

Article

Mapping Lithologic Components of Ophiolitic Mélanges Based on ASTER Spectral Analysis: A Case Study from the Bangong-Nujiang Suture Zone (Tibet, China)

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Abstract: ASTER (Advanced Spaceborne Thermal Emission and Reflection) satellite imagery is useful in assisting lithologic mapping and, however, its effectiveness is yet to be evaluated for lithologic complex such as tectonic mélange. The Muganggri Group (MG), the signature unit of the Bangong-Nujiang suture zone (BNSZ), Tibet and consisting of ophiolitic mélanges, was previously mapped as a single unit due to its poorly-described internal structures and an informative map with refined lithologic subdivision is needed for future petrologic and tectonic studies. In this paper, based on a combination of field work and ASTER data analysis, the MG is mapped as five subunits according to our newly-proposed lithologic subdivision scheme. In particular, we apply a data-processing sequence to first analyze the TIR band ratios to reveal approximate distribution of carbonates and silicate-dominated lithologies and then the VNIR/SWIR band ratios and false color images to differentiate the lithologic units and delineate their boundaries. The generalized procedures of ASTER data processing and lithologic mapping are applicable for future studies in not only the BNSZ but also other Tibetan ranges. Moreover, the mapping result is consistent with that the MG represents an accretionary complex accreted to the south Qiangtang margin as a result of northward-subduction of the Bangong-Nujiang oceanic crust.

Keywords: ASTER; mapping; Bangong-Nujiang suture zone (BNSZ); Muganggri Group; mélange; spectral analysis

1. Introduction

Geologic mapping provides essential knowledge for regional geologic studies and remotely-sensed images have been effectively applied assisting geologic mapping for decades [1]. Since its launch in 1999, ASTER has become one of the most widely used multi-spectral satellite imagery for assisting geologic mapping due to its suitable bands and moderate spatial resolution (e.g., [1–6]). The Himalayan and Tibetan ranges are mostly poorly-vegetated with good rock exposure. Providing such an essential condition for remote-sensing application, ASTER-assisted geologic mapping has rarely been applied in the areas [4] and, thus, its effectiveness needs to be evaluated.

The Bangong-Nujiang suture zone (BNSZ) in Tibet (Figure 1) represents the relicts of the Bangong-Nujiang Tethyan Ocean (BNO) and records the collisional orogeny between the Qiangtang and Lhasa terranes (e.g., [7–15]). Along its east-west stretch, the BNSZ is represented by a lithotectonic unit, the Muganggri Group (MG), which consists of coherent deep-water deposits and ophiolitic

mélanges [16,17]. Ophiolitic fragments from the MG have been studied extensively and revealed critical information about the BNO evolution [9,18–23]. However, it is still highly controversial concerning, for example, nature and subduction polarity of the BNO and origin of multiple ophiolite belts along the BNSZ [9,15,22,23]. The MG was previously mapped as a single unit at the scales of 1:250,000 [16] and 1:100,000 [11] (Figure 1B), because lithologic components and internal structures of the MG were poorly defined and its formative environment needs better clarification. The background information is critically important for the understanding the origin of the MG ophiolitic components and an informative map with refined lithologic subdivision and indication on mélangé distribution is needed for further petrologic and tectonic studies. Moreover, because the giant Duobuza porphyry copper deposit and related epithermal deposits have been discovered to north of the BNSZ, near the town of Gaize (e.g., [24]), the BNSZ and especially the part near Gaize have gained high attention from exploration geologists and the availability of detailed map and an easy-to-use mapping method are helpful for future exploration activities.

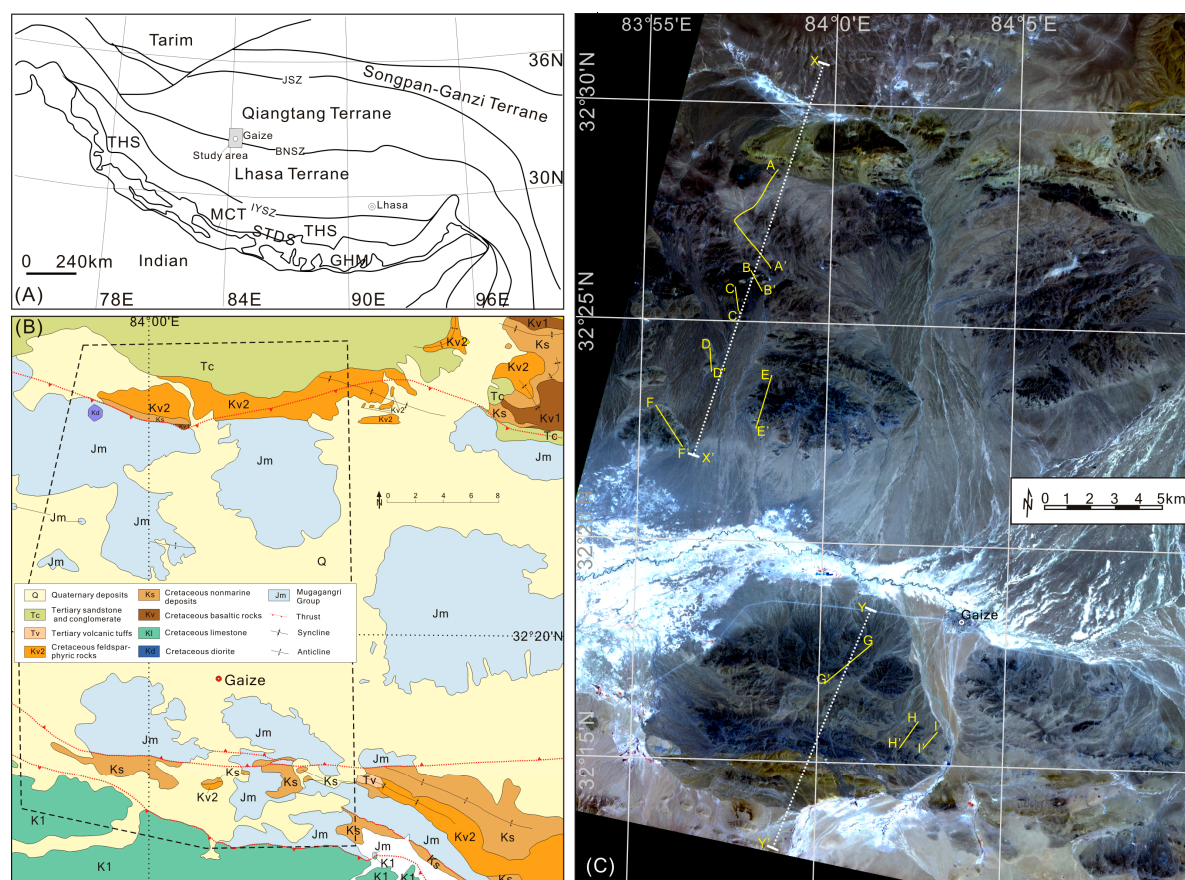


Figure 1. (A) Tectonic map showing terranes and suture zones of the Tibetan plateau (From [7]). The location of the study area is indicated by the dash box; (B) Geological map of the study area, Gaize, Tibet (Modified from [11,16,25]); (C) ASTER false color composite image (Red—band 3; Green—band 2; Blue—band 1) of the study area. Yellow solid lines (e.g., A–A') indicate field-investigated sections and white dash lines (X–X' and Y–Y') indicate composite cross-sections constructed based on the field sections.

In this paper, we aim at presenting our research results on the MG from two aspects: (1) lithologic composition and internal structure of the MG are studied in detail based on field investigations near the town of Gaize, Tibet; and (2) lithologic subunits of the MG and especially the mélanges are mapped by straightforward comparison between field lithologic characterization and ASTER spectral analysis.

The resultant map reaches a scale of 1:50,000 and it is the first attempt mapping the MG as refined subunits and the mappable features shed lights on formative processes and tectonic setting of the MG. Moreover, the generalized procedures and techniques of geologic mapping via combined field geology and ASTER spectral analysis will be demonstrated to be a strong tool for future geologic studies in the BNSZ and the wide Himalayan-Tibetan tectonic belts.

2. Geologic Background

The Tibetan plateau consists of a series of terranes, including Tethyan Himalaya, Lhasa, Qiangtang and Kunlun (Figure 1A), which were originated from the northern margin of the Gondwana and accreted onto the south margin of the Eurasia [7,26]. The BNSZ is the convergent boundary between the Qiangtang and Lhasa terranes that were once separated by the BNO (Figure 1A) [7,11,26]. The BNO had probably experienced a complete Wilson cycle [7,26]. However, the nature and timing of different stages of this Wilson cycle are still under intense debate (e.g., [9,15,23]).

The BNSZ mainly exposes Mesozoic and younger lithologic units, among which the MG is generally considered as a signature unit [11,17]. The MG was initially defined as a formal stratigraphic unit [27] and was interpreted to be remnant strata of an oceanic basin [28] or a forearc basin related to the northward BNO subduction [10]. However, it has been gradually realized that tectonic mélanges are closely associated with the MG, which has been redefined as a tectostratigraphic unit [16,25]. Nonetheless, the tectonic environment of its formation still needs to be better clarified.

The MG is unconformably overlain by younger, Late Jurassic to Early Cretaceous strata, which mainly comprise, in ascending order, deep-water flysch-type successions, shallower shelfal deposits and nonmarine conglomerates, reflecting overall a shallowing-upward cycle and a marine to nonmarine transition [11,16,25]. Volcanic rocks are frequently found to be intercalated within the strata (e.g., [11]), suggesting synchronous volcanism was persistently active.

3. Materials and Methods

3.1. Field Data Collecting

The study area is located in west-central Tibetan plateau, near the town of Gaize (Figure 1), which is poorly vegetated with well-exposed bed rocks. Average altitude of the study area reaches ca. 4700 m, which, along with the poor transportation conditions, imposes major difficulties on geologic mapping. Field study was conducted collecting lithologic and sedimentological data along N-S sections (A–A' to I–I') across the BNSZ (Figure 1C) and base on the segmental sections, two composite cross-sections were constructed (Figure 2). Meanwhile, structural features were examined to understand their controls on the distribution of lithologic units (Figure 2). Representative samples were investigated petrographically, in order to identify mineralogic information pertinent to ASTER data analysis and interpretation.

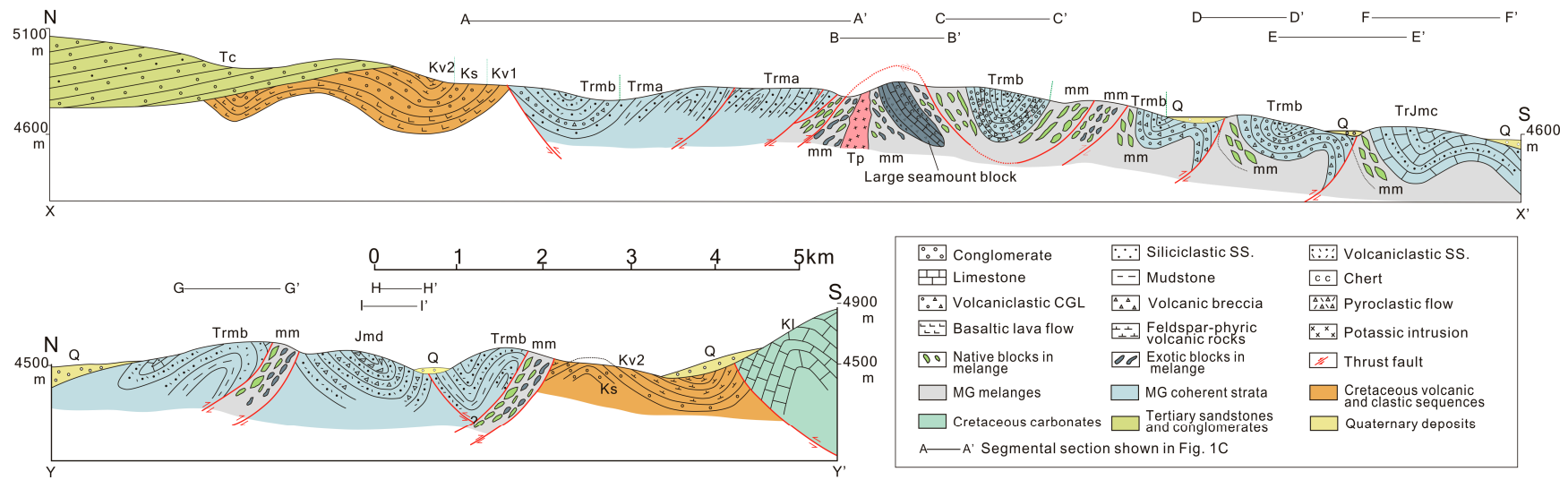


Figure 2. Composite cross-sections (X–X' and Y–Y') constructed based on the segmental sections through the studied traverse. Location of the sections is shown in Figure 1C. See text for details (Modified from [17]).

3.2. ASTER Data Pre-Processing

The ASTER instrument was launched on board NASA's Terra spacecraft in 1999 [1]. It measures earth spectra in fourteen bands, including three bands (band 1–band 3) in the visible-near infrared (VNIR) range, six bands (band 4–band 9) in the short-wave infrared (SWIR) range and five bands (band 10–band 14) in the thermal infrared (TIR) range (Table 1) [29]. Spatial resolutions of the VNIR, SWIR and TIR subsystems are 15 m, 30 m and 90 m, respectively (Table 1).

Table 1. ASTER bandpass and spatial resolution.

Subsystem	Band	Spectral Range (μm)	Spatial Resolution (m)
VNIR	1	0.52–0.60	15
	2	0.63–0.69	15
	3	0.76–0.86	15
SWIR	4	1.60–1.70	30
	5	2.145–2.185	30
	6	2.185–2.225	30
	7	2.235–2.285	30
	8	2.295–2.365	30
	9	2.36–2.43	30
TIR	10	8.125–8.475	90
	11	8.475–8.825	90
	12	8.925–9.275	90
	13	10.25–10.95	90
	14	10.95–11.65	90

A scene of cloud-free level-1B ASTER data (Granule ID: ASTL1B 0405070516470602160011, acquired on 7 May 2004) was used in this study. In order to effectively analyze the ASTER data for lithologic discrimination, the level-1B radiance-at-sensor data were spatially and radiometrically corrected by a series of pre-processing procedures (Figure 3). First of all, the SWIR bands were corrected for crosstalk effects using the software developed by Iwasaki et al. [30]. Thereafter, atmospheric correction procedures were applied to obtain the radiometrically-corrected data. The VNIR and SWIR at-sensor radiance were transferred into surface reflectance by the Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) module of ENVI [31]. As for the TIR bands, the atmospheric effects were corrected by the ENVI module Thermal Atmospheric Correction [32]. Afterwards, the SWIR and TIR bands were resampled by cubic-convolution interpolation method to a spatial resolution of 15 m such that all the three subsystems could be stacked and compared spatially. The data were then cut to a subset that fits the study area, which locates in the southwest corner of the ASTER granule, and, as a result, the boundary of the subset is irregular (Figure 1C). The study area is poorly vegetated, as reflected by that the Normalized Difference Vegetation Index (NDVI) values, calculated as $(\text{band } 3 - \text{band } 2) / (\text{band } 3 + \text{band } 2)$, were all below 0.2 [33]. Moreover, visual observation revealed that almost no pixels were covered by cloud and ice/snow, which was consistent with that most band 3/band 4 ratios were less than 1 [33]. Therefore, no pixels were masked out and all pixels were treated as rocky or soil for the followed ASTER spectral analysis and lithologic mapping.

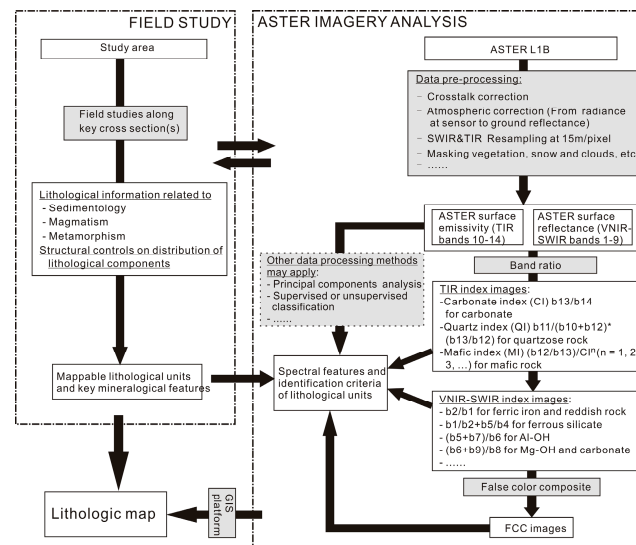


Figure 3. Generalized procedures of lithologic mapping based on combined studies of field geology and ASTER data analysis.

3.3. ASTER Spectral Signatures

The VNIR wavelength range, in which the ASTER has three bands (Table 1), is characterized by absorption features induced by the effects of color center, conduction band, crystal field or charge transfer [34–36]. In particular, charge transfer effect of ferric irons causes conspicuous absorption near $0.55 \mu\text{m}$ [35] and decrease in reflectance from the ASTER bands 2 to 1 [3]. Therefore, the ASTER band ratio band 2/band 1 could reflect the relative abundance of ferric irons [2], which is characteristic of red-color lithology. On the other hand, crystal field effects of ferrous irons in silicates (e.g., diopside, hornblende and chlorite), especially those contain the Mg-OH bond, usually induce a broad-wavelength reflectance depression in the $0.6\text{--}1.2 \mu\text{m}$ region (between ASTER bands 2 and 4) [34,35], and, therefore, reduce the reflectance of band 2 relative to band 1 and of band 4 relative to band 5 (Figure 4A) [3,34]. Hence, the band ratio (band 1/band 2 + band 5/band 4) highlights the rocks rich in ferrous silicates.

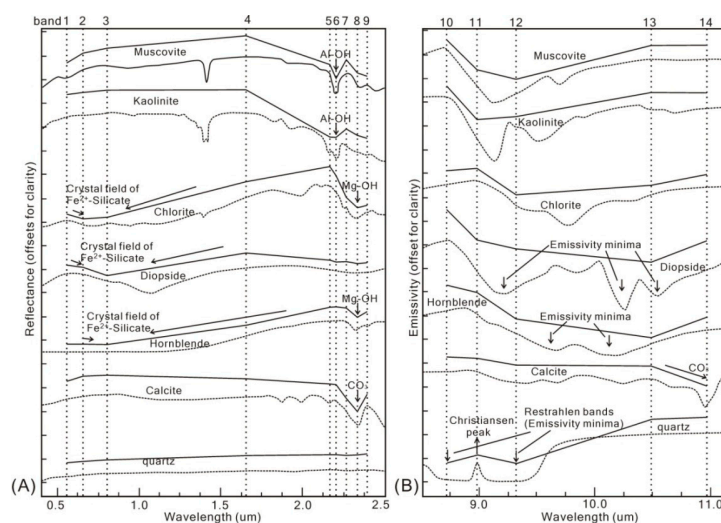


Figure 4. Reflectance (A) and emissivity (B) spectra of key rock-forming minerals. Dash lines show the laboratory spectral data, which are resampled to ASTER bandpass and shown as solid lines. (Modified from [3,34]).

Vibrational processes of metal-OH bonds of phyllosilicates induce diagnostic spectral signatures in the SWIR region [35], in which the ASTER provides six bands (Table 1). In particular, the Al-OH absorption centering at 2.2 μm is detected by the ASTER band 6 and, thus, the abundance of Al-OH bearing minerals, e.g., muscovite and kaolinite, could be estimated by the band ratio (band 5 + band 7)/band 6 (i.e. Relative Band Depth of band 6, RBD6) (Figure 4A) [36]. Similarly, as absorption induced by Mg-OH at ca. 2.34 μm [35] is detected by ASTER band 8, the abundance of Mg-OH bearing minerals, typically amphibole, chlorite and biotite, could be estimated by band ratio (band 6 + band 9)/band 8 (RBD8) (Figure 3A) [3]. Although carbonates, e.g., calcite and dolomite, also lead to strong band 8 absorption and high RBD8 value (Figure 4A), they could be distinguished from the Mg-OH bearing minerals by their distinct TIR signature, which will be introduced below [2].

The TIR spectra in the 8–14 μm atmospheric window are characterized by thermal emittance of surface minerals and the five TIR bands (Table 1) could be used to characterize relative abundances of nonhydrous silica-bearing minerals and carbonates (Figure 4B) [2,35,37]. Specifically, silicates display emissivity minima (so-called “restrahlen bands”), related to vibrational fundamentals of Si-O bonds [35]. Meanwhile, emissivity maxima could be induced by the Christiansen frequency before the onset of main absorption, resulting in narrow emissivity peaks within broad restrahlen bands [33,35]. The Christiansen frequency of quartz at ~8.6 μm is measured by the ASTER band 11, while the broad emissivity minima (restrahlen bands) on both sides by bands 10 and 12, respectively (Figure 4B) [37]. Based on the spectral feature, two band ratios (Quartz Index, QI) were proposed for assessing relative abundance of SiO_2 , such as (band 11 $\times$ band 11)/(band 10 $\times$ band 12) [2] and band 11/(band 10 + band 12) $\times$ (band 13/band 12) [37]. (On the other hand, as overall SiO_2 abundance in silicate rocks decreases, for example, from granite to gabbro, the restrahlen band shifts toward longer wavelength [2]. Accordingly, the Mafic Index (MI), band 12/band 13, was proposed to measure the tendency of increasing mafic composition [2]. Another important mineral group, carbonates, shows characteristic emissivity minimum at ~11.2 μm corresponding to the ASTER band 14 (Figure 4B), and, therefore, the Carbonate Index (CI), defined as band 13/band 14, can reveal the presence of carbonates [37]. Moreover, inasmuch as the MI also generates high DN values for carbonate and causes confusion, a modified Mafic Index, $\text{MI}_n = \text{MI}/(\text{CI})^n$ ($n = 0, 1, 2, \dots$), is proposed by [2] to separate mafic lithology from carbonate.

Band ratio was used as a principal data-processing method to highlight the abovementioned spectral signatures of characteristic lithologic compositions (e.g., [6]). The band-ratio images were also classified in terms of index values into color maps for more informative visualizations. In addition, false color composite (FCC) was performed to display grayscale maps into color image and visualize combined spectral signatures. The band-ratio and FCC images, as graphic presentations of diagnostic spectral signatures, were used as base maps for lithologic discrimination and matching, delineation of lithologic boundaries and, finally, the geologic map generation. The generalized procedures of lithologic mapping based on the combined field study and ASTER data analysis are shown in Figure 3. All the data processing procedures were implemented by ENVI software and later visualization, mapping and vectorization were conducted on ARCGIS platform.

4. Results

4.1. Mapping Units

The composite cross-sections (X–X' and Y–Y') show lithologic components and structural relationship across the BNSZ in the study area [17] (Figure 2). They reflect that the MG strata and mélanges were deformed into a south-vergent fold-and-thrust system. The south-vergent thrusts of the MG's interior appear to be imbricated and are inferred to sole into a basement decollement [11], which is most probably represented by the tectonic mélanges underlying the MG sedimentary subunits (Figure 5) [38]. On the other hand, the distribution of younger Cretaceous rocks appears to be

controlled by north-vergent thrusts (Figure 2). Based on lithologic assemblages recognized in the field, lithostratigraphic units that are mappable are summarized in Figure 5 and introduced below.

Units		Lithostratigraphic column	Age references	Descriptions
Quaternary	Q			
Tertiary	Tc			Reddish to yellowish conglomerates interbedding with finer clastic rocks
	Kl			Shallow marine carbonates; Fossiliferous
	Kv2		109±1Ma (Kapp et al., 2003)	Feldspar-phyric volcanic rocks with red-bed intercalations
	Ks			Nonmarine conglomerates, sandstones and marls
Cretaceous			116±2Ma (Kapp et al., 2003)	Vesicular basaltic rocks
Late Triassic–Jurassic Mugangri Group				Interbeds of volcanoclastic sandstone and mudstone; Pyroclastic flow deposits intercalated
			ca. 200Ma (Zeng et al., 2016)	Laminated micritic to silty carbonate; Few volcanoclastic sandstones intercalated
			ca. 210Ma (Zeng et al., 2016)	Conglomerates and volcanic breccias rich in the lower part, grading upward into volcanoclastic sandstone; Overall fining-upward succession;
			ca. 220Ma (Zeng et al., 2016)	Flysch-like interbeds of turbiditic sandstone and mudstone; Oolitic olistostromes intercalated; Poor in volcanogenic clasts;
				Block-in-matrix fabric; Blocks dominated by "native" sandstones; "Broken formation"-type melange.
				Block-in-matrix fabric; Blocks dominated by exotic oceanic crustal (ophiolitic) materials; Large seamount block included.

Figure 5. Lithostratigraphic columns of the study area. Internal structure of the Mugangri Group is revealed: (1) Tectonic mélanges and coherent strata are both essential components; (2) coherent strata are subdivided into four subunits, coded as *Trma*, *Trmb*, *TrJmc* and *Jmd*; (3) the mélanges are internally stratified with lower part dominated by exotic oceanic materials and upper part by native sedimentary materials. Age data are referred to [11,17]. See text for detailed description.

4.1.1. Mugagangri Group (MG)

The MG accounts for over 70% of base-rock exposures in the study area and includes two types of lithologies: tectonic mélanges and coherent sedimentary successions. The coherent strata were previously interpreted to be Jurassic based on sparse biostratigraphic controls (e.g., [16,25]). However, depositional ages constrained by detrital zircon U-Pb dating from the volcanoclastic beds suggest that the lower part was probably late Triassic (Figure 5) [17]. The coherent strata could be subdivided into four subunits with distinct sedimentological and lithologic characteristics (Figure 5). The four subunits are coded as *Trma*, *Trmb*, *TrJmc*, *Jmd* in ascending order based on stratigraphic relationships and depositional ages constrained by youngest detrital zircon ages (Figure 5). The basal subunit (*Trma*) (Figure 5) features flysch-type siliciclastic turbidites composed of graded sandstones interbedded with mudstones (Figure 6A). Carbonate grains are occasionally rich and few horizons of oolitic olistostromes are intercalated within the turbiditic sandstones (Figure 6A), suggesting the existence of a coeval carbonate platform in updip shelf areas [39]. Very few volcanic clasts are contained in the over 500 m-thick subunit *Trma* and it suggests the *Trma* provenance was volcanically inactive [40].

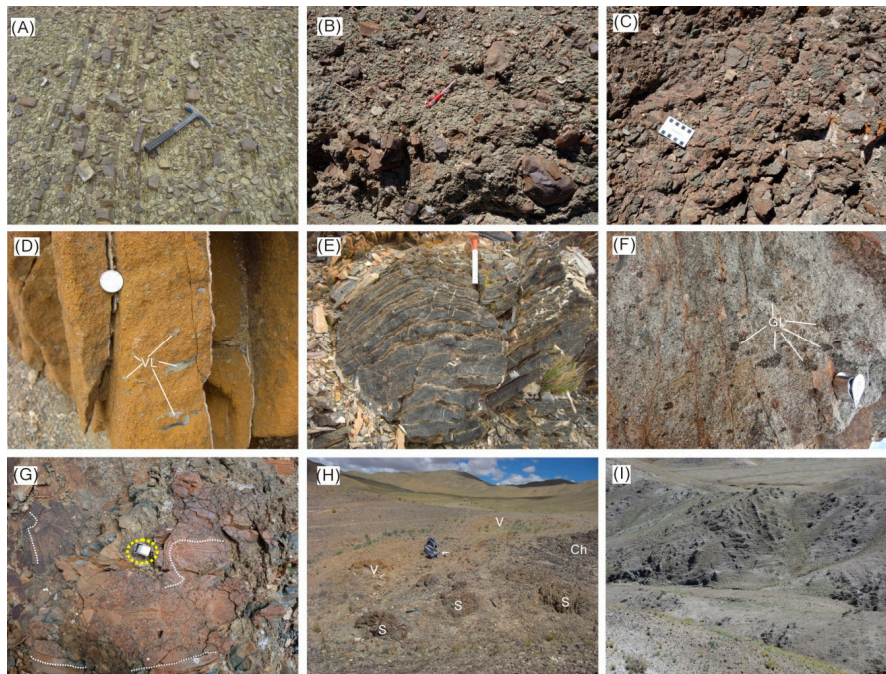


Figure 6. Typical field exposures of the MG subunits. (A) Interbedded graded sandstones and mudstones of subunit *Trma*. The hammer as scale is ~30 cm long; (B) Normally graded conglomerate of the basal part of subunit *Trmb*. The pebbly-cobbly sized clasts are dominantly sandstone with lesser carbonate and volcanic rocks. The ball-point pen is ~10 cm long; (C) Volcanic breccias intercalated within the basal part of subunit *Trmb*. Volcanogenic material accounts for >85% of the overall constituents. Length of the scale card is 10 cm; (D) Volcaniclastic sandstone of subunit *Trmb*. Light gray fragments are lithic lapillis (VL) with greater size than surrounding sands, suggesting a fall-out origin. Diameter of the coin as scale is ~1.5 cm; (E) Laminated calcisiltites of subunit *TrJmc* interpreted as deep-water facies. Folding is resulted from later structural deformation rather than depositional processes. The marker is ~12 cm long; (F) Pyroclastic flow of subunit *Jmd*. The dark angular clasts are glassy lapillis (GL) and the finer white-gray clasts are dominated by feldspar and lithic fragments. The lens as scale is 4 cm; (G) Convoluted mudstones included in the bottom of the *Jmd* pyroclastic bed. The lens as scale is ~4 cm; (H) Typical block-in-matrix fabric of the MG mélangé. The blocks are composed of sandstone (S), volcanic rocks (V), chert (Ch) and carbonate. The bag is ~50 cm long; (I) A view (looking toward the southwest) of the broken formation type mélangé resulted stratally-disrupted *Trma* sediments. Note the dark greenish color as a result of lower greenschist metamorphism.

A second subunit (*Trmb*) (Figure 5), which is contrarily rich in volcanogenic components, is conformably overlying subunit *Trma*. The lower part of subunit *Trmb* is a >60 m-thick fining-upward succession, which mainly consists of conglomerates, volcanoclastic sandstones and tuffaceous beds (Figure 6B–D). Beds of volcanic breccias (Figure 6C) are intercalated within the conglomerates. The conglomerates are polymicts, composed of fragments of sandstone, carbonate and volcanic rock (Figure 6B,C). The fragments, up to boulder size, are moderately rounded and poorly sorted, suggesting rapid deposition and low degree of reworking (Figure 6B). The most prominent contrast to the underlying subunit *Trma* is the relative richness in volcanic components (Figure 6C,D). The transition from subunits *Trma* to *Trmb* is represented by a sharp contact underlying the conglomerates, suggesting that they resulted from rapid structural uplift rather than due to a secular eustatic factor. Moreover, the sudden input of substantial amount of volcanogenic materials indicates initiation or renewed volcanism in the provenance area.

A succession characterized by limestones (over 50%) interbedded with volcanoclastic sandstones was designated as the third MG subunit (*TrJmc*) (Figure 5). No exposure was observed to show its contact relationship with subunit *Trmb*. Nonetheless, as subunit *Trmb* contains few limestone intercalations that increase in abundance upward, a gradual transitional relationship was inferred between subunits *Trmb* and *TrJmc*. The limestones of subunit *TrJmc* are mainly laminated calcisiltites and micrites with few amounts of bioclasts (Figure 6E), which are interpreted as deep marine facies according to their very fine grain-size and millimeter-scale lamination [41]. The sandstone interbeds are usually graded turbidites. The intercalations of deep-water carbonate facies within the volcanoclastic sequences of subunit *TrJmc* reflect the presence of short-lived carbonate platform in updip shallow seas [42,43]. The distribution of subunit *TrJmc* is relatively limited, suggesting the coeval carbonate platform probably have not developed in a massive scale in the presence of active volcanism.

A fourth and the youngest subunit (*Jmd*) of the MG coherent strata is defined in terms of its characteristic interbeds of pyroclastic flow within the flysch sequence (Figure 5). The pyroclastic rocks are mainly composed of ash and glassy lithic lapillis (Figure 6F). Convoluted mudstones are sometimes included in the pyroclastic beds (Figure 6G), suggesting they were resulted from rapid turbulent flow of syn-volcanic pyroclastic materials, which were capable of shearing off substrate muddy sediments [44]. The occurrence of pyroclastic interbeds is distinctive from the subunits described above and indicates that volcanic eruptions were possibly intensified in the provenance area. Carbonate grains are rich in certain stratigraphic intervals of subunit *Jmd* and carbonate cementation is also widely developed.

Tectonic mélanges (*mm*), with typical block-in-matrix fabrics (Figure 6H,I), structurally underlie the sedimentary subunits (Figure 2) [11]. The matrix consists of shaly, sandy and lesser volcanic materials with typical scaly cleavages, whereas the blocks comprise “native” sandstones mainly originated from the MG sediments and “exotic” oceanic crustal or ophiolitic fragments such as basalt and chert, scrapped off the subducting BNO (Figure 6H) [45]. In terms of block lithologies, the mélange appears to be internally stratified: the deeper part is dominated by the oceanic-crustal fragments and the shallower part dominated by components from the MG strata (Figures 2 and 5). During our field study, a large block (>100 m thick across the bedding) was found to be contained within the mélange and show well preserved stratigraphy of cycles of volcanic-sedimentary rocks (Figure 2). The volcanic rocks are basaltic pillow lavas flow and basaltic-andesitic breccias to lapilli-stones, while the sedimentary rocks are dominated by carbonate, chert and volcanoclastic turbidites (Figure 2). We interpreted the large block as scraped-off a subducted seamount [46], the occurrences of which were previously reported from the BNSZ [47,48]. The MG coherent strata and mélanges were deformed into a south-vergent fold-and-thrust system [17].

The MG is widely affected by lower greenschist metamorphism, which features the metamorphic mineral assemblage of chlorite, epidote, sericite, calcite and quartz (Figure 7) [16]. The mélanges appear to be greenish, as a result of metamorphic crystallization of chlorite and lesser epidote (Figures 6I and 7A). It is notable that the volcanoclastic sandstones of subunit *Trmb*, especially in the north of the traverse, are endowed a gray-yellow dusty appearance due to sericite and clay minerals replacing volcanic

clasts during the low-grade metamorphism or diagenesis (Figures 6D and 7B). The addition of these metamorphic minerals results in characteristic spectra to some of the lithologic units and, however, could also lead to complications.

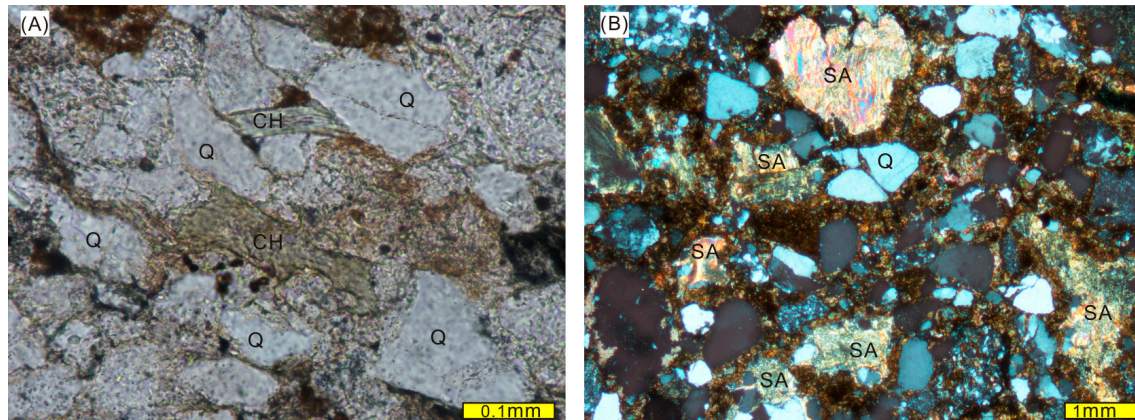


Figure 7. (A) Photomicrograph of a sandstone block from the MG mélange. Note that chlorite (CH) crystallized along boundaries among the quartz grains, possibly replacing matrix or cements. Finer epidote crystals also occur; (B) Photomicrograph of the volcaniclastic sandstone from subunits Trmb. Note that the sample is rich in volcanic clasts that are intensively sericitized. CH—chlorite; SA—sericitized volcanic clast; Q—quartz.

4.1.2. Cretaceous and Younger Units

Cretaceous volcanic and volcaniclastic rocks occur along major north-vergent thrusts (Figure 2). The volcanic rocks vary from rhyolitic to basaltic, with the tendency of becoming more felsic upwards. Nonmarine conglomerates, finer clastic rocks and carbonates or marls are intercalated within the volcanic rocks [11]. Kapp et al. [11] subdivided the Cretaceous rocks into three lithologic units in ascending order: (1) vesicular basaltic rocks (Kv1); (2) nonmarine conglomerates, sandstones and marls (Ks); and (3) feldspar-porphyritic volcanic rocks with red-bed intercalations in the upper part (Kv2). Early Cretaceous shallow marine carbonates (Kl) crop out to the south of the BNSZ, as allochthonous blocks over-thrusted to the north overlying the suture zone [11].

Tertiary conglomerates (Tc) in the study area mainly occur to the north of the suture zone. They consist of reddish to yellowish polymict conglomerates interbedded with finer clastic rocks. Because the Tertiary conglomerates generally have very shallow dipping angle and are not well cemented, they are covered with loose taluses and not well exposed. At localities exposed, they show a reddish color and fining-upward cycles and imbricated gravels. Quaternary sediments (Q) are widely distributed in the study area, as semi- to un-consolidated sedimentary cover in relative low areas. Their compositions are generally closely related to adjacent base rocks.

Intrusive rocks in the study area are mainly Cretaceous in age. Cretaceous dioritic porphyry (Kd) and diabasic dikes are found to be intruded into the MG [16]. Potassic intrusion (Tp) is discovered in the study area for the first time. It is characterized by west-east distribution and porphyritic texture with nepheline phenocrysts. Argillic alteration is intensively developed around the potassic intrusion. According to common characteristics of the potassic magmatic rocks reported from central Tibet, we infer that the potassic intrusion is related to post-collisional magmatism in the late Eocene time [49,50].

4.2. ASTER Spectral Analysis and Mapping

ASTER image spectra (Figure 8) were collected from the pixels representative of the mapping units shown in Figure 5 and we referred to outcrops observed in the field to select the representative pixels.

The ASTER image spectra show diagnostic signatures that are consistent with dominant mineralogic and lithologic characteristics of the units (Figure 8) and are distinguishable in the band-ratio index maps (Figures 9–11), based on which relative band-ratio intensities of the lithologic units are summarized in Table 2. We applied a data analysis sequence that the TIR bands were first analyzed to show approximate distribution of carbonates and silicate-dominated lithologies and the VNIR/SWIR bands were then processed to differentiate the lithologic units and delineate their boundaries.

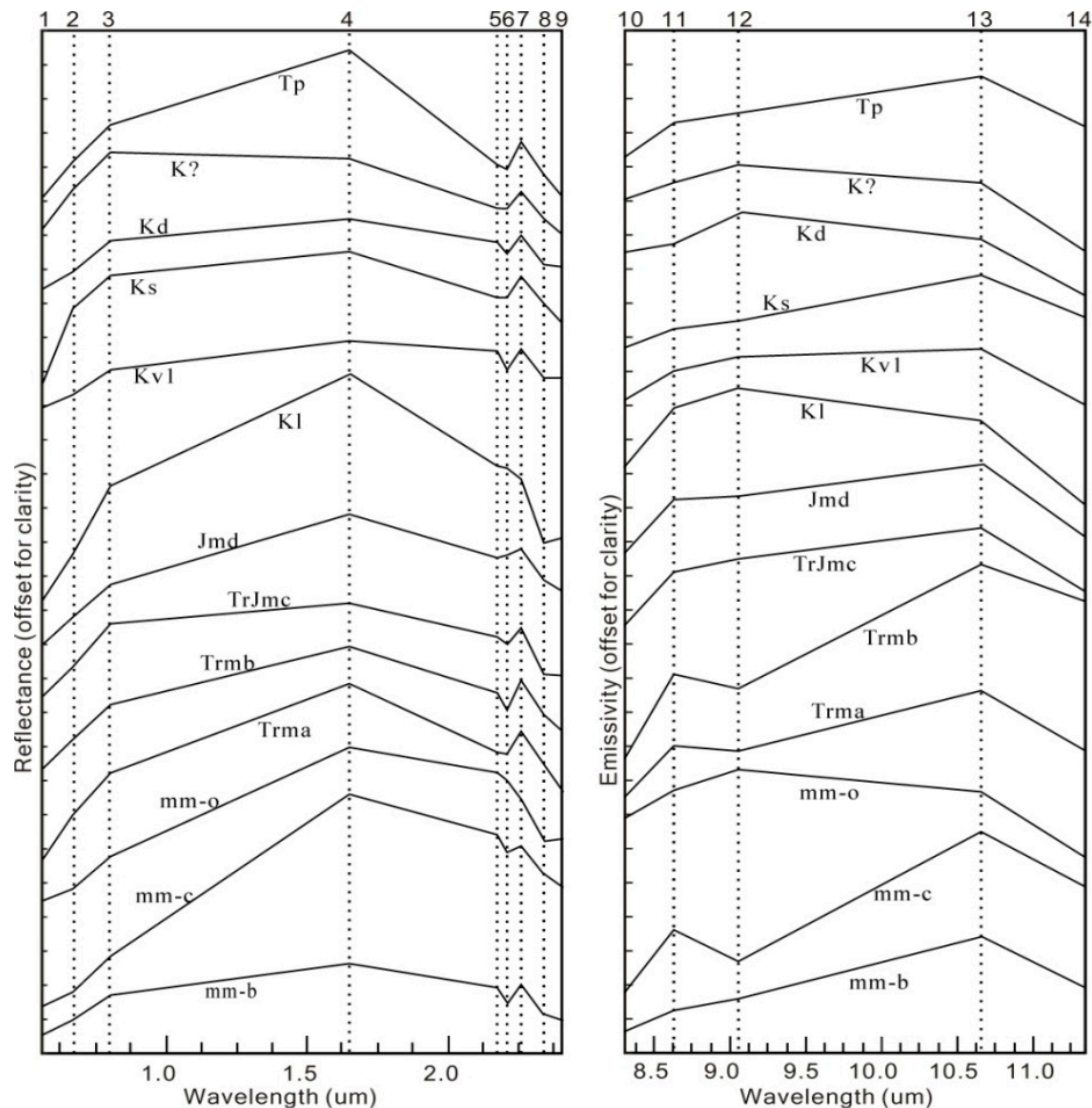


Figure 8. ASTER image spectra of important lithologic units in the study area. *Tp*—Tertiary potassic intrusive rocks; *Kd*—Cretaceous diorites; *Ks*—Cretaceous red beds; *Kv1*—Cretaceous basaltic rocks; *Kl*—Cretaceous carbonates. *Trma*, *Trmb*, *TrJmc* and *Jmd* represent the four subunits of the MG sedimentary successions. Three lithologic types of the MG mélanges (*mm*): *mm-o* for components dominated by oceanic basalts, *mm-c* for components dominated by chert and *mm-b* for components dominated by sedimentary materials. See text for detailed description of the lithologic units.

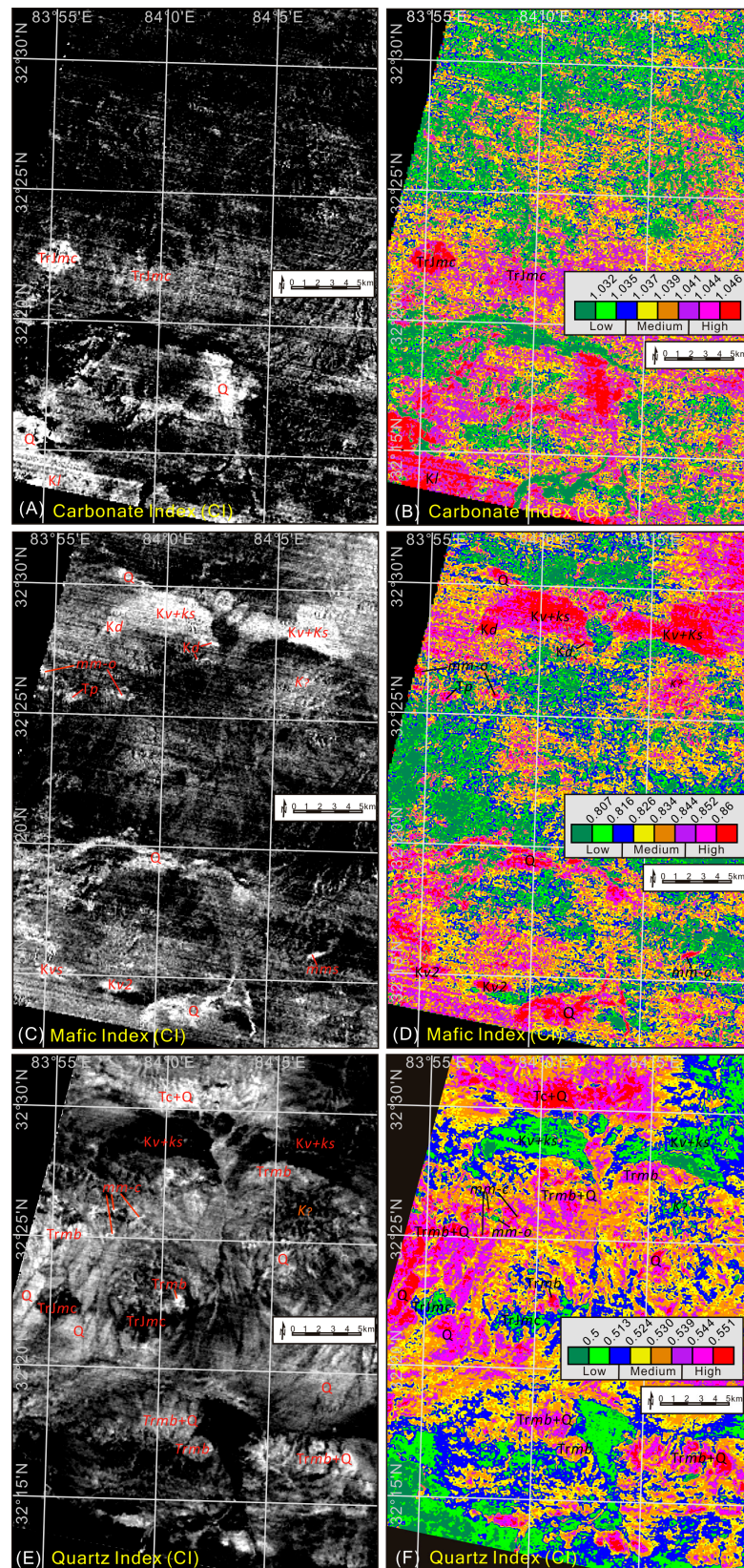


Figure 9. Grayscale and classified color images of the TIR indexes: (A,B) Carbonate index (CI); (C,D) Mafic index (MI₄); (E,F) Quartz Index (QI). See text and Figure 8 for interpretation of the labels of lithologic units.

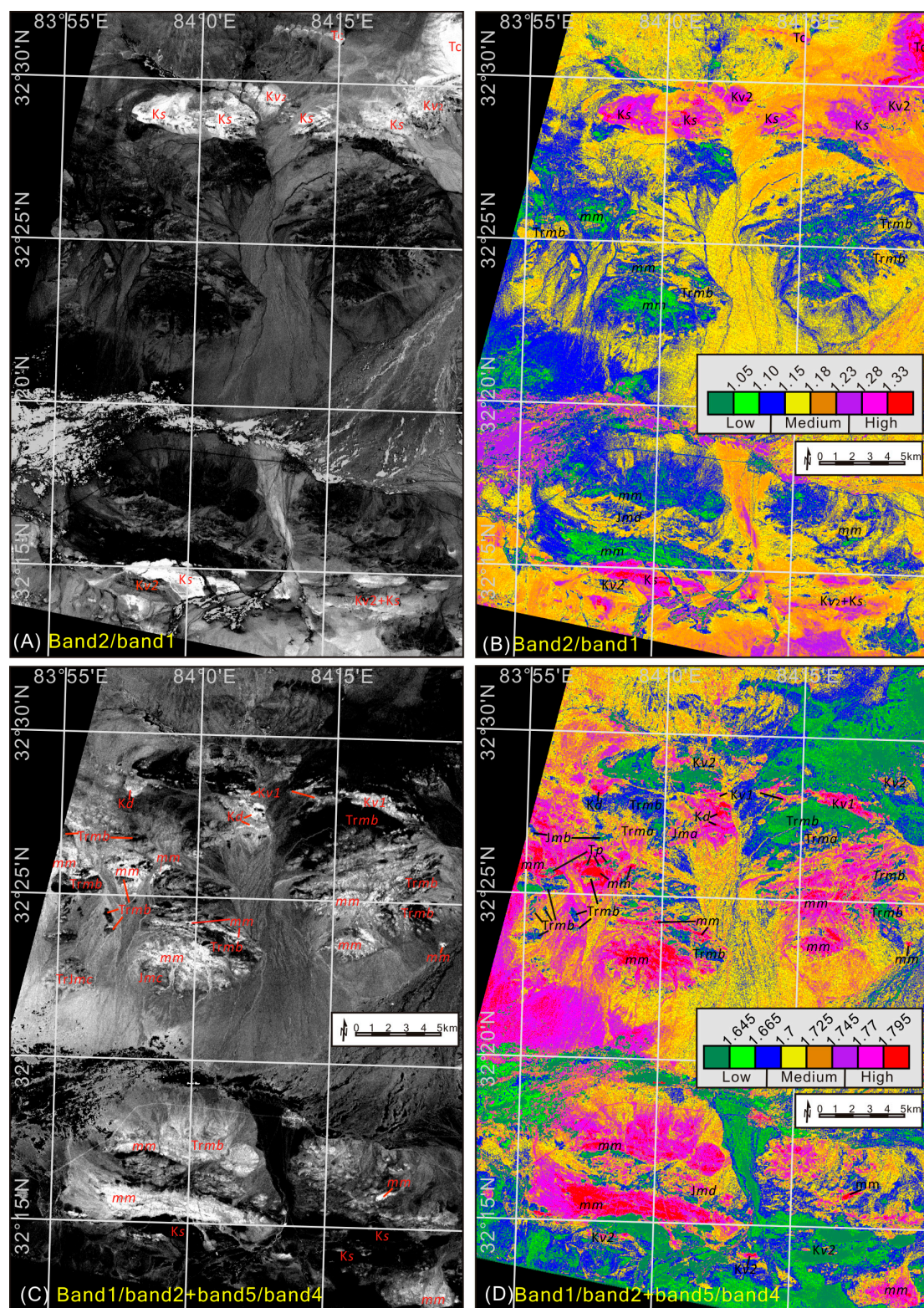


Figure 10. Grayscale and classified color images of VNIR band ratios. (A,B) Band ratio band 2/band 1; (C,D) Band ratio (band 1/band 2 + band 5/band 4). See text and Figure 8 for interpretation of the labels of lithologic units.

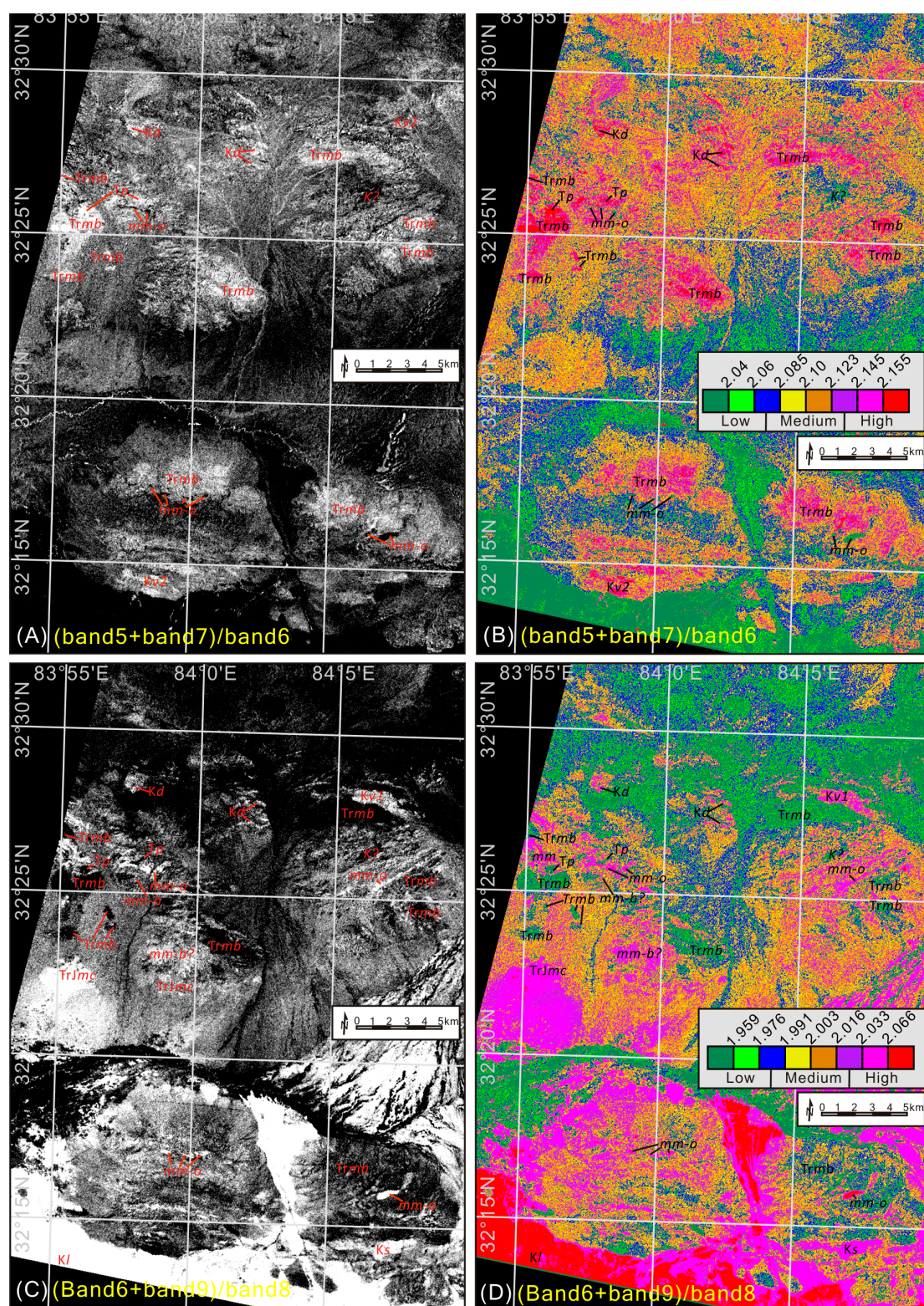


Figure 11. Grayscale and classified color images of SWIR indexes. (A,B) Band ratio (band 5 + band 7)/band 6 ; (C,D) Band ratio (band 6 + band 9)/band 8. See text and Figure 8 for interpretation of the labels of lithologic units.

Table 2. Summary of relative band-ratio intensities of the mapping units in the study area.

	QI	CI	MI4	B2/B1	B1/B2 + B5/B4	(B5 + B7)/B6	(B6 + B9)/B8
Tc	M-H			H(1.3–1.41)	L		
Trp	L	L	M	L-M	L	H(2.20–2.28)	L
K?	L	L	H	L	M	L-M	L
Kd	L	L	H(0.856–0.893)	L	M-H	H(2.09–2.20)	M
Kv2	L	L	H	Interbedded H (1.2–1.29)	M-H	Interbedded H	L-M
Ks	L		Partially H	H(1.29–1.40)	L	L	Partially H
Kv1	L	L	H(0.866–0.885)	L	H(1.72–1.85)	L	H(1.90–1.98)
Kl	L	H(1.047–1.051)		M	L	L	H(2.21–2.40)
Jmd	L	M	M	L-M	Interbedded M	L	Interbedded M-H
TrJmc	L	H(1.046–1.049)		L	M	M	H(2.02–2.12)
Trmb	M-H			M	L-M	H(2.14–2.22)	L
Trma	M-H	M		L-M	M	L-M	Locally M
mm	L			L	H(1.80–1.87)	L-M	M-H
mm-o	Blocky H (0.548–0.558)	Blocky H	Blocky H (0.851–0.883)	L	H(1.81–1.93)	L-M	Blocky H (2.06–2.14)

Notes: (1) Explanation of the lithologic units in first column can be found in section “4.1 Mapping Units”; (2) Formula and usages of the band ratios listed in the first row are referred to Section 3.3; (3) Abbreviations: H—High; M—Moderate; L—Low. Incline indicates key signatures for identifying the units; (4) Data in brackets are intensity ranges for some of the units.

4.2.1. ASTER TIR Data Analysis

The index maps of CI, MI₄, and, QI are shown in Figure 9. The carbonate-dominated units, subunit TrJmc and the early Cretaceous limestones (Kl), display high values on the CI image (Figure 9A,B). The high MI₄ values are mainly correlated with the Cretaceous volcanic rocks (Kv1 and Kv2) and porphyritic diorite (Kd) (Figure 9C,D). The portion of mélanges rich in ophiolitic fragments is also illustrated as moderate to high value pixels on the MI₄ image (Figure 9C,D).

Both of the Quartz Indexes from [2] and [37] are generated in order to evaluate the quartz abundance. The results from both indexes show comparable spatial distribution of DN values. However, we prefer the result of [37] based on the facts that: (1) The index of [37] also takes advantage of the lowered emittance of band 12 relative to band 13 and is considered to better reflect the spectral signature of restrahlen band, in comparison to the index of [2]; and (2) the result of the index of [37] appears to be more effective in correcting the stripping noise associated with the ASTER TIR data than that of the index of [2], probably due to the latter index involves a quadratic calculation of the bands. Therefore, in the rest part of the paper, the QI image refers to the result of the index of [37]. The high values in the QI image are intensively affected by quartz-rich Quaternary sediments and eolian sands, the latter of which are especially well-developed in Tibet [51]. Nonetheless, cherty blocks within the mélanges are correlated to high values on the QI image and it is a useful indicator of tectonic mélange (Figure 9E,F). Subunit Trmb is also displayed as moderate to high value pixels, which probably reflects the combined TIR emissivity spectra of sandstones and alteration minerals, sericite and kaolinite [3] (Figure 9E,F). The bright pixels on the CI and MI₄ images are shown to be dark on the QI image and the mutual exclusiveness demonstrates the ASTER TIR indexes are effective in discriminating main lithologic groups with contrastive concentrations of quartz, carbonates and mafic silicates (Figure 9).

4.2.2. ASTER VNIR-SWIR Data Analysis

The high value pixels in the image of band 2/band 1 (Figure 10A,B), which correlates with surface abundance of ferric iron, is consistent with the distribution of reddish-colored rocks, mainly the Cretaceous red beds (Ks) (Figure 8). The Cretaceous feldspar-porphyritic volcanic rocks (Kv2) are partially high in the image due to the presence of reddish sedimentary interbeds. The Tertiary conglomerates (Tc) are also reddish; however, they are not well-exposed due to extensive coverage of talus and eolian sands except at the northeast edge of the study area that is undergoing active erosion (Figure 10A,B). The rest of the base rocks have low to moderate values of this band ratio

(Figure 10A,B). In particular, the MG mélanges, which mainly appear dark green in the field due to mineralogic imprints of low-grade metamorphism, are illustrated as low values on the band 2/band 1 image (Figure 10A,B).

Lithologic exposures relatively rich in ferrous silicate are displayed by high values in the image of (band 1/band 2 + band 5/band 4) (Figure 10C,D). Three lithologic units are indicated: (1) Cretaceous basaltic rocks (*Kv1*); (2) Cretaceous diorite (*Kd*); (3) the MG mélanges. The high band ratios of the latter are mainly originated from the ophiolitic basaltic fragments and the addition of the metamorphic chlorite and epidote (Figures 4, 7A and 8). In contrast to the low values in the north, subunit *Trmb* is moderately high in the south (Figure 10C,D) and it is interpreted to be caused by the addition of metamorphic chlorite. It is also worth noting that the Tertiary potassic intrusions (*Tp*) are shown as isolated irregularly-shaped dark pixels, standing out of the bright surroundings of mélangé, because of the lack of ferrous silicates (Figure 10C,D).

The images of band ratio (band 5 + band 7)/band 6 (RBD6), which reflects the intensity of Al-OH absorption, are shown in Figure 11A,B. The most conspicuous Al-OH absorption are related to subunit *Trmb*, which contains abundant sericite that has replaced volcanic clasts (Figure 7B). The Cretaceous diorite (*Kd*) and Tertiary potassic intrusion (*Tp*) also display high values (Figures 8 and 11A,B), due to their abundant muscovite and clay constituents, the latter of which is probably resulted from argillic alteration. Notably, the volcanic and carbonate blocks of the mélanges stand out as the lowest values in the RBD6 image (greenish in Figure 11B), which could be effectively discriminated from later intrusive bodies (i.e., *Kd* and *Tp*).

The lithologic units, rich in carbonates and Mg-OH bearing minerals, induce prominent absorption at ASTER band 8, which is evaluated by the band ratio (band 6 + band 9)/band 8 (RBD8) (Figure 11C,D). With respect to the TIR carbonate index (Figure 9A,B), the high values in the RBD8 image corresponding, respectively, to carbonates and Mg-OH bearing rocks are differentiated: (1) the bright pixels largely overlapping with those in the CI image indicate the Cretaceous carbonates (*Kl*), subunit *TrJmc* and the carbonate blocks of the mélangé (Figures 9A and 11C,D); (2) The Mg-OH vibrational absorption is responsible for the high band ratios of the volcanic blocks in the mélangé, Cretaceous basaltic rocks (*Kv1*) and dioritic intrusions (*Kd*) (Figures 8 and 11C,D). In comparison to the band ratio image of (band 1/band 2 + band 5/band 4), which shows the mélanges with relatively-uniform high values (Figure 10C), the RBD8 image (Figure 11C) illustrates the mélanges in a blocky pattern, reflecting that different lithologic blocks or components of the mélanges induce absorption with varied depths at band 8 (Figure 8). In particular, the ophiolitic fragments (carbonates and basalts) are displayed as brighter pixels than the matrix and native sandstone blocks (Figure 11C) and we infer that this is because metamorphic chlorite is the dominant Mg-OH bearing mineral of the latter (Figure 7A) and induces shallower band 8 absorption than minerals such as calcite and hornblende of the ophiolitic fragments (Figures 4 and 8). However, when the native blocks involve the *TrJmc* strata, which consist of abundant carbonate, the difference is hard to be discerned.

4.2.3. False Color Images

Three false color composite (FCC) images are created in order to better visualize the combined spectral signatures and delineate boundaries of the mapping units (Figures 1C and 12). The ASTER bands 3-2-1 RGB color composite clearly illustrates the boundaries between the base rocks and the Quaternary (Figure 1C). The base rocks as erosional landscape generally appear as rugged relief, whereas the Quaternary sediments are characterized by the smooth appearance of topography and presence of radiating or sub-parallel lineaments representing seasonal fluvial or alluvial channels (Figure 1C).

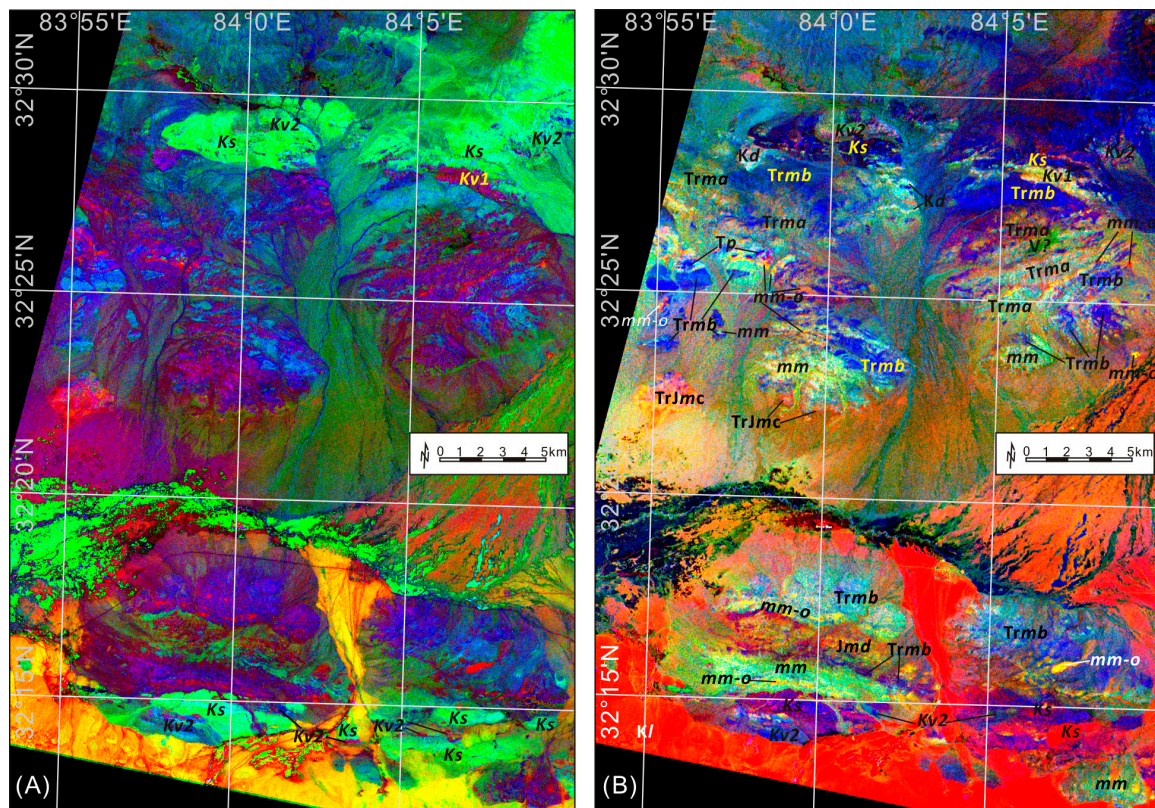


Figure 12. FCC images of the VNIR-SWIR band ratios. (A) Red—(band 6 + band 9)/band 8, Green—band 2/band 1, Blue—(band 5 + band 7)/band 6 ; (B) Red—(band 6 + band 9)/band 8, Green—(band 1/band 2 + band 5/band 4), Blue—(band 5 + band 7)/band 6. See text and Figure 8 for interpretation of the labels of lithologic units.

The FCC image of band ratios Red—(band 6 + band 9)/band 8, Green—band 2/band 1 and Blue—(band 5 + band 7)/band 6 enables us to discriminate the Cretaceous units: (1) the red beds of Ks are highlighted in green color resulted from the high band 2/band 1 values; (2) the Kv2 volcanic succession displays blue color due to its moderate high RBD6 values with some cyan to green interbeds corresponding to the intercalated red beds; and (3) the Cretaceous carbonate Kl is highlighted in orange as a result of the high RBD8 values and moderate band 2/band 1 values (Figure 12A). The Kv1 volcanic rocks appear in dark magenta, corresponding to strong Mg-OH absorption at band 8 and moderate RBD6 values.

On the other hand, the FCC image of the band ratios Red—(band 6 + band 9)/band 8, Green—(band 1/band 2 + band 5/band 4) and Blue—(band 5 + band 7)/band 6 is effective in mapping the MG subunits (Figure 12B). The areas in blue correspond to high RBD6 values and strong Al-OH absorption, which are characteristic of subunit Trmb. As the occurrence of carbonate increases up-section, orange-red intercalations are present within the Trmb blue pixels. The mélanges, characterized by high (band 1/band 2 + band 5/band 4) values (Figure 10C,D), mainly appear in green to cyan if dominated by native materials. On the contrary, if the mélanges are dominated by oceanic crustal materials, they are characterized by a blocky pattern with yellow to orange patches, corresponding to oceanic blocks with high RBD8 values (Figure 11C), included by the greenish background (Figure 12B). Based on the image features, the portion of mélange dominated by oceanic or ophiolitic materials (labeled as mm-o) could be separated from the rest of the mélanges (Figure 12B). Subunit Trjmc is illustrated by the red pixels in the middle of the study area due to its prominent carbonate composition and strong band-8 absorption (Figures 11 and 12B). Subunit Jmd is characterized by interbedded orange and greenish layers, corresponding, respectively,

to carbonate-rich beds (with moderate RBD8 values) and pyroclastic rocks (with moderately high (band 1/band 2 + band 5/band 4) values) (Figure 12B). Subunit *Trma* is less characteristic; nonetheless, it is discriminated by a dark green color with scattered orange pixels that represent lesser carbonate interbeds and olistostromes and its close spatial relationship with the mélanges and subunit *Trmb* (Figure 12B). The mélanges resemble the *Kv1* volcanic rocks in both Figure 12A,B. However, with respect to the TIR (i.e. QI and MI4) index maps they are readily differentiated by that the *Kv1* rocks display a uniform pattern, reflecting uniform lithologic distribution, whereas the mélanges consist of pixels with various values, representing mixing of different lithologic components (Figure 8).

The intrusive rocks (*Kd* and *Tp*) are irregular in shape and show different spectral characteristics. The Cretaceous diorites (*Kd*) have relatively high values of all three band ratios (band 6 + band 9)/band 8, (band 1/band 2 + band 5/band 4) and (band 5 + band 7)/band 6 (Table 2) and are therefore the only unit shown as white to bright gray in Figure 12B. Although the Tertiary potassic intrusive rocks (*Tp*) have similar spectral signatures to subunit *Trmb* in the VNIR-SWIR bands (Figures 10–12), they are differentiated according to the TIR signature that the latter has greater QI values than the former, which is deficient in silica relative to alkalis such that no quartz was crystalized (Figures 8 and 9; Table 2).

4.2.4. Lithologic Mapping and Interpretation

While generating the lithologic map, contacts between Quaternary deposits and base rocks were firstly delineated based on the contrasting topographic features illustrated in Figure 1C, as mentioned above. The FCC images of band ratios were then used as base maps to draw boundaries of the base-rock units, based on the color contrasts that correspond to spectral signatures resulted from contrasting chemical compositions and internal fabrics (Figure 12). Relative intensities on individual band-ratio images were double-checked for lithologic matching (Figures 9–11; Table 2). Mixtures of lithologic components certainly occur at a variety of scales and the assignment of lithologic units to an area with mixed rock types was implemented according to the dominant color. Field-located base-rock exposures were also used as critical references to the lithologic interpretation.

We assume that all important rock types are included by the lithologic units observed in the field and listed in Table 2. In fact, most of the pixels are able to be interpreted as one of the known lithologic units. Nonetheless, two anomalous bodies (labeled as K?) occur within the MG. They show high values on the MI4 image (Figure 9C), moderate values on band 2/band 1 band ratio image (Figure 10B) and greenish on the FCC image (Figure 12B). They apparently have not been affected by the low-grade greenschist metamorphism, which otherwise should have induced an Mg-OH absorption signature. The features resemble the *Kv2* volcanic rocks to some degree. Therefore, we interpret them to be intrusive bodies synchronous to the *Kv2* volcanism.

In the process of delineating lithologic boundaries, we followed the rule that the lithologic units are mainly east-west trending, reflecting prominent north-south contractional features [7,11]. Contacts between the MG coherent subunits and the mélanges were all marked as fault boundaries. Offsets of the east-east features (namely lithologic belts and boundaries) along northeast- or northwest-trending lineaments are interpreted as later strike-slip faulting, which is consistent with the Cenozoic deformation pattern in Tibet summarized by [7,52]. The new lithologic map (Figure 13) reaches the scale of 1:50,000 and contains greater details than the previous map (Figure 1A), while the major lithologic boundaries are largely consistent on both maps.

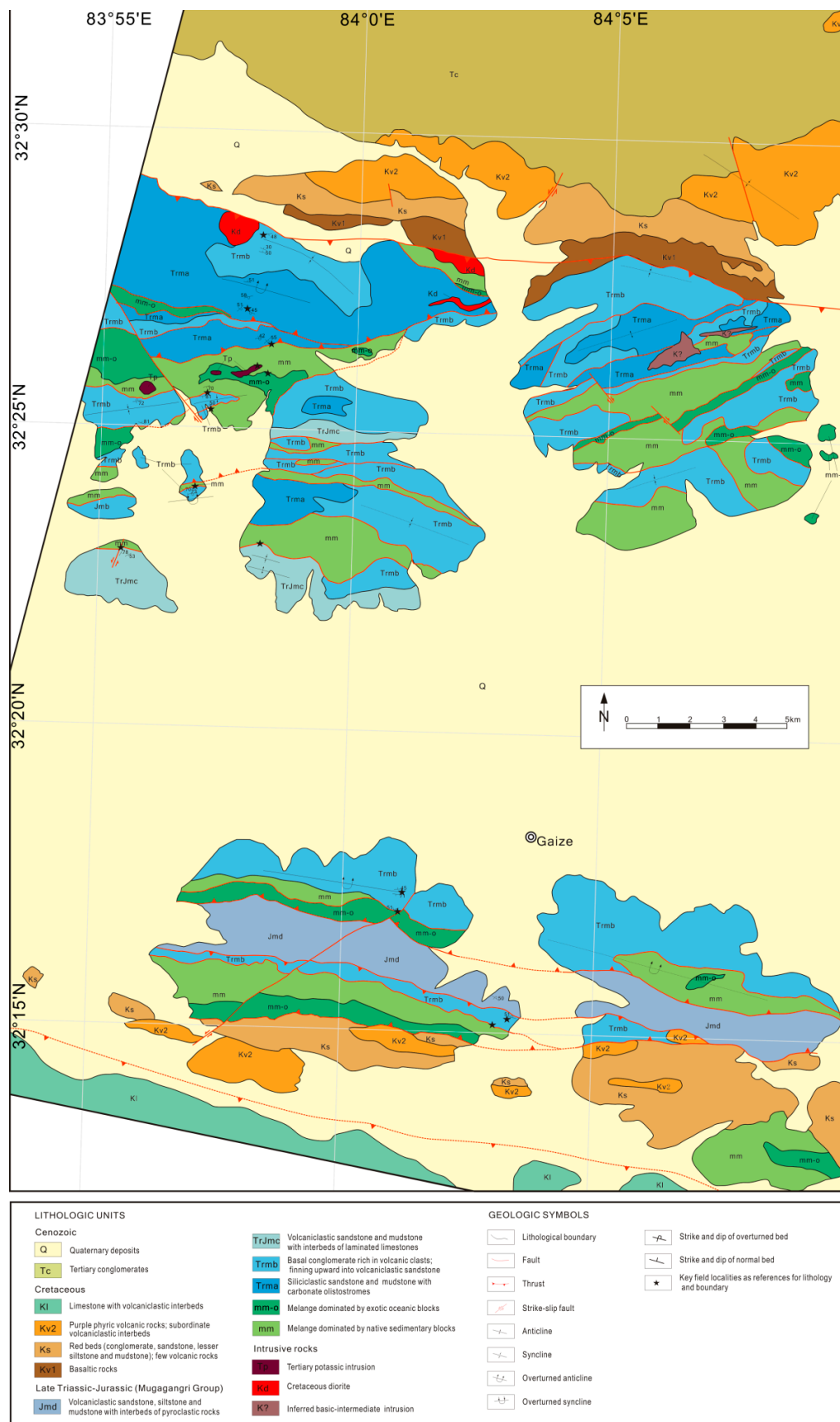


Figure 13. New lithologic map of the study area generated based on the combined analyses of field and ASTER data.

5. Discussion

5.1. Mappable Features of the MG and Tectonic Implications

Summing up above field and ASTER data analyses, the MG subunits (Figure 5) are lithologically and spectrally distinctive (Table 2) and the MG is successfully mapped to be represented by these subunits (Figure 13). Therefore, we propose a subdivision scheme for the MG (Figure 5): (1) according to structural features, the MG is classified into mélanges and coherent strata; (2) the coherent strata are further subdivided into four subunits (*Trma*, *Trmb*, *TrJmc* and *Jmd*) with respect to sedimentological and lithologic characteristics. The subdivision scheme is potentially applicable to future geologic mapping projects in the BNSZ. Nonetheless, regional distribution of the coherent subunits needs to be verified. Furthermore, distribution of the mélanges is well manifested and the mélanges could be further separated into two parts with respect to lithologic types dominating the blocks (Figures 5 and 13). The blocky pattern of the mélanges with highlighted Fe- and Mg-rich blocks shown in the ASTER images (Table 2) is diagnostic and readily differentiable from other lithologic classes and it is, therefore, potentially applicable for future studies on the BNSZ ophiolites.

The mappable features reveal internal structure of the MG and bear implications on its formative processes. The mélanges are structurally underlying the coherent strata (Figure 2) and internally stratified with the lower part more concentrated with ophiolitic fragments. These features suggest that during the mélange formation the oceanic crust, as the source of the ophiolitic fragments, was the footwall plate moving downward below the mélanges, which most probably represent the fault rocks developed in the subduction channel [45]. Therefore, the south-vergent fold-and-thrust system composed by the MG subunits (Figure 2) is interpreted to be an accretionary complex [46,53] formed above the subducting BNO and accreted to the south margin of Qiangtang [17].

With respect to the accretionary-wedge setting, the MG coherent strata are inferred to be deposited in a trench-slope basin [17]. The four subunits of coherent strata have distinctive sediment components, corresponding to sequential changes in provenance. The basal subunit *Trma* is non-volcaniclastic, in contrast to the younger subunits, which are volcanoclast-rich. The sudden input of volcanogenic components in *Trmb* overlying the non-volcaniclastic subunit *Trma*, probably reflects the initiation of arc volcanism [17]. The increasing abundance of limestones up-section from subunit *Trmb* into *TrJmc* probably suggests that arc-volcanism experienced periodical quiescence and, therefore, short-lived carbonate platform was built up on elevated arc surfaces and then shed carbonate sediments into the deep basin [42]. The fact that subunit *Jmd* is intercalated with pyroclastic rocks probably suggests that arc-related pyroclastic processes was directly influencing the study area, which probably corresponded to the intensified arc-volcanism or that edifices had migrated towards the trench. The new lithologic map (Figure 13) reveals that the coherent subunits become overall younger to the south, which is consistent with that the accretionary prism was growing southward (seaward) and sequentially accreting the trench fills and oceanic crustal materials [46]. Nonetheless, because stratigraphic contacts between the subunits *Trmb*, *TrJmc* and *Jmd* were not observed in the field, it is unable to rule out that, for some periods, the depo-center was a piggyback basin sitting on the accretionary wedge.

Previously, the MG was regarded as a stratigraphic unit or a tectostratigraphic unit that contains ophiolitic blocks, without clearly-defined relationship between the coherent strata and ophiolitic mélanges (e.g., [10,11,16,25]). The field geologic findings and mapping results of this study indicate they are both essential components of an accretionary wedge accreted to south Qiangtang. Therefore, the MG, previously considered as the signature unit of the BNSZ that represents the boundary between the Qiangtang and Lhasa terranes (e.g., [10,11,16,25]) (Figure 1), could no longer represents the suture but a part of south Qiangtang. The actual suture should be located to the south and pertinent studies should be conducted to further clarify this issue.

The coherent strata and mélanges of the MG, seemingly chaotically coexisted, were actually organized into an overall south-vergent fold-and-thrust system of the accretionary wedge, as revealed from the new lithologic map (Figure 13). This understanding could provide critical

background information for interpreting the origin and emplacement mechanism of various types of ophiolites reported from the BNSZ, because previous studies were mostly petrology- and geochronology-oriented [18–23].

5.2. Generalized Lithologic Mapping Methodology

The generalized procedures of lithologic mapping based on field geologic study and ASTER imagery, exemplified by our case study from Gaize, Tibet, are summarized in Figure 3. Field data collection and ASTER data analysis are emphasized as two interdependent parts of this framework. Lithologic discrimination could hardly be achieved merely based on the remotely-sensed data. Field investigations to establish refined lithologic classification and structural relationships are prerequisite for the ASTER data analysis. Moreover, preliminary ASTER interpretation conducted before a field study enables a better targeting for the field study, while the ASTER interpretation revised after the field study could in turn improve the understanding of field facts, because ASTER images enable a more informative visualization of the spatial distribution pattern of geologic features [4,54,55]. The mapping methodology has the advantage of being spontaneous in areas like Tibet that is mostly poorly-vegetated, less-accessible due to the high altitude and poor transportation conditions and, more importantly, lacking precise and detailed geologic maps [4].

In the sequence of procedures (Figure 3), pre-processing of the ASTER L1B data is standard and critical for followed analysis and serves to eliminate the unwanted effects on the image spectra mainly arisen from cross-talking, topographic irregularities and atmospheric interference [33,34,56]. The pre-processed ASTER spectra are supposed to be comparable to laboratory spectra and are mostly used as qualitative references for interpreting corresponding mineralogic assemblages (e.g., Figure 8 in this study [3,5,56]). Nonetheless, quantitative analysis of ASTER image spectra were also demonstrated to be useful in discriminating subtle spectral differences among minerals, for example, the Al-OH absorptions of muscovite, kaolinite and dickite [54–56].

Band ratio and false color composite are two basic methods applied here for matching spectral signatures with lithologic types [5,34,55]. We suggest a processing sequence of first TIR bands followed by VNIR and SWIR bands. The TIR bands and indexes can subdivide the base rock exposures into three dominant groups, namely quartzose rock, quartz-deficient rock and carbonate [2] (Figure 9). Although the relative lower resolution (90 m) of the TIR band limits their utility in accurately mapping the groups, they can be used as references for subsequent reflectance spectra analysis [55]. As for the VNIR/SWIR data, numerous band ratios have been applied successfully in identifying the spectral signatures of Fe^{3+} , Fe-silicates, carbonates and Al-OH and Mg-OH bearing minerals [3,5,33,34,36,55]. However, it is worthwhile to note that only part of major rock-forming minerals, e.g., amphibole, muscovite and calcite, are potentially identifiable based on the band ratios. Moreover, a great number of minerals with significant VNIR/SWIR signatures are subordinate and could be imposed by later hydrothermal and/or metamorphic processes, which could be either lithology selective or not. As a result, there are possibilities that different lithologic types with similar subordinate mineralogic assemblage could be misinterpreted as the same type. Although in situ field observation is probably the only way of solving this problem, the TIR signatures may provide useful constraints. For example, in this study subunit *Trmb* is mainly characterized by a strong Al-OH absorption induced by secondary sericites (Figure 6B) and shows very similar VNIR-SWIR signatures to the *Tp* alkaline intrusion (Figures 10 and 11). They were separated by the fact that the *Trmb* sandstones have much higher QI value than the *Tp* intrusion, because of the combined TIR signature of quartz and sericite in the former and the quartz-free nature of the latter (Figure 9). The fact demonstrates that integrated analysis of both VNIR/SWIR and TIR data is of paramount significance for correctly discriminating lithologic types.

The data processing methods applied here (i.e. band ratio and color mapping methods) are considered as qualitative in comparison to the more quantitative methods, such as principal components analysis (PCA), supervised or unsupervised classification and match filtering [3,5,36,55,56]. Besides, quantitative thresholds have been proposed for some band ratios (e.g., [56]). The quantitative

methods have all been demonstrated to be effective in lithologic discrimination [3,5,36,55,56] and, because they are more data-driven, they are considered to be able to generate more objective results. However, based on our limited experiences, the results may be less intuitive and be complicated by unexpected effects related to talus, soil cover and mixing of lithologic types at varied scales. No matter qualitative or quantitative methods are applied, the ultimate goal of ASTER spectral analysis is to provide an effective tool assisting geologists to acquire lithologic information. Moreover, according to the demand of many geologists, as we know, the capability of presenting results that could be directly related to lithologic information is one of the essential conditions of evaluating the goodness of a remote-sensing data analysis method and band ratios are considered as simple and easy to use, because they are designed to highlight spectral signatures that directly reflects chemical compositions of rocks. Finally, considering that geology is always complicated, a realistic lithologic interpretation of the graphic presentation of ASTER data analysis, either qualitative or quantitative, is only possible if the geology could be well-understood based on detailed field observations and interpreter's geologic experiences are critical to realize the goal.

Remote sensing images are important tools for assisting geologic mapping. In this paper, the generalized procedures of ASTER data processing and spectral characterization are shown to be effective in lithological mapping, as long as lithologic and structural controls could be achieved along one or two profiles. It is not a more precise way of mapping in places like Tibet that has experienced such a complicated evolution history [7] and could never replace the traditional field mapping method. However, it is probably a way more economic and less time- and labor-consuming without much deteriorating the mapping accuracy.

6. Conclusions

In this paper, based on a combination of field study and ASTER imagery analysis, we mapped out a traverse across the Bangong-Nujiang suture zone (BNSZ) in Gaize, Tibet. Field study along the traverse indicated that the Muganggri Group (MG), as the signature unit of the BNSZ, represents an accretionary wedge accreted to the south margin of Qiangtang, resulted from the northward BNO subduction [17]. The MG was subdivided into four sedimentary subunits, in terms of lithologic and sedimentological features and one mélangé subunit. These subunits, along with other younger rock units (Cretaceous and Tertiary), were shown to be distinctive in terms of ASTER spectral signatures and, therefore, discriminable based on the band ratio methods. In particular, we propose a data process sequence that the ASTER TIR bands are processed first to general the images of Quartz, Mafic and Calcite Indexes to reveal distribution of prominent lithologic types, including quartzose rock, quartz-deficient rock and carbonate and establish references for followed lithologic matching. The VNIR/SWIR band-ratio indexes are then demonstrated to effectively highlight spectral features related to lithologic composition of Fe^{3+} , Fe-silicate, Al-OH, Mg-OH and carbonate. Thereafter, by means of false color images, we established the criteria for discriminate the lithologic units. The resultant lithologic map reaches a scale of 1:50,000 and, more importantly, it is the first attempt mapping the MG as five subunits and rendering more detailed lithologic information across the BNSZ. The generalized procedures of lithologic mapping are demonstrated to be applicable for future studies in not only lithologic mapping but other related geologic subjects in the Tibetan plateau.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASTER	Advanced Spaceborne Thermal Emission and Reflection
BNSZ	Bangong-Nujiang suture zone
BNO	Bangong-Nujiang Tethyan ocean
MG	Mugangri Group
FCC	False color composite

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