Structural relationship between the Karakoram and Longmu Co fault systems, southwestern Tibetan Plateau, revealed by ASTER remote sensing

Wendy Bohon¹, Kip V. Hodges¹, Alka Tripathy-Lang²,³, J Ramón Arrowmith¹, and Christopher Edwards⁴

¹School of Earth and Space Exploration, Arizona State University, 781 South Terrace Rd., Tempe, Arizona 85287, USA
²Department of Earth and Planetary Science, University of California, Berkeley, 479McCone Hall, Berkeley, California 94720-4767, USA
³Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, California 94709, USA
⁴Department of Physics and Astronomy, Northern Arizona University, 527 S. Beaver St., Flagstaff, Arizona 86011, USA

ABSTRACT

The western margin of the Tibetan Plateau is defined by the NE-striking, sinistral Longmu Co fault system and the NW-striking, dextral Karakoram fault system. The region of convergence of these two systems is remote and politically sensitive, precluding systematic geologic mapping in the field. As a consequence, there is considerable controversy regarding the relationship between these regionally important structural features. Analysis of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) multispectral data and validation with field mapping provide new insights via the production of a lithologic map. Detailed analysis of the ASTER data shows that the two fault systems do not intersect but instead become parallel. Additionally, the geometry and sense of motion of the two fault systems imply that they are acting as a conjugate fault pair, in conjunction with the normal Angmom fault system, allowing for the extrusion of Tibetan lithosphere toward the east.

INTRODUCTION

Strain from the collision between India and Eurasia is accommodated by active fault systems, including large strike-slip faults that allow for the extrusion of portions of the Himalayan-Tibetan orogenetic system. In the Ladakh region of northwest India, the southwestern margin of the Tibetan Plateau is defined by two of these faults: the NW-SE-striking, dextral Karakoram fault system and the NE-SW-striking, sinistral Longmu Co fault system (Fig. 1). Kinematically, the slip along these late Cenozoic structures is consistent with E-W extension across the central and southern plateau (e.g., Robinson, 2009). These two continental-scale fault systems come into close proximity, but their intersection has not been mapped in detail. The locations of fault intersections play a critical role in the evolution and transfer of strain as well as lend insight into the accumulation of deformation during orogenesis (Van der Woerd et al., 2000; Ando et al., 2004; Spotila and Anderson, 2004).

In order to advance our understanding of the relationship between these two systems and evaluate the role they play in the evolution of the Himalayan orogen, it is imperative to have a comprehensive geologic map of the area. However, mapping in this part of the world is notoriously problematic. Many parts of this region are roadless, remote, and at high elevations (up to 7000 m), making traditional geologic mapping extremely difficult. The Ladakh region also includes disputed borders among India, Pakistan, and China, such that access is unavailable due to military-imposed restrictions. This area was only opened to foreign scientists in 1993, and large parts of the region are still off-limits, including the northwestern Nubra Valley, the eastern and central Chang Chenmo Range, much of the area north along the Shyok River, and most of the southern bank of Pangong Tso (Fig. 1). Because of these limitations, only a few areas are consistently accessible to foreign scientists, and the geology of those areas has been studied extensively and the results have had a disproportionate influence on perceptions of the regional geology.

Here we use Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) visible, shortwave infrared, and thermal infrared remote sensing data to facilitate the regional compositional lithologic mapping of Ladakh and adjacent Tibet to gain insight into the fault architecture of this section of the northeastern Himalaya (Fig. 1). The overarching goal of the study is to develop a more comprehensive map of the distributions and variations of bedrock geology surrounding the southwestern margin of the Tibetan Plateau and particularly the areas near the implied junction of the Karakoram and Longmu Co faults. We then use this information to examine the relationship between the Karakoram and Longmu Co fault systems.

GEOLOGIC SETTING

The remote Ladakh Himalaya and adjacent Tibet (Fig. 1) feature several major tectonic structures. The Bangong, Shyok, and Indus-Yarlung suture zones mark the closure of ocean basins during the accretionary evolution of Tibet and the culminating event of India-Eurasia collision (e.g., Gansser, 1964; Yin and Harrison, 2000). The Karakoram fault system marks the southwestern margin of the Tibetan Plateau (e.g., Armijo et al., 1989; Searle, 1991), while the...
northwestern margin is marked by the sinistrally displaced Longmu Co fault system (Liu, 1993; Raterman et al., 2007; Fig. 1).

In this region, the southern section of the Longmu Co fault system is proximal to the central Karakoram fault system, but there is controversy as to the nature and location of the intersection of these systems (Raterman et al., 2007; McCarthy and Weinberg, 2010; Van Buer et al., 2015). The interaction of these faults over geologic time scales has profound implications for both local and regional tectonics, with some authors speculating that their interaction has caused a significant bend in the Karakoram fault system (Robinson, 2009; Raterman et al., 2007) or that their intersection has changed the amount of slip accommodated on the Karakoram fault system to the north (Robinson, 2009). Others (McCarthy and Weinberg, 2010) have dismissed these possibilities. Recently, Van Buer et al. (2015) proposed that the Karakoram and the Longmu Co fault systems do not actually intersect, but are linked by a series of north-south-striking faults in the Chang Chenmo Range, which they call the Ang-mong fault system. Because sensitive geopolitical boundaries and extreme topography in this area currently preclude direct observations of the key geologic structures that could demonstrate the faulting relationships, researchers are tasked with finding alternative ways to evaluate these regions. The motivation for this work is to assess the extent to which a more systematic analysis of remote sensing data, particularly the thermal infrared bands available on the ASTER instrument, might provide better mapping coverage of these key tectonic areas in general, and provide new insight into the relationship between the Longmu Co and Karakoram fault systems in particular.

### PREVIOUS MAPPING

Many geologic maps have been made of Ladakh and adjacent Tibet (e.g., Srimal, 1986; Searle, 1996; Dunlap et al., 1998; Ravikant, 2006; Phillips, 2008, Bornemann et al., 2015; Van Buer et al., 2015), but the results are sometimes...
contradictory (e.g., the Karakoram fault system northern strand location, between Ravikant et al. [2007] and Phillips [2008]) and the regional mapping is incomplete (e.g., Dunlap et al., 1998; Ravikant, 2006). Without the benefit of topographic base imagery, the boundaries and locations of units shown in many older maps of the region are difficult to accurately locate and compare (e.g., Thakur, 1981; Srimal, 1986; Dunlap et al., 1998; Rolland and Pêcher, 2001). Alternately, there are several excellent maps showing the geologic complexities of specific areas, such as the well-traveled transect through the Pangong Range between Tangtse and Muglib (e.g., Weinberg et al., 2009; Leloup et al., 2011; Phillips et al., 2013) and the area around the confluence of the Nubra and Shyok Rivers (Rolland et al., 2000). Regionally, Phillips (2008) produced a very detailed map focused on the area proximal to the Karakoram fault in the south from 35°45′N, 78°45′E to 34°45′N, 77°30′E in the north. However, the map does not cover most of the Ladakh Range or the Chang Chenmo Range and has limited detail within the eastern Karakoram Range. A map by Van Buer et al. (2015) provides the most recent detailed map of the Chang Chenmo Range and breaks out several units in that range, including the Chang Chenmo batholith, Chang Chenmo Basement Gneiss and low- and high-grade metasediments. It also describes a new fault system between the Karakoram and Longmu Co faults—the Angmong normal fault. However, their map stops at the southern strand of the Karakoram fault system southwest of the Pangong Range.

## DATA PROCESSING

**ASTER Image Analysis**

The ASTER instrument—a high-resolution, multi-spectral imaging system aboard the Terra satellite—is commonly used in terrestrial ground surface and atmospheric remote sensing (Yamaguchi et al., 1998). It records radiance data representing: (1) three bands of the visible and near-infrared (VNIR) spectrum at wavelengths between 0.5 and 1.0 µm on the electromagnetic spectrum; (2) six bands of the short-wave infrared (SWIR) spectrum (1.0–2.5 µm); and (3) five bands of the thermal infrared (TIR) spectrum (8–12 µm). The multi-spectral imager collects data at different resolutions for the three spectral regions: VNIR, 15 m/pixel; SWIR, 30 m/pixel; and TIR, 90 m/pixel (Abrams et al., 2004; Corrie et al., 2010). All spectral bands have geologic applications, but only the TIR, which is primarily used for mapping rock-forming mineral distributions (e.g., Hunt and Salisbury, 1976; Rowan and Mars, 2002; Cooper et al., 2012), is discussed in detail here. Data from the SWIR spectral range are useful for identifying alteration phases (Rowan et al., 2006; Ducart et al., 2006; Di Tommaso and Rubinstein, 2007), while the VNIR data are typically used for true color and the generation of digital terrain models (e.g., Yamaguchi et al., 1998).

ASTER image analysis has been successfully applied to a variety of different geologic mapping problems in the Himalaya. For instance, Bertoldi et al. (2011) mapped the Buraburi Granite, a previously unknown granitic body in western Nepal, by searching for both the spectral signature for granite and the spectral signature for lichen that grows specifically on granite. Cooper et al. (2012) used ASTER image analysis to map the position of the South Tibetan fault system in Bhutan by contrasting the primarily carbonate-bearing rocks of the hanging wall with the primarily silica-dominated rocks of the footwall. In the region south of the Ladakh batholith, Tripathy (2011) used ASTER imagery to generate a lithotectonic map of the rugged and largely inaccessible Indus Basin that contains stratigraphy critical to constraining the timing of collision along the Indus suture zone.

The ASTER Level 1B (L1B; radiance at the sensor) and AST_05 (atmospherically corrected surface emissivity) data used in this study were acquired from the U.S. Geological Survey Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/). All ASTER images were processed using Davinci, which is an open-source software package created specifically for remote sensing image analysis (http://davinci.asu.edu/). The images were mosaicked and map projected in JMARS (Java Mission-Planning and Analysis for Remote Sensing) for Earth, an open-source geographical information system (GIS) application (http://jmars.asu.edu/).

When undertaking a lithologic mapping project, it is critical to utilize the appropriate processing level of ASTER data. ASTER Level 1A (L1A) data sets are unprocessed digital instrument data that consist of the image and the radiometric and geometric coefficients as well as other auxiliary data. L1B data sets are radiometrically calibrated and geometrically co-registered. AST_05 data comprise a Level 2 product that contains U.S. National Aeronautics and Space Administration (NASA) temperature-emissivity corrected data at 90 m/pixel resolution applied to atmospherically corrected surface radiance data (Abrams et al., 2004). Atmospheric removal and surface retrievals are imperative because without this, the measured spectra are a combination of both surface and atmospheric absorptions, complicating the interpretation of the data. Without conducting a temperature emissivity separation on the radiance data, it is not appropriate to compare spectral data from locations with different temperatures, as the temperature of the surface and not the composition will dominate the spectra. Because most rock-forming minerals show distinct emissivity spectral features in the thermal infrared (Fig. 2), the AST_05 product is useful for most lithologic mapping exercises (Abrams et al., 2004). Often, variations in the detector readout voltages or various instrument instabilities can produce unwanted noise in the data. It is necessary to remove this instrument noise before proceeding with additional processing. The techniques applied to the ASTER data presented in this work have been extensively documented and applied to other infrared instruments (e.g., the Thermal Emission Imaging System, THEMIS; Christensen et al., 2004), and the effect of the algorithms on the data have been characterized in detail. For more information on the data processing algorithms applied to ASTER, see Edwards et al. (2011), Nowicki et al. (2013a), and Nowicki et al. (2013b).

ASTER L1B and AST_05 data were processed through a set of image noise reduction algorithms and were map-projected into the final, common projection for the area. First, ASTER images were processed to remove line-to-line noise, likely due to variations in the detector readout voltage (Bandfield et al.,
This line-to-line noise typically manifests itself in pushbroom imagers as a second-order spectral variation (Edwards et al., 2011). The algorithm applied operates across all spectral bands simultaneously, looking at interband correlations using a windowed approach with directional averaging (Nowicki et al., 2013a). Next, the data were processed through a white or “salt-and-pepper” noise removal routine (Nowicki et al., 2013b). The noise removal routine obscures subtle variations since they are sometimes interpreted to be noise and removed. This algorithm uses interband correlation of surface features and principal components analysis to identify “salt-and-pepper” noise and removes this noise from the image with no loss of spatial resolution (Nowicki et al., 2013b). After the removal of these instrumental noises, images were map-projected to a common projection and mosaicked.

Figure 2. Two different Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes from the Ladakh region. The location of A–C is shown as a blue box in Figure 1, and the location of D–F is outlined by a red box in Figure 1. Images A and D are false color ASTER images provided for reference (they are from U.S. Geological Survey Land Processes Distributed Active Archive Center). In images B and E, we used a 12-11-10 decorrelation stretch. In this stretch, carbonates and ultramafic rocks reflect all bands, and so appear peach and tan (example circled in black on E). Quartz-rich rocks will appear greenish (example circled in white on E), and more mafic rocks will appear more yellow (example circled in yellow on B). In images C and F, we used a 14-12-10 decorrelation stretch, which is ideal for locating carbonate due to its strong absorption feature at band 14. Because carbonate is absorbed at band 14, it manifests as blue-green in this stretch (example shown by a black circle on F). Mafic and ultramafic rocks appear white or washed out (marked by a yellow circle on C), and felsic rocks will appear red (shown by a white circle on F). In D and E, note the crispness of the contact along the Longmu Co fault where the carbonate unit is juxtaposed against silicic rocks (marked with arrows in F).
using JMARS to create a large-scale full-resolution data product useful for image analysis across multiple ASTER scenes. Next, data exclusion masks were created and applied and further image processing was done to highlight compositional differences between pixels. These steps, which are detailed below, rely on additional wavelength channels, which were used to enhance the color variability of the material of interest in decorrelation stretches, as well as ensure elimination of pixels that were not primarily composed of the material of interest (e.g., vegetation was excluded from the analysis and rocks were not; Cooper et al., 2012). Finally, the spectra from different locations were compared, and a lithologic map, based on the interpretations of those spectra, was created.

**Data Exclusion Masks**

Data exclusion masks are created in order to obscure pixels within each ASTER scene that have significant contributions of material other than exposed rock. For most scenes, three masks are created (Cooper et al., 2012): the normalized difference vegetation index (NDVI) mask that masks vegetation (NASA Earth Observatory, https://earthobservatory.nasa.gov/); the normalized difference snow and ice index (NDSII) mask that masks snow, ice, and liquid surface water (Xiao et al., 2001); and the cloud mask (Cooper et al., 2012). See Cooper et al. (2012), for a detailed description of data exclusion masks.

**Image Processing**

After masking, a decorrelation stretch is applied to the data. A decorrelation stretch maximizes the spectral variation (related to the first, second, and third principal components) in the scene of interest so that mineralogical differences are exaggerated and easily noted (Gillespie et al., 1986). In this study, we use various combinations of the thermal infrared bands to examine compositional differences. We select three TIR bands, and place each band in the red, blue, and green channels, respectively. Different combinations of bands emphasize different rock compositions. For example, in a 12-11-10 decorrelation stretch, the green highlights quartz-rich compositions (Figs. 2B and 2E), whereas in the 14-12-10 decorrelation stretch, the green highlights calcite-bearing rocks (Figs. 2C and 2F).

We applied various decorrelation stretches to arrive at a first-order view of the distribution of major compositional changes across the region. Because different band combinations highlight different mineral abundances within the rocks, we were able to make educated guesses about bedrock composition by comparing the stretched values within each image. However, the exact color differences produced by decorrelation stretches are unique to each image (though typically similar between images when the same materials are in view), so identifying color variations between adjacent images is a critical step to extend compositional analysis beyond a single scene. This visual analysis is followed by a quantitative comparison of ASTER spectra from different areas.

**ASTER Spectra of Key Localities**

We produced pixel-averaged spectra from the ASTER imagery for two types of sites: those with rocks that are accessible in the field and those with rocks that are not field accessible. This process involves the use of an average of several pixels from a small area to form a composite spectrum, effectively increasing the signal-to-noise ratio. For rocks that we were able to access and identify in outcrop, we compared their pixel-averaged spectra with regions of similar signature in the decorrelation stretches. In Figure 3, we show pixel-averaged spectra from field-identified rock types LL and PG, which comprise limestone and granite, respectively. We then compared these spectra with other locations that we were unable to visit but that were spectrally similar, and were able to identify additional limestone and granite bodies (locations KG, TL, and BL in Fig. 4B).

However, some distinct compositions identified during the decorrelation stretch analysis were for units wholly inaccessible in the field. In these cases, we compared these spectra to accessible locations with similar spectra in the Ladakh region as well as to TIR spectra collected from another region, in this case the well-studied area of Mountain Pass, California (USA) (Fig. 5; Rowan and Mars, 2002). The striking similarity of the spectral signatures between the locations where the surface rocks have been positively identified and the locations where the outcrops were inaccessible corroborated our assumptions about the composition of the surface rock in these locations (Fig. 5).

![Figure 3. Examples of spectra from ASTER images. Granites from within the Pangong Range (PG) and limestone and skarn along the Shyok River (SL) were identified using ASTER and then verified in the field. We were not able to access areas of interest within parts of the Karakoram Range, part of Tibet, and the Bangong suture (marked here and on Fig. 4B as KG, TL, and BL, respectively). However, based on similar spectral characteristics to our field located outcrops, we were able to assign lithologies to these units. Note the similarities in spectral shape between units of the same rock type. KG—granite in the Karakoram Range; TL—Tibetan limestone; BL—limestone in the Bangong suture area. Locations are shown in Figure 4B.](image-url)
Figure 4. (A) Lithologic map of the Ladakh region created from a combination of field work and ASTER remote sensing data overlaid on a 30 m shaded-relief digital elevation model. Small black squares mark villages. The large white and black circles are locations where field samples were collected and ASTER data was pixel averaged (shown in Fig. 5). The small white and black circles indicate areas that were pixel averaged but samples were not collected. The stars indicate locations shown in Figure 3. Dashed lines show inferred locations of faults and contacts. (B) ASTER 12-11-10 decorrelation stretch showing the same extent as the map in A. This stretch highlights differences in the amount of quartz present in the rocks. In this case, pink indicates silicic rocks, blue indicates more mafic rocks, and tan and peach show carbonates. Various stretches were used while mapping to accentuate differences in mineral composition. The black areas are regions of snow, ice, water, clouds, or vegetation that have been removed. Abbreviations show the location of pixels sampled in Figure 3. KG—granite in the Karakoram Range; PG—granite in the Pangong Range; TL—Tibetan limestone; BL—limestone in the Bangong suture area; SL—limestone in the Shyok River area.
Information on spectrometer calibration and configuration, see Ruff et al. (1997). The wavelength range of ~2.5–50 μm (200–4000 cm⁻¹ wavenumbers). For information using a Nicolet Nexus 6700 spectrometer, which allows us to obtain data from different units and create a regional lithologic map (discussed below; Fig. 4), which we then use to create an informed geologic map and interpretation.

Laboratory Spectra

In order to further assess the robustness of the ASTER remotely sensed data, we collected laboratory spectra from a suite of hand specimens collected from across the Ladakh batholith (sampling locations of included samples are shown in Fig. 4). All spectral data from hand specimens were collected at the Arizona State University (ASU) Thermal Infrared Emission Spectroscopy Laboratory using a Nicolet Nexus 6700 spectrometer, which allows us to obtain data from the wavelength range of ~2.5–50 μm (200–4000 cm⁻¹ wavenumbers). For information on spectrometer calibration and configuration, see Ruff et al. (1997).

Whole rock samples were placed in an oven at 80 °C for at least two days to drive off any excess adsorbed water that could compromise spectral clarity and to raise the signal-to-noise ratio of the emission spectroscopy measurement (Ruff et al., 1997). Samples were then placed in the attached emission spectral chamber, and the thermal infrared spectra were acquired. Hot (100 °C) and warm (70 °C) cone-blackbody calibration targets were also measured in a full aperture calibration to convert the uncalibrated instrument response to calibrated spectral radiance and ultimately emissivity.

Laboratory analysis of hand specimens produces high-resolution (2 cm⁻¹) spectral data that provide information about mineral type and abundance (e.g., Ramsey and Christensen, 1998; Feely and Christensen, 1999). However, spectral data collected from ASTER TIR images provides information in five broad (~0.25–0.5 μm wide) spectral bands covering only a fraction of the wavelengths of the laboratory instrument (8.125–11.65 μm as compared to ~2.5–50 μm in ~1900 spectral bands). Thus, it is necessary to downsample, or decrease the resolution, of any data collected in the laboratory to the same spectral resolution as data collected from the ASTER images using the ASTER spectral filter functions that describe the instrument response over the spectral band in question. The characteristic features of the high-resolution laboratory spectra do not fully disappear when resampled to the lower ASTER resolution, and useful mineralogical determinations, especially relative properties, can be ascertained.

Downsampled laboratory spectra may not exactly match the spectra collected from ASTER images for a variety of reasons including: problems relating to sensor resolution and signal-to-noise ratio, acquisition geometry, environmental conditions during data collection (Ehlers, 1991; Kruse et al., 1993), variations in blackbody calibrations, atmospheric corrections, and grain size effects. These factors can all affect the shape and clarity of the spectra. Additionally, scaling factors, arising from relating a 90 m × 90 m square pixel to a laboratory sample a few centimeters across, can be an issue. Because of these potential complications, we use a qualitative approach, identifying spectral shape similarities when comparing resampled laboratory spectra and ASTER spectra. In particular, we look for similar emissivity spectral shapes at certain bands (e.g., Rowan and Mars, 2002).

To test if the laboratory spectra were able to accurately reflect the ASTER spectra, we examined regions of color variability within the Ladakh batholith seen on the ASTER data (Fig. 4B) and compared these data to laboratory-derived data from hand samples from the same locations. We pixel-averaged (10 × 10 pixels) multiple locations on the ASTER data from within different colored areas: the “pink” and the “purple” areas shown in Figure 4B. The spectra from the same color from different locations in the batholith were very similar, but the differences between the spectra from the pink areas and those from the purple areas were significant. Figure 6 shows the spectra from two different locations within each color (shown in Fig. 4B by the large and small white circles). Also plotted are laboratory spectra from hand samples collected in the field from these locations (collection locations are marked in Fig. 4B as sample A and sample B). Sample A is a diorite from the pink area, while sample B is a...
Figure 6. Spectra collected from ASTER data within the Ladakh batholith (Fig. 4B). Spectra are from two different locations within each color. Spectra locations are from the locations where Sample A and Sample B were collected (indicated in Fig. 4B by large white circles) and in the locations in Fig. 4B marked by small white circles. Laboratory spectra measurements from field samples collected from these locations are shown with black solid and dashed lines. Sample A is a diorite from the “pink” area, while sample B is a granite from the “purple” area.

granite from the purple area. The difference between the sets of spectra from the pink and purple areas shows that ASTER data are able to resolve subtle variability between rocks, in this case between more felsic and more mafic rocks. Additionally, the excellent match between the laboratory spectra and the ASTER image-derived spectra for each sample highlight the scalability of this technique; it is reliably able to match hand sample–scale laboratory spectra with large-scale ASTER-derived spectra. This lends additional confidence to our lithologic interpretations.

Another potential concern when using ASTER remotely sensed data is the presence of weathering and alteration products on the exposed surface of the rock. Because remotely sensed data only provide information about the uppermost surface (i.e., typically tens of microns for TIR), any varnish or weathering products on the surface of the rocks can significantly alter the spectral signature (Rivard et al., 1993). To examine the variability this produced, we tested a suite of granites from the region. We measured laboratory spectra from samples that had both fresh and natural surfaces then degraded the laboratory spectra to the five-band ASTER resolution to assess the variability of the spectra in relation to the presence of weathering and alteration phases. In some cases, we found almost no variability between the fresh-surface and natural-surface spectra. However, with other samples, there was a small amount of variability in the spectral shape, resulting in some reduction in the ability to adequately distinguish between subtypes of granite (Supplemental Fig. S1').

MAPPING

As outlined above, ASTER remote sensing allows broad classification of rocks by mineralogy, thus allowing interpretations about lithology. This lithologic information, when coupled with careful field observations and laboratory analysis, permits us to create maps showing the distribution of rock types throughout a region. This allows for the creation of geologic maps of previously poorly described areas from which we can make more informed tectonic interpretations. We can also use the remotely sensed data in conjunction with laboratory analysis to further subdivide major lithologic units and examine the extent to which we can use ASTER data to resolve variability within rock types. There are limitations to this technique; for instance, in some cases we are not able to discern areas of scree, rockfall, or alluvium from adjacent in-place source units. Because we are not able to differentiate between in situ units and near-sourced alluvial deposits, we map the entire area based on its predominant spectral characteristic. In these situations, additional geomorphic interpretation and field observation can aid with alluvial mapping.

Our ASTER map (Figure 4) reflects a classification of rocks by bulk mineralogy, and thus lithology, but we do not necessarily assign specific geologic units defined by previous workers to the spectrally mapped units. It is worth explicitly mentioning that there is also an additional interpretative leap that occurs between determining rock assemblage and assigning tectonostratigraphic units when using this technique. To help verify our interpretations, we compared this map to existing maps, where possible, which helps to refine our lithologic interpretations. For example, a comparison between our map and that of Phillips (2008) shows that many of the units are directly comparable (Fig. S2 [footnote 1]). In the cases where our ASTER mapping clearly delineates the same units and has the same lithology as maps made by previous authors, we inform our lithologic interpretations with more detailed descriptions supplied from their field observations. These instances are noted below.

The map is separated into three geographic regions: the Karakoram complex, which comprises mainly the rocks north of the southern strand of the Karakoram fault; the Ladakh complex, which is the rocks of the Ladakh batholith; and the Shyok suture zone complex, found mainly between the Nubra and Shyok Rivers in the Saltoro Range (Fig. 4A).

The Karakoram Complex

Based on ASTER mapping and field observations, we have grouped the Karakoram complex into three domains: low-grade rocks of the Tethyan metasedimentary domain (units Kt1–Kt3; name from Sinha et al. [1999]), meta-

Supplemental Figures. Figure S1: Laboratory spectra from three different granitoid samples within the Ladakh batholith. Figure S2: Correlation between units mapped in this study and units from the Phillips (2008) map. Figure S3: Comparison of mapping done by Sinha et al. (1999) and the mapping done in this study. Figure S4: Field photos from transect along the Shyok River. Please visit http://dx.doi.org/10.1130/GES01915.01 or the full-text article on www.gsapubs.org to view the Supplemental Figures.
The ASTER data. (2015) also observed the Ki3 unit interior to the Karakoram Range between the River and was verified in the field by Borneman et al. (2015). Borneman et al. served on the ASTER data northwest of Panamik on the west side of the Nubra of the Karakoram fault system in two locations. A small sliver of Ki3 was ob-

Within the Pangong Range, see Phillips [2008] and Leloup et al. [2011]). Addi-

them all as unit Ki3. (For a more in depth discussion of the geologic variability of rocks within the central and southern Pangong Range; instead, we classify the Angmong fault and south of the Longmu Co fault. Phillips (2008) grouped many small-scale (meter to submeter) granitic intrusions (unit Ki3; Fig. S4 [footnote 1]). To the south, a massive granitoid batholith (unit Ki2) gradually transitions into amphibolites, calc-silicates, and migmatites with many small-scale (meter to submeter) granitic intrusions (unit Ki3; Fig. S4 [footnote 1]). The boundaries of these units match relatively well with the mapping done by other authors. For example, the “sheared plutonic injection zone complex” and “high-grade metasediments” mapped by Van Buer et al. (2015) roughly correspond to our Ki2 and Ki3 units respectively, particularly west of the Angmong fault and south of the Longmu Co fault. Phillips (2008) grouped what we call units Ki2 and Ki3 into one group that he named the “Arganglas Hbl-Bt diorite”. Unlike many authors (e.g., Dunlap et al., 1998; Phillips, 2008; Leloup et al., 2011), we did not subdivide the well-studied but complex suite of rocks within the central and southern Pangong Range; instead, we classify them all as unit Ki3. (For a more in depth discussion of the geologic variability within the Pangong Range, see Phillips [2008] and Leloup et al. [2011]). Additionally, the Ki3 unit has been located in the field and on ASTER imagery south of the Karakoram fault system in two locations. A small sliver of Ki3 was ob-

erved on the ASTER data northwest of Panamik on the west side of the Nubra River and was verified in the field by Borneman et al. (2015). Borneman et al. (2015) also observed the Ki3 unit interior to the Karakoram Range between the Shyok and Nubra Rivers. This finding is consistent with what we observe in the ASTER data.

**Low-Grade Tethyan Metasedimentary Domain**

Using the ASTER data, we were able to clearly distinguish and map three basic units within the Tethyan metasedimentary domain: a cherty calcareous sedimentary unit (Kt1), a clastic and volcaniclastic sedimentary unit (Kt2), and a clastic sedimentary unit (Kt3). Our ASTER-based mapping matches well with the map and description of these units by Sinha et al. (1999) (Fig. S3 [footnote 1]), and we have supplemented our unit descriptions with their field observa-

**Karakoram Batholith and Proximal Country Rocks Domains**

Field observations coupled with ASTER data allowed us to subdivide the Karakoram batholith and proximal country rocks into three units distinguished by varying amounts of igneous rock intruded into the metasedimentary country rocks. We observed these lithologic changes in the field along the Shyok River (Fig. S4 [footnote 1]), and used GPS-located field observations to determine which ASTER color and pattern were best associated with each lithologic unit. However, because the boundaries between these particular units are grada-
tional there is some subjectivity as to exact location of the contact. In the Kt1 unit, large granitic plutons have intruded into metasedimentary Tethyan rocks (Fig. S4X [footnote 1]). To the south, a massive granitoid batholith (unit Ki2)

gradually transitions into amphibolites, calc-silicates, and migmatites with many small-scale (meter to submeter) granitic intrusions (unit Ki3; Fig. S4 [footnote 1]). The boundaries of these units match relatively well with the mapping done by other authors. For example, the “sheared plutonic injection zone complex” and “high-grade metasediments” mapped by Van Buer et al. (2015) roughly correspond to our Ki2 and Ki3 units respectively, particularly west of the Angmong fault and south of the Longmu Co fault. Phillips (2008) grouped what we call units Ki2 and Ki3 into one group that he named the “Arganglas Hbl-Bt diorite”. Unlike many authors (e.g., Dunlap et al., 1998; Phillips, 2008; Leloup et al., 2011), we did not subdivide the well-studied but complex suite of rocks within the central and southern Pangong Range; instead, we classify them all as unit Ki3. (For a more in depth discussion of the geologic variability within the Pangong Range, see Phillips [2008] and Leloup et al. [2011]). Additionally, the Ki3 unit has been located in the field and on ASTER imagery south of the Karakoram fault system in two locations. A small sliver of Ki3 was ob-

erved on the ASTER data northwest of Panamik on the west side of the Nubra River and was verified in the field by Borneman et al. (2015). Borneman et al. (2015) also observed the Ki3 unit interior to the Karakoram Range between the Shyok and Nubra Rivers. This finding is consistent with what we observe in the ASTER data.

**Metamorphic Domain**

The third domain of the Karakoram complex, the metamorphic domain, primarily includes rocks exposed within the Chang Chenmo Range, within the northern Pangong Range, and along the northern edge of the Nubra Valley. Along the Nubra Valley just to the north of the northern Pangong Range, we identify an exposure of metapelitic schists, marbles, and volcanics that we designate as unit Km1. While we observed these rocks in the field from a distance, the unit description is based primarily on ASTER remote sensing results and is supplemented with descriptions from Phillips (2008). Along the northern section of the Pangong Range and just south of most Km1 exposures, a unit of schists, calc-silicates, marble, and amphibolite bands is defined as unit Km2; this unit was examined in the field. Two predominantly calcareous units (Km3 and Km4) were distinguished by the spectral mapping and observed in the field in several locations along the Shyok River. Based on field reconnais-
sance, Km3 includes calcareous schists and calc-silicate gneisses, whereas Km4 tends to be a less-siliceous marble. We interpret this distinctive pair of units to be slices of the Karakoram metasedimentary rocks that experienced contact metamorphism as a consequence of intrusion of the Karakoram batholith. Both units were highly strained where they were viewed in the field along the Shyok River, and we consider it important that the southernmost exposures of the Longmu Co fault zone mapped by Raterman et al. (2007) are marked by them. We tentatively correlate these rocks with the Saser Formation as mapped by Phillips (2008) north of the intersection of the Shyok suture zone and the Karakoram fault system. Unit Km5 in the Chang Chenmo Range was mapped exclusively using the ASTER data, and based on the spectral signature it is likely composed primarily of clastic and metasedimentary rocks. Van Buer et al. (2015) also clearly identified this unit, but they called it the “Chang Chenmo basement gneiss”. South of the Km5 unit lies the Bangong suture zone and the Karakoram complex (e.g., Phillips, 2008), which on our map are grouped together into unit Km6—volcaniclastic and clastic sedimentary rocks with ophiolitic blocks and carbonate bands. This level of lithologic differentiation comes directly from field observation of these units coupled with additional observations and mapping from Phillips (2008). Many of the carbonate bands and some of the larger ophiolitic blocks are visible in the ASTER images in certain stretches. Van Buer et al. (2015) called the southeastern part of this unit the “suture zone rocks”.

**The Shyok Suture Zone Complex**

The Shyok suture zone complex lies south of the Karakoram fault system. It consists of the Saltoro molasse (unit Ssm), volcanic rocks (unit Ssf), and intrusive igneous rocks (unit Sf). We observed all of these units in the field along the flanks of the Saltoro Range but relied exclusively on the ASTER data to map their extent. What we have called “intrusive igneous rocks” matches well with what is commonly called the Triti granite (i.e., Phillips, 2008), although we extend this unit further north than most previous maps (e.g., Rai, 1983; Rolland
et al., 2000). However, our extent of the Si unit is comparable to that seen on the map by Phillips (2008). The similarity in spectral signature for the Ssm and Ssf units made them difficult to interpret using the ASTER data. Our spectrally mapped interpretation of the location and extent of these units is most similar to those of the map of Phillips (2008), but that map shows more complexity and resolution than we were able to determine using our method.

**The Ladakh Complex**

The Ladakh complex lies south of the Karakoram fault system. We subdivided this complex into three primary units based on the ASTER data, our field observations, and the work of previous authors (e.g., Weinberg and Dunlap, 2000; Dunlap and Wysoczanski, 2002; Phillips, 2008). The three units are: the plutons of the Ladakh batholith (unit Lb), which comprise the majority of the batholith; the felsic, extrusive Khardung volcanic units (unit Lkv) found on the western side of the Ladakh Range; and the Chilam granite (unit Lcg) located along the southern strand of the Karakoram fault system. This unit is spectraly very distinct in the ASTER data (see Fig. 4B), and our map agrees closely with the maps of previous authors (cited above).

As noted above, our map agrees well with previously published maps of well-studied areas. For instance, the boundaries of most major units northeast of the Karakoram fault system are in good agreement between our map and that of Van Buer et al. (2015). Our Km1 unit clearly corresponds to the Nubra Formation mapped by Phillips (2008) in the Nubra Valley area. Our map also correctly identifies rocks and contacts that we were unable to access, but that have been accessed previously by other groups (Sinha et al., 1999; Fig. S3 [footnote 1]). These similarities lend additional confidence to our lithologic interpretations.

**DISCUSSION**

One of the most significant revelations of our ASTER mapping efforts was that the Km4 unit appears to mark the trace of the Longmu Co fault as mapped by Raterman et al. (2007) on the easternmost side of our study area (Fig. 4). This relationship can be followed westward to ~78°24′E, beyond which Km4 extends discontinuously westward in two belts, one trending north-northwest parallel to the upper reaches of the Shyok River, and the other trending north-west toward Panamik. We posit that these belts indicate a bifurcation of the Longmu Co fault into two strands. We were able to observe the single Km4 belt in the field east of the bifurcation high on the ridge on the eastern side of the Shyok River (Figs. 7D–7E). The unit appeared to be steeply north-dipping, which is consistent with observations by Van Buer et al. (2015) in other locations. On the western side of the Shyok River, one of the Km4 lenses was observed in the field; it is marked by a yellow star in Figure 4A and is shown in Figure 7D. This lens of Km4, ranging up to a few tens of meters in thickness near the base of the outcrop, consists of banded marble, a more siliceous skarn, and metachert. A sharp, near-vertical fault separates it from granitic rocks to the south, but the Km4 contact with granitic and metamorphic rocks to the north was obscured.

West of 78°20′E, the northern unit Km4 exposures cannot be distinguished in the ASTER imagery, and we are unable to trace the NNW-striking fault into the mixed granitic and metamorphic rocks beyond. However, the Km4 lenses and geomorphic observations on the other, more southerly strand permit the tracing of that structure ~60 km westward from the bifurcation, through the Karakoram batholith. Due to a combination of the spatial resolution of the ASTER data and loss of data due to glacial masking, we are not able to continuously resolve this unit in the ASTER data anywhere between the western side of the Shyok River and Tirith. However, the combination of a long, linear valley west-northwest of the exposure on the Shyok River and other small outcrops to the west that are too small to be resolved using ASTER imagery, but can be seen in Google Earth, lead us to believe this is the fault trace. Additionally, we saw no evidence for faulting south of where we placed the location of the Longmu Co fault strand crossing the Shyok Valley (marked by the yellow star in Fig. 4A). Instead, we observed a gradual transition from primarily massive granitic plutonics interspersed with metasedimentary rocks to primarily metasedimentary and maigneous gneisses with small, discontinuous granitic intrusions (Fig. S4 [footnote 1]). The length of this more westerly striking segment suggests that it is the main strand of the Longmu Co fault system as it passes through the Karakoram Range. Between 78°24′E and ~77°50′E, this strand gradually rotates into parallelism with the Karakoram fault system (Fig. 4).

Along the eastern side of the Shyok River, just to the south of unit Km4 (between 34°17′06″N, 78°18′05″W and 34°11′39″N, 78°16′39″W), both the metamorphic rocks and the igneous intrusions of units K12 and K13 have been folded into large antcinal structures with fold hinges trending ~340° (Fig. 4A). At the southern end of this series of folds, ~10 km from the trace of the Karakoram fault system, the rocks abruptly change character, showing little to no folding and becoming more fractured. A similar but less well-defined series of folds may be present on the western side of the Shyok River between 34°14′45″N, 78°16′20″W and 34°10′11″N, 78°14′57″W; however this was observed only in satellite imagery. The orientation of these folds implies roughly NE-SW shortening of the area to the south of the Longmu Co fault system. This shortening is counterintuitive based solely on the conjugate sense of slip directions and orientation of the Longmu Co and Karakoram fault systems, which would produce SW-SE extension. However, oblique motion along the Longmu Co fault system without linkage to the Karakoram fault system would produce folding in this orientation. We propose that units Km3 and Km4 mark the trace of the southern Longmu Co fault system in India, and that this fault, in the vicinity of the Shyok River and potentially to the west of the Shyok River, is not purely translational but rather oblique. This is similar to the interpretation of Van Buer et al. (2015); their map shows the Longmu Co fault as a thrust where it crosses the Shyok River.
Figure 7. Stretched ASTER images, a Google Earth image, and a field photo of the trace of the Longmu Co fault through the Chang Chenmo Range on the western side of the Shyok River. Location of A–C is shown in Figure 1. (A) False color ASTER image. Imagery obtained from the U.S. Geological Survey Land Processes Distributed Active Archive Center. (B) 12-11-10 decorrelation stretch of ASTER data. The peach and white unit is a carbonate unit (unit Km4 in Fig. 4) marking the Longmu Co fault system. The large white box shows the location of D; the small white box shows the location of E. (C) 14-12-11 decorrelation stretch of the same region. (D) Google Earth image of the trace of the Longmu Co fault where it crosses the Shyok River. The arrows indicate the fault trace. (E) Field photo of the Longmu Co fault in the same area as D (marked by arrows).
Based on the results of our mapping, we propose that the southernmost tip of the Longmu Co fault system in India does not terminate near the northern end of the Pangong Range as previously argued (Raterman et al., 2007), but continues through the Karakoram Range parallel to the Nubra Valley to at least Panamik. Thus, we regard it as unlikely that motion along the Longmu Co fault system was responsible for the formation of the bend in the Karakoram fault system. On the other hand, our mapping and observations are consistent with the hypothesis put forward by McCarthy and Weinberg (2010) that the bend in the Karakoram fault system is the result of transpression and uplift of the Pangong Range. In particular, the oblique sense of motion of the Longmu Co fault and the folding north of the Pangong Range support their conclusion that the bend in the Karakoram fault system is the result of ongoing regional transpression. While we do not see explicit evidence in the ASTER data for a linkage between the Karakoram and Longmu Co fault systems by the Angmong fault as proposed by Van Buer et al. (2015), our data do not preclude this possibility, and a north-south-trending normal fault in the location that they propose is compatible with our mapping of the continuation of the Longmu Co fault system.

The kinematic relationship between the Karakoram and Longmu Co fault systems, coupled with their proximity, suggests that they have acted as a conjugate fault pair. Passchier and Platt (2017) described the geometry and behavior of such conjugate ductile shear zone junctions; under their classification, this is a bi-sense $\lambda$-type junction, and we would further classify it as either a pure closing zipper or a dextral closing zipper (Fig. 8; for a full discussion of this new method of classifying shear zone junctions, see Passchier and Platt (2017)). Lack of slip on the Karakoram fault system north of Ladakh (Robinson, 2009) suggests that this junction may have evolved from a dextral closing zipper into a pure closing zipper system, similar to the junction between the North and East Anatolian faults in Turkey (Passchier and Platt, 2017; Fig. 8). In this location, we do not observe a “trailing gap” (as described by Taylor et al. (2003)) bound by steep, upper-crustal faults, but the low-angle, normal-sense Angmong fault system described by Van Buer et al. (2015) could be interpreted as accommodating the necessary extension through the extrusion of middle crust from underneath the eastward-escaping brittle upper crust. The orientations of folds observed along the Shyok River and described above are incompatible with the stress field required for extension along the Angmong fault system as envisioned by Van Buer et al. (2015), but these structures could substantially predate development of the fault system. An alternative interpretation is that the folds are further evidence that the relationships between the Karakoram and Longmu Co fault systems are more complicated than what might be expected from a simple conjugate fault model as described above. In addition to eastward lateral extrusion of the crust between the fault systems, both have been affected by continuing convergence between greater India and Eurasia since development of the conjugate pair, resulting in a partitioning of deformation between the faults and associated folds, and in an evolution in fault kinematics over time from predominantly strike slip to predominantly oblique with a significant shortening component. Such an interpretation is consistent with interferometric synthetic aperture radar (InSAR) data showing no significant interseismic velocity changes across the Longmu Co fault system that would be consistent with strike-slip motion on this segment (Wright et al., 2004).

## CONCLUSION

This work illustrates how ASTER thermal infrared data interpretation can be a powerful tool for informing lithologic mapping in remote locations. The geologic and lithologic interpretations drawn from ASTER image analysis, spectroscopic analysis of field samples, and field observations have allowed us to better understand the complex geology of the Ladakh region of northwestern India and adjacent Tibet, and to create a regional lithologic map to inform new tectonic interpretations. We found that the Karakoram and Longmu Co fault systems do not intersect near the northern end of the Pangong Range as suggested by Raterman et al. (2007) but instead trend parallel to one another along the Nubra Valley. Field observations and remote-sensing imagery also reveal that the Longmu Co fault system is not is purely translational but rather oblique. Additionally, folds between the Longmu Co and Karakoram fault systems suggest ongoing regional transpression between the fault systems. This new mapping and previous work strongly favor a conjugate relationship between the Karakoram and Longmu Co fault systems that is accommodated in part by extension on the Angmong fault system, folding, and a transition from strike-slip to oblique deformation on the Longmu Co fault system.
ACKNOWLEDGMENTS

We would like to thank the ASU Mars Space Flight Facility for the use of their facilities and resources, Lela Prashad for her assistance acquiring the ASTER data, Nathaniel Borneman for his help in the field, and Frances Cooper, Byron Adams, and Scott Dickenson for their assistance and input with the data processing. CP Dorjaj and his excellent team of drivers and field assistants also deserves our most sincere thanks! We would also like to thank reviewers Alex Robinson, Roberto Weinberg, and Nick Van Buer for their thoughtful and thorough reviews of this work; their insights and suggestions strengthened and improved the manuscript immensely. This work was completed using funds from U.S. National Science Foundation grant EAR-0642771.

REFERENCES CITED


Bohon et al. | Structural relationship between Karakoram and Longmu Co fault systems

Research Paper


