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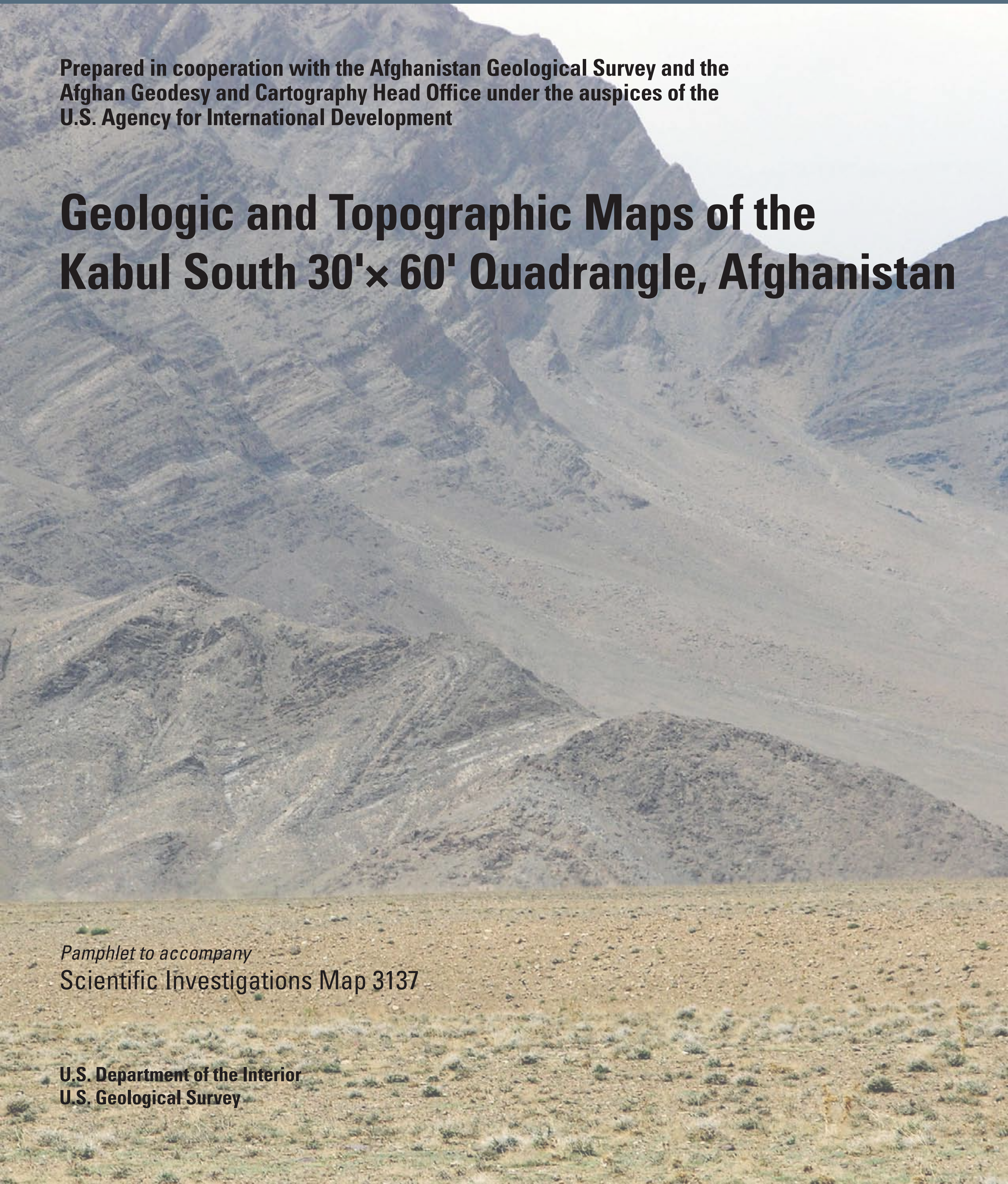

Prepared in cooperation with the Afghanistan Geological Survey and the Afghan Geodesy and Cartography Head Office under the auspices of the U.S. Agency for International Development

Geologic and Topographic Maps of the Kabul South 30'× 60' Quadrangle, Afghanistan

Pamphlet to accompany

Scientific Investigations Map 3137

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph: View to the north of west-dipping and strongly folded beds of Lopingian and Guadalupian reef limestone (Pkl) in the Tangi-Garu Formation of Donov, Abdullah, and Chmyriov, 2008. The dark rocks on the right (east) side of the photo are amphibolite in the Welayati Formation (Neoproterozoic) that unconformably underlay a thin basal clastic sequence of beds in the Tangi-Garu. The clastic sequence appears as the slightly resistant unit exposed in the saddle. This photograph was taken by the author in March of 2004 in the western part of Logar valley near the Anyak copper district.

Geologic and Topographic Maps of the Kabul South 30'× 60' Quadrangle, Afghanistan

By Robert G. Bohannon

Prepared in cooperation with the Afghanistan Geological Survey and the Afghan Geodesy and Cartography Head Office under the auspices of the U.S. Agency for International Development

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Altitude, as used in this report, refers to distance above the vertical datum.

It should be noted that there are many variant spellings and pronunciations of features and geologic terms in this region. Spellings and terms have been chosen for consistency only.

Geologic and Topographic Maps of the Kabul South 30' × 60' Quadrangle, Afghanistan

By Robert G. Bohannon

Introduction

This work has been funded by the United States Agency for International Development (USAID) as a part of several broader programs that USAID has designed to stimulate growth in the energy and mineral sectors of the Afghan economy. The maps that are included in this report represent works-in-progress in that they are simply intended to be the best possible product for the time available and conditions that exist during the early phases of reconstruction in Afghanistan. Most of the geologic interpretations and all of the topographic data were derived exclusively from images. A limited amount of fieldwork, in the spring of 2004 and the fall of 2006, was carried out within the quadrangle, but all the potential dangers present in Afghanistan restricted its scope, duration, and utility.

The main objective is to provide maps that will be used by scientists of the Afghan Ministry of Mines, the Afghanistan Geological Survey, and the Afghan Geodesy and Cartography Head Office in their efforts to rebuild the energy and mineral sectors of their economy. At the same time the maps provide a jump-start for the fledgling internal mapping programs of those agencies. It is hoped that the same set of maps will emerge eventually in new and improved versions as Afghan earth scientists modify them in response to knowledge gained from more detailed field-oriented studies.

The U.S. Geological Survey has produced a variety of geologic, topographic, Landsat natural-color, and Landsat false-color maps covering Afghanistan at the 1:250,000 scale. These maps may be used to complement the information presented here.

Mapping Methodology

Base topography and culture were derived from multiple sources. Shuttle Radar 90 m digital topography (SRTM 90 m, *http://srtm.csi.cgiar.org/selection/inputcoord.asp*) provided the basic elevation data. Cultural features and hydrography were digitized from DigitalGlobe Images (*http://www.digitalglobe.com/*) pan-sharpened to better than 1-m resolution, and from 1-m natural-color orthorectified aerial-photography. The photography was flown in summer and fall of 2006 in a cooperative effort by the U.S. Geological Survey (USGS) and U.S. Naval Research Laboratory that was funded by the Afghanistan Ministry of Mines as part of a broader geophysical survey of the country. The base-map projection is Universal Transverse Mercator (UTM, zone 42N) in the World Geodetic System (WGS 84) coordinate system.

The geology was derived and differentiated from several different image sources, including Landsat in false-color (National Aeronautics and Space Administration (NASA), *http://landsat.gsfc.nasa.gov/images/*), DigitalGlobe in 'natural color', color aerial photography, AVNIR (Advanced Visible and Near Infrared Radiometer) data in 'natural color' (European Space Agency, *http://earth.esa.int/*), ASTER-multi-spectral data (Advanced Spaceborne Thermal Emission and Reflection Radiometer, Jet Propulsion Laboratory (JPL), *http://asterweb.jpl.nasa.gov/index.asp*) primarily using thermal bands, and HyMap hyper-spectral imagery. DigitalGlobe data are provided either by the IKONOS or QuickBird satellites. AVNIR data are one of the products of the Advanced Land Observation Satellite (ALOS). An airborne survey was conducted over the entire quadrangle using a HyMap hyper-spectral optical sensor system (for example, Cocks and others, 1998) to gain additional mineralogical data. Afghanistan is an ideal place for image-based geologic interpretation because of the lack of vegetation and soil in most areas. Rocks are laid bare to the sky, but the high relief does create issues. Most images, particularly the high-resolution images, were geo-registered to the UTM map projection and ortho-rectified to the topography.

Each image type corresponds to a unique view of the geology. The geologic interpretations presented here are the result of comparing and contrasting between the various images and making the best uses of the strengths of each image type. For example, the high-resolution photographs, DigitalGlobe and AVNIR scenes, provide the most accurate locations and views of features such as contacts, faults, internal layering, and points, but they do not yield much information regarding rock composition. False-color Landsat images are excellent for differentiating rock bodies, but their low resolution obscures any detailed information concerning contacts or internal structure. The multi-spectral and hyper-spectral data types provide a limited range of actual compositional information. Thermal-band ASTER is particularly good at identifying and discriminating between silica, carbonate, and mafic components, whereas hyper-spectral HyMap data can be used to separate different types of carbonate minerals, serpentine, epidote, iron, micas, and clays.

The Landsat imagery was pan-sharpened to 14.28-m resolution and displayed with two combinations of false-color using bands: 7, 3, and 1 (RGB, red, green, and blue), or bands 7, 4, and 1 (RGB). Chromatic variations between the two band groups are only slight where rocks are exposed, but are significant for vegetation, which appears green in one (7, 4, and 1) and black in the other (7, 3, and 1). For more details about the analysis of the imagery, please see sheet 1. Landsat data cover the entire quadrangle in cloud- and snow-free scenes that were combined in a mosaic after removal of atmospheric affects and following color correction. The false-color images provide good chromatic contrast between adjacent rock bodies, although the colors produced are not necessarily calibrated to any established lithologic or mineralogic standards. The Landsat image (7, 3, and 1 version) is included as a layer in the digital geologic map file (layered PDF) so mapped units can be compared to their image counterparts. Minor differences in the spatial location of some contacts might be apparent, since most were located using the higher resolution files. The slight inaccuracy of the Landsat is probably a function of its lower resolution, and the lower resolution of the digital elevation model to which it was orthorectified.

High-resolution images provided the control for all of the linework and point data shown on the geologic map (sheet 1). DigitalGlobe visible- and infrared-spectrum images cover most of the quadrangle. Most of the western and northern parts are covered by the overlapping scenes of color aerial photography, and one AVNIR visible-and-infrared-spectrum scene covers almost all but the western edge (fig. 1 on sheet 2). The DigitalGlobe images are available in 4-band color at resolutions of either 4 m (IKONOS) or 2.4 m (QuickBird) and panchromatically at resolutions of 1 m (IKONOS) or 0.61 m (QuickBird). Both IKONOS and QuickBird data were used, depending on availability, and in both cases bands 3–2–1 (RGB) were pan-sharpened to approximate natural color at the highest possible resolution. The color aerial photography is available as digital RGB files at 1-m resolution. AVNIR data come in 4-band color at a spatial resolution of 10 m. AVNIR data can be pan-sharpened with another of the ALOS products (ALOS Micrographics Corp., 2006), PRISM data with a 2.5-m resolution, but this was not done for this study.

The high-resolution coverage is nearly complete over the surface area of the quadrangle, but no single dataset, except Landsat, provided complete coverage. The high-resolution images provided the best horizontal control for the edges of rock bodies identified using Landsat and many additional geologic features, not resolved by Landsat, could also be identified and located. Horizontal accuracy falls well within the 50-m U.S. standard for 1:100,000-scale maps, and mapped features were found to correspond reliably with Global Positioning System (GPS) measurements of the feature where ground-checked.

ASTER and HyMap datasets facilitate lithologic identification primarily because they provide many more bands of restricted width over a greater total bandwidth than any of the other image types. Spectral libraries are available that can be used to relate high reflectance within the bands to real-earth features, such as specific mineral abundances. ASTER data have proven useful because thermal emission bands are included that provide useful data on surface abundance of certain rock-forming minerals. The combination of thermal bands 3–2–1 (RGB) yields a distinct color pattern in which quartz (red), calcite or dolomite (green), and various mafic minerals (blue) can be easily distinguished. The HyMap data have proven particularly useful in differentiating various carbonate minerals and serpentinite. Care must be taken using these techniques for bedrock identification. Ground penetration at available energies and wavelengths is minimal such that even thick dust deposits, which are common in Afghanistan, can lead to spurious identifications. Using these images in conjunction with the various high-resolution images helps to ameliorate this problem.

Chromatic variations that appear on the images are used as a descriptive characteristic of different rock bodies throughout this text, especially in the absence of real lithologic information. However, the chromatic range differs between the different image types, and within each type, it depends strongly on the bands used and the order in which they are stacked. Fortunately, there is good chromatic consistency across the entire Landsat dataset as it is processed. Landsat provides one of the better correlation controls available, even if one is forced to guess a bit as to what type of lithology each color corresponds to. The color-and-contrast problem is pronounced in the high-resolution image types. Nonetheless, the apparent colors proved to be very useful in defining rock bodies, so they are retained as a descriptive element. Described chromatic variations are coded to the image source. Landsat colors are coded with ‘L’ and include a numeric designation such as 731 that represents the RGB-band-order. The L–731 designation is followed by the apparent color (such as L–731-blue-green). The ‘natural colors’ derived from high-resolution images are identified by ‘NC’ (natural color), followed by the apparent color. ASTER colors are designated A–321 followed by the color. HyMap data are commonly color coded, but colors are arbitrarily assigned, so mineralogic identifications based on HyMap are simply stated as such.

Even with the highest quality images, lithologic identifications can be dubious. Published geologic studies, although rare, are available in the area, and they helped guide the mapping. The countrywide geologic map of Afghanistan (Abdullah and Chmyriov, 1977) gives a rough outline of the geologic units present in each area. That map, which is not widely available anymore, was re-released by Doebrich and Wahl (2006) at 1:850,000-scale. Bohannon and Turner (2007) compiled the Kabul-Chak-e-Wardak 1:250,000-scale map, also based on Abdullah and Chmyriov’s (1977) version. No attempt was made on either of the latter maps to modify or re-interpret the original geology, so lithologic and geologic descriptions based on preexisting maps are attributed to Abdullah and Chmyriov (1977), although the newer maps are more easily obtained and show the same thing. The geology in the south half of Afghanistan was compiled by Wittekindt and Weippert (1973) and that 1:500,000-scale compilation covers the quadrangle. The small-scale geology as portrayed commonly differs substantially between the Abdullah and Chmyriov (1977) and the Wittekindt and Weippert (1973) versions and neither conforms well to what can be seen in modern imagery. Still, the small-scale maps can be used as a rough guide and were useful in that context. Mennessier (1973a–e) provided five maps at 1:100,000 scale covering the central and southern parts of the quadrangle (fig. 1 on sheet 2). His maps proved a valuable asset, as they covered an area of complex structure and stratigraphy that would have been very hard to resolve using images alone. Mennessier (1972) also provided a good biostratigraphic and a limited lithostratigraphic analysis of the region in which he established the age control for most of the mapped units. Fisher (1971) conducted a detailed stratigraphic study of the southern part of the Koh-i-Sofe, a range in the central part of the Kabul North quadrangle (Bohannon, 2010), and that work included a map. Fisher's detailed descriptions of the Khengil series, which is continuous into the Kabul South quadrangle, proved invaluable, and the map units and descriptions used in this report follow from his work.

This report consists of two map sheets, this pamphlet, and a collection of database files. Sheet 1 is the geologic map that includes three highly speculative cross sections, and sheet 2 is a topographic map that comprises all the support data for the geologic map. Both maps (sheets 1 and 2) are produced at 1:100,000 scale and are provided with GIS spatial data that preserves the original layering, some attribute information, and the georegistration. The georegistered files, presented here as geospatial PDF's, can be viewed in Adobe Acrobat 9 or Acrobat Pro (free reader available at *http://www.adobe.com*). The database files include images of the topographic hillshade (shaded relief) and color-topography files used to create the topographic maps, a copy of the Landsat image, and a grayscale basemap. The image data are saved as georegistered TIF-image files. Vector data from each of the layers that comprise both maps are provided in the form of Arc/INFO shapefiles.

Structural attitudes are shown on the map where they could be estimated from the imagery and topography. These include strikes and dips of bedding, metamorphic layering, and igneous layering. In rare cases these measurements are based on direct field observations, but more commonly they are derived from image analysis. Strike direction can be measured directly on the image in most cases. Dip value was determined from a three-dimensional drape of a high-resolution image over the best-available digital elevation model. Results are dependant on the vertical exaggeration chosen, so the optimal value of computer-generated exaggeration was determined by comparing derived results with known field values in the few places where accurate data exist.

Geologic Setting

Afghanistan, from a geologic perspective, is a complex amalgamation of small tectono-stratigraphic terranes, each with its own unique geologic history. None of these terranes, save maybe the northwestern one, can be said to presently be in the place that it originated. Instead, most of Afghanistan was assembled bit-by-bit out of pieces that came from someplace else. Deciphering what constitutes a contiguous terrane or how many there actually are has proven difficult and no consistent pattern has emerged. Leven (1997) presented the most thorough picture to date and his conclusions are summarized on figure 1. In his view, the only stable terrane in Afghanistan is the one called the Turan plate (fig. 1, no. 1), which always was part of the Asian continental landmass. All the other terranes on figure 1 have been somehow thrust onto, slid by, or collided with the southern margin of Asia during a complex series of events that took place since the middle Mesozoic as the Paleo-Tethyan and Tethyan oceans slowly closed up, culminating in the collision of India and Asia. The timing of these events as well as the points of origin and travel-path histories of the various Afghan terranes are all very poorly understood. Papers by Tapponnier and others (1981, 1986), Sengor (1988), and Treloar and Izzatt (1993) represent viable attempts to reconstruct the Afghan terranes in a sensible manner, but all suffer from a general lack of knowledge regarding the detailed internal character and the boundary conditions between them.

Numerous small terranes form an east-northeast grouping that bisects central Afghanistan between the northeast corner of the country and the western border with Iran (fig. 1, nos. 2, 6, 10, 12, 13, 14, 15, 23, 24, 25, 26, and 27). This grouping is distributed along a large system of faults that can collectively be referred to as the Har-i-Rud/Panjshir/Wakhan (HPW) fault system (fig. 1, fault system A). Leven (1997) pointed out that the Permian fusulinid assemblages that he studied define separate sub-basins that have been fragmented along the HPW fault system in a way that suggests that there might be hundreds of kilometers of displacement, probably right lateral, on the system between China and Iran (note particularly tectonic area (or terrane) 13 on fig. 1). However, no detailed slip history has been resolved. Leven (1997) also observed that the Permian carbonate facies and fusulinid assemblages of the HPW group and those to the north are characteristic of tropical shelves. This fact contrasts with temporally equivalent facies in southern Afghanistan that are siliciclastic, lack fusulinids, and contain other fossils typical of low-latitude (cool-to-cold water) Perigondwanan seas (Leven, 1997).

The terranes south of the HPW fault zone such as the Farahrud trough (fig.1, no. 16), the Hilmand-Argandab (fig. 1, no. 17), the Kabul massif (fig. 1, no. 19), and the Nuristan massif (fig. 1, no. 22), are thought to have originated as continental island masses that converged on southern Asia from the south as the Paleo-Tethyan sea closed up during the Cretaceous (Sengor, 1988; Treloar and Izzatt, 1993). Ultramafic

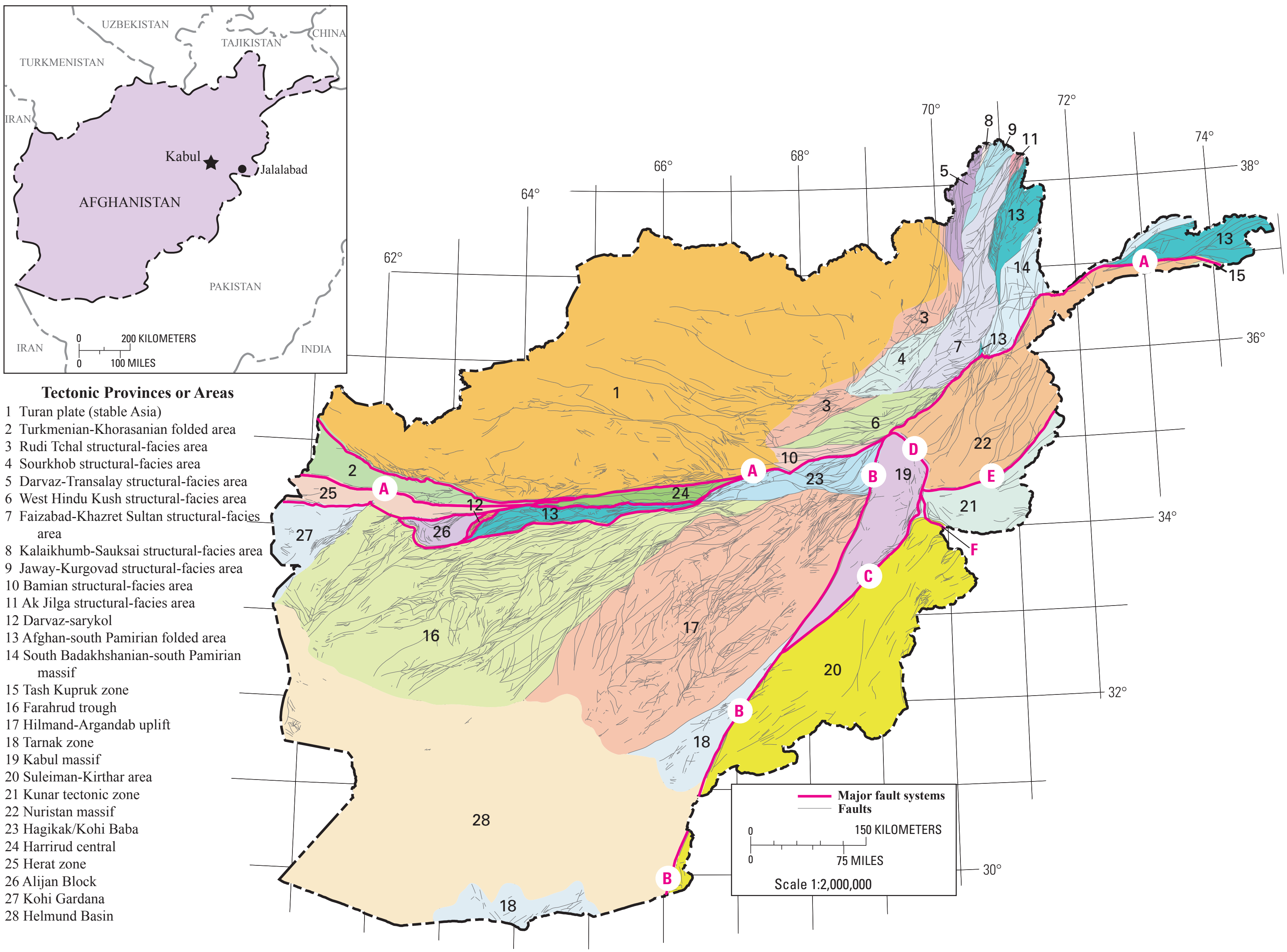


Figure 1. Afghanistan subdivided into tectonic provinces or areas according to Leven (1977). This is only one of the ways that Afghanistan has been subdivided. The numbered list of tectonic provinces or areas corresponds to the numbered areas on the figure. Major faults and fault systems discussed in text are as follows: A, Har-i-Rud/Panjshir/Wakhan (HPW) fault system; B, Chaman-Paghman fault system; C, Gahzni fault; D, Tagab fault; E, Kunar fault; and F, Sorubi fault. Other faults are from Abdullah and Chimriov (1977).

rocks in tectonic slices along the HPW fault zone and between some of the terranes is cited as evidence for suturing of these blocks to southern Asia, as well as to each other (Tapponnier and others, 1981). Other terranes such as the Suleiman-Kirthar area (fig. 1, no. 20) and the Kunar zone (fig. 1, no. 21) probably became part of Afghanistan during the collision of India with Asia between 42 Ma and the present.

The Kabul South quadrangle is in east-central Afghanistan (fig. 2) where it includes large parts of three of Leven's (1997) terranes and a small segment of a fourth. The western half of the quadrangle is in Leven's Kabul massif, and the eastern third is in the western part of his Kunar zone. The north end of the Suleiman-Kirthar area (also commonly called Katawaz basin) is exposed in the southeast and a sliver of the Nuristan massif occurs along the northeast border. Some of the terranes described by Leven (1997) can be further subdivided based on knowledge garnered from the mapping of this quadrangle, the Kabul North quadrangle (Bohannon, 2010), and in Pakistan to the east as summarized by DiPietro and others (2000), and DiPietro, Ahmad, and Hussain (2008). These areas are treated in some detail in the Tectonics section of this report.

Most of the central and southeast parts of the quadrangle are rugged, remote, and mountainous, at elevations of 2,000 to 4,500 m. The highest peaks are slightly above 4,500 m in the western Spin Ghar (known locally as Kohe Safed) along the border with Pakistan (sheet 2). The Logar valley (which contains the Logar Rud, or river, sheet 2) in the western third of the quadrangle is lower, typically between 1,800 and 2,500 m. The lowest part of the quadrangle is its northeast corner near the Kabul River (referred to as the Kabul Rud, sheet 2).

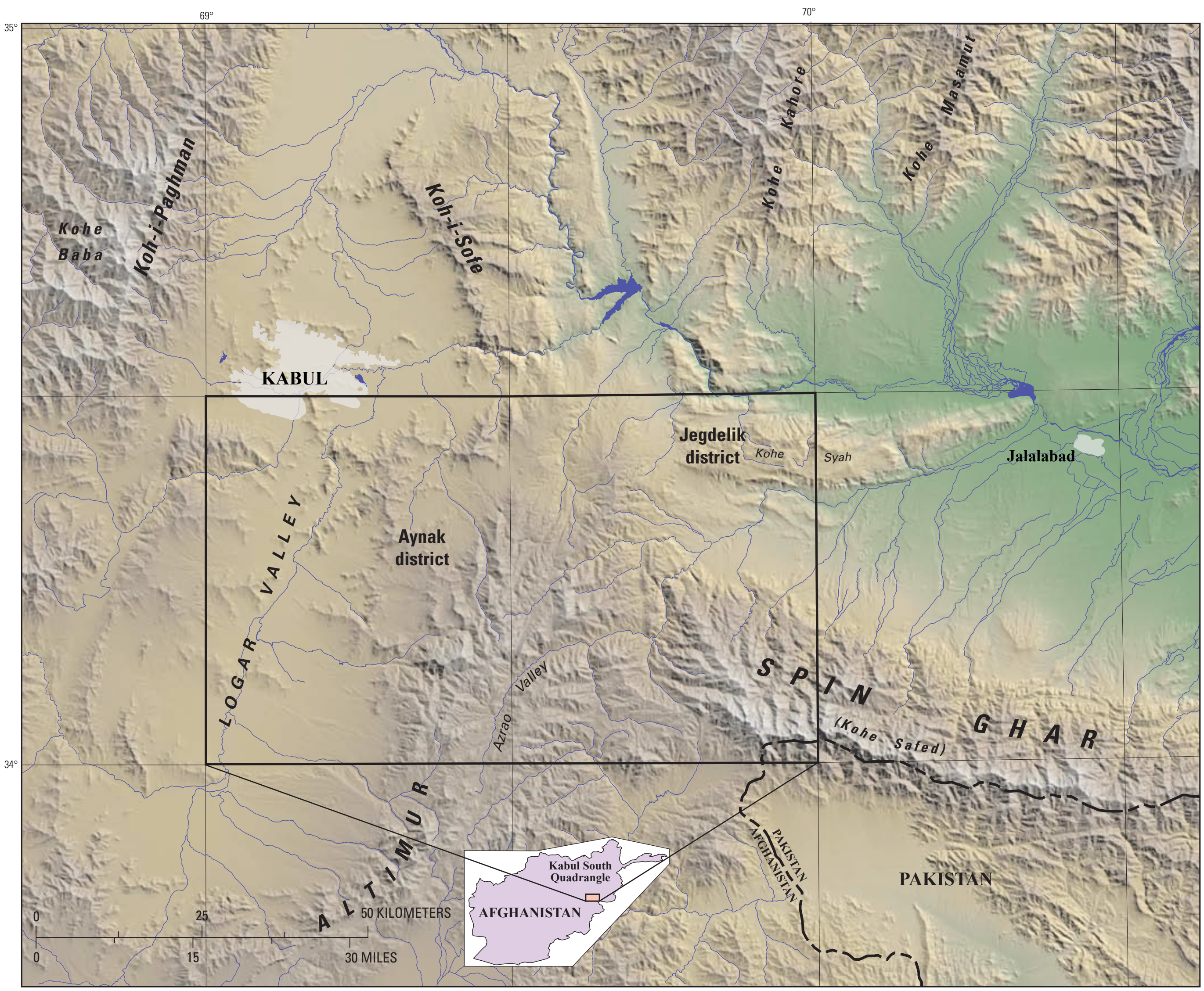


Figure 2. Location of Kabul South quadrangle relative to Kabul, Jalalabad, and the border with Pakistan. Two mineral districts discussed in the text are also shown.

Synopsis of Mapped Units

A brief synopsis of the units that appear on the geologic map (sheet 1) is presented here. They are mostly described from oldest to youngest, except that in some cases groupings with a wide temporal span are kept together. Much of what is known about many of the units is based more on the character of their optical reflectivity in the images rather than on actual lithologic or mineralogical investigations. Thus, the descriptions reflect that in many cases. Basic lithologies are inferred unless otherwise noted. In Afghanistan there is very little surviving published literature in which the original lithostratigraphic nomenclature was officially defined. The nomenclature that appears here follows as well as possible the usage established by prior workers, but my interpretation of that usage may not be correct in each case. This is a field of study that is need of future work, primarily by the next generation of Afghan scientists.

Precambrian Rocks

Amphibolite-and higher-grade Precambrian rocks in the Logar valley region consist of compositionally variable gneiss, schist, quartzite, marble, and amphibolite of the Sherdarwaza series, Kharog and Welayati Formations, which are intruded by small lenticular and stock-like metamicrogabbro and migmatitic granite bodies (British Geological Survey, 2005). Exposures of gneiss in the northeast corner of the quadrangle belong to the Nuristan series, and these rocks are mapped as being Precambrian, although there is some doubt about their age (see appropriate following discussions). The Spin Ghar fault block, exposed in the southeast corner of the quadrangle, is underlain by gneiss, quartzite, schist, marble and amphibolite that are intruded by irregular granitic and gneissic-aplite bodies. These rocks are probably the crystalline basement of the northern Indian plate. Greenschist-grade metasediments of Vendian to Cambrian age are also present in the Logar valley region, and they are called the Loy Khwar and Gulkhamid Formations. Some of the best surviving descriptions of the Precambrian rocks are included in Dronov and others (1982), and Dronov, Abdullah and Chmyriov (2008), and many of the descriptions that appear here are largely abstracted from those works.

Sherdarwaza Series

Gneiss, migmatite, and schist make up most of the Sherdarwaza series, along with ancillary amphibolite, quartzite and marble. The different lithologies occur in rhythmic sequences, which when complete consist from the base upwards of quartzite, gneiss, mica-schist, amphibolite, and marble. The gneisses consist of biotite-gneiss, quartz-muscovite gneiss and garnet-biotite gneiss (Xsgn). Textures vary and include lepido-granoblastic, blasto-clastic, granoblastic, and porphyro-blastic varieties that range in scale from being micro-laminated to coarsely banded. Quartz, potassium feldspar, and plagioclase typically comprise up to 85 percent of the gneiss. Schist (Xss) includes biotite, epidote-biotite-muscovite, muscovite, staurolite-garnet-muscovite, and other varieties, with biotite schist being the most common in places that I have seen this unit (fig. 3). Phyllonitic and lepido-granoblastic textures predominate. Quartz, albite, potassium feldspar, and epidote comprise up to 80 percent of the schist in many places. Garnet and staurolite occur rarely. Migmatite is described in areas where dark and light gray bands are evident due to alternating mica-rich and quartzo-feldspathic layers, although Dronov and others (1982) did not present evidence for partial melting. No attempt has been made to differentiate migmatite from gneiss on the geologic map (sheet 1). Ortho- and para-amphibolite types are both described by Dronov and others (1982) in the Sherdarwaza series. Ortho-amphibolite consists of hornblende (35 to 50 percent), biotite (20 percent), plagioclases (15 to 30 percent), quartz (5 percent) and epidote (10 percent). Its texture is nematoblastic and blastoporphyric; the structure is schistose. Para-amphibolite normally occurs in thin beds, groups of beds and lenses alternating with crystalline schists with the following mineral composition: hornblende (35–40 percent), plagioclases (45–50 percent), biotite (10 percent) and quartz (5 percent). The texture is nematoblastic and granonematoblastic, the structure is schistose (Dronov, Abdullah, and Chmyriov, 2008). Quartzite is heterogranoblastic in texture and micro-plicated in structure. It consists chiefly of quartz, decomposed plagioclase, and biotite replaced in places by chlorite. Quartzite occurs in lenticular interbeds (0.2–1.5 m) in biotite gneiss and crystalline schist (Dronov, Abdullah, and Chmyriov, 2008). I was not able to identify and differentiate amphibolite or quartzite reliably on the images, so they are included in the gneiss and schist units. Marble, where it occurs, is a light gray and white, fine- and medium-crystalline, massive, banded rock in which dolomitic, dolomite-lime and lime-dolomite varieties are recognized (Dronov and others, 1982).

Some lithologic complexity in the Sherdarwaza is apparent on the Landsat image by its highly varied false-color. Gneiss and schist both vary between L–731-pinkish-red, L–731-blue-gray, and L–731-red, probably depending on the amount and type of mafic material and the presence or absence of desert varnish. There is no simple way to identify gneiss from schist on most of the images. Both units are typically a shade of NC-gray on the natural-color images. Megascopic layering is commonly visible at high resolutions, and gneiss was mapped everywhere distinct compositional banding could be discerned. Schist is typically characterized by its pervasive fabric, but it has an absence of visible banding giving the outcrop a uniform gray appearance. Muscovite, or some similar mica, shows up in many places on the Hymap data in the gneiss areas, and the schist commonly has a strong iron signature. Amphibolite is easy to identify by its darker color, typically NC-black or NC-dark gray, on the natural-color images, and it is commonly L–731-deep-red-brown where it is present in large enough masses to appear on Landsat. Marble is NC-white and L–731-white-tan where it is in large enough masses to map.

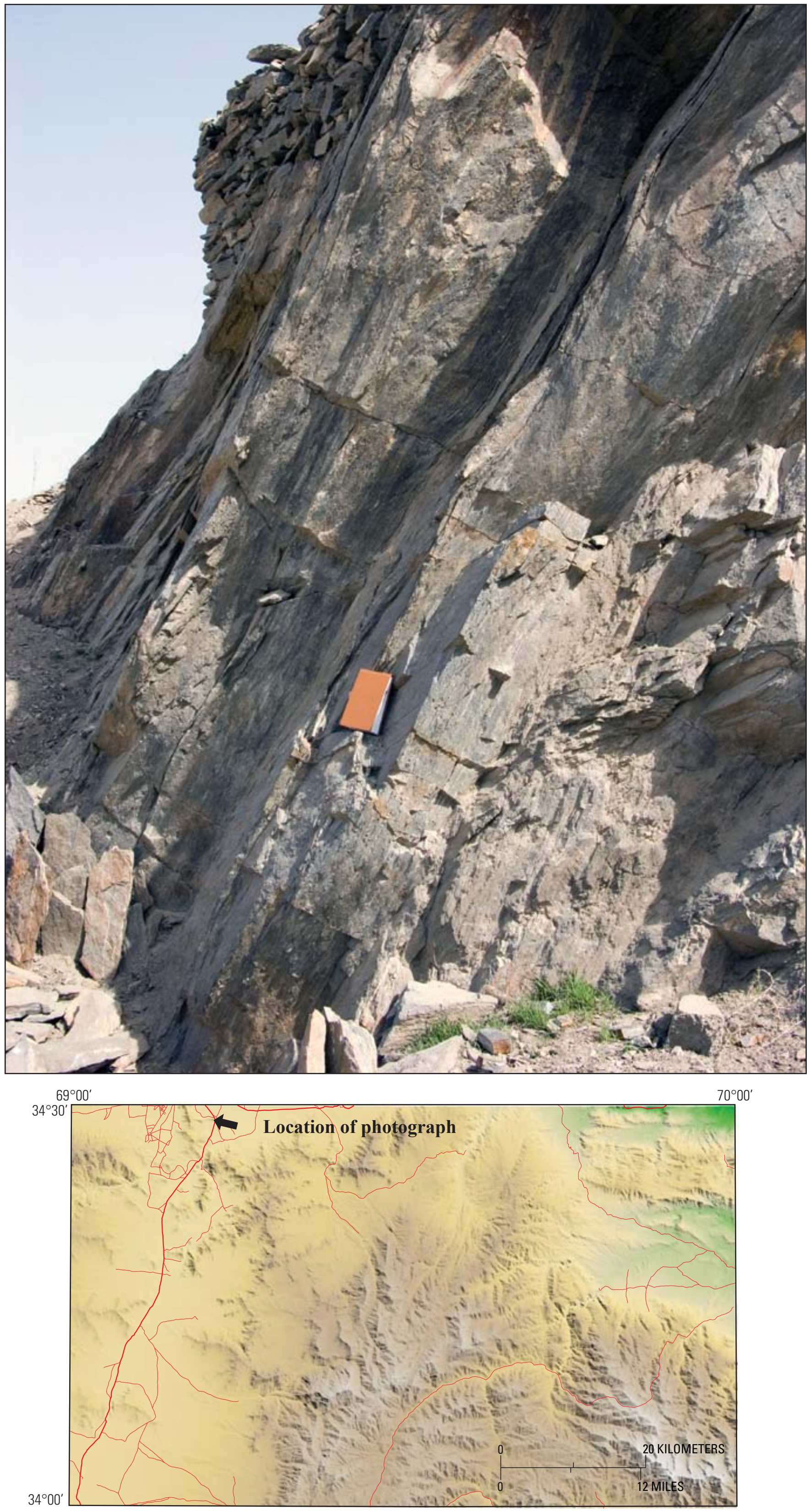


Figure 3. Typical schist outcrop of Sherdarwaza Series of Early Proterozoic age. This photograph was taken in a rock quarry located a few kilometers south of the Kabul city limits. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

The Paleoproterozoic age assignment of the Sherdarwaza series comes from U/Pb-zircon age determinations (laser-ablation) of 2,383 Ma from amphibolitic schist (table 1) near the area of the photograph of figure 4 at lat 34.48564°N. and long 69.21608°E. and of 2,378 Ma from gneiss east of Kabul at lat 34.56955°N. and long 69.40446°E. (Lawrence W. Snee, USGS, written commun., 2007). Further analysis of these zircon data prompted Wayne R. Premo (USGS, written commun., 2008) to propose two possibilities for the schist sample:

1. the protolithic mafic igneous rock was emplaced at 2,394 Ma and later thermally overprinted at 1,820 Ma, or
2. this rock was actually a mafic metasediment that was metamorphosed at 1,820 Ma, but contained a variety of inherited zircon components.

Near-concordant, pseudo-arrays exist at about 1,970, 2,180, and 2,345 Ma, but these are dominated by the 2,395-Ma provenance. Andritzky (1971) reported much younger K/Ar ages of 928 and 938 Ma from schist north of Kabul, but these most likely reflect cooling ages.

Nuristan Series

Dronov, Abdullah, and Chmyriov (2008) described the Nuristan terrane as a region of chiefly amphibolite-grade gneissic and schistose country rock affected by extensive granitization, including widespread injection zones. Zones of cataclasis and retrograde metamorphism are also common. They subdivided the Nuristan series into three parts. The lower part consists of the Nejrab, Chebak, and Kamdesh Formations, the middle part consists of the Waygal Formation, and the upper part consists of the Kamal Formation. The Nejrab Formation consists of biotite, garnet-biotite, sillimanite-biotite and garnet-sillimanite-biotite gneiss, plagiogneiss, injection gneiss and migmatite. Amphibole and biotite-amphibole gneiss, amphibolite, quartzite, and marble are less common. The Chebak Formation consists of interbeds of

1. quartzite;
2. biotite, garnet-sillimanite-biotite, and biotite-amphibole gneiss;
3. amphibole and garnet-staurolite-biotite schist; and
4. calcareous-silicate rocks. Rare marble beds and lens-like amphibolite bodies are also present.

The Kamdesh Formation is fine-to-medium grained biotite, garnet-biotite, garnet-sillimanite-biotite, biotite-amphibole and amphibole gneiss, plagiogneiss, migmatite, and injection gneiss. Rare quartzite and marble beds (1 to 10 m thick) also occur. The Waygal Formation consists of alternating units of marble, crystalline schist, and quartzite. The Kamal Formation consists of dark-gray biotite, garnet-biotite, and garnet-staurolite-biotite schist, which in places grade to gneiss interbedded with quartzite and marble.

Dronov, Abdullah, and Chmyriov (2008) did not describe the distribution of each of the formations and none of them appear on the regional geologic map of Abdullah and Chmyriov (1977) where rock bodies are differentiated only by their interpreted age. Consequently, it is not possible to say which unit name those authors would have associated with the gneiss in the Kabul South quadrangle. The banded biotite gneiss (Xngn), leucocratic gneiss (Xnlgn), and marble (Xnm)

Table 1. U/Pb (laser ablation) and Ar/Ar age determinations from the Kabul South quadrangle.

[Samples provided by Lawrence W. Snee, USGS, written, commun., 2009; U/Pb Analytical results provided by Daniel P. Miggins and Lawrence W. Snee, USGS, written commun., 2009; Ar/Ar analytical results provided by Lawrence W. Snee, written commun., 2009]

Sample number	Latitude	Longitude	Rock unit	Rock type	Primary age (Ma)
U/Pb (laser ablation)					
LS 4–10–05–7	34.48564	69.21608	Xss	Amphibolite Schist	2394
LS 4–13–05–5	34.43673	69.81626	Kigr dike	Granodiorite	76.22
LS 4–13–05–7	34.43604	69.81683	Kigr dike	Granodiorite	75.82
LS 4–13–05–8	34.43604	69.81683	Kgn	Biotite gneiss	86.3
LS 4–13–05–10	34.43673	69.81626	Kgn	Augen gneiss	94.5
LS 4–13–05–3	34.43673	69.81626	Kgn	Augen gneiss	97.2
Ar/Ar					
Afghan 1–12–62	34.43673	69.81626	Km	Mica from marble	39–47
Afghan 2–13–62	34.45003	69.8034	Km	Mica from marble	41
Afghan 3–14–62	34.4657	69.7596	Kigr/Kgn	Muscovite	19
Afghan 3–15–62	34.4657	69.7596	Kigr/Kgn	Muscovite	19

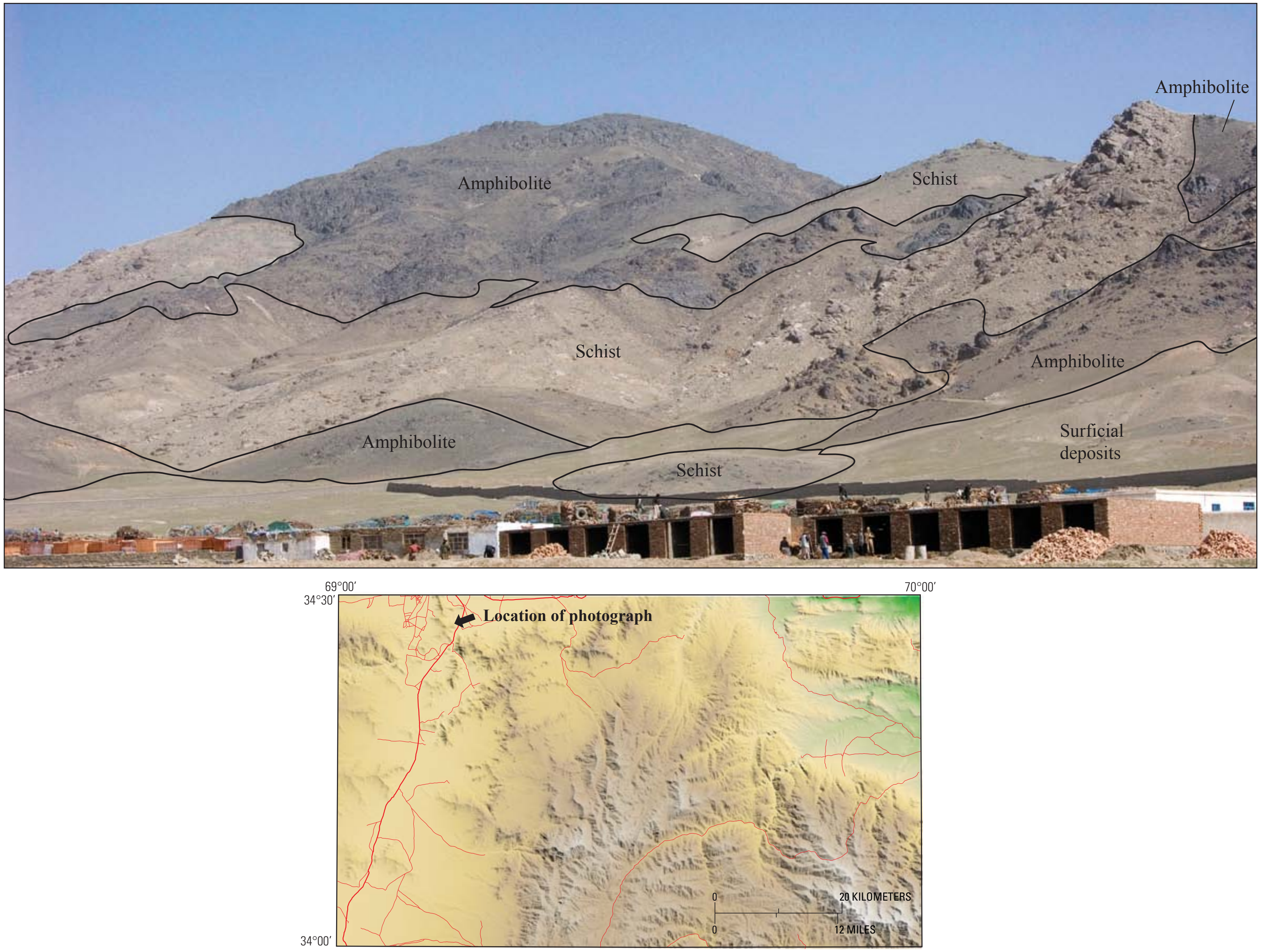


Figure 4. Irregular amphibolite (Zwa) body in undifferentiated Welayati Formation (Zwu). This photograph was taken roughly 6 kilometers south of the Kabul city limits. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

that are mapped in the northeast corner of the quadrangle are probably consistent with the Kamdesh Formation, which is mostly composed of those three lithologic types. The banded biotite gneiss in this area is L–731-red-brown-to-tan and NC-medium-to-dark-gray. It lacks any internal structure that is apparent on high-resolution images, save irregular large stringers and blobs of white (quartz-plagioclase?) rock that might make up 10 to 20 percent of the unit. The leucocratic gneiss is L–731-tan and NC-medium-brown-gray. It contains numerous sub-parallel white (quartz-plagioclase?) layers. The marble is L–731-white and NC-white-to-light-brown. The marble has irregular subparallel layering that is defined by color contrasts and small rock ledges visible on high-resolution images.

No age data exist for the Nuristan metamorphic rocks. Their lithology, as described by Dronov, Abdullah, and Chmyriov (2008), and their uniform NC-gray appearance is consistent with a pelitic protolith. Similar amphibolite-grade pelitic rocks nearby in Pakistan are thought to be Paleozoic or Mesozoic age (Calkins and others, 1981). However, a definitive determination as to the age of the protolith or the time when the metamorphism took place cannot be made with existing data. Thus, the Nuristan series is assigned a Paleoproterozoic age in this report based solely on the interpretations of Dronov, Abdullah, and Chmyriov (2008) and Abdullah and Chmyriov (1977).

Spin Ghar Crystalline Complex

The Spin Ghar series is interpreted to be uplifted crystalline basement of the Indian continental plate that has been thrust southward over Indian shelf sediments as young as Miocene (Badshah and others, 2000). These rocks are not well described in the literature. Badshah and others (2000) simply said they are composed of granite, augen gneiss, and migmatite that are intruded by granite, aplite, and dolerite sheets. The latter authors also reported local metamorphosed carbonate rocks. Dronov, Abdullah, and Chmyriov (2008) described them as quartzite, biotite-gneiss, garnet-biotite schist, muscovite-biotite schist, garnet-staurolite-biotite schist, marble, and amphibolite.

Imagery did not prove particularly useful for delineating various types of schist, gneiss, and marble so those rocks are lumped together as unit Xkgn in this report. The uniform NC-medium-dark-gray color of the latter unit is consistent with a mostly pelitic composition, as is its A-blue-purple hue, which indicates abundant mafic-to-intermediate minerals, on ASTER images. Granitic stocks, characterized by their L–731-yellow-brown color, have been delineated based on imagery (Xkgn). ASTER images suggest a mix of quartz and mafic minerals. Less extensive plutons in the northwest part of the complex have been delineated as small granodiorite stocks (Xkgd) based on their NC-dark-gray color, L–731-light-tan, and an A-turquoise ASTER signature suggestive of a mafic-to-intermediate composition.

Little is known about the age of the Spin Ghar complex, except that Wittekindt and Weippert (1973) and Badshah and others (2000) reported K/Ar cooling ages of 20 to 40 m.y. These ages mostly reflect young uplift and the consequent denudation of overburden, but they may also be indicative of heat input during Phanerozoic intrusive events. Amphibolite and aplite bodies, described by prior workers as being Proterozoic in age, also intrude local Paleozoic shelf rocks and are thus, assigned to a tentative Mesozoic age in this report, but they could be even younger than that.

Proterozoic rocks have also been mapped north of the Spin Ghar fault in the Kunar tectonic terrane (Abdullah and Chmyriov, 1977; Wittekindt and Weippert, 1973). Two large rock bodies are present according to Wittekindt and Weippert, (1973); one a garnet-mica-schist with intercalated amphibolite, marble, and quartzite (included in unit Xkgn in this report), and another of banded gneiss and migmatite (Xkbgn). I also differentiated a unit that I interpret to be pelitic schist based on its distinct L–731-blue-green and NC-uniform-gray coloration on respective images (Xkps).

Kharog Formation

The Kharog Formation (Zk) overlies the Sherdarwaza series in the Aynak district (west-central part of the quadrangle). It probably has a wider distribution than is shown on the geologic map (sheet 1) where it appears only as identified on an unpublished geologic map held in the archives of the Afghan Geological Survey in Kabul (see fig. 2 on sheet 1 for location). Elsewhere, it might be included with the undifferentiated Welayati Formation (Zwu).

The Kharog Formation is chiefly quarzite that is interbedded with conglomerate, schist, gneiss, amphibolite, and marble according to Dronov, Abdullah, and Chmyriov (2008), who provided the following basic descriptions. The quartzite is parallel bedded and cross bedded, fine-grained, and has granoblastic texture. Conglomerate occurs in the lower parts of the formation as lenses in quartzite. Clasts are mostly quartzite and vein quartz, but also include rare two-mica granite, albite, and amphibolite. The schist, amphibolite, and marble occur in the upper part of the formation and are similar in composition, texture, and metamorphic grade to counterparts in the Sherdarwaza series. The Kharog Formation is L–731-light-brown and NC-gray on the respective images. The age of the Kharog Formation is not well documented. It is assumed to be Neoproterozoic in this report.

Welayati Formation

The Welayati Formation (Zw) is conformable on the Kharog Formation (Zk) and is distributed throughout the Anyak district and northern Logar valley (fig. 4). The Welayati is composed of schist at the base, amphibolite in the middle, and alternating schist and amphibolite at the top according to Dronov, Abdullah, and Chmyriov (2008). They described biotite, staurolite-garnet-biotite, biotite-quartz, muscovite-quartz, and muscovite schist, among other types. The amphibolite, which is mapped separately in places (Zwa), was interpreted by Dronov, Abdullah, and Chmyriov (2008) to be of volcanic origin based on

1. its invariable composition,
2. its uniform schistose structure,
3. relics of plagioclase phenocrysts and amygdales of epidote and quartz,
4. its blastopyroclastic and blastoporphyric texture,
5. relict columnar jointing, and
6. the presence of finely faced apatite granules.

The Welayati is a nondescript NC-gray and is L–731-deep-red-to-blue-red on the respective images. The marble, Zwm, is NC-white, L–731-white, and A-green on the respective images. The age of the Welayati Formation is not well documented. It is assumed to be Neoproterozoic in this report.

Phanerozoic/Neoproterozoic Rocks

Calcareous-terrigeneous schist and volcano-sedimentary schist, both of greenschist-facies, overlie the Welayati Formation. The calcareous schist is called the Loy Khwar Formation (€Zlk) and is the older of the two schists. The volcano-sedimentary schist is called the Gulkhamid Formation (€g). The age of these units is uncertain. Stromatolite remains in the Loy Khwar mostly point to its Neoproterozoic age, but the presence of one in particular, *Tannuofia,* suggest that it may be Early Cambrian (British Geological Survey, 2005; Dronov, Abdullah, and Chmyriov, 2008). Thus, it is commonly assigned a Cambrian/Vendian age. The overlying Gulkhamid Formation is assigned a Cambrian age in this report, but it is apparently azoic. The Loy Khwar and Gulkhamid Formations appear on sheet 1 only as identified on an unpublished geologic map held in the archives of the Afghan Geological Survey in Kabul (see fig. 2 on sheet for location). Elsewhere, these units might be included in unit €Zu.

Loy Khwar Formation

The Loy Khwar Formation is the sedimentary host rock for the Anyak copper deposit. Consequently, it is one of the better-studied rock units in the quadrangle. Nonetheless, the British Geological Survey (2005) reported that an unsystematic and confusing scheme of subdivision has been used in describing these rocks, involving up to seven members and numerous submembers, all inconsistently used. Part of the problem is that many of the subdivisions are thin (2 to 6 m thick in places) and may be discontinuous laterally. No attempt has been made to sort out internal stratigraphic inconsistencies in this report.

The lower Loy Khwar Formation is lithologically varied, consisting of basaltic conglomerate, actinolite schist, calcareous-biotite schist, fine-grained breccia, banded biotite schist, quartzite, and banded dolomitic marble. Pyrite, chalcopyrite, bornite, chalcocite, pyrrhotite, and traces of molybdenite are present near the base of the formation. Marble, sandstone, quartzite and carbonate-rich schist make up most of the middle parts of the Loy Khwar. Much of the bornite mineralization occurs in the middle part. The lower and middle parts were mostly encountered in boreholes in the vicinity of the Anyak deposit, but they may be exposed elsewhere. The upper parts of the formation are exposed at Anyak and consist of carbon-quartz schist with dark-gray dolomite intercalations and gray, fine-grained, banded dolomite marble (figs. 5 and 6). The Loy Khwar Formation is NC-tan, L–731-gray-green-to-blue-gray, and has a strong A-green hue on respective images in most areas. There is a calcite signature on HyMap imagery.

Gulkhamid Formation

Very little descriptive information has been published for the Gulkhamid Formation, although it is widespread in the Anyak district. Dronov, Abdullah, and Chmyriov (2008) do not mention it in their descriptions, possibly because these rocks were at one time thought to be part of the Welayati Formation. The British Geological Survey (2005) pointed out that the Gulkhamid cannot be Welayati because it overlies the Loy Khwar and stated that it is a sequence of metamorphosed intermediate volcanic rocks composed of conglomerate, meta-sandstone, and schistose tuff at the base and interstratified green-gray lava, tuff, breccia and tuffaceous sandstone of andesitic to dacitic composition in the upper part. The Gulkhamid is L–731-red to mottled, NC-gray, and A-turquoise-blue on the respective images.

Intrusive Rocks

Numerous small intrusive bodies occur in the Aynak district (€Zi). These are described as mainly plagiogranite porphyry and syenite porphyry (British Geological Survey, 2005). They mostly intrude the Welayati, Loy Khwar, and Gulkhamid Formations, but some also occur in the Sherdarwaza Formation in places. They were assigned a Vendian age by Gusev and Safonov (1979), but they may be Cambrian because they occur in the Gulkhamid Formation. They can be identified by their distinct NC-orange-brown coloration on the high-resolution images and they appear as L–731-orange and A-green on the respective multi-spectral images. There is also a small dark-colored ring dike (€md) that intrudes unit €Zi in the north-central part of the quadrangle. This dike is NC-gray and L–731-gray on the respective images and HyMap indicates that mafic components are present.

Phanerozoic Rocks

Daradar Dolomite

The Daradar Dolomite (Sdd) is present in the southeast corner of the quadrangle on the northeast side of the Sorubi fault. It overlies the Spin Ghar crystalline rocks and thus, was deposited on the Indian continental plate. Meager descriptive

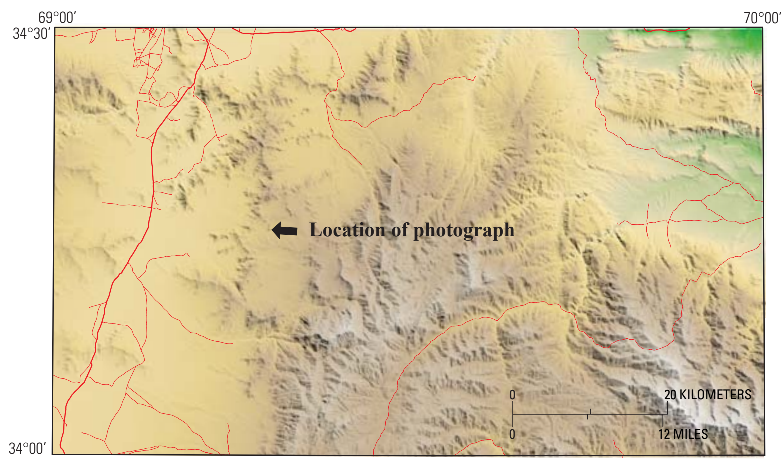
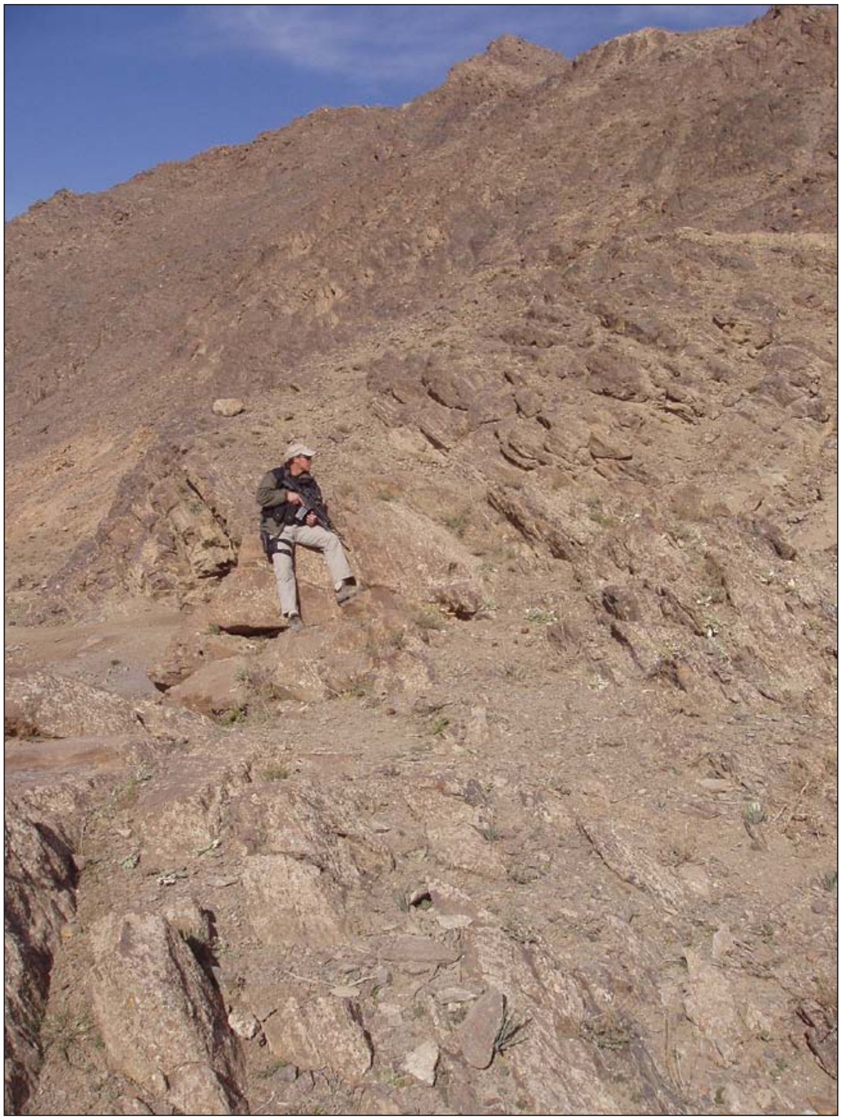


Figure 5. Typical internal megascopic structure of carbonate schist (€Zlk) in the Loy Khwar Formation of Vendian or Cambrian age. This photograph was taken in a small ancient copper digging near the main Anyak copper exploration site in the Logar Province. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.



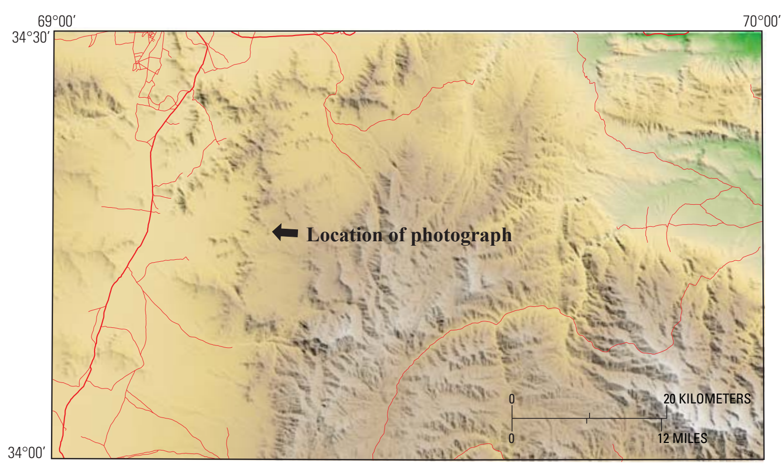


Figure 6. Hillside composed of carbonate schist of Loy Khwar Formation (ЄZlk) near the main Anyak copper exploration site in the Logar Province. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

information is available, but Badshah and others (2000) described the Daradar as Silurian and possibly Devonian siliceous dolomite. It is intruded by dolerite, possibly related to the Mesozoic amphibolite (Mza), with soapstone present along the intrusive contacts. Silver-rich, lead-copper mineralization occurs locally. The Daradar is L–731-pale-blue; NC-light-gray; A-green on respective images.

Sikarum Series

Badshah and others (2000) mapped Carboniferous and Permian strata known as the Sikarum series in the region south of the Spin Ghar crystalline complex. Like the Daradar, it was deposited on the Indian continental plate. The Sikarum is mostly slate and graphic schist in its upper part and claystone and carbonaceous shale in its lower part according to them. Badshah and others (2000) did not endeavor to explain the apparent inversion of metamorphic grade that they described.

I was able to differentiate two units within the Sikarum series using the imagery. One unit (PCsp), which may be the claystone and carbonaceous shale, is probably very pelitic in nature based on its NC-dark-blue, L–731-dark-blue-green, and A-purple coloration patterns on the respective images. Another unit (PCsgs) is interpreted to be the slate and graphic schist, based on its NC-purple-gray, L–731-magenta, and A-dark-blue coloration patterns on the respective images

Shalkalay Series

A thick and monotonous sequence of gray pelitic schist and sandy schist of probable Carboniferous and Early Permian age is widely exposed just west of the quadrangle tectonically beneath the ultramafic rocks (TRPup and TRPusp) that occur along the west quadrangle edge. These rocks crop out all along the Kabul River within the quadrangle near its northwest corner (fig. 7). In the Argandab area to the west the Carboniferous and Permian rocks are called the Shalkalay series and they have been divided into three units in the Logar area (Abdullah and Chymriov, 2008). The Logar units are the Wakak, Bokan, and Dony-Yarchy. No attempt was made to identify the latter three units in the quadrangle, so the simple term Shalkalay series is used to desribe them. Two units are distinguished with Landsat data. One, possibly a more sand-rich rock, appears as L–731-red (PCss), and the other, possibly more lime rich, appears as L–731-blue (PCsls).

Sangae Limestone

The Sangae Limestone (Psls) of Permian age is distributed at two localities along either side of the trace of the Ghazni fault in the south-central part of the quadrangle. Mennessier (1973b, c) provided the best map of its distribution and his work is followed in this report with minor modifications in accordance with information on the high-resolution images. He briefly described it as black limestone with a greenish-gray patina (Mennessier, 1972). Its bedding is regular and the beds form low benches. Fossils are rare and it is greater than 600 m in thickness. The Sangae Limestone is NC-medium-gray, L–731-brown, and A-green on the respective images.

The Sangae is one of several shelf carbonate rock units that are partially incorporated in the Kotagai melange. It occurs in fragmented exposures and is everywhere in fault contact with surrounding rocks. It is unclear what substrate it was originally deposited upon, but each exposure is for the most part internally intact.

Abtchakan Formation

Mennessier (1973a, b, c) mapped the distribution of the Abtchakan Formation, which consists of a limestone unit (Pals) and a dolomite unit (Pad), in the south-central part of the quadrangle and his map is followed within additional constraints provided by high-resolution image data. The limestone is extensive in the hanging wall of a complex low-angle fault system near the center of the quadrangle where it tectonically overlies Kotagai melange. Other discontinuous exposures of limestone and dolomite are strung out along the west side of the southwest-oriented Ghazni fault system. Due to faulting, the depositional substrate and setting of the Abtchakan is not known any better than it is for the Sangae Limestone, but Mennessier (1972) described the former overlying the latter.

The limestone was briefly described by Mennessier (1972) as several hundred meters of black and reddish sandy limestone with schistose sandstone interbeds. The limestone is NC-dark-gray, L–731-brown, and A-green on the respective images. Fossils include fusulinids, tetra corals, brachiopods, and bryozoans. The dolomite occurs in the upper part of Abtchakan (Mennessier, 1972) and is NC-white, L–731-white, and A-green on the respective images.

Large Masses of Ultramafic Rocks

Abdullah and Chmyriov (1977) and Wittekindt and Weippert (1973) mapped ultramafic bodies of dunite, peridotite, and serpentinite in several places in the Logar valley region on the west side of the Kabul South quadrangle. The most extensive rock type is serpentinized peridotite (see fig. 8) (TRPusp) that has a distinct coloration of NC-brown, L–731-yellow-green, A-turquoise on the respective images and has a strong signature of calcite or serpentine on the HyMap image. Several areas within the larger bodies of serpentinized rock are darker in color and are NC-orange-brown, L–731-yellow-green-to-green and A-blue on the respective images with a HyMap signature indicative of iron-goethite-jarosite (TRPug). The pure blue on ASTER suggests an abundance of mafic minerals and these areas are interpreted to be mostly peridotite without extensive serpentinization (TRPug). The ultramafic bodies of Logar valley tectonically overlie Kotagai melange and mica schist of the Shalkalay Formation (fig. 7), as well as most of the other local bedrock units, on a regionally flat

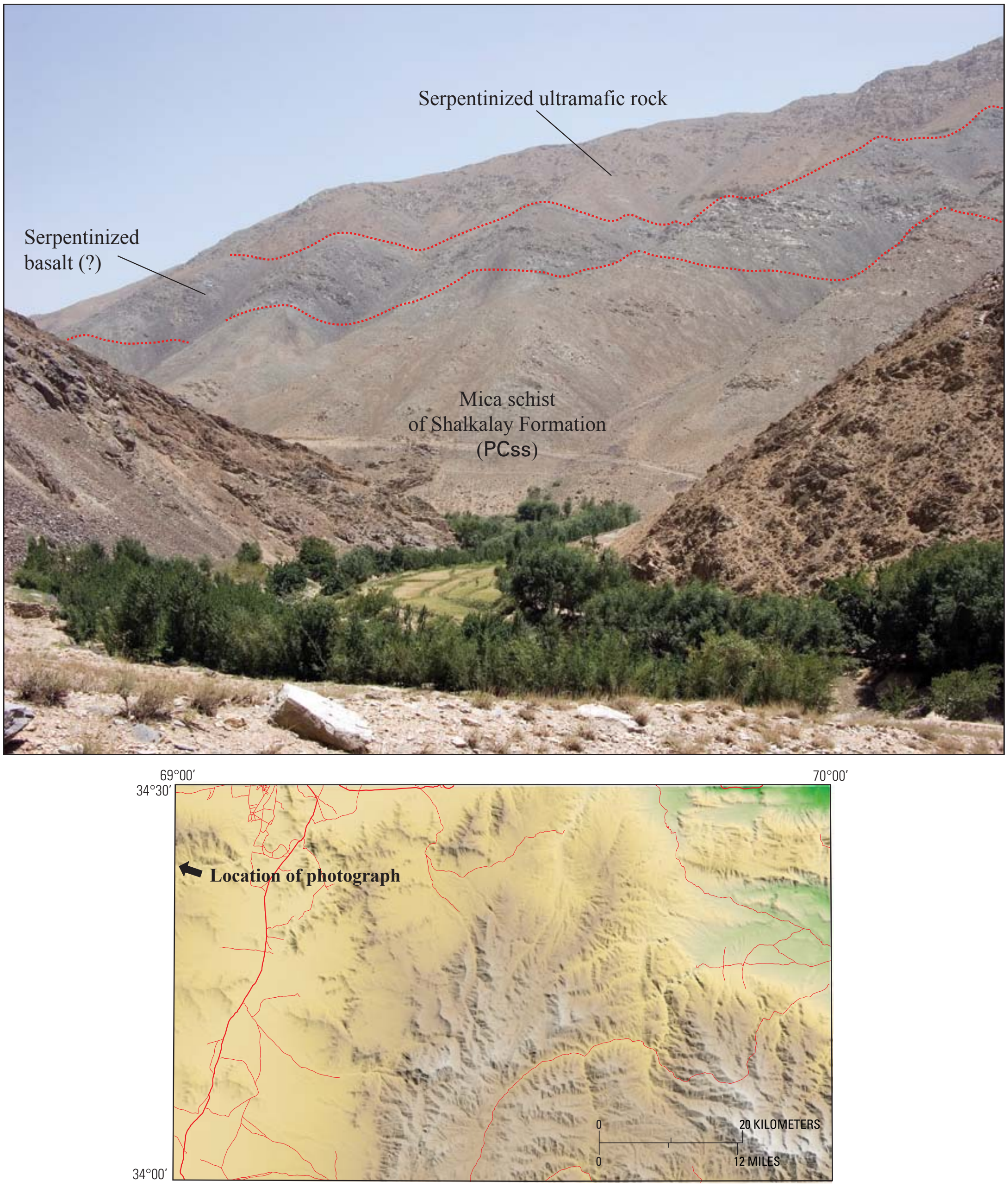


Figure 7. View to the east-southeast in the canyon cut by the Kabul River (Kabul Rud) to the southwest of Kabul city limits. All of the brown-colored rocks in the lower canyon walls are mica schist comprising part of the Shalkalay Formation (PCss). Midway up the south canyon wall a dark band of rock is interpreted to be serpentinized basalt that tectonically overlies the schist. Serpentinized peridotite makes up the skyline and it probably is tectonically emplaced over the basalt. The latter units are lumped as unit TRPusp on the geologic map. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

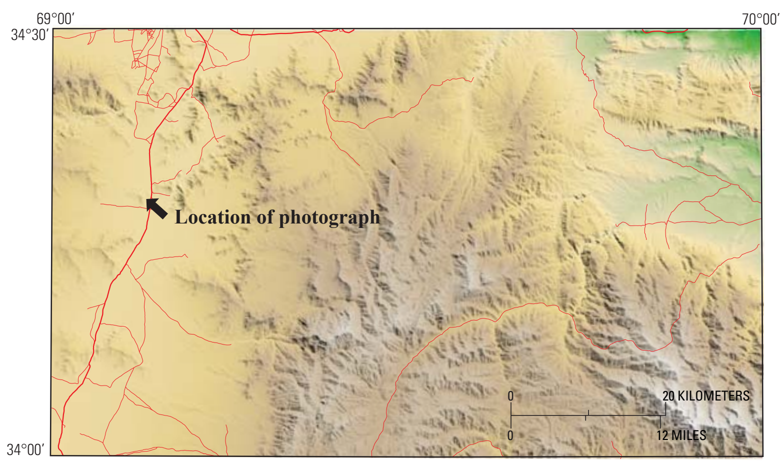


Figure 8. Close-up of typical serpentinized peridotite in Logar valley area. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

system of faults. Another group of ultramafic exposures mapped by Abdullah and Chmyriov (1977) in the northern part of the quadrangle appears to be integrated into the melange (ŦPup). These exposures are NC-dark-gray-to-black and L–731-purple-to-purple-red on the respective images, and they are mapped separately from the melange in this report in order to coincide with the way they were mapped in the quadrangle just to the north (Bohannon, 2010).

No ages are available for any of the ultramafic rocks. Tapponnier and others (1981) stated that the oceanic lithosphere that was subducted (and presumably obducted) during the formation of Afghanistan was mainly Permian to Triassic in age, although they did not elaborate on how they knew this. The ultramafic rocks are assigned these ages on the geologic map (sheet 1).

Khengil Series

The term Khengil series is used to describe a thick section of carbonate rocks that is widely exposed east and south of Kabul. The Khengil series unconformably overlies continental basement of Paleoproterozoic to earliest Cambrian age. The carbonate platform section was most recently described, measured, and mapped by Fisher (1971) in the Koh-i-Sofe, a range due east of Kabul in the Kabul North quadrangle (fig. 2), and the short descriptions herein are derived from his work. Although Abdullah and Chmyriov (1977) mapped the entire platform section as Permian and Triassic, Fisher (1971) noted that upper part of the section is Jurassic age. He subdivided the platform carbonate rock section into seven units on the geologic map (sheet 1). They are as follows:

1. Guadalupian basal conglomerate (Pkc);
2. Lopingian and Guadalupian reef limestone (Pkl);
3. Lower Triassic ceratiten-bearing limestone (Ŧkc);
4. Middle and Upper Triassic limestone, dolomite, and tuff (Ŧklt);
5. Jurassic (Lias to Dogger) nerineen-ammonite-bearing limestone (Jkn);
6. Jurassic (Dogger to Malm) belemnite-bearing limestone (Jkb); and
7. undifferentiated limestones of mostly Jurassic age (Jku).

Dronov, Abdullah, and Chmyriov (2008) referred to the Permian part of the series as the Tangi-Garu Formation and it includes units Pkc and Pkl. The basal conglomerate (Pkc) is discontinuous and was not identified except in some northern outcrops (sheet 1). It is quartz-rich and is about 40 m thick at the most. Internal bedding, some of which is visible on high-resolution images, is lenticular and discontinuous. The conglomerate is barely resolved on the Landsat image, but is easily picked out as NC-tan-colored layer on the high-resolution images. The Permian reef limestone (Pkl) is 250 to 300 m thick. The lower one quarter of the section is fusulinid-bearing arenaceous limestone and the top three quarters is productid-bearing and flinty limestone with small lenticular reef bodies at about mid-section. Bedding is locally parallel and uniform, being well defined by thick alternating light and dark layers (fig. 9). The unit is NC-medium-gray, L–731-blue-green with one or more L–731-pinkish, sandy horizons on the Landsat image, A-green on respective images.

The Lower Triassic parts of the Khengil series were not assigned a formational status by Abdullah and Chmyriov (2008). The Lower Triassic ceratiten-bearing limestone (Ŧkc) is a distinct recessive unit that is only about 50 m thick (fig. 9). It forms a nick in the slope that can be reliably identified on most high-resolution images and it commonly appears as a continuous NC-brown horizon that facilitates mapping. Fisher (1971) indicated that it is fine-bedded (mostly too fine to resolve on the images). The ceratiten-bearing unit was only identified in some northern exposures.

The Middle and Upper Triassic parts of the Khengil series were assigned to the Saparae and Gozak Formations by Abdullah and Chmyriov (2008). The Saparae Formation corresponds to unit Ŧklt and it has a distinct L–731-light-blue color and a well-defined calcite/dolomite signature on HyMap images, making this one of the most easily traceable units on the map. These coarse multi-band and hyper-band characteristics enabled the reliable identification of this unit even where fine-scale internal structural complexities obscured its otherwise distinct reflective character on high-resolution images. The limestone, dolomite, and tuff section is about 350-m thick and has continuous, parallel, and uniform beds, a meter or so thick, that are apparent on the high-resolution images (fig. 9). It is mostly pure NC-light-tan-weathering carbonate that is commonly quarried for cement where it crops out in accessible areas. Contacts with the other carbonate units are well defined and easily mapped in many places. Tuffaceous horizons mostly occur in the upper half of the section (Fisher, 1971). The Goznak Formation corresponds to a thin (30 m) megalodon-tooth-bearing limestone above the tuffaceous dolomite. This megalodon unit can be identified on some images, but not consistently, so it was not mapped separately.

Fisher (1971) described and documented Jurassic rocks in the upper Khengil series, but he did not name them. The Jurassic nerineen- and belemnite-bearing limestones of Fisher (1971) are similar on the images, but can be differentiated where a distinct topographic ledge that commonly is present between the two units (Jkn and Jkb) can be identified on the high-resolution images. Where they could not be separated they are mapped together as undifferentiated limestone (Jku). These limestones are L-731-blue-green and L-731-yellow-blue-green. Both units have parts that are thick-bedded and these look like they are discontinuous laterally on the high-resolution images.

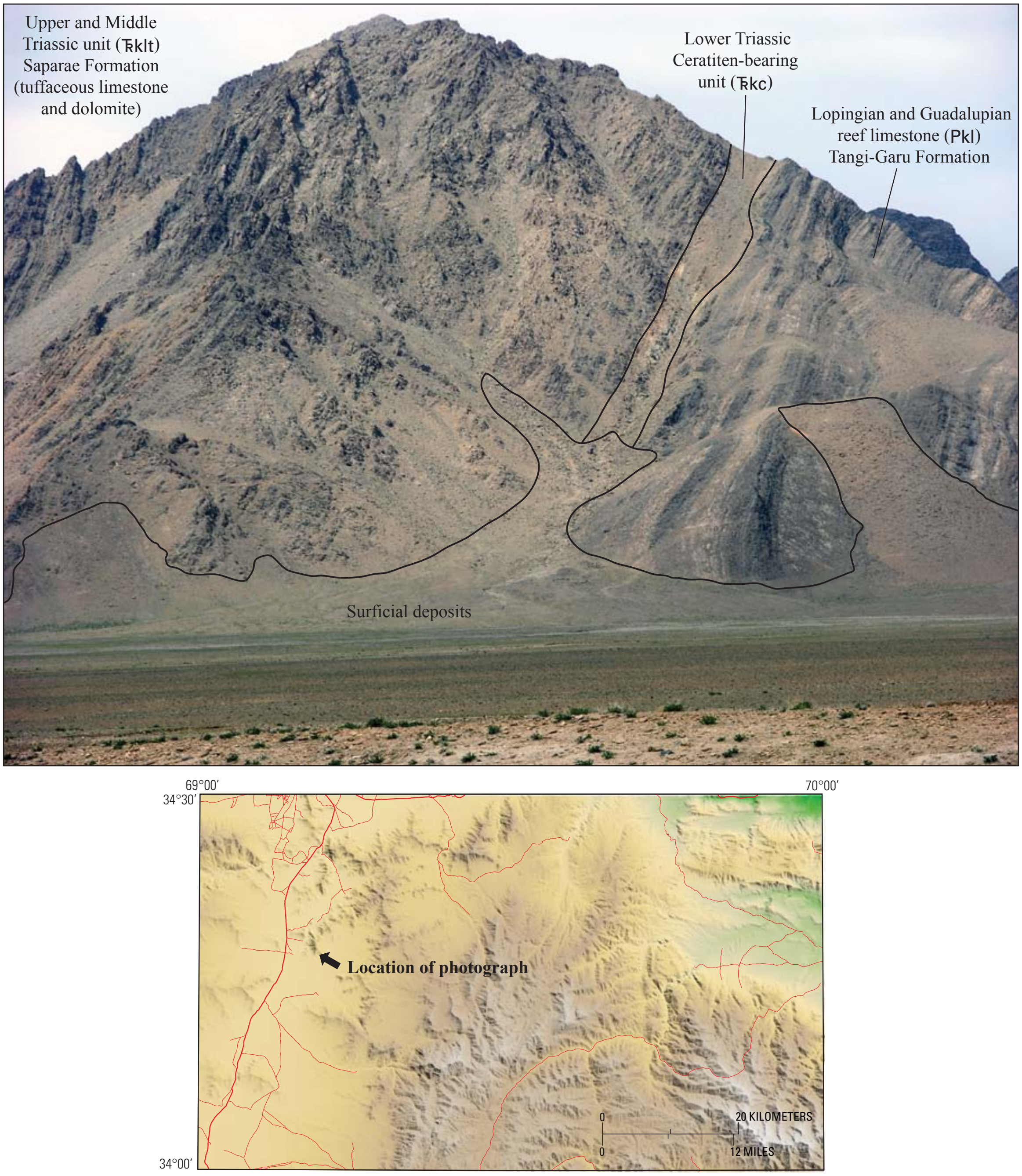


Figure 9. Khengil series limestone and dolomite of the Saparae (TRklt) and Tangi-Garu (Pkl) Formations. View to the north taken from road leading to Anyak copper district east of Logar Valley. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

Sedimentary and Metasedimentary Rocks of the Kunar Tectonic Zone

It is easy to recognize and separate several different metasedimentary and igneous rock units in the Indian plate area and in the Kunar terrane based on their distinct image characteristics, but published maps present a confusing picture of the age and nature of these rocks. High-grade gneiss, marble, limestone, quartzite, and pelitic schist in the northern half of the Kunar terrane have been mapped in one case as Proterozoic continental basement (Abdullah and Chmyriov, 1977) and in another as Cenozoic orthogneiss (Wittekindt and Weippert, 1973). Figure 10 summarizes the differences in the published maps. Due east, in Pakistan, similar rocks have been documented to be Phanerozoic Indian-shelf metasediments (for example, see DiPietro, Ahmed, and Hussain, 2008).

Several new unpublished radiometric age determinations from the Jegdelik ruby mines have shed light on the temporal history of the rocks in the Kunar terrane (table 1). Zircon from augen gneiss was dated at 95 to 97 Ma by U/Pb-zircon-laser-ablation-ICP–MS techniques (Daniel P. Miggins and Lawrence W. Snee, USGS, written commun., 2009). The original sedimentary nature of this gneiss is supported by intercalated marble horizons and the fact that compositional and textural layering is ubiquitous at nearly all scales (fig. 11). An interpretation of the laser-ablation data provided by Wayne R. Premo (USGS, written commun., 2009) is that the 95–97 Ma age represents the primary age of most zircons, although zones in some of the zircons give a hint of a Neoproterozoic source as well. Biotite gneiss is also present in the ruby mines and zircon from this source dated at 86 Ma by the same techniques (Daniel P. Miggins and Lawrence W. Snee, USGS, written commun., 2009). Both types of gneiss and the marble are intruded by coarse-grained biotite-granodiorite sills that have been dated at 76 Ma by the same techniques (Daniel P. Miggins and Lawrence W. Snee, USGS, written commun., 2009). Thus, a Late Cretaceous protolith age is likely for this section. Unpublished Ar/Ar ages on muscovite from rocks in the same area are as young as 19 Ma, indicating that the ruby-bearing strata were still at temperatures near 400°C at that time (Lawrence W. Snee, USGS, written commun., 2009).

Compositional layering is subparallel to the internal rock fabric within the different gneiss types. Augen gneiss and marble are intercalated in the western part of the ruby district where the large-scale compositional layering, visible in figure 11, results from biotite-augen gneiss (dark layers) and marble (lighter layers). The marble, mapped as unit Km, and the strong compositional layering are prevalent west and north of the ruby mines, but both are absent to the east. Biotite gneiss is widespread to the east of the ruby mines and it might be an orthogneiss, as this is the way it was mapped in that area by Wittekindt and Weippert (1973). I was not able to differentiate the two types of gneiss on sheet 1; they both comprise unit Kgn. A pronounced white layer and debris pile in the central fore- and mid-ground of figure 11 is the site of a biotite-granodiorite sill (fig. 12). The sills are also internally deformed, but since biotite is rare, the deformation is less visible than it is in the gneiss. The sills could be the same as Cretaceous granite sills (Kigr) that are mapped elsewhere. Rubies occur along the contacts of granodiorite sills and marble country rock (fig. 13). The sills are generally thin and hard to detect amongst the marble layers, which they resemble on the images. Ruby diggings are easy to pick out and sills are mapped on sheet 1 at each dig site. More sills are probably present, but most of the light layers that appear on the images are mapped as marble. The marble also corresponds to a widespread A-green area on the ASTER image.

Unit Kgn is NC-gray and L–731-pink and unit Kgnb is NC-gray and L–731-brown on respective images. Another, possibly older gneiss body (Kmgn), borders the ruby district to the north and south and is L–731-dark-red-brown. It is probably amphibolite gneiss, based on its A-dark-blue appearance on ASTER. Marble (Km) is L–731-white, A-white, and A-green on respective images.

Additional sedimentary and metasedimentary rock units that are present near the ruby district include pelitic schist or slate (Kps), quartzite (Kq), white dolomite (Kd), and white, bedded limestone (₽Kls). None of these units are adequately described or differentiated in prior mapping or in published reports, so what is known about them comes solely from image analysis. Pelitic schist is mainly exposed south of the Jegdelik ruby district in the hangingwall of a large south-vergent thrust fault. The schist is L–731-dark-blue-gray; NC-dark-gray, and A-purple-to-red on the respective images and it has a strong calcite signature on HyMap. The dolomite, which is also in the upper plate of the thrust, is L–731-pale–blue, A-green, and NC-white on the respective images. Parallel and continuous bedding, with a steep south dip, is conspicuous in the dolomite. Quartzite, which is white to pale brown on the images, is interbedded with the schist. Limestone to the east-northeast of the ruby district appears to unconformably overlie most other rock units. Thus, it is probably younger, and might be early Paleogene in age. The limestone is well bedded, with moderate dips, on the high-resolution images and it is L–731-white, A-pale-green, and NC-white-to tan on the respective images.

Plutonic Rocks of the Spin Ghar and Kunar Tectonic Terranes

Possible Mesozoic plutonic rocks intruding the Spin Ghar crystalline complex include undifferentiated Mesozoic white aplite or pegmatite (Mzap) and dark-colored amphibolite (Mza). Plutons in the Kunar terrane include a large laccolith of gabbro or diorite (₽Kigb) and sills and dikes of granitic rock (Kigr). Both units are assigned a Cretaceous age, but that assignment is based entirely on the mapping of Abdullah and Chmyriov (1977) in the case of the gabbro, and it is based on a speculative correlation to the 76 Ma granodiorite sills in the ruby district. The gabbro, in particular, may well be younger based on the speculative Paleogene age of the limestone country rock (₽Kls). The gabbro is L–731-dark-pink-to-brown,

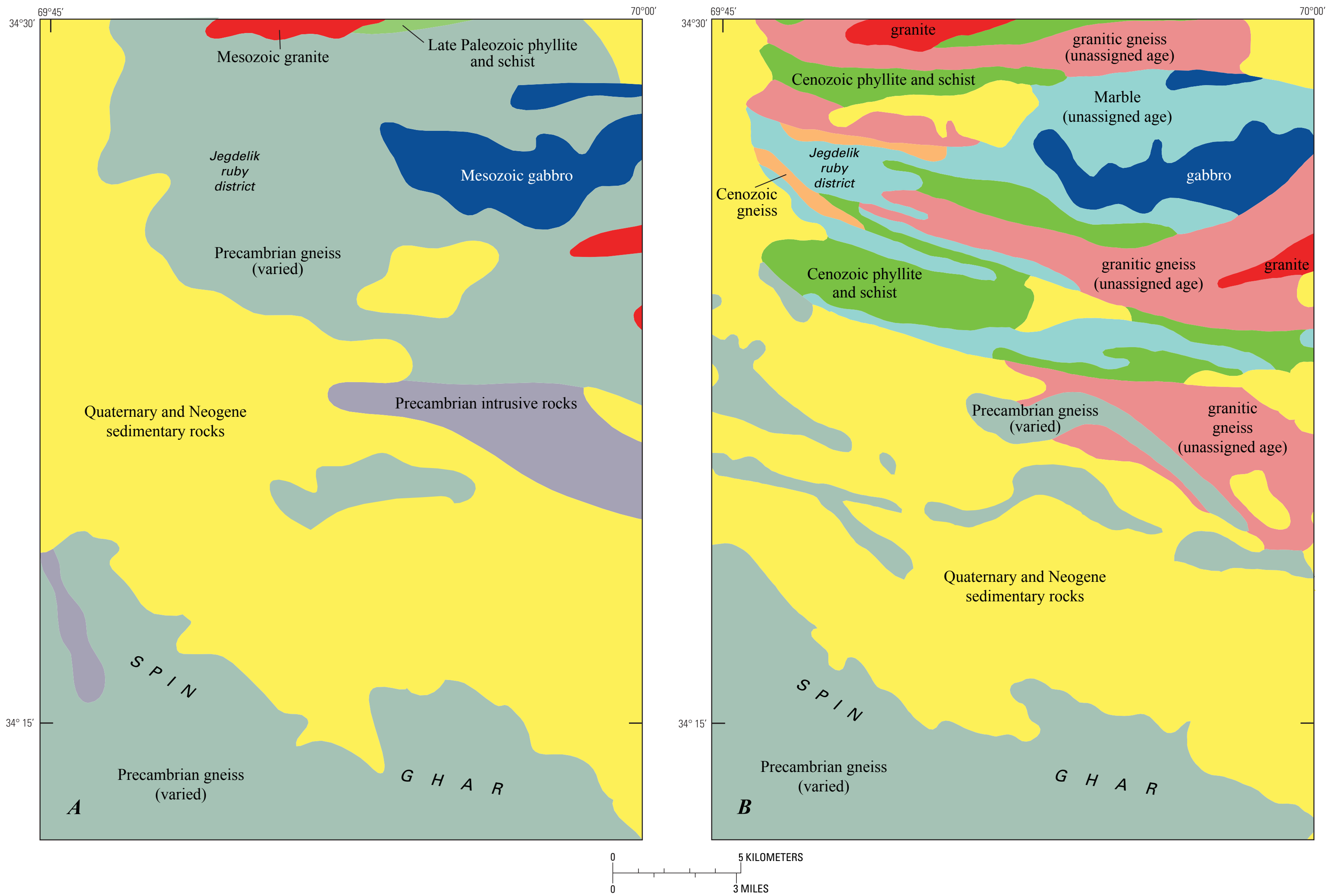


Figure 10. Two simplified maps of the same area in the northeastern corner of Kabul South quadrangle that includes the Jegdelik ruby district. Map *A* is based on the interpretation of Abudullah and Chmyriov (1977) and it shows no distinction in age or character of the rocks from the Spin Ghar to the southern extent of Nuristan terrane. All are simply an undifferentiated collection of early Paleoproterozoic gneiss and related rocks in this version. Map *B*, based on the Wittekindt and Weippert (1973) interpretation, suggests many of the rocks of the Jegdelik ruby district and its surroundings, including many of those to the north in Nuristan terrane, might be Cenozoic age.

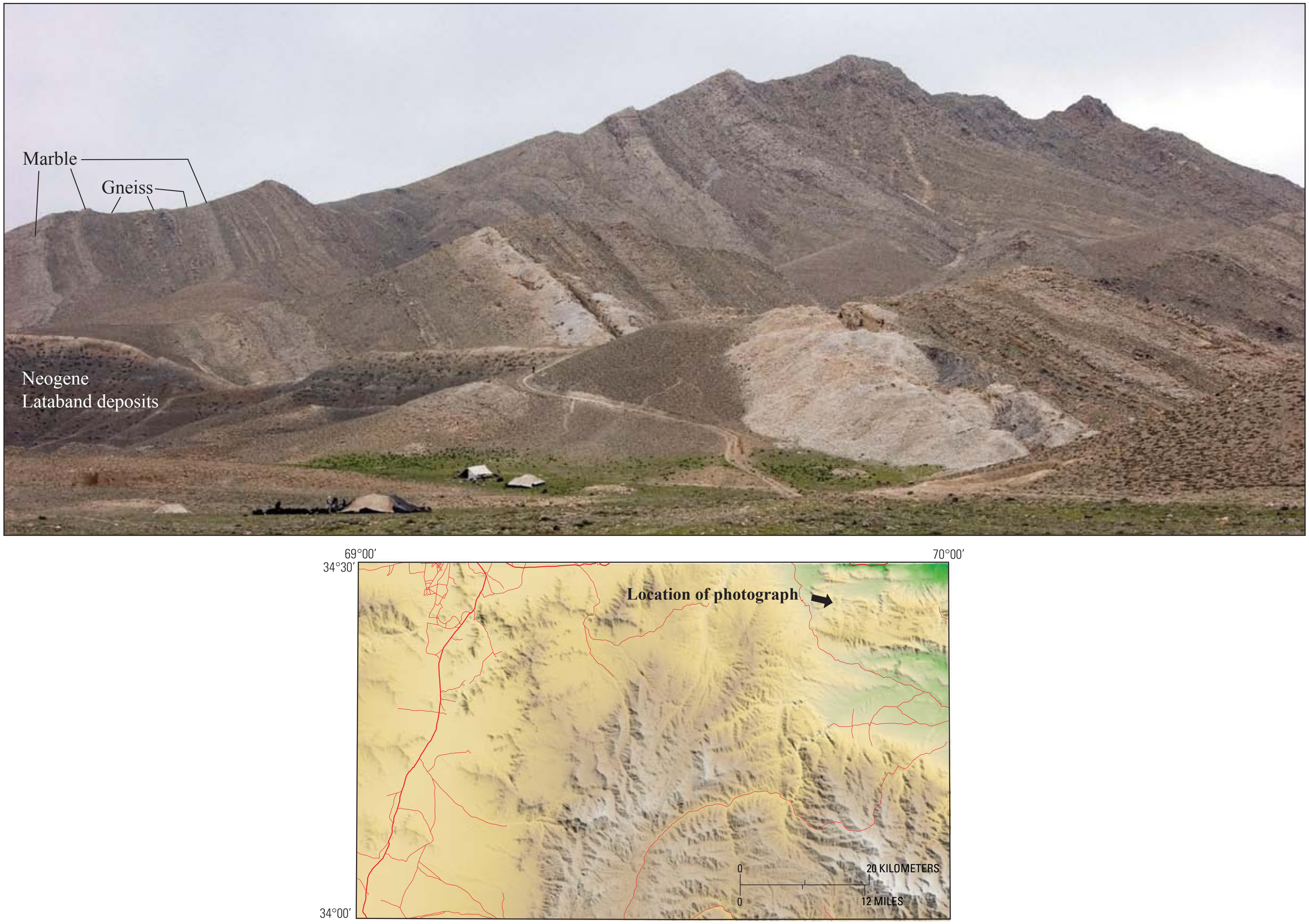


Figure 11 View to the west of the section of rocks in the vicinity of the Jegdelik ruby district. The north-dipping rocks on the ridgeline are gneiss (dark-colored layers, unit Kgn) and marble (light-colored layers, unit Km). The fine scale of the intercalation of these two rock types indicates the sedimentary origin of the gneiss, although Wittekindt and Weippert (1973) interpreted most of it as orthogneiss. The white diggings in the fore and middle ground are the result of ruby mining, which has taken place along the contact zone between small granodiorite sills and marble layers. Samples taken nearby yielded U/Pb ages of 97 to 95 Ma on augen gneiss, 85 Ma on biotite gneiss, and 76 Ma on granodiorite (see main text). Thus, the sedimentary protolith is interpreted to have been deposited and then intruded during the Late Cretaceous. Other samples yielded Ar/Ar ages as young as 19 Ma, suggesting that these rocks remained at temperatures near 400° C until at least then. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

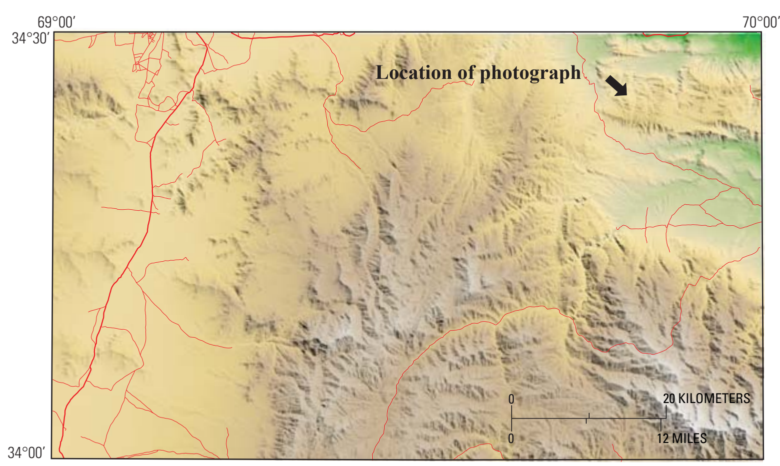


Figure 12. One of the biotite-granodiorite sills that intrude marble and gneiss in the Jegdelik ruby district. These sills have a weak penetrative deformation caused by foliation and lineation in biotite. The percentage of biotite is much lower in the granodiorite than it is in the gneissic country rocks so the metamorphic deformation seems to be greater in the gneiss, but this may not be entirely true. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

Figure 13. View to the west-northwest of one of the ruby diggings in the Jegdelik area. The ruby pits are dug along the intrusive contacts between granodiorite sills and marble units. The subparallel nature of the intrusive contact and that of the internal fabric in the marble is apparent in the photograph. Gneissic fabric and that in the granodiorite are the same, although not as apparent in this image. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

A-blue, and NC-dark-purple-gray on the respective images. Topographic geometry indicates that the basal contact of the gabbro above the limestone is regionally subhorizontal suggesting that it is a laccolith. Although the limestone host rock is folded in broad, open folds, the base of the intrusion is not.

Wach Sach Limestone

The Wach Sach Limestone (JTRwsls) of Triassic and Jurassic age is bedded limestone with thin yellow clayey interbeds, its fossils include *Ceratites*, *Pentacrinus*, and fragments of brachiopods, and it is 100–800 m thick (Mennessier, 1972). The Wach Sach Limestone probably overlies the Abtchakan Formation (Pad) and probably underlies the Kamarkae Dolomite (KJkd), but the only exposures of it are in the south-central part of the quadrangle where it is in fault contact with all adjacent rock units, including the Kotagai melange (₽Kku) in places. The Wach Sach is NC-medium-gray, L–731-gray, and A-green on the respective images.

Kamarkae Dolomite

The Kamarkae Dolomite (KJkd) of Jurassic and Cretaceous age consists of interbeds of light gray dolomite and limestone that are compact and fine-grained (Mennessier, 1972). It contains ammonites and rudistid and chaetetes corals (Mennessier, 1972). Exposures are limited to the eastern part of the Kotagai deformed zone where it tectonically overlies melange in most places. It is characterized by its distinct L–731-pink, NC-light-gray, and A-green coloration on the respective images.

Rokian (Kurram) Series

The Rokian series is composed of limestone (Krls) of Campanian and Santonian age and sandstone (JTRrs) of Jurassic to Triassic age. The term Kurram was used for these rocks by Badshah and others (2000), but they were originally mapped as Rokian series by Mennessier (1973c) whose more detailed maps are followed in this report. Mennessier (1972) also described the Kurram as gray schist that underlies the Rokian sandstone in the Khost region south of this quadrangle. The limestone is mostly marl with interbeds of sandstone (Mennessier, 1972) and it is characterized by its distinct L–731-pink, NC-light-gray, and A-green coloration on the respective images. The limestone crops out along the southern quadrangle border in the east part of the map. The sandstone is a thick sequence of sandy flysch containing varicolored conglomerate and radiolarian cherts that extends from the southern part of the quadrangle to the region of Khost in the south (Mennessier, 1976). It is widely exposed in the southeastern part of the quadrangle. On the Landsat image it has a range of colors between L–731-light-blue and orange-brown. It is NC-brown-gray and A-blue-and-green on the other images.

Kotagai Melange

The term Kotagai has been widely used throughout the region east and south of Kabul (Abdullah and Chmyriov, 1977; Mennessier, 1976). This unit appears on the regional map of Abdullah and Chmyriov (1977) as a volcanic and sedimentary section (Cretaceous to Eocene) that rests unconformably above the Khengil series. Fisher (1971) also described it as a mostly volcanic and marine sedimentary section (Upper Cretaceous to lower Eocene), but he recognized that it was probably emplaced by large thrust faults. Mennessier (1976) later inferred that parts of the Kotagai might be as old as late Paleozoic and he concluded that large transport to the northwest was needed to explain the modern structural position of these rocks. Some of this should have been self-evident from the beginning, since the Kotagai has ubiquitous strong penetrative deformation, extensive serpentinization, and a modest overprint of thermal metamorphism. These factors make it unlikely that the Kotagai is simply the youngest part of an otherwise unmetamorphosed sequence. Mennessier (1976) described Campanian and Santonian microfossils from limestone olistostromes within the Kotagai just north of Kabul River gorge. He referred to these limestones as Ali-Pai-Bel limestone (for example, Mennessier, 1973f) on his geological map to the north of the Kabul South quadrangle. The age range of the Kotagai is uncertain since it has been tectonically emplaced, it is unfossiliferous in most places, and no numeric ages have been determined.

The geological maps of Mennessier (1973a–e) cover much of the Kotagai exposure in Kabul South quadrangle and he showed that it forms a wide belt of deformed rock that bisects the quadrangle in a north-south direction. The Kotagai is probably also widespread in the western half of the quadrangle, but it mostly lies tectonically beneath thin sheets of ultramafic rock there. Additional exposures are present in the northwestern part of the quadrangle.

On Mennessier's (1973a–e) maps the Kotagai is consistently referred to as sandstone of Cretaceous or Late Cretaceous age. By my image analyses I infer that it is a highly disrupted melange of at least 11 different units in the Kabul South quadrangle.

A large part of Mennessier's sandstone appears on sheet 1 as undifferentiated Kotagai melange (₽Kku). The undifferentiated unit is a rock that exhibits very little, if any, internal character on any of the images in the range of resolutions available for this study. It could easily be all sandstone as Mennessier (1973a–e) suggested, but all vestiges of original bedding have apparently been destroyed or otherwise obscured, possibly by post-depositional internal deformation. The undifferentiated unit is L–731-brown, A-red-purple, and NC-gray-brown on the respective images.

Some parts of the Kotagai can be more readily differentiated on the images and the Landsat data proved to be particularly useful in this regard. As such, the descriptive nomenclature used in this report is keyed in most cases to the Landsat false colors as they appear in the L–731 version. An

L–731-blue-colored unit (ꝐKkb) is interpreted to be chiefly carbonate-rich greywacke schist based on its A-magenta color on ASTER (indicating the presence of both quartz and mafic components) and its calcite signature on HyMap data. An L–731-dark-blue-colored unit (ꝐKkdb) is interpreted to be a mafic phyllite or schist based on one field examination of a similar unit exposed in the gorge cut into the Koh-i-Sofe by the Kabul River in the Kabul North quadrangle. HyMap data suggest the possible presence of serpentine in this unit. An L–731-blue-gray-colored unit (ꝐKkbg) is interpreted to be sandy schist based on its A-red-purple color that suggests the presence of both quartz and mafic components. An L-731–white-colored unit (ꝐKkw) is interpreted to be metatuff based loosely on its color and the fact that Mennessier (1976) described tuff in the Kotagai elsewhere. An L–731-light-blue-colored unit (ꝐKklb) is interpreted to be shale based on its A-purple color on the ASTER image (suggesting mostly mafic components) and its NC-light-gray appearance on high resolution images. Limestone olistostromes are also present within the melange (ꝐKkls). The olistostromes might be the Ali-Pai-Bel Limestone of Mennessier (1976) that he described as a nummulitic limestone of Cretaceous age.

Mafic and ultramafic igneous components are also included in the Kotagai melange in this report. Two subtly different peridotite units, an L–731-blue peridotite (ꝐKkp) and an L–731-brown peridotite (ꝐKkpb), appear on the map as irregular, fault-bounded blobs within the undifferentiated and light-blue Kotagai units. Although these units look different on the Landsat image, both were mapped as peridotite by Mennessier (1973a–d) and each appears as a similar A-purple and NC-brown on other images. A large uniform body that Mennessier (1973b) mapped as dolerite (ꝐKkd), is present in the south-central part of the quadrangle. The dolerite stands out and is easily mapped because of its distinct L–731-dark-green-brown-and-purple, A-green-to-blue, and NC-deep-blue-black colors on the respective images. It is everywhere in fault contact with other parts of the melange based on Mennessier's (1973b) mapping and on my image interpretation. An exposure of rocks at the north end of the main dolerite body is mapped separately as altered or weathered dolerite (ꝐKkda) due to its subdued relief and lighter coloration on the Landsat image.

Azrao Flysch

The Azrao Flysch is Ypresian (Eocene) in age according to Mennessier (1972). It consists of a widespread zone of red and gray beds in the Azrao Valley (east central part of the map) west of the Sorubi fault as mapped by Mennessier (1973a–d). Numerous Eocene fossils were recovered and listed by Mennessier (1972). It consists of a fine-grained (Ꝑaf) and a coarse-grained (Ꝑafc) facies. Red marls that include abundant crystals of gypsum are interbedded with limestone beds that contain foraminifera and oysters in the fine-grained facies (Mennessier, 1972). The red marly facies appears as L–731-dark-green-blue; A-light-blue; and NC-deep-red on respective images. The coarse-grained facies is a multicolored conglomerate that contains clasts of radiolarian chert from ophiolites (Mennessier, 1972). The coarse-grained facies appears as L–731-dark-green-blue; A-light-blue; and NC-gray-red on the respective images. The strong contrast between the NC-red and NC-gray facilitated differentiation of the two facies on the high-resolution images.

Nummulitic Limestone

Eocene nummulitic limestone (Ꝑnls) tectonically overlies the Rokian series sandstone (JŦrs) and the Azrao Flysch (Ꝑaf and Ꝑafc) according to Mennessier (1973b, c). This is a bedded limestone that is several hundred meters thick (Mennessier, 1972). The unit is resistant and forms a high mountainous ridge system that is conspicuous on all of the images in the south-central part of the map southwest of the Sorubi fault. Numerous microfossils, listed by Mennessier (1972), provided the early Eocene age determination. It appears as L–731-brown; A-green; and NC-gray on the respective images.

Dobandi Flysch

The Dobandi Flysch (Ꝑdf) of Ypresian and Lutetian age is a thick unit of mostly gray schist and subordinate green sandstone according to Mennessier (1972). The schist and sandstone are interbedded with thin limestone lenses, red-and-green-radiolarian chert beds, and white limestone beds. The flysch has yielded a variety of microfauna including *Nummulites* (Mennessier, 1972). The Dobandi crops out in the central part of the quadrangle near the southern border at 34° latitude where it overlies Rokian sandstone (JŦrs) south of the quadrangle border. It is at least 2 km thick (Mennessier, 1972). It appears as L–731-light-pink-to-brown, A-red-purple, and NC-light gray on the respective images.

Lataband Series

Lataband is the term used for various basin-fill and fan deposits of Neogene age that are regionally exposed throughout the Kabul South quadrangle. Much of this fill probably accumulated through most of the Miocene and Pliocene, but no attempt was made to differentiate Miocene from Pliocene deposits in those units that span the two stages. Six units have been mapped:

1. Nlc, NC-light-brown conglomerate;
2. Nlfw, fine-grained L–731-white-to-light-yellow;
3. Nlfp, fine-grained L–731-pale-purple deposits;
4. Nlcp, L–731-olive-drab peridotite-bearing conglomerate;
5. Nlch, coal-bearing deposits; and
6. Nlfg, fine-grained L–731-gray-to-brown-gray deposits.

Conglomerate is probably the most widespread unit, forming dissected fans and bajadas near some of the major mountain fronts and erosionally isolated hilltop exposures in other places. The various fine-grained units, differentiated primarily by their distinct false-colors in the Landsat data, are present in the region of the Anyak copper deposit (fig. 14), throughout the Logar valley region, and in the area north of the Spin Ghar. In many cases the fine-grained deposits occur adjacent to mountain fronts where they lap on to dissected bedrock (fig. 15). The coal-bearing unit is limited to a small exposure near the settlement of Chalaw in the north-central part of the quadrangle. The peridotite-bearing conglomerate occurs adjacent to the larger serpentinized peridotite (₹Pusp) bodies near the western map border.

Surficial Deposits

Surficial deposits (Pleistocene to Holocene) in the Kabul South quadrangle are chiefly various ages of alluvium that are differentiated by the levels of dissection and surficial morphology that are apparent on the images. Fine-grained deposits of wind-born material, landslide masses, and agriculturally altered ground are also present.

The oldest alluvium (Qoa) is preserved as deeply dissected remnants of thick fan deposits that are now isolated at the tops of low hills in the southeast part of the quadrangle. Three divisions of more continuous alluvial deposits (Qa_1, early; Qa_2, intermediate; and Qa_3, young) are mapped throughout the quadrangle, primarily based on height above currently active streambeds. Young alluvium (Qa_3) is being actively deposited at stream level in the bottoms of modern canyons. Each of the older units is at least several meters above the next younger unit and more dissected. Alluvial sheet deposits (Qas) are mapped on the steep western slopes of the ranges bordering the Logar River valley where they form very thin, but widespread aprons that were locally derived in the nearby rocky highlands. Deposits on steep slopes, such as colluvium and rock falls, are mapped jointly (Qcr), since it is too difficult to differentiate in-place deposits from those that have tumbled down from higher outcrops with images alone. River alluvium (Qra) is mapped in the wider, active floodplains of rivers in the eastern half of the quadrangle. The Logar River and its tributaries in the west half of the quadrangle also have extensive river flood-plains, but those are mapped as unit Qa because of the ubiquitous agricultural alteration that is present in that area.

Eolian desert loess accumulations (Qdl) represent a slightly unusual type of surficial deposit, but one that is common in some of the mountainous parts of the Kabul South quadrangle. Loess is equally common on steep mountain slopes, ridges, flatlands, and in valleys. It is widespread in the Spin Ghar, Altimur, and Kabul River areas, but is only mapped where the deposits are of significant thickness and extent to conceal large areas of bedrock.

Several landslide, slump, and other mass-waste deposits (Qls) are mapped on the steep slopes in the eastern half of the quadrangle. Glacial moraines (Qgm) were identified along the crest of the Spin Ghar, mostly at elevations above 3,500 m in the southeast corner of the quadrangle. Several lacustrine deposits (Ql), which are basically clay and peat beds in flat lying lowland areas that occasionally collect standing water, occur on the Logar-River floodplain and in southern Kabul valley.

Structure and Tectonics

Much of the following discussion centers on the three interpretive cross sections provided on sheet 1. Also, figure 16 shows several tectono-stratigraphic environments within the Kabul South quadrangle, in addition to those delineated by Leven (1997), that are important to understanding its geologic evolution. Leven's Kabul massif, for example, is much more complicated than its name implies. His Kunar zone is very different from the way it is portrayed on existing geologic maps. The Nuristan terrane, which Abdullah and Chmyriov (1977) thought was chiefly a region of Proterozoic gneiss intruded by Mesozoic plutons, is very poorly understood and may not be that at all. The Suleiman-Kirthar terrane might be the northernmost extension of the Makkran accretionary prism. Large and complex bounding fault zones, that are poorly understood at best, separate these different terranes.

A quick examination of the geologic map (sheet 1) demonstrates to the viewer that the region between the Chaman and Ghazni faults, which is commonly called Kabul massif, is so highly fragmented and structurally complex that the term massif is hardly applicable. Two distinctly different ancient geologic environments can be found within the area (fig. 16).

One environment consists of a Permian to Jurassic marine platform-carbonate section and its basement of Paleoproterozoic crystalline gneissic and schistose rocks (fig. 16, no. 2), a combination commonly found in slowly subsiding and thermally mature regions of thick and well-evolved continental crust. Its ancient thermal history is confirmed by the Paleoproterozoic U/Pb ages and the Mesoproterozoic K/Ar ages from its crystalline basement rocks. The upper Paleozoic and Mesozoic platform carbonates that once covered the basement are also unmetamorphosed.

The other (fig. 16, no. 3) is a widespread belt of sandy-pelitic-and-mafic schistose melange, termed the Kotagai melange that is tectonically overlain by large, intact, peridotite nappes (Mennessier, 1976; Tapponnier and others, 1981). A variety of carbonate shelf rocks and mafic and ultramafic rock bodies are tectonically incorporated to one extent or another into the large-scale fabric of the melange. The melange rocks are variably metamorphosed and have a well-developed, pervasive fabric in many cases, even though they might be younger than the unmetamorphosed platform rocks that they are proximal to.

The two contrasting environments are tectonically juxtaposed by a complex, regional, low-angle fault system that I have termed the Kotagai roof fault and the Kotagai overthrust (KRF and KOT, respectively, in fig. 16). Platform rocks and crystalline basement tectonically overlie melange

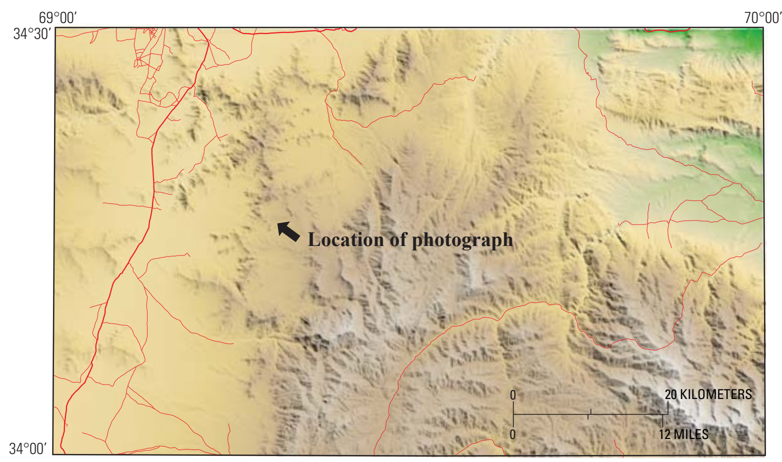


Figure 14. View to the east-northeast of the Lataband series in the Anyak copper district. These rocks are typical of the fine-grained, white colored unit (Nlfw). The Lataband series may be as thick as 1 km. Here it is known by drilling to cover a widespread occurrence of copper mineralization within the Loy Khwar Formation (ЄZlk). Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.

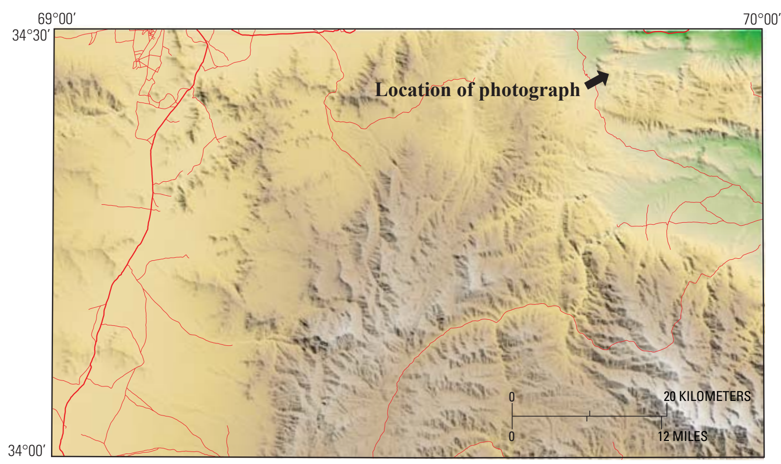
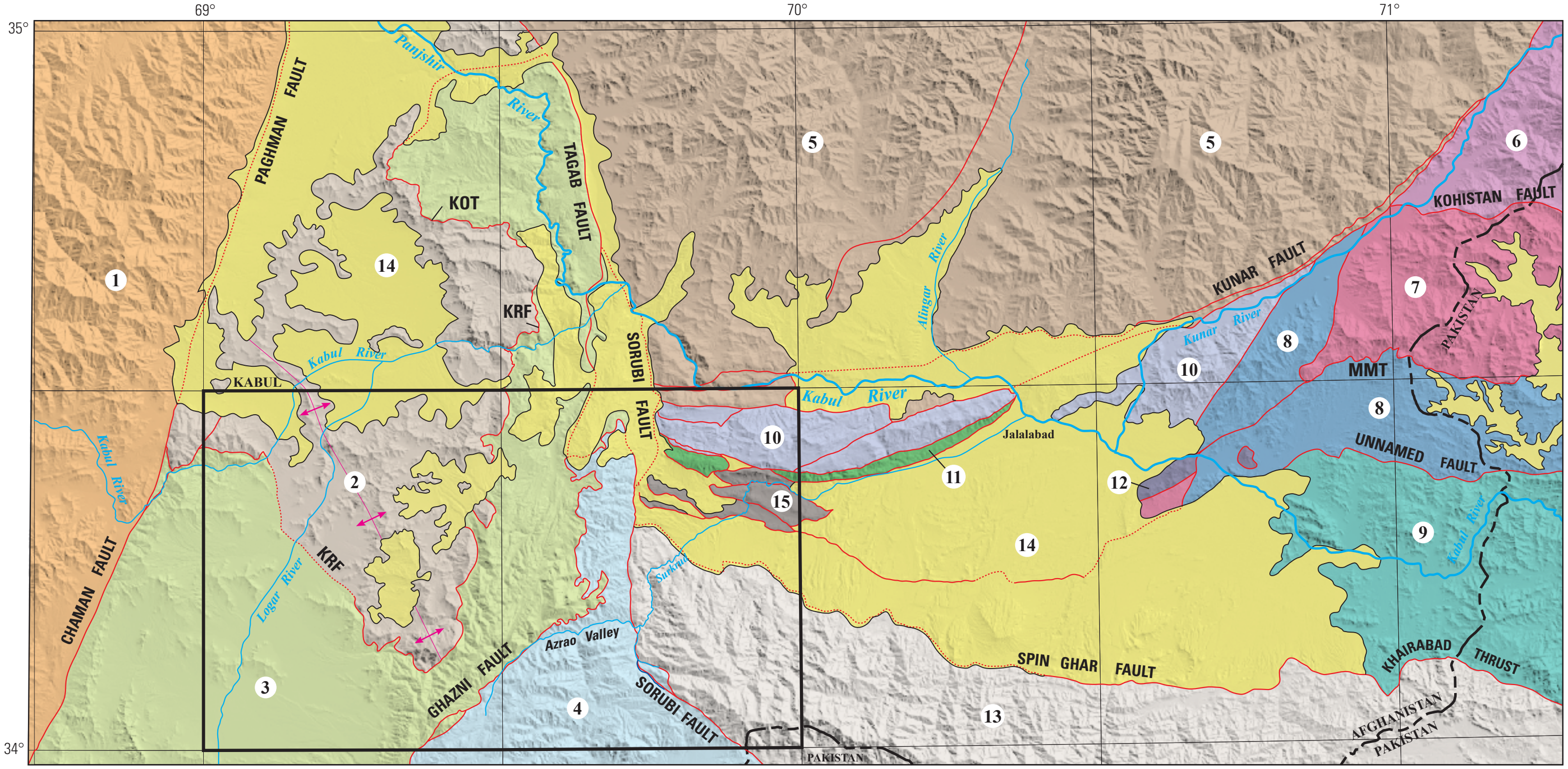


Figure 15. In many places in the Kabul South quadrangle, fine-grained deposits of the Neogene Lataband series onlap steeply tilted and metamorphic rocks that form the ranges. In this view, taken to the northeast in the Jegdelik region, gently deformed carbonate-claystone of the Lataband series overlap strongly tilted Cretaceous metasedimentary rocks that were at high temperatures until early Miocene time. Location of photograph is shown on accompanying index map of the Kabul South quadrangle, partial road network shown in red. Photograph by Robert G. Bohannon, 2006.



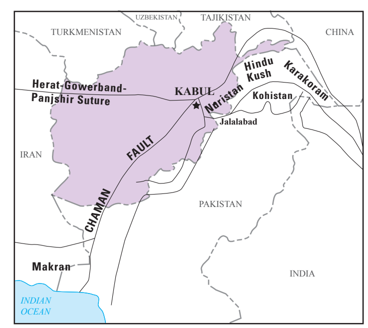
Tectono-Stratigraphic Terranes

1. Paghman metasedimentary and intrusive terrane
2. Kabul Paleoproterozoic crystalline and platform carbonate terrane
3. Kotagai melange and ultramafic terrane
4. Azrao and Rokian flysch terrane
5. Nuristan metasedimentary and intrusive terrane
6. Kohistan arc
7. Indus suture zone
8. Layered Indian shelf rocks
9. Paleozoic Indian shelf and rift
10. Granite, gneiss, and marble of the Jegdelik and related terranes
11. Triassic Indian deep water pelitic rocks
12. Ultramafic rocks of unknown genesis
13. Spin Ghar crystalline terrane and related superjacent strata of the Indian continental plate
14. Thick Neogene and Quaternary deposits
15. Crystalline rocks mapped as Proterozoic that might instead be lateral equivalents of terranes 8 or 9

0 10 20 30 40 50 KILOMETERS
0 10 20 30 MILES

EXPLANATION

Faults
Anticline
Terrane boundary
Kabul South quadrangle boundary
International boundary



General tectonic features in region

Figure 16. Simplified map of the different tectono-stratigraphic terranes found in and around the Kabul South quadrangle. The numbered list of tectonic provinces or terranes corresponds to the numbered areas on the figure. Abreviations are MMT, main mantle thrust; KRF, Kotagai roof fault; KOT, Kotagai overthrust.

on the Kotagai roof fault in most places and melange overlies platform rocks on the Kotagai overthrust in the northern Koh-i-Sofe (Bohannon, 2010) and locally in the mountains southwest of Kabul. Regional relations, especially those within the Kabul South quadrangle, strongly suggest that the Kotagai roof fault is a widespread low-angle structure above which the platform/crystalline terrane is preserved as a thin hanging wall flake of continental rocks (sheet 1, cross sections). Since melange also tectonically overlies platform rocks locally, the continental flake may have acted as a subduction backstop at times (Bohannon, 2010). The highly disrupted platform sedimentary section rims the outer edge of the platform terrane with Paleoproterozoic basement in the core region around Kabul (sheet 1 and Bohannon, 2010). The broad structure is that of a basement-cored arch, oriented north-northwest, with complexly faulted flanks (fig. 16).

Kunar Tectonic Zone

The Kunar zone of Leven (1997) is complex and poorly understood. Much of what might be said about it derives from studies conducted in Pakistan 100 or more kilometers to the east of the Kabul South quadrangle where numerous workers (Coward and others, 1988; DiPietro and others, 2000; Anczkiewicz and others, 2001; Treloar and others, 2003; Treloar and others, 2007; and DiPietro, Ahmad, and Hussain, 2008) have attempted to explain the metamorphism and subsequent exhumation of Indian plate shelf sediments during the accretion of the Kohistan arc and the collision of the Indian continent with Asia since the Late Cretaceous. While complete concensus is lacking in significant details, there is agreement on several important things:

1. The Kohistan arc accreted to Asia sometime in the Late Cretaceous. In Afghanistan the modern contact is along the much younger Kunar fault (see fig. 16);
2. The rocks south of the Kohistan arc and the Kohistan suture zone to its south (fig. 16, nos. 6 and 7), belong to the Indian plate and mostly they are shelf sediments that were deposited on Indian continental basement of some type (fig. 16, 8 and 9);
3. The metamorphism of the Indian shelf sediments, which in many places reached garnet grade and higher, postdates the accretion of the Kohistan arc;
4. Exhumation and cooling of the shelf-sediment package took place during the collision and indention of India, possibly as late as the middle Miocene.

The exact timing of events, the causes of burial and heating, and the nature of the exhumation process remain unresolved to everyone's satisfaction (see DiPietro, Ahmad, and Hussain, 2008, for a brief summary).

There are four potentially different subterranes that make up the Kunar terrane in the Kabul South quadrangle. The southern one (fig. 16, no. 13) is a widespread crystalline belt in the Spin Ghar (Kohe safed) that is a strongly uplifted piece of Indian plate continental basement (Pakistan Geological Survey, 1993). The northern one (fig. 3, no. 10) is composed of layered gneiss and marble that are intruded by granodiorite dikes in the Jegdelik ruby district and it does not appear to extend east as far as Pakistan, so nothing like it has been described there. In between Wittekindt and Weipert (1973) mapped widespread Proterozoic rocks (fig. 3, no. 15) that they interpreted to be part of the Indian basement. Their basement is due west of a body of Paleozoic to Triassic rocks identified as the Indian shelf-and-rift sequence (fig. 16, nos. 8 and 9) by DiPietro and others (2000) and DiPietro, Ahmad, and Hussain (2008) in Pakistan. As the name implies the rocks in Pakistan may have once been part of the northern rift margin and subsequently developed marginal shelf of the Indian plate, prior to its collision with Asia. Although poorly described, these rocks are metasediments of various types, including schist, phyllite, marble, quartzite, and dolomite (Pakistan Geological Survey, 1993). A possibility remains that tectonic zone 15 (fig. 16) is similar and has been misinterpreted as basement, but more work is needed to determine this. There is also a narrow, fault-bounded zone of pelitic and carbonate rocks (fig. 16, no. 11) described as Cenozoic phyllite and schist by Wittekindt and Weippert (1973).

My analysis of the modern imagery, color photography, and new age data, as expressed in the geology portrayed on sheet 1, paints an entirely different picture from that of Abdullah and Chmyriov (1977), and it nominally differs from that of Wittekindt and Weippert (1973). I followed the lead of Wittekindt and Weippert (1973) by mapping extensive Proterozoic basement (Indian plate) throughout the southern half of the Kunar terrane. This seemed prudent in the absence of any better information, although I am left wondering whether the Indian shelf metasediments along the Afghanistan/Pakistan border might not continue into this area (fig. 16, nos. 8 and 9). I was unable to assess that possibility with the imagery alone. The rocks in the Jegdelik ruby district, between the Proterozoic exposures and the Kunar fault (fig. 16, nos. 10 and 11) are now mapped as Cretaceous and Paleogene, not Proterozoic following Abdullah and Chmyriov (1977) or Cenozoic following Wittekindt and Weippert (1973). This is based on the U/Pb dating of 95 to 97 Ma protolithic zircon and the 76 Ma intrusion of granodiorite sills, which indicate that the sedimentary package in the immediate vicinity of the ruby district was deposited in the interval between those ages. The ages of some of the rocks nearby the ruby district are far less constrained.

When did the metamorphism occur? The gneiss and marble in the ruby district have a strong metamorphic fabric. The granodiorite sills also have a penetrative fabric indicated by a weak lineation and foliation of micas, but it is not as well developed. Some, if not all, of the metamorphism probably post-dates the sills since K/Ar and Ar/Ar determinations that range between 19 and 40 Ma indicate that these rocks were hot long after the Cretaceous, but its precise timing remains uncertain.

Cooling ages, based on the K/Ar and Ar/Ar determinations, give an approximation of the time and amount of uplift and exhumation. The 19 to 40-Ma age ranges have been reported for the rocks of the ruby district (Lawrence W. Snee, USGS, upublished dates, written commun., 2009) and those in the Spin Ghar crystalline complex (Badshah and others, 2000). The 19 Ma ages in the ruby district were on muscovite, suggesting temperatures of around 400°C, which could easily correspond to depths of 7 to 10 km or greater, depending on the thermal gradient. Exhumation from those depths must have been completed prior to the deposition of the fine-grained Lataband sediments that are observed to lap onto the strongly tilted metasediments in the ruby district (see fig. 15). The Lataband series is thought to be Miocene and Pliocene, but the exact age of the onlap is uncertain.

The metasedimentary rocks south of the Kunar fault are in the footwall of the Main Mantle thrust (DiPietro, Ahmad, and Hussain, 2008), whose upper plate comprises the Kohistan arc and Kohistan suture zone (fig. 16). Other south-vergent thrusts with general east-west orientations cut the shelf and basement rocks south of the Kunar fault in Afghanistan (sheets 1 and 2). Wittekindt and Weippert (1973) mapped ultramafic rocks east of Jalalabad (fig. 16) indicating that oceanic lithospheric-mantle rocks might also be involved in the thrusting. Several of these faults have emplaced metasediments and basement over fine-grained Lataband units, so their displacement is at least in part Miocene in age. Likewise, the main thrust south of the Spin Ghar in Pakistan, known locally as the Khairabad thrust, is inferred to have Miocene displacement (DiPietro, Ahmad, and Hussain, 2008). Thus, south-directed thrusting is a likely candidate to explain the rapid Miocene uplift and exhumation required by the age determinations. An opposing thought that north-side-down detachment faults might explain the exhumation (Anczkiewicz and others, 2001; Treloar and others, 2003) is untenable in Afghanistan where there are no faults with the required older-on-younger or north-side-down geometry that would satisfy such a model.

Nuristan Terrane

The Nuristan massif of Leven (1977) is a widespread mountainous belt northwest of the Kunar fault (fig. 16, no. 5). It is continuous to the northeast with the Hindu-Kush/Karakoram metamorphic zones in Pakistan that Searle (1991) and Hildebrand and others (2000) regarded as the southern margin of Asia from Jurassic time until the accretion of the Kohistan-Ladakh island arc along the Shyok suture zone (also called the Northern suture). The accretion took place by northward subduction at the suture zone, which crosses the Pakistan/Afghanistan border and follows the Kunar River south to about Jalalabad where it bends west to the Tagab fault (the Kunar fault on fig. 16). If true, that means that the Nuristan terrane is likely part of the same southern-Asia subduction margin, but Abdullah and Chmyriov (1977) characterized this terrane as consisting of widespread Paleoproterozoic gneisses of various types, a thick and mostly clastic section of Carboniferous to Triassic sedimentary rocks, and numerous granitoid intrusions of Cretaceous and Oligocene age. Just across the border in northwest Pakistan the adjacent rocks are mapped as Devonian to Jurassic metasedimentary rocks and Cretaceous greenstone and slate, all intruded by Cretaceous granitoid rocks (Calkins and others, 1981). Proterozoic gneiss is rare in northwest Pakistan, which casts doubt as to the amount of Proterozoic basement that might actually be present in the Nuristan terrane. The Nuristan gneisses and their lateral equivalents in Pakistan originated to the north of the Kohistan arc, so they were once either part of the southern Asian shelf (if they were Phanerozoic metasedimentary rocks) or were a small continental island mass that collided with the Asian margin sometime prior to the accretion of the Kohistan arc (if they were Paleoproterozoic). The widespread plutonism makes sense with either interpretation, if it occurred in the Cretaceous prior to the accretion of the Kohistan arc. Widespread Oligocene plutonism would be hard to explain because it would post-date arc accretion during a time when the Indian continental mass was already well indented into Asia and most subduction had undoubtedly ceased. My preferred interpretation, pending further studies, is one of metamorphosed Asian-shelf sediments of Phanerozoic age intruded by Cretaceous plutons. No island-continent collision is required in that case, although I have left the Paleoproterozoic interpretation of Abdullah and Chmyriov (1977) intact on the geologic map (sheet 1) for lack of any better actual age control.

Suleiman-Kithar Terrane

The north end of the Suleiman-Kirthar terrane of Leven (1997), which is also called the Katawaz Basin, is present in the southeastern part of the quadrangle. This is tectonic zone 4 on figure 16 and it is chiefly a very thick section of clastic and carbonate sedimentary rocks that are commonly referred to as flysch and represented by the Azrao Flysch and sandstone of the Rokian series in this report. The Katawaz Basin is quasi-continuous to the south with rocks of the Makkran accretionary belt that is widely exposed in the coastal hills of southwest Pakistan. The Katawaz rocks originated as shelf, slope, and trench deposits, probably in some type of accretionary prism that formed as part of the south Asia subduction system during the Paleocene and Eocene. As India converged on Asia and indented the larger continental mass the Katawaz Basin was compressed, thrust over and partially coupled to the Indian plate, and dragged to the northeast along with India.

Terrane-Bounding Faults

The large northeast-oriented faults of eastern Afghanistan also came into being as a result of the indention of the Indian plate (Tapponnier and others, 1981; Treloar and Izzatt, 1993). Plate motion studies (Patriat and Achache, 1984) indicate that the minimal northward indention of India, relative to the interior of Afghanistan, was on the order of 1,200 km and that the collision may have resulted in 2,000+ km of shortening in central Asia. The Chaman and Paghman faults (fig. 16) extend from Pakistan to the HPW fault zone and are perfectly oriented to accommodate the large amount of the strain that must have developed between India and the Afghan interior. Consequently a large, but unknown, amount of Neogene left-slip is typically assumed for these faults. Related structures such as the Ghazni, Sorubi, and Tagab faults (fig. 16) are not as ideally oriented, nor are their displacement histories potentially as straightforward. The Ghazni fault, as identified in this report, dips east at low angle and may have a thrust or even normal/detachment displacement. The Sorubi fault has a sharp bend at the west end of the Spin Ghar (Kohe Safed) and with the highest topography consistently to its east, it may have a strong normal component (down-to-the-west). The Tagab fault has a well-developed down-to-the-east normal component and it may also have had a large, but unknown right-slip component (Bohannon, 2010). Because the three faults each separate very different terranes, large lateral motions must be inferred, since vertical movement alone is insufficient to explain the various continental-to-oceanic terrane juxtapositions that are observed. If such lateral motion proves to have occurred in a right sense, the region between the eastern three faults and the Chaman/Paghman faults would have itself been an indenter. All these faults, save parts of the Ghazni, show evidence for Quaternary activity (Ruleman and others 2007).

Outstanding Issues

1. Several other important issues are identified here that warrant further investigation. As these issues are resolved, new and better versions of these maps can be produced.
2. Each rock unit needs to be investigated in the field. Better lithologic descriptions should be compiled for all of them.
3. More of the igneous and metamorphic rock bodies should be dated radiometrically. It is important to tailor sampling to resolve issues of emplacement ages, metamorphic ages, and protolith history.
4. Faults that have been identified as having youthful activity should be investigated in the field with modern trenching techniques and qualitative field characterization.
5. The Neoproterozoic, Vendian, and earliest Cambrian age rock units in and surrounding the Anyak copper district should be studied in greater detail. This is critical for a thorough understanding of this mineral district.
6. Proper place names should be added to the topographic map. This includes checking the names of all cities and towns for spelling and location.
7. Peak elevations can be more accurately measured in the field. Digital elevation models average the elevation over the area of a pixel, which yields a lower-than-actual peak elevation. This is compounded to the published vertical error in the model.

Obviously these are not simple tasks, but they are essential for understanding Afghan geology and geography. It is hoped that the Afghanistan Ministry of Mines, Afghanistan Geological Survey, and the Afghan Geodesy and Cartography Head Office will be well positioned and provisioned to work on solving these kinds of problems in the future.

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