Group (Table 2), a sequence of limestone, sandstone, and shale deposited on India's continental slope (Beck et al. 1996). This group has been shown on maps of regions north of Waziristan (Cassaigneau, 1979). The edge of the ophiolite complex was located on the image from drainage patterns and fieldwork.

Dominating the right side of the image is a variegated pinkish/red to orange, discontinuously ridged unit assigned to the Kurram Group (Table 2)—shale, limestone, chert, sandstone, and some volcanic and mafic rocks that were deposited on India's outer shelf (Beck et al. 1996). Toward the top of the image bordering the right side is a red area with a rough texture assigned to the Shahur Tangi Formation (Table 2). This formation contains shale, limestone, and sandstone and was deposited on India's inner shelf (Beck et al. 1996). North of the Tochi River, the Shahur Tangi forms a V that opens to the northeast (Fig. 5). Inside the V is the pink, Jurassic Zer Gar Formation (Table 2), a deep marine limestone deposited on India's outer to middle shelf. The most notable features in the bottom right corner are the lime green areas. These are the Parh and Goru Formations (Table 2), which are deep marine limestone and shale. The shoeprint–shaped feature at the very bottom of the image is more middle Eocene Kirthar Limestone underlain by Ghazij Formation (Table 2). Left and north of the limestone lies the yellow/orange, Lower Cretaceous Sembar Formation (Table 2), a deep marine shale and limestone deposited on India's inner shelf (Beck et al. 1996), and more of the light pink Ghazij Formation. At the extreme right side of the interpretation lies the Litra Formation. The contact between the Litra Formation and the Kirthar Formation was added using Hemphill and Kidwai's (1973) previously published maps and other unpublished satellite images.

Comparison of the New Map to Previously Published Maps

Ganss (1970) worked along the Afghanistan-Pakistan border building on the biostratigraphic data and fieldwork of Kaever (1967) (Fig. 2). He created a structural map from aerial photos. His exploration and research allowed for identification of some rock types, but his map focused mainly on topographic expressions of the under-

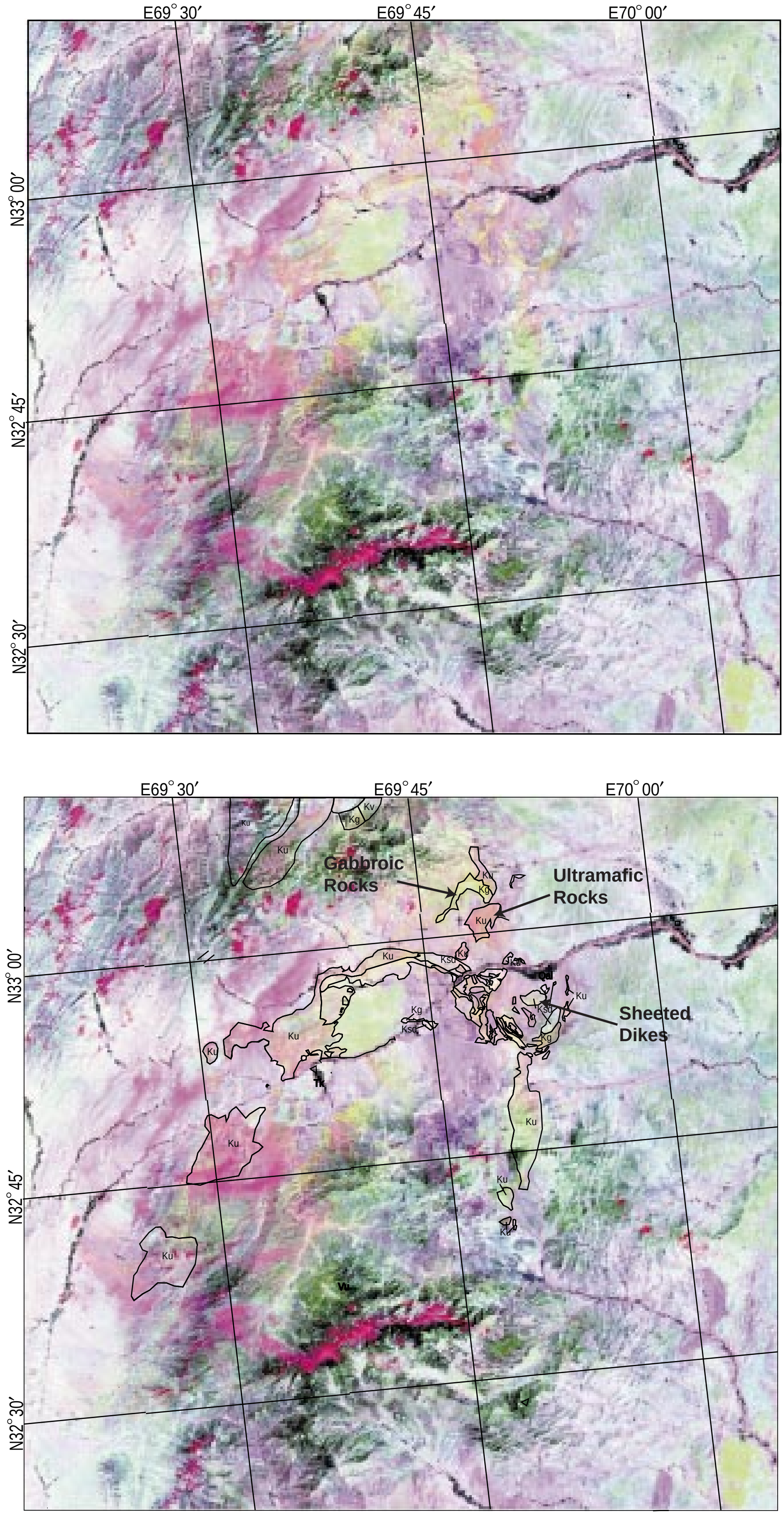

Figure 4. (A) Uninterpreted spectral ratio image displaying ratios 3/4, 5/4, and 7/5 RGB. This image distinguishes the igneous rock types of the ophiolite. For explanation of the geologic symbols, refer to Figure 3. (B) Interpreted spectral ratio image. For symbol descriptions, see Figure 3.

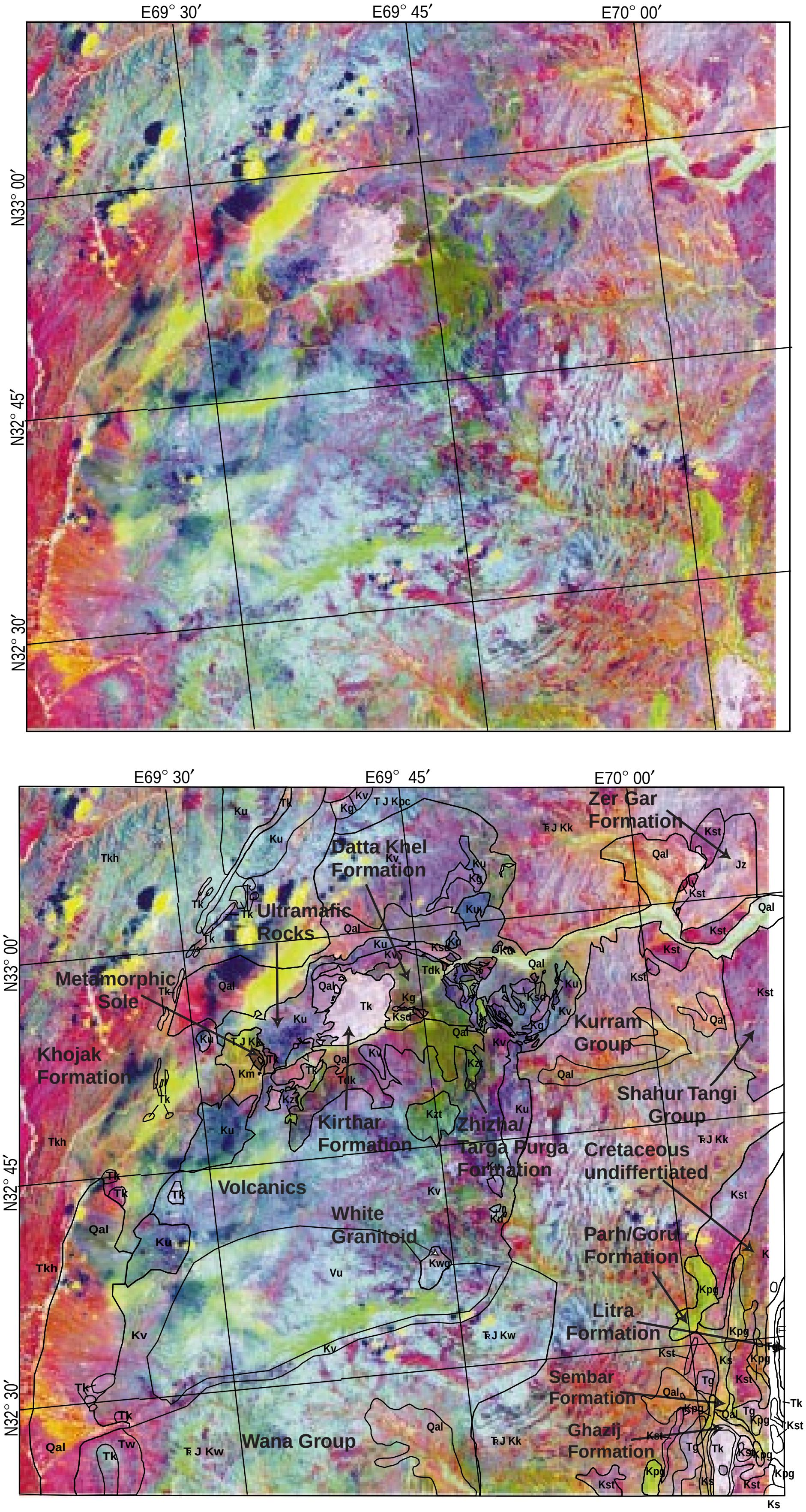

Figure 5. (A) Uninterpreted principal component analysis image, which displays the first, second, and third principal components of TM bands 4, 5, and 7 RGB. This image distinguishes the major tectonic units and the sedimentary units of the region. For the geologic symbols, refer to Figure 3. (B) Interpreted principal component analysis image. For symbol descriptions, see Figure 3.

lying geologic structures. Ganss did not enter the ophiolitic area. Our image processing and analysis has allowed us to add lithologic contacts between the Khojak Formation and Kirthar Formation in the northwest corner and between the Kirthar Formation and Wersek Formation in the southwest corner of the image to the structures defined by Ganss.

Hemphill and Kidwai (1973) worked along the eastern border of Waziristan (Fig. 2). They compiled the stratigraphy of the Bannu Quadrangle and created a geologic map of the area that displays rock types and contacts. The deformed nature of the strata in the area and security reasons forced them to lump most of the strata into generalized units; consequently, they did not differentiate the Cretaceous and, locally, the Cretaceous from the Jurassic strata. They identified the Pab and Mugal Kot Formations and lumped the Parh and Sembar Formations. We were able to identify the Pab and Mugal Kot Formations as the Shahur Tangi Group, based on the lack of a gray shale matrix in the Shahur Tangi and depositional environment. We were also able to distinguish between the Parh and Sembar Formations, while identifying the Goru Limestone. Hemphill and Kidwai did not enter the ophiolite region. Image processing and analysis allowed the differentiation of many of the generalized units based on the spectral characteristics of the individual rock units (Fig. 3, Table 2).

Cassaigneau (1979) worked along the northern border of Waziristan in the Khost region. His major focus was on the igneous rocks in the area. He did not differentiate among the different Tertiary rock units, which lie on the west side of his map area. Interpretation of the satellite images allowed differentiation of these Tertiary rocks, and the five tectonics units were defined (Fig. 3, Table 2). Cassaigneau's map contained strike-slip faults that could not be confirmed on the satellite images and were not added to the new geologic map. Further fieldwork is needed to confirm the existence of these faults.

Badshah et al. (1985) published the only FATADC map of the ophiolite proper. The map focused on the southern half of the ophiolite (Fig. 2). Their map agrees well with the spectral signatures observed during this study, but the tectonostratigraphy of the associated sedimentary nappes was not well delineated. The use of satellite imaging allowed a much larger area to be mapped, and allowed the associated sedimentary nappes to be documented more completely. Image processing also allowed for more detail in the final map (Fig. 3, Table 2).

The Landsat TM data provided an objective, reproducible and synoptic overview that allowed synthesis and some reinterpretation of scattered earlier work. On the whole, image processing techniques allowed a greater level of detail to be added to existing maps. The result is one geologic map for the Waziristan region (Fig. 3).

Cross Section. A more complete understanding of the tectonic units introduced in the new geologic map was gained from a cross section of the study area (Fig. 3). The cross section has been divided into three segments to facilitate description and is described from northwest to southeast. In segment one, the Khojak and Kirthar Formations (Table 2) overlie the Waziristan ophiolite. The Khojak and Kirthar Formations were deposited in a transtensional basin west and locally unconformably above the ophiolite. The ophiolitic rocks in this area consist of ultramafic rocks, volcanic rocks, sheeted dikes, and gabbros. The ophiolite was underthrust by the Wana Group, which is the basal unit in this segment. Compression after the Eocene folded the Kirthar and Khojak Formations, as well as the underlying ophiolite.

In segment two, the distal sediments of the Kurram Group (Table 2) tectonically overlie the ophiolite, which was underthrust by the Wana Group and the Zer Gar Limestone. Southward, the Wana Group grades into an inner shelf sequence and then into a shallow marine sequence, the limestone and shale of the Jurassic Zer Gar Formation (Beck et al. 1996). This sequence of marine sediments directly underlies the fourth nappe (composed of the Kurram Group) for the majority of this segment of the cross section.

In segment three, the upper unit consists of undifferentiated Cretaceous strata unconformably overlain by Tertiary strata (Table 2). The Kurram Group was underthrust by marine strata as young as Maastrichtian (Shahur Tangi Group; Table 2). This implies that the final emplacement of the uppermost nappe must postdate the middle Maastrichtian and predate the lower Eocene in this cross section and locally predate the late Paleocene (Beck et al., 1995).

Revised Geologic History. From previous work, tectonostratigraphy, biostratigraphy, and geologic structure derived with the aid of remote sensing data, a tectonic history can be constructed for the Waziristan area.

Triassic to Jurassic. Paleomagnetic studies indicate that India was part of Gondwana and formed the southern margin of the Neotethys Ocean during Triassic and Jurassic time (Besse and Courtillot, 1988). Foraminifers from the Wana Group and Kurram Group suggest that these groups were deposited on India's outer shelf and on the Tethys Ocean floor, respectively (Beck et al., 1996).

Early to Late Cretaceous. Early Cretaceous strata of the Waziristan area record the breakup of Gondwana and the beginning of India's northward movement (Besse and Courtillot, 1988). During the early Cretaceous, the Sembar and the Parh/Goru strata (Table 2) were deposited in a shallow marine environment on the Indian shelf (Beck et al., 1996). The overlying Shahur Tangi Group (Table 2) was deposited in a foredeep as Indian shelf strata. $^{40}Ar/^{39}Ar$ radiometric studies of hornblende from the metamorphic sole of the Waziristan ophiolite imply that south-directed intraoceanic thrusting began in the Neotethys between 96 and 90 Ma (E. Gnos, 1997, personal commun.).

The deep marine and slope deposits of the Wana through Shahur Tangi Groups were thrust under oceanic crust to obduct the Waziristan ophiolite ca. 85 Ma. This date is based on a sudden increase in the rate of shelf subsidence and the formation of a deep-water synobduction flysch basin that may be related to the load of the obducting ophiolite. The rapid subsidence is represented by a thick sequence of the Shahur Tangi Group in eastern Waziristan and a juxtaposition of fauna of similar age from bathyal and shallow-water depths in strata of the Shahur Tangi Group. Khajuri Post strata (Table 2) of the upper Shahur Tangi Group consist of a quartzose belt of sandstone that is interpreted as submarine fan deposits that accumulated in a deep narrow foredeep as the Indo-Pakistani craton was thrust northward beneath the ophiolite (Beck et al., 1996). This conclusion is supported by 80 Ma $^{40}Ar/^{39}Ar$ ages from alkaline igneous intrusions that crosscut tectonic contacts in the ophiolite (E. Gnos, 1997, personal commun.). These crosscutting relationships prove that the ophiolite was tectonically shuffled prior to 80 Ma and that the timing of deformation is consistent with the timing of foredeep development in front of the obducting ophiolite.

Paleocene. During Paleocene time, Triassic–Cretaceous deep marine strata of the Kurram Group were underthrust by the dismembered ophiolite (Beck et al., 1996; Badshah et al., 1999). This event created a foreland basin to the southwest of the Waziristan ophiolite that was filled by the Paleocene Patala and the lower Eocene Ghazij Formations (Beck et al., 1996). The clastic Datta Khel Formation was deposited above the deformed belt as the ophiolite eroded (Badshah et al., 1999). The deposition of the Ghazij Formation coincides with late Paleocene through early Eocene deformation on the southern margin of Asia (Sullivan et al., 1993; R. A. Beck, J. A. Bellian, J. Robinson, and N. Shafique, unpublished data) and is interpreted as marking incipient India-Asia collision (Beck et al., 1995, 1996).

Eocene. In early Eocene time, the Ghazij Formation was deposited in the southern part of the foreland basin (Beck et al., 1996; Pivnik and Wells, 1994). The transtensional Katawaz basin opened to the north and west as India moved past the Kabul block. The Wersek Formation, a time equivalent to the Ghazij, began filling the Katawaz basin (Beck, 1995). During the middle Eocene there was a pause in the deformation in northwest Pakistan that coincided with a global highstand in sea level (Harland et al., 1982). A shallow marine environment spread over most of the region and is recorded by the deposition of the Kirthar Formation (Beck et al., 1996). The late Eocene brought a relative drop in sea level that ended deposition of the Kirthar Formation. Flysch deposition continued into the Oligocene in the Katawaz basin west of the Waziristan ophiolite (Beck et al., 1996).

Oligocene through Miocene. The Oligocene and Miocene Epochs are represented by an unconformity in the Waziristan region. Apatite fission-track dates from nearby Kurram indicate an episode of renewed uplift in the mountain belt ca. 10 Ma (Meigs et al., 1995).

Pliocene. As the Pliocene began, detritus from the mountain belt accumulated as the Litra Formation in the transpressional foreland basin east of Waziristan (Hemphill and Kidwai, 1973), and represents the suturing between India and Asia along the total length of the suture zone. The suturing of India and Asia has slowed rather than stopped India's northward motion. Evidence of the continuing movement of India can be seen in the uplifted and tilted, unconformable, Tertiary and Quaternary sedimentary sequence.

CONCLUSIONS

Landsat TM data were used to create principal component and ratio images of the Waziristan area. The first, second, and third principal components of bands 4, 5, and 7 permitted separation of the ophiolite and associated sedimentary rock types as a whole, as well as into different sedimentary units (e.g., Rothery et al., 1990). Also, the ratio image of 3/4, 5/4, 7/5 RGB was very useful for discriminating among ophiolitic rock types.

The satellite images, in combination with available geologic maps, limited field work, and biostratigraphic, lithostratigraphic, and radiometric studies were used to create an important and coherent geologic map of Waziristan. The map portrays well the five separate tectonic units in the region. The first, or lowest unit, is comprised of Indian shelf sediments that were thrust under the Waziristan ophiolite. The ophiolite has been tectonically shuffled and consists of the next two separate tectonic units. The fourth unit, or top thrust sheet, is a nappe comprised of distal Neotethyan sediments that were underthrust by the ophiolite riding on Indian shelf strata. The fifth and uppermost unit contains unconformable Tertiary and younger strata.

The documentation of the tectonic units of the region provides a new and more detailed regional tectonic history. From the Triassic to the Cretaceous, the Kurram and Wana Groups and the Zer Gar Formation were deposited along the southern shore of the Neotethys Ocean. During the Early Cretaceous, the Sembar Formation was deposited in a shallow marine environment on the Indian shelf as the subcontinent moved northward. By 96–90 Ma, there was intraoceanic thrusting in the Neotethys. Ophiolite obduction onto northwestern India, ca. 85 Ma, caused the flysch of the Shahur Tangi Group to be deposited in a bathyal foredeep. The ophiolite was tectonically shuffled before it was crosscut by igneous intrusions at 80 Ma. During the Paleocene, the uppermost nappe, the Kurram Group, was underthrust by the ophiolite. The underthrusting created a foreland basin on northwestern India into which lower Tertiary sediments were deposited. The Himalayan collision caused the transtensional Katawaz basin to open west of the Waziristan ophiolite, where Paleocene, Eocene, and locally Oligocene marine flysch deposition took place. Continued India-Asia convergence, from Miocene through the present time, deformed the Waziristan region, caused flexural subsidence of the northwestern Indian shelf, and supplied a fluvial molasse basin east of the Waziristan ophiolite with sediment to form the Siwalik Group.

ACKNOWLEDGMENTS

The authors would like to acknowledge the U.S. Geological Survey at the EROS Data Center for archiving and providing the Landsat data; Amoco, the Swiss National Science Foundation, and the Geology Department of Miami University, who funded field work; and ER Mapper for an educational software grant.

REFERENCES CITED

Ahmad, W., and Hamidullah, S., 1987, Island arc signatures from the Waziristan Igneous Complex, N.W.F.P., Pakistan: Geological Bulletin of the University of Peshawar, v. 20, p. 161–180.

Badshah, M. S., 1985, Development potential of Waziristan copper: Peshawar, Records of the FATA Development Corporation, v. III, p. 1–14.

Badshah, M. S., Gnos, E., Jan, M. Q., and Afridi, M. I., 1999, Stratigraphic and tectonic evolution of the northwestern Indian plate and Kabul Block, *in* Khan, M. A., Treloar, P. J., Searle, M. P., and Jan M. Q., eds., Tectonics of the Nanga Parbat syntaxis and the Western Himalaya: Geological Society (London) Special Publication 170, p. 467–475.

Beck, R. A., 1995, Late Cretaceous ophiolite obduction and Paleocene India-Asia collision in the westernmost Himalayas [Ph.D. thesis]: Los Angeles, University of Southern California, 550 p.

Beck, R. A., Afzal, J., Barndt, J. K., Berry, J. R., Burbank, D. W., Cheema, A., Jurgen, H., Khan, A. M., Lawrence, R. D., Metie, J., Riley G. W., Sercombe, W. J., and Shafique, N. A., 1995, Stratigraphic evidence for an early collision between northwest India and Asia: Nature, v. 373, p. 55–58.

Beck, R. A., Burbank, D. W., Khan, A. M., Lawrence, R. D., and Sercombe, W. J., 1996, Late Cretaceous ophiolite obduction and Paleocene India-Asia collision in the westernmost Himalaya: Paris, Geodinamica Acta, v. 9, p. 114–144.

Besse, J., and Courtillot, V., 1988, Paleogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic: Journal of Geophysical Research, v. 93, p. 1791–1808.

Cassaigneau, C., 1979, Contribution a l'étude des sutures Inde-Eurasie: La zone de suture de Khost dans le Sud-Est de l'Afghanistan, l'obduction Paléocene et la tectonique tertiare [Ph.D. thesis]: Montpellier, France, Université des Sciences et Techniques du Languedoc, 125 p.

Coulson, A. L., 1940, The mineral resources of the North West Frontier Province: Records of the Geologic Survey of India, v. 75, p. 1–55.

Ganss, O., 1970, Zur Geologie von Suedost-Afghanistan; II, Geologie des Gebietes um Mukur und Ob-i-Istada: Hannover, Geologisches Jahrbuch, Beihefte, v. 84, p. 113–195.

Grove, C. I., Hook, S. J., and Paylor, E. D., II, 1992, Laboratory reflectance spectra of 160 minerals, 0.4 to 2.5 micrometers: Pasadena, California, Jet Propulsion Laboratory Publication 92-20, p. 395.

Hall, E. L., 1979, Computer image processing and recognition: New York, Academic Press, 584 p.

Haq, S., and Davis, D., 1997, Oblique convergence and the lobate mountain belts of western Pakistan: Geology, v. 25, p. 23–26.

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G., and Walters, R., 1982, A geologic time scale: Cambridge, United Kingdom, Cambridge University Press, 131 p.

Hayden, H. H., 1896, On some igneous rocks in the Toche Valley: India Geological Survey Records, v. 29, pt. 3, p. 63–69.

Hemphill, W. R., and Kidwai, A. H., 1973, Stratigraphy of the Bannu and Dera Ismail Khan areas, Pakistan: U.S. Geological Survey Professional Paper 716-B, p. 1–36.

Hunting Survey Corporation, 1960, Reconnaissance geology of part of western Pakistan: Toronto, Government of Canada, Colombo Plan Cooperative Project Report, 550 p.

Jan, M. Q., Khan, A., and Windley, B. F., 1985, The Waziristan ophiolite, Pakistan, general geology and chemistry of the chromite and associated phases: Economic Geology, v. 80, p. 294–306.

Kaever, M., 1964, Über Assilina lacunata CIZANCOURT, aus dem Unter-Eozän, Afghanistans: Geologisches Jahrbuch, v. 82, p. 131–142.

Kaever, M., 1967, Zur Geologie des Gebietes von Khost und Yakubi—SE Afghanistan: Neues Jahrbuch für Geologie und Paläontologische, Monatshefte, v. 6, p. 361–383.

Krishnan, M. A., 1953a, General report of the Geological Survey of India for the year 1941: Records of the Geologic Survey of India, v. 79, p. 167–285.

Krishnan, M. A., 1953b, General report of the Geological Survey of India for the year 1942: Records of the Geologic Survey of India, v. 79, p. 285–304.

Mattauer, M., Proust, F., Tapponnier, P., and Cassaigneau, C., 1978, Ophiolites, obductions et tectonique globale dans l'Est de l'Afghanistan: Comptes Rendus de l'Academie des Sciences, Série D, Sciences Naturelles, v. 287, p. 983–985.

Meigs, A. J., Burbank, D. W., and Beck, R. A., 1995, Late Miocene (~11 Ma) initiation of the Main Boundary thrust in the western Himalaya: Geology, v. 23, p. 423–426.

Meissner, C. R., Master, J. M., Rashid, M. A., and Hussain, M., 1974, Stratigraphy of the Kohat Quadrangle, Pakistan: U.S. Geological Survey Professional Paper 716-D, 30 p.

Meissner, C. R., Hussain, M., Rashid, M. A., and Sethi, U. B., 1975, Geology of the Parachinar Quadrangle, Pakistan: U.S. Geological Survey Professional Paper 716-F, 24 p.

Pivnik, D. A., and Wells, N. A., 1994, Eocene closure of the Tethys as recorded in NW Pakistan: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A-181.

Qayyum, M., Niem, A. R., and Lawrence, R. D., 1996, Newly discovered Paleogene deltaic sequences in Katawaz basin, Pakistan, and its tectonic implications. Geology, v. 24, p. 835–838.

Robinson, J., Badshah, M., Beck, R., Gnos, E., and Vincent, R., 1997, New geologic insights for northwest Pakistan from Landsat (TM) and field data: Implications for copper

prospecting: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 60.
Robinson, J., 1998, New geologic insights for northwest Pakistan from Landsat Thematic Mapper [Master's thesis]: Miami, Ohio, Miami University, 94 p.
Rothery, D. A., Abrams, M. J., and Pontual, A., 1990, Subdivision of mapped units in the Oman ophiolite using enhanced Landsat Thematic Mapper images, *in* Proceedings, the Troodos 1987 Symposium: Nicosia, Cyprus, Ministry of Agriculture and Natural Resources, p. 367–374.
Smith, F. H., 1895, On the geology of the Tochi Valley: Records of the Geologic Survey of India, v. 28, p. 106–110.
Stuart, M., 1922, The geology of the Takki Zam Valley, and the Kaniguram-Makin area, Waziristan: Records of the Geologic Survey of India, v. 54, p. 87–102.
Sullivan, M. A., Windley, B. F., Saunders, A. D., Haynes, J. R., and Rex, D. C., 1993, A palaeogeographic reconstruction of the Dir Group: Evidence for magmatic arc migration within Kohistan, N. Pakistan, *in* Treloar, P. J., and Searle, M. P., eds., Himalayan tectonics: Blackwell, Geological Society of London Special Publication 74, p. 139–160.
Tapponnier, P., Mattauer, M., Proust, F., and Cassaigneau, C., 1981, Mesozoic ophiolites, sutures, and large-scale tectonic movements in Afghanistan: Earth and Planetary Science Letters, v. 52, p. 355–371.
Treloar, P. J., and Izatt, C. N., 1993, Tectonics of the Himalayan collision between the Indian plate and the Afghan block: A synthesis, *in* Treloar, P. J., and Searle, M. P., eds., Himalayan tectonics: Blackwell, Geological Society of London Special Publication 74, p. 69–87.
Verchere, A. M., 1867, Kashmir, the western Himalaya and the Afghan mountains, with a note on fossils by M. Edouard de Vernueil: Asiatic Society Bengal Journal, v. 36, no. 1, p. 9–50, 83–114, 201–229.
Vincent, R. K., 1997, Fundamentals of geological and environmental remote sensing. Englewood Cliffs, New Jersey, Prentice Hall, 366 p.
Vincent, R. K., and Thomson, F., 1971, Discrimination of basic silicate rocks by recognition maps processed from aerial infrared data, *in* Proceedings of the Seventh International Symposium on Remote Sensing of Environment: Ann Arbor, Environment Research Institute of Michigan, p. 247–252.

Manuscript Received by the Society January 15, 1999
Revised Manuscript Received September 14, 1999
Manuscript Accepted November 9, 1999

Printed in U.S.A.