Mapping of ophiolites: A study in the Indus Suture Zone of north-western Himalaya, using IRS-1C/1D data

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Ophiolites, which have been tectonically emplaced along continental margins and island arcs, are significant to the understanding of mountain belt evolution. At the same time mapping of ophiolites in the hostile and inaccessible mountainous terrains of Himalaya has always posed a great challenge to geologists. The emphasis in the present study is on the mapping of the geological features especially the lithological inferences in the Nidar Ophiolitic Complex of the Indus Suture Zone of the Ladakh and Karakoram range of NW Himalaya using high resolution IRS-1C/1D satellite data and refinement of the existing geological maps. While the published geological maps show sequential distribution and occurrence of a number of litho-units, the satellite images have helped not only in delineating the lithological boundaries more precisely but also in demarcation of a number of sub-units within the already mapped litho-units. The study shows that the outcrops of the dissimilar lithological units are better delineated on satellite data-based map and hence can be used to refine the existing map of the terrain.

GEOLOGICAL mapping in the hostile and inaccessible mountainous terrains of the Himalaya has always posed a great challenge to geologists. Nevertheless, a number of geologists have undertaken such arduous mapping expeditions in the past and prepared excellent geological maps of these terrains. However there always existed disputes on the accuracy of lithological boundaries and structural details in these maps. This is not surprising because many of these boundaries and structural features were completed through extrapolation and/or interpolation as the ruggedness and inaccessibility of a large part of the terrain forbids physical examination of every outcrop. It is in this context that the potential of remote sensing is appreciated. The greatest advantage of the satellite image is the synoptic view it provides, which gives a regional and integrated perspective of and interrelations between various land features such as lithological variations, geological structures, landforms, vegetation cover, drainage pattern, etc. which can be better perceived on the image than on the ground. This is of greater relevance in the inaccessible and difficult terrains of the Himalaya, especially in the cold barren desertic conditions of the Greater and Trans-Himalayan

regions where the rocks are directly exposed to the satellite sensors without interference from the vegetation components. Easy availability of multispectral and high resolution data and advanced capabilities of digital image processing techniques in generating enhanced and highly interpretable images have further enlarged the potential of satellite remote sensing in delineating the lithological contacts and geological structures in greater details and with better accuracy. The objective of the present study is to map the geological features and to gather lithological and structural inferences of the Zildat and Nidar Ophiolites in the inaccessible terrain of the Ladakh and Karakoram range of north-west Himalaya, using high resolution IRS-1C/1D satellite data as an attempt to improve the existing geological maps.

The study area falls in the Trans-Himalayan range of the Indus Suture Zone (ISZ) where the two crustal plates, the Indian and Asian, collided during the Tertiary orogeny of the Himalaya (Figure 1). The ophiolitic suite of rocks seen along this suture zone from Hanle in the south-east to the Dras-Kargil sector in the north-west marks the remnants of the compressed uplifted wedge of the oceanic crust between the two colliding continental masses. These ophiolites are temporally and spatially correlated with the culminating phase of the Himalayan orogeny. The Indus River flows to its north, separating the ophiolite from the Trans-Himalayan litho-units (Figure 2). This belt enjoys cold and arid climate with summer temperatures showing a large range between subzero in the night and a maximum of 30°C in the day. Winters record a very low trend in the two extremes. Except a few grassy and cultivated patches, the area is devoid of much vegetation. Higher slopes are snow-covered and supply the snow-melt water mostly as subterranean drainage. The foothills and valleys are covered by alluvial and colluvial deposits.

Ophiolites, which have been tectonically emplaced along continental margins and island arcs, are signifi-

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Figure 1. Location map of the study area.
Figure 2. Regional geological map of the area. (Inset) the study area (after Thakur and Misra10).

cant to the understanding of mountain belt evolution. They also provide an insight into the structural, petrologic and geochemical attributes of oceanic lithosphere and thus a better understanding of the processes that form the lithosphere. Earlier workers have attempted application of satellite data for mapping ophiolites. Landsat Thematic Mapper (TM) data have been used to improve the existing maps of the extensive Oman ophiolite1-2. This study has also shown that many of the discrepancies found between the published maps of Oman ophiolite and those derived from the imagery, as proved through subsequent field work, were entirely due to omissions or errors in the earlier maps. Landsat TM data have also been used to evaluate the lithologic mapping capabilities over the ophiolite melange zones in the Meatiq dome area in the hyper-arid Eastern Desert of Egypt3,4. The results have demonstrated that appropriate image enhancement of Landsat TM data can significantly improve lithologic discrimination on the image and thus aid field observations for lithologic mapping of large areas in arid regions. In a study on Alaskan ophiolites5, it has been observed that certain

Landsat TM false colour composites exhibited in red, green and blue were useful for visually distinguishing the various constituents of the ophiolites. The study of Tibetan ophiolites6 also highlighted the usefulness of TM data in differentiating the major mafic and ultramafic units. In this study, the decorrelation stretch and band ratio image enhancement techniques have been applied to a Landsat TM scene covering the inaccessible Xigaze ophiolite of southern Tibet. Landsat TM data have also been used to map the ophiolitic belt in a densely vegetated terrain in Manipur along the Indo-Burmese border7. Various FCCs including those of Principal Component Analysis and Brightness Index have highlighted the ophiolite in certain parts of the belt. In this context, the present study is an attempt in the mapping of ophiolites using Indian Remote Sensing Satellite data.

The ISZ marks the boundary between the Indian and Eurasian plates8. It probably represents the remnants of Neo-Tethyan Sea, when the latter closed as a result of northward subduction under the Eurasian plate. The ophiolitic rocks in this suture zone are composed of
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chaotic blocks of schistose basic volcanics, agglomerates, amygdaloidal basalt, chlorite schist, deformed conglomerate schist, glaucophane schist, slate and large lenses of pelagic limestones dispersed in a turbiditic matrix\textsuperscript{5–12}. The other major units of this zone include the sedimentary sequences of the Indus and Kargil formations consisting of conglomerate, sandstones, siltstones and shale. The published geological maps of this area show existence of a number of lithological units such as the Zildat ophiolitic melange, Nidar Ophiolitic Complex (NOC), Kargil and Indus Formation, Ladakh plutonic complex and the Puga Formation (Figure 2).

The IRS-1C-LISS-III sensor provides data in four bands: two bands in visible (green: 0.52–0.59 and red: 0.62–0.68 microns), one band in near infrared (NIR: 0.77–0.86 microns) with a spatial resolution of 23.5 m and one band in short-wave infrared (SWIR: 1.55–1.70 microns) with a spatial resolution of 70.5 m. The pan-chromatic data of IRS-PAN camera have a high spatial resolution of 5.8 m. The data used in this study include IRS-1C-LISS III (2 November 1996) and IRS-1D-PAN (5 July 1997). Apart from this, the Survey of India topographic maps and the geological map of the region prepared by Thakur and Misra\textsuperscript{10} as the reference map have been used. The IRS-LISS-III and PAN data have been merged and the product has been digitally processed for feature enhancement and interpretation.

The IRS-LISS-III data have been visually studied to understand the regional geological set-up and the landform and land cover pattern of the area. A subscale of 940 km\textsuperscript{2} area covering Nyoma, Nidar and Kyun Tso regions was extracted from the digital data. Initially Band 4 (SWIR band of 70.5 m resolution) was resampled and registered with the first three bands (23.5 m resolution) of LISS-III data. Subsequently, IRS-PAN data (5.8 m resolution) have been rectified and registered with the IRS-LISS-III data. A number of standard image enhancement techniques\textsuperscript{13} were tested for their ability in the discrimination of known lithologic units in the Nidar ophiolite area. These included contrast stretching, band ratioing, principal component (PC) analysis, edge enhancement (using Sobel edge operator), IHS transformation, decorrelation stretching and finally colour compositing of the output bands. Of these, the decorrelation stretching edge enhancement and IHS transformation were found to be the best techniques for enhancement of features of the area.

The Sobel edge detection filters were used on red and near infrared IRS bands for the feature enhancement. In this filtering technique, two 3 × 3 templates were used to calculate the gradient value in two perpendicular directions. In the present case the following filters have been used and the computation was made using the relationship:

\[\text{Sobel gradient} = \sqrt{X^2 + Y^2}\], where \(X\) and \(Y\) are the outputs of the following linear operators:

\[
\begin{align*}
X &\Rightarrow -2 & 0 & 2 \\
Y &\Rightarrow 0 & 0 & 0 \\
-1 & 0 & 1 & -1 & -2 & -1
\end{align*}
\]

Decorrelation stretching has been carried out to force the variance between multispectral image channels to be maximized using a PC transform\textsuperscript{14}. In the present case the red and near-infrared bands of the IRS data have been decorrelated. Though the resulting image is quite similar to the original image, maintaining the average grey level and dynamic range, the details have been improved, especially in areas which were 'uniform' in colour in the original data (i.e. correlated).

PC analysis is a data compression and decorrelation technique by which the information content (variance) in several correlated bands is extracted and redistributed in a few uncorrelated bands or PCs. PC analysis involves a linear transformation that rotates and translates the original \(n\)-dimensional image vector to a new coordinate system whose axes are not correlated\textsuperscript{13}.

The IHS transformation converted red, green and blue image channels to intensity, hue and saturation image channels. This is found to be useful for enhancing and controlling the output colours for the given set of input red/green/blue imagery. In the present case IRS-LISS-III bands 2, 3 and 4 were subjected to IHS transformation and then the Intensity component (I) was replaced by PAN data and transformed back to RGB.

The digitally processed data were then contrast enhanced and displayed as colour composites (FCCs) of various combinations and the best combinations which show maximum discrimination between litho-units in distinct colour tones were selected for visual interpretation. The following combinations have been used for visual interpretation:

(a) Contrast enhanced FCC of LISS-III bands NIR (4), red (3) and green (2) in RGB (Figure 3);
(b) Combination of edge enhanced PAN, NIR (4) and red (2) in RGB;
(c) Combination of edge enhanced PAN (in red) with hue and saturation components from the IHS transformation of bands 2, 4 and 5 (in green and blue);
(d) Combination of edge enhanced PAN (in red) PC-1 of PC analysis using all the LISS-III bands (in green) and saturation image from IHS transformation of bands 2 and 5 (in blue) (Figure 4).

Hard copy outputs of these images were used to differentiate litho-units within single ophiolite exposures and also to relate litho-units between exposures. In the present study the constructive use of the LISS-III and PAN data with appropriate ground data has provided a wealth of information about the detailed geology of this region.
The detailed visual analysis of the digitally processed images has shown that refinement of the lithological boundaries is quite possible using the enhanced IRS data. Differentiation of the rock units is essentially based on their spectral differences that are manifested on the image in the form of colour or tonal variations. Morphologic features such as drainage density and texture are supplementary features that help differentiate rocks. In this study the lithologic units that are delineated include bodies of rocks that (1) consist predominantly of one lithologic type or combination of types, (2) are characterized by a distinctive and extensively homogeneous spectral reflectance, (3) have easily perceivable boundaries, and (4) are large enough to be represented on a geologic map.

The geologic interpretations were carried out on overlays superimposed on a variety of digitally enhanced colour composites. It was found that these colour composites clearly differentiated the ophiolite rock types and they were most easily interpreted due to the direct relationship between image colour and spectral response of litho-units in different bands and also due to the effect of topography in the image as indicated by shadow.

The Nidar ophiolite area exhibits considerable topographic relief within the elevation ranging between 4200 and 5625 m. The high relief of approximately 1400 m and steep slopes typically in the range of 25–45°, reaching even to vertical pose some difficulties in accurately interpreting the image data. In an attempt to improve the existing maps of the extensive Oman ophiolite, Rothery1 and Abrams, Rothery and Pontual2 have demonstrated that a decorrelation stretch applied to TM data clearly displayed colour variations associated with bedrock lithology that was not excessively affected.
by slope variations and under conditions of thin vegetation or soil cover. Similar conditions exist in the well-exposed NOC too.

It is important to note that one of the significant factors influencing the interpretation of IRS data in this region is the combined effect of organic and inorganic coatings on the rock outcrops. These coatings influence the spectral signature of lithologic units measured by the satellite sensor. Each surface contamination pulls the spectral signatures away from that of the pure exposed rock in a unique direction and causes extensive spectral overlap of otherwise distinct lithologic units. Another major factor influencing interpretation of the IRS data is the debris material mixing due to both down-slope and glacial transport. Though the ophiolites are spectrally distinct from the enclosing rocks, sub-pixel contamination by snow, surface oxide coatings, organic coatings and severe topography limit the discrimination of lithologic units within the ophiolites. It has been shown that small amounts of vegetation on rocks can greatly affect the reflectance, particularly for near-infrared wavelengths at which the reflectance due to chlorophyll in vegetation is very high compared to typical rock reflectance. Incidentally the rocks in the Nidar ophiolite region have no significant vegetation cover. Therefore vegetation interference was least during the interpretation. On the other hand, mineral staining is much more conspicuous within the gabbro and the spectral differences between ophiolite rock units are also due to the mineral composition of the weathered rock surfaces.

The distribution of litho-units as mapped on the satellite images is shown in Figure 5. The major lithological units occurring in this area are the Ladakh plutonic complex of rocks (predominantly granites), the Indus and Kargil formations (sedimentary), the rock units of the NOC (i.e. the volcanics with chert and jasper, gabbro, ultramafic rocks) and finally the Zildat ophiolitic

![Image of a lithological outcrop map](image)

**Figure 5.** Lithological outcrop map prepared using digitally processed IRS-IC-LISS-III and PAN data showing 1. Ladakh Plutonic Complex; 2. Kargil Formation; 3. Lian Molasse; 4. Indus Formation; 5. Chert, jasper and clastics; 6. Volcanics; 7. Gabbro; 8. Dunitic; 9. Ultramafic; 10. Alluvium/colluvium; 11. Zildat Ophiolite Melange; 12. Lake; 13. Stream; 14. Unclassified (refer to Figure 2 also).

![Image of depositional contact](image)

**Figure 6.** a. Depositional contact of chert, jasper of clastics with Indus Formation (IF) as observed on digitally processed satellite image; b. Closeup view of Lian Molasse (LM) as observed on digitally processed satellite image.
melange. In the present study only the outcrops of the individual litho-units have been mapped and the lithological boundaries have not been interpolated (Figure 5). Though the earlier published map has clearly defined the boundaries of the above units (Figure 2), the present study shows that delineation of the boundaries of dissimilar lithological units in the area is not as simple as depicted earlier. For instance, in Figure 2 the volcanics are shown as a single unit within the NOC, while using the satellite image a subunit of chert, jasper and clastics could be clearly delineated within this unit (Figure 6a). Similarly the Lian Molasse (an equivalent to Kargil formation), which is missing in the earlier map could be clearly demarcated on the image (Figure 6b). Also the dunes could be separated as a unit within the ultramasics of the NOC using the satellite data. There are also units which are quite distinct from the associated litho-units and these are represented as unclassified units in the interpreted map. A detailed field examination only can confirm their association with the surrounding rock units and classify them accordingly.

Multispectral satellite data are commonly used to deduce surface cover characteristics. The focus of the study has been to determine the extent to which IRS-IC/1D data can be used to delineate the ophiolites and to map the lithologic variations within and around them. It has been observed that the high altitude cloudless skies and the arid and unvegetated environment provide the best possible conditions for the use of satellite data for lithological mapping. The synergistic use of the data provided by four spectral bands of the IRS-1C/1D LISS-III sensor with the high-resolution panchromatic data of the PAN sensor has been helpful to differentiate the main rock types of the Nidar ophiolites. The most striking contrast between the image-based lithologic map and the lithologic information contained in the earlier map is that there is considerable increase in details shown in the image-based map. While there is reasonable congruity between the two maps, there are discrepancies in lithologic boundaries between the two, which are probably due to extrapolations made in the earlier map, where the rugged nature of the terrain rendered mapping inaccessible outcrops difficult. An improved version of the lithologic map (Figure 5) for the Nidar area has been prepared using the colour composite images as a mapping base. This gives a more precise synopsis of the distribution of lithologies compared to the previously published maps. Some features existing on the image-based map which do not appear in the previous map demand further field verifications. The high-resolution IRS data are remarkably useful for studying remote, inaccessible regions such as Nidar, where field studies are logistically arduous and expensive. The information on lithological distributions and structures obtained from interpretations of the IRS 1C/1D images in conjunction with ground data is being used to strengthen the ongoing studies of the ophiolites of the ISZ.


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