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A review paper synergistic approach to evaluate the mineral resources : A new perspective

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Abstract
India has a variety of geological – tectonic domains on its landmass of 3.2 million km, which evolved through the entire course of geological past and developed varied mineral potential. India has an important heritage of mining dating back to prehistoric times, which continues to this day.
The process of finding a concentration of minerals is called mineral exploration. Mineral exploration can be complex and has numerous stages; Mineral exploration and geological mapping through conventional geological techniques are tedious, expensive and time-consuming. Mapping and targeting an economic deposit through traditional techniques involves extensive fieldwork, structural mapping, study of landforms, petrography, mineralogy and geochemical analyses.
With the advent of multispectral sensors (e.g. ASTER, Landsat) having bands in the Shortwave Infrared (SWIR) and Thermal Infra-Red (TIR) regions, lithological discrimination and mineral potential mapping were possible from space/airborne platforms. Synergistic approach is the approach in which multiple approaches' used to detect or evaluate mineral resources.

Keywords: synergistic approach, mineral exploration, hyperspectral analysis, radar data, spectral signature, multispectral sensor

Introduction

Mineral exploration is a backbone of economy for any states or countries. Mineral exploration can be complex and has numerous stages; Mineral exploration and geological mapping through conventional geological techniques are tedious, expensive and time-consuming. Mapping and targeting an economic deposit through traditional techniques involves extensive fieldwork, structural mapping, study of landforms, petrography, mineralogy and geochemical analyses.

These techniques need a strong laboratory database to discern slight variation in composition of ore grades. With the advent of multispectral sensors (e.g. ASTER, Landsat) having bands in the Shortwave Infrared (SWIR) and Thermal Infra-Red (TIR) regions, lithological discrimination and mineral potential mapping were possible from space/airborne platforms. However, detailed understanding on precise mineral composition and relative abundance of constituents within Field of View (FOV) was not possible with these data due to coarse bandwidth and poor spectral contiguity. However, when spectroscopy, radiometry and imaging techniques were bundled as imaging spectroscopy, limitations of multispectral remote sensing were overcome.

The Hyperspectral sensors on the other hand, are capable of acquiring images in 100–200 contiguous spectral bands. This ability to acquire laboratory-like spectra from an air/space borne sensor is a major breakthrough in remote sensing. As a result, hyperspectral sensors provide a unique combination of both spatially and spectrally contiguous images that allow precise identification of minerals. Over the last two decades, mineral mapping and lithological discrimination using airborne hyperspectral sensors like AVIRIS, HYDICE, DAIS, HyMAP have been extensively attempted.

The use of radar images in geological surveys is a well-established procedure, and has been employed in several studies in the moist tropics, such as integrated, multisource data procedures, monoscopic and stereoscopic visual analysis, and digital classification based on textural attributes. In all these cases, the data were analysed based on the amplitude or intensity of the backscattered signal. These approaches exploit primarily the brightness and texture of the images in different configurations of viewing geometry, polarization, and frequencies.

However, when using intensity, only part of the signal attributes is available for deriving target information. This limitation can be overcome through the use of polarimetric data, on which intensity and vector phase representing the electromagnetic wave polarization of each pixel are fully measured and recorded. Techniques based on the target decomposition theory and statistical properties of the backscattered signal constitute the primary approach to the radar polarimetric classifications, which are used mainly in environmental applications, particularly for forest type classifications. On the other hand, geosciences applications using polarimetric data are still scarce in radar literature, given that this kind of data has only become available with the advent of ALOS (2004) and RADARSAT-2 (2007) satellites.

Methodology and Results

Beiranvand *et al*., 2015 [1]. tried to find out the applicability of data from the recently launched Landsat-8 for mapping hydrothermal alteration areas and litho- logical units associated with porphyry copper exploration in arid and semi-arid regions. For this author selected Sar Cheshmeh copper mining district in the Urumieh-Dokhtar volcanic belt in south-eastern Iran.

Cloud-free level 1T (terrain-corrected) Landsat-8 images were used in this study. The Landsat-8 image of the target site was processed with Environment for Visualizing Images version 4.8 software. Landsat-8 data were converted to surface reflectance by the internal average relative reflection method, which is recommended for calibration in mineralogical mapping, as it does not require prior knowledge of samples collected in the field. The 90-m resolution TIR bands were re-sampled to correspond to 30-m spatial dimensions for some image processing applications. Nearest neighbour re-sampling was used to preserve the original pixel values in the re-sampled images.

Several red–green–blue (RGB) colour combination images and band ratios were created with Landsat-8 bands based on laboratory spectra of the minerals related to hydro thermal alteration and lithological units. Different colour combination images were used to enhance hydrothermally altered rocks and lithological units at regional scale. Band ratios are useful for highlighting certain features or materials that cannot be seen in raw bands.

Analytical imaging and geo-physics Hyperspectral analysis processing methods were applied to Landsat-8 bands to map hydroxide and carbonate mineral assemblages in hydrothermal alteration zones and documented with Environment for Visualizing Images software.

The data were analysed by this approach to determine unique spectral end-members and their spatial distribution and abundance and to produce detailed mineral maps.

The analysis consisted of the following steps: spectral compression, noise suppression and dimensionality reduction by minimum noise fraction transformation; spatial data reduction with the pixel purity index; extraction of end-member spectra with the n-dimensional visualizer identification of end-member spectra by visual inspection, automated identification and spectral library comparisons and production of material maps with a variety of spectral mapping methods, including spectral angle mapper, linear spectral unmixing, matched filtering, mixture-tuned matched filtering(MTMF), spectral feature fitting and binary encoding.

Sridhar M *et al*., 2015 [7]. In this study author's discussed generation and validation of a geological model for uranium exploration by integrating geological, geochemical, geophysical and remote sensing datasets along the south central margin of Chhattisgarh Basin. A knowledge driven integrated Geographical Information Systems (GIS) model has been simulated for uranium exploration by extracting and integrating exploration relevant information viz., heat source, metal source, transport pathways, traps etc. from the spatial datasets.

The present study lies along the south central margin of Chhattisgarh basin and depending on the age of the litho units, lithology and structural favourability, the likely types of uranium mineralisation that can be expected in this geological domain are unconformity related type; vein/fracture controlled type and quartz-pebble conglomerate (QPC) type.

Landsat Enhanced Thematic Mapper (ETM+) digital data sets were utilized in mapping geological structures and lithology, and in identifying anomalous concentrations of hydroxyl & ferrous minerals alteration associated with buried uranium mineralization in the present work.

Several image-processing procedures were attempted on the ETM+ data to identify, isolate and enhance mineralogical information as false color composite. These data sets were processed, analysed & interpreted, and thematic layers of lineament and alteration zone were generated for further integrated studies

Principal component analysis (PCA) is successful tool used in delineating alteration zones (Crosta *et al*., 1989) [3]. In this study, seven ETM+ multi-spectral bands (i.e., 1, 2, 3, 4, 5,6(1) and 7) were used to perform PCA and 7 independent principal components (PC) were extracted. The iron oxide and hydroxyl mineral zones extracted from PCA were classified into in-situ and transported materials utilising Shuttle Radar Topographic Mission (SRTM) elevation data.

Mokhtari *et al*., 2015 [5]. In this research, Image processing techniques were applied on the digital subset ETM+ data covered the Siah-Jangal area. These techniques generated several products of enhanced satellite imagery, such as colour composite images, ratio images and principal component analysis images. These techniques have been successfully used in mapping of hydrothermal alteration and mineralization zones in the study area. The colour composite and band ratio methods show very clearly the hydrothermal altered zones of clay minerals and iron oxides in and around the Siah-Jangal area. The principal component analysis using the Crosta technique also enabled us to represent undoubtedly the altered hydroxyl and iron-oxide mineral zones as well.

Ratio transformations of the remotely sensed data can be applied to reduce the effects of environment (i.e. topographic slope and aspect, shadows, or seasonal changes in sunlight illumination angle and intensity). The ratio image provides unique information and subtle spectral-reflectance or color differences between surface materials that are often difficult to detect in a standard image

PCA application creates a new set of images with reduced spectral redundancy. Principal component analysis is a well-known method for lithological and alteration mapping in metallogenic provinces. Crosta *et al*., 1989 [3] describe a methodology called Feature Oriented Principal Components selection (FPCS) or Crosta technique.

The Crosta technique is applied to six (1, 2, 3, 4, 5 and 7) and two sets of four (1, 3, 4, 5 and 1, 4, 5, 7) and one set of three (1, 3 and 5) bands of ETM+ data in the study area. The covariance eigenvector matrices of the principal component analysis for Crosta technique using six ETM+ bands (1, 2, 3, 4, 5 and 7). Iron oxides are one of the most important mineral groups that associated with hydrothermally altered rocks. These minerals have low reflectance in band 1 and higher reflectance in band 3 of ETM+ data. Based on spectral characteristics of iron oxide, we can predict that iron oxides can be distinguished by dark pixels in the PC3. But in order to display the iron oxide minerals in bright pixels an inverse of this PC is necessary.

Pour *et al*., 2015 [6]. In this paper author's try to evaluate the capability of Advanced Land Imager (ALI) and Hyperion Earth Observing-1 (EO1) data for lithological and hydrothermal alteration mapping. Several image processing methods were applied to ALI and Hyperion images covering the Meiduk and Sar Cheshmeh porphyry copper mining districts, SE Iran. The achievements of this investigation indicate considerable implications for geologists to use Earth Observing-1 data for porphyry copper and epithermal gold exploration.

Two cloud-free level 1B ALI and Hyperion images were used in this study, ALI and Hyperion images of both target sites were processed using the ENVI (Environment for Visualizing Images) version 4.5 software package.

Pre-processing was involved destriping and atmospheric correction. After radiometric corrections, there is still a pronounced vertical striping pattern in the Hyperion data. Desteriping of the Hyperion Level 1B data was accomplished before atmospheric correction.

To correct the atmospheric effects, Atmospheric COR reaction Now (ACORN) software was used to retrieve the surface reflectance. ALI Level 1B data were also converted to surface reflectance using ACORN software.

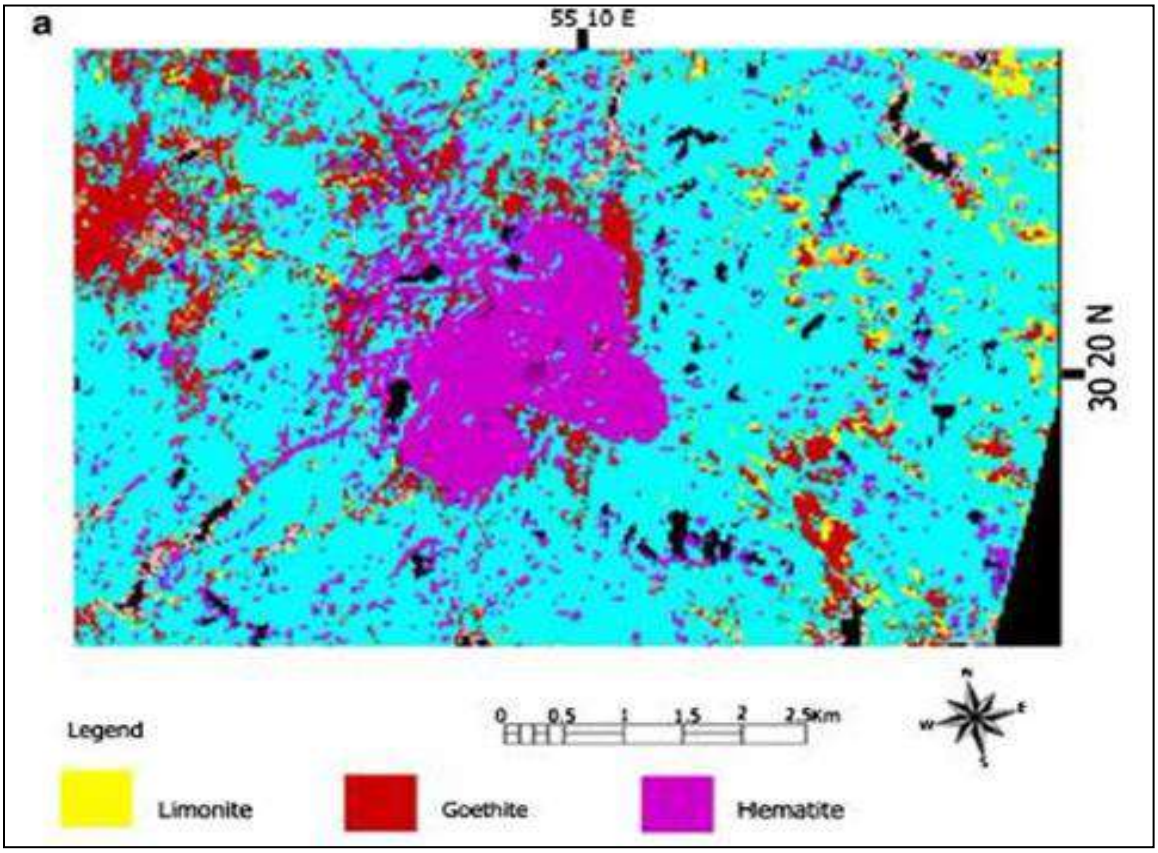

Fig 1: MTMF Visual Result

To evaluate the ALI data, the feature-oriented principal components selection, different band rationing and minimum noise fraction methods were applied for enhancing the hydrothermally altered rocks associated with porphyry copper mineralization, lithological units and vegetation at regional scale.

Spectral angle mapper, linear spectral unmixing (LSU), and mixture-tuned matched-filtering were tested on SWIR bands of ALI to discriminate the hydrothermally altered areas associated with porphyry copper mineralization from surrounding environment at regional scale.

Analytical imaging and geophysics (AIG)-developed hyperspectral analysis processing methods are applied on VNIR and SWIR bands of Hyperion for mapping iron oxide/hydroxide minerals and clay mineral assemblages in hydrothermal alteration zones at district scale.

Geological locations were measured by a Magellan GPS with an average accuracy 7 m. The field photographs of the geomorphology, rock units and hydrothermally altered rocks were taken. Samples for XRD analysis and spectral reflectance measurements were collected from two sites within the open-pit quarry of the Meiduk and Sar Cheshmeh mines and surrounding areas in December 2010.

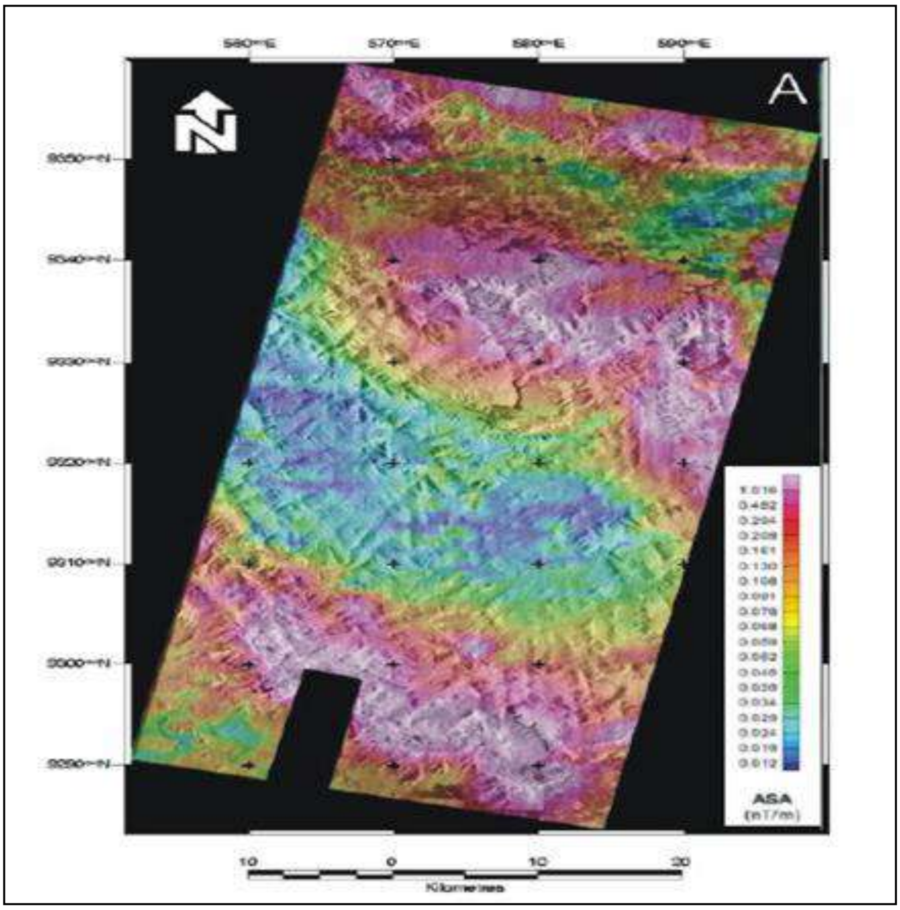

Fig 2: MAPSAR fused with Magnetometric Image

Spectral angle mapper (SAM), linear spectral unmixing (LSU) and mixture-tuned matched-filtering (MTMF) methods were performed to discriminate hydrothermally altered rocks from unaltered rocks at regional scale.

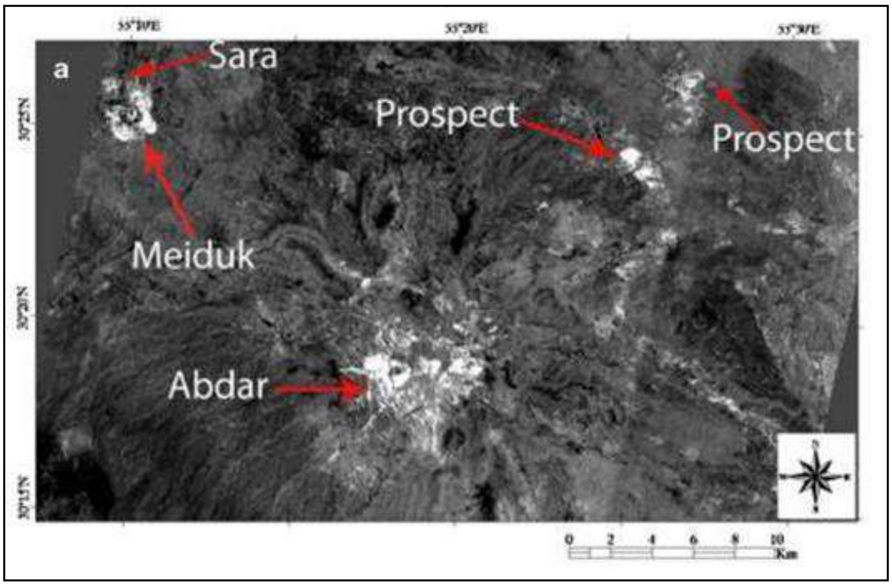

Fig 3: SAM Result

Crosta *et al*.,2007 [2]. This paper presents the results of the interpretation of simulated MAPSAR (Multi-Application Purpose SAR) data, integrated with aero geophysical data, over a portion of the Province. The integrated SAR-geophysical data were assessed as auxiliary tools for geological and structural mapping, using data fusion techniques for generating imagery for geological interpretation. SAR images were produced by the SIPAM R99-B system and the airborne geophysical data by the Brazil-Canada Geophysical Project. Prior to fusion, SAR and geophysical data were individually processed for enhancing geological information. The results allowed establishing the relationship between the features extracted from fused images and the main lithologic and geomorphologic domains known in the area.

MAPSAR data were simulated by the R-99B SAR system operating with the same specifications to be used by the future satellite system: L-frequency (23,9cm, 1.27 GHz), multi-polarization (HH, VV and HV), 10m spatial resolution and incidence angle in the range 45o through 53o.

Prior to data fusion with the simulated MAPSAR data, aero geophysical data were processed according the methods described next.

The first step was to examine the data for artifacts which could affect subsequent processing, such as noise in the original digital records. The methods "Fourth Difference" and "P parameter" were employed for this purpose, allowing identifying records with values outside the standard-deviation from the total record population. Both types of data, magneto metric and gamma spectrometric contained such artifacts, which were then identified and eliminated from the data set.

The next step was to remove from the data base the contributions of the IGRF/DGRF (International/Definitive Geomagnetic Reference Field). Magnetic anomalous field and gamma data were then used for generating regular grids with cells spaced of 500m, by interpolating the original data points, thus producing a first set of grids.

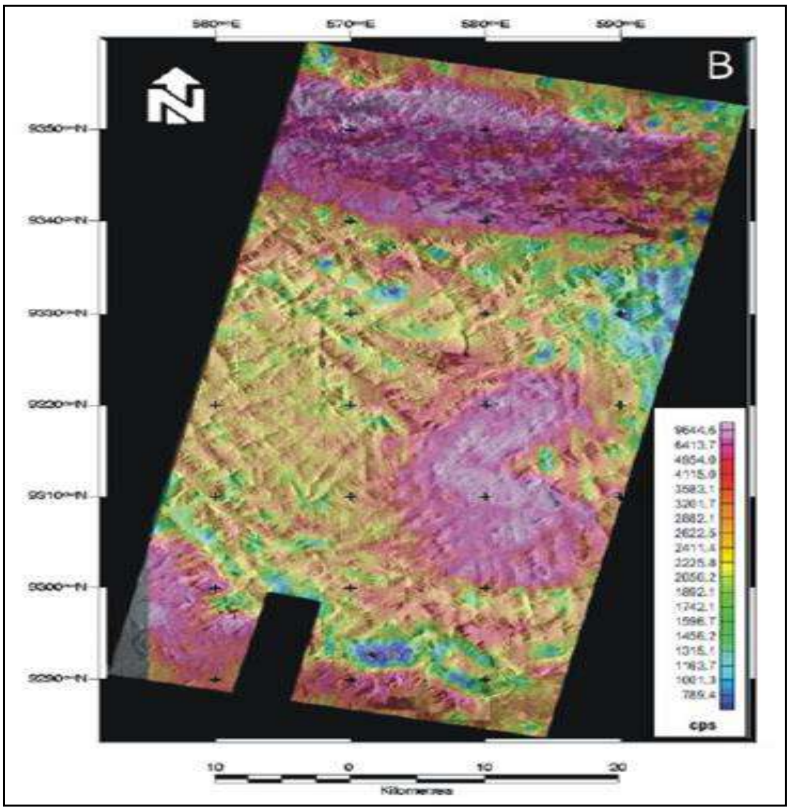

Fig 4: MAPSAR fused with Gammaspectrometric Image

The next step was to apply a micro-levelling technique for correcting small artifacts, proposed by Minty (1991). Magnetic anomalous field was then used to produce an image of the amplitude of the analytical signal (AS). This image depicts the depth of magnetic sources and is useful for positioning magnetic anomalies in relation to their deep sources.

After applying these correction techniques, the data were submitted to interpretation in order to define geological boundaries, structural features, depths of magnetic bodies and other geological features.

Image fusion was applied for fusing simulated MAPSAR data, representing the higher spatial resolution image (10m), with gamma spectrometric and magneto metric data, representing the lower spatial resolution (500m), "spectral" data.

The fused images allowed the analysis of the spatial variation of AAS values, represented by different colors produced with the use of the pseudo-coloring (or color slicing) technique applied on the original black-and-white image, depicting at the same time textural elements due to topographic relief from SAR images as intensity attributes.

Liu *et al*.,2013 [4].

In this study authors evaluate Landsat Enhanced Thematic Mapper (ETM+) and Quickbird data of the study area in mapping lithological units, small intrusions, and alteration zones. False color composites of the first principal component analyses (PCA1), PCA2, and PCA4 in red (R), green (G), and blue (B) of the ETM+ image, and relevant hue-saturation-intensity (HSI) color model transformations, were performed.

This led to the identification of lithologic units and discrimination of granitic intrusions from wall-rocks. A new geological map was generated by integrating the remote sensing results with two internally published local geologic maps and field inspection data.

For the selected region, false color composites from PCA and relevant HSI-transformed images of the Quickbird data delineated the details of small intrusions and identified other unknown similar intrusions nearby. Fifteen separate potash-feldspar granites and three separate hornblende biotite granites were identified using ETM+ and Quickbird data. The principal component analysis-based Crosta technique was employed to discriminate alteration minerals.

Some of the mapped alteration zones using the Crosta technique agreed very well with the known copper deposits. Field verification led to the discovery of three copper mineralization and two gold mineralization for the first time. For this study authors were used Landsat 7 ETM+ data and Quickbird data for the selected area. Pre-processing of the satellite imagery included both geometric and radiometric corrections.

The images were geometrically corrected by picking ground control points (GCPs) from 1:50,000 scaled topographic sheets and GPS points that were taken during field work. The radiometric correction was implemented using the method in which calibrated Digital Numbers (DNs) were converted to Top-Of-Atmosphere (TOA) reflectance.

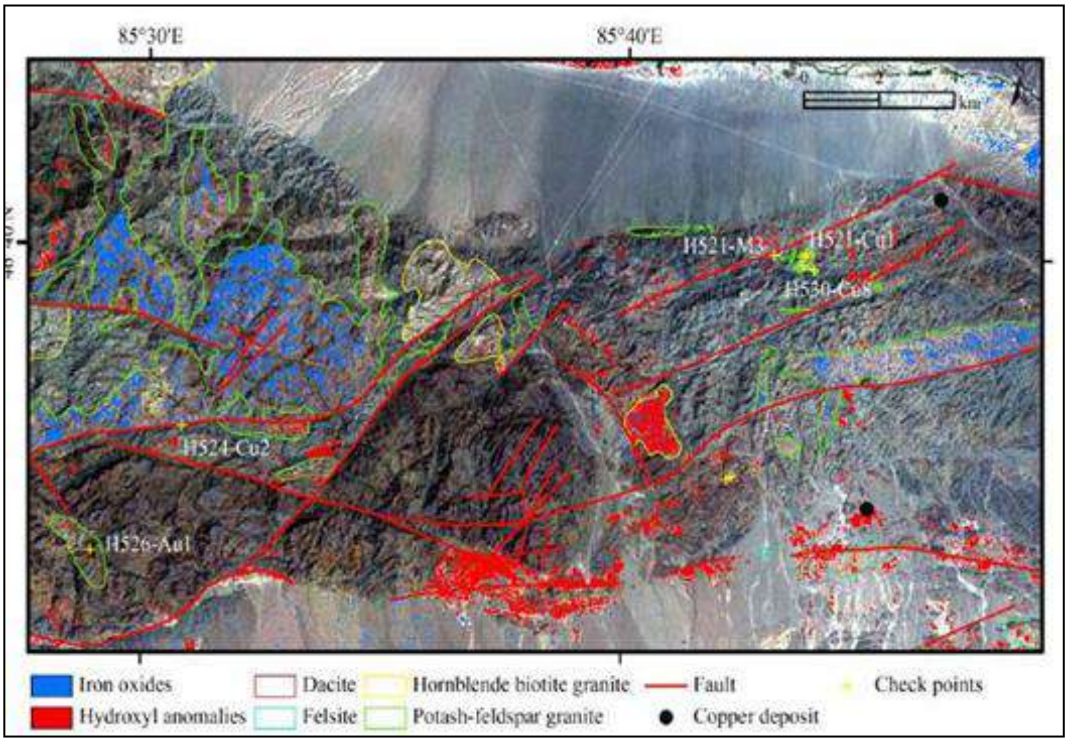

Fig 5: Color Composite Overlaid with the remote sensing anomalies using the Crosta techniques

In this study, a series of image processing methods were used. First, image enhancement methods including principal component analysis (PCA) and HSI color model transformation were applied to process ETM+ data to outline the small intrusions and generate a new geological map for the Xiemisitai area.

Second, for the selected region with small intrusions identified, PCA and HSI color model transformation methods were used to process Quickbird data to delineate the details of small intrusions and find other unknown similar intrusions nearby.

Third, the alteration minerals were mapped using the Crosta technique [7,9,19], a principal component analysis-based method using the association of bands 1, 4, 5, and 7 for extracting hydroxyl-bearing and carbonate minerals and that of bands 1, 3, 4, and 5 for iron oxides.

In targeting new mineralization prospects, the existing geological controls (as derived from the geological map) of the study area were overlapped with the remote sensing results obtained herein. The geology and remote sensing overlaps deduced were verified on the ground through field inspection. PCA and HSI color model transformation methods were used to process Quickbird data to better outline the small intrusions and/or their details.

Discussion and Conclusion

The first spectral band of Landsat-8 (0.433–0.453m) is a deep-blue band designed for studies of coastal water and aerosols and cannot be used to detect geological features. The textural characteristics of igneous rocks can be discriminated from those of sedimentary rock, and the structural features and sedimentary texture of rocks at the site are readily recognizable with this natural RGB colour combination of the visible bands.

Hydrothermally altered rocks are recognizable as a yellow area in the belt of crystalline igneous rocks, Clay and carbonate minerals have absorption features of 2.1–2.4µm (band 7 of Landsat-8) and reflectance of 1.55–1.75µm (band 6 of Landsat 8). Iron oxides were mapped with bands 2 and 4.

Band ratios derived from image spectra (4/2, 6/7, 5 and 10 in RGB) allow the identification of altered rocks, lithological units and vegetation. Geological features are more visible in the 4/2, 6/7 and 10 band ratio images because of the presence of the TIR band (band 10) in the RGB combination.

The aeromagnetic and airborne gamma ray spectrometric data were taken up for processing and interpretation to establish controls of mineralization and subsurface structures. Total magnetic field intensity data is acquired using a cesium vapor magnetometer (Scintrex make) with a sensitivity of 0.001 nT at every 0.1 s.

ETM+ band combination of 754 in RGB is better suited in discrimination of geologic rock type and soil boundaries, as well as soil moisture content.

The principal components transformation of ETM+ bands 1, 4, 5, and 7 were selected to extract areas of hydroxyl bearing minerals. The bands 2 and 3 have been intentionally eliminated to prevent mapping iron oxides.

Iron oxide/hydroxide minerals exhibit spectral absorption features in the visible to middle infrared from 0.4 to 1.1 μm of the electromagnetic spectrum. Landsat bands 1 (the equivalent to ALI band 2) and 3 (the equivalent to ALI band 4) have been used to map limonite-rich rocks containing limonite, goethite and hematite, which are a potential indicator of supergene deposits. Hence, bands 2 (0.450–0.515 μm) and 4 (0.633–0.690 μm) of ALI contain typical features that can be used to map iron oxide/hydroxide minerals.

Clay minerals have absorption features from 2.1 to 2.4 μm (band 9 of ALI) and reflectance from 1.55 to 1.75 μm (band 8 of ALI) that correspond with bands 7 and 5 of ETM+, respectively. It is evident that bands 2, 4, 8 and 9 of ALI can be used for hydrothermal alteration mapping.

Mapping of iron oxides is carried out using bands 2 and 4 of ALI because iron oxide/hydroxide minerals such as hematite, jarosite and limonite have high reflectance within 0.63 to 0.69 μm (the equivalent to ETM+ band 3) and high absorption within 0.45 to 0.52 μm (the equivalent to ETM+ band 1).

A band ratio derived from image spectra (4/2, 8/9, 5/4 in RGB) has been developed. This band ratio allows the identification of altered rocks, lithological units and vegetation. The alteration minerals (hydrothermally altered rocks) are outlined in the images where they appear as yellow color around known and mined porphyry copper deposits. The locations of the known and mined copper deposits and identified prospects are highlighted. Vegetation is shown as blue color, and lithological units are identifiable as variety of colors in ALI scenes.

MNF transformation is performed to SWIR bands of ALI and Hyperion for detecting hydrothermally altered rocks and lithological units. SWIR bands of Hyperion data were linearly transformed using the minimum noise fraction transformation. The bands 1, 2 and 3 were assigned to RGB by considering the higher eigenvalues.

MTMF (Fig. 1) visual results shows bright pixels which represent hydrothermally altered rocks associated with the known and mined copper deposits and identified prospects in the ALI images.

The SAM method (Fig. 2) highlights the altered areas as hematite dominated (VNIR subset) and sericite dominated (SWIR subset). Hematite is represented as purple pixels and goethite as red pixels, and limonite is portrayed as yellow pixels in Mieduk/Sara subset

ALI and Hyperion data will be used to extract geologic information for hydrothermal alteration and lithological mapping using some selected image processing methods. FPCS, band ratio and MNF methods have yielded spectral information for identifying iron oxide/hydroxide, clay minerals and lithological units using ALI data at regional scale. SAM, LSU and MTMF methods differentiated hydrothermally altered

Rocks associated with the known and mined porphyry copper deposits and identified prospects from unaltered rocks using SWIR bands of ALI. Hematite, limonite, jarosite and goethite were detected in supergene altered area using VNIR bands of Hyperion

Fused SAR+geophysics image products clearly display the boundaries of the main litho geophysical domains known in the study area. Most of these boundaries coincide with conspicuous topographic features, revealing a clear relationship between different lithologies and relief patterns. Geophysical filtering techniques, such as AAS, are quite effective for enhancing magnetic anomalies in low latitude areas, as in the case of the Carajás Mineral Province. In the MAPSAR+Mag/AAS fused image these anomalies can be readily related to surface (relief) patterns.

Variations in the lithologic composition, as well as sharp changes in relief texture caused by different geologic units, can be readily interpreted from the fused SAR+gamma image product.

The comparison between the results obtained by SAR+geophysics image fusion shows that MAPSAR data was able to enhance textural and tonal attributes which were not clearly depicted in higher spatial resolution RADARSAT-1 data. This investigation shows that the integrated analysis of fused MAPSAR+geophysics images is especially useful for geologic mapping.

Standard PCA will be applied to the ETM+ data to enhance the lithological differences. The transformation was applied using the related covariance matrix. The first principal component (PCA1) is composed of a positive weighting from all six bands. PCA1 accounts for 83.8% of the total variance of the data.

From image interpretation, the potash-feldspar granites have relatively high reflectance in band 3 and low reflectance in bands 1 and 2. Authors therefore predict that potash-feldspar granites can be distinguished by bright pixels in PCA4. As suggested by the greatest loadings for bands 5 (−0.581) and 7 (0.511), and the opposite signs, the spectral information of hydroxyls should be contained in PCA5. PCA6 is the noisiest component and does not contain useful information.

The hue-saturation-intensity (HSI) color model allows independent control over hue, saturation, and intensity, the quantities of which are definitely measurable and easily interpretable. Through trial and error studies, transforming some PCA combinations from RGB to HSI space can properly enhance the differences among lithological units.

The Crosta technique (fig. 5) is also known as a feature-oriented principal component selection, which has been widely used in mineral exploration to identify the diagnostic features of hydroxyl minerals, carbonate bearing minerals and iron oxides are been used in this study.

Acknowledgement

We have collected a large set of scientific papers where, for the sake of accessibility for the reader, we have largely restricted ourselves to the journal papers. Inevitably we had to make a selection and hence some papers have been omitted as this is the nature of any review. We apologize to those authors whose papers have not been included. Discussions with various researchers in geologic remote sensing helped in shaping the discussion and conclusion section. We gratefully acknowledge the review of the anonymous referees.

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