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Lithological Mapping of Kimberlite Clan of Rocks Using Airborne Hyperspectral AVIRIS Data in Eastern Dharwar Craton, India

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Abstract
We have utilized the Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) datasets to delineate new kimberlite locations. The objective of this work is to map and locate new kimberlite formations. We applied two classification algorithms, Matched Filtering and Adaptive Coherence Estimator (MF and ACE). The pure spectra from the known kimberlite bodies on the Bhukosh GSI map were used as a reference to map and locate unknown kimberlite bodies. New circular anomalies were found in the image that were similar to the known bodies. SAM classification was performed to map the associated minerals in the image and validate these unknown kimberlite bodies. The unknown bodies' spectral absorption characteristics matched the known kimberlites' pure spectra in the SWIR range. Further, lineaments in the study area were delineated using the two datasets, AVIRIS and ASTER, to find their association with kimberlites.

Keywords
List the keywords covered Kimberlite, AVIRIS, ASTER, MF, ACE

Introduction

The igneous rock group that arises from the mantle-derived magmas and silica undersaturated, rich in Olivine, about 50 modal %, is called Kimberlites. They are potash-rich and deficient in Al_2O_3 (~3.0 wt%), enriched in CO_2 and H_2O. Kimberlites are hybrid rocks of primary magmatic, hydrothermal, and xenocrystal minerals, making it impossible to find the primary melt from the whole composition (Mitchell et al., 2019). Kimberlite and Kimberlite Clan of Rocks (KCR) are diamonds' most significant host rocks. They are known for their potassic and ultrapotassic mafic compositions and are similar to lamproites. These rocks are found worldwide in various Proterozoic and Archean Cratonic settings (Guha et al., 2021). The southern part of India encompasses a large-scale series of Proterozoic rocks above Archean cratons. Later, the Archean craton evolved into three cratons: the Dharwar, Singhbhum, and Aravalli (Naqvi et al., 1974). In the Eastern Dharwar Craton and the Cuddapah basin, many lamproites and kimberlites were laid during the Proterozoic era in the southern part of India (Rao, 2004). According to (Verma, 2000), four major Archean cratons in India are adjoined by rift zones with high heat flow, typically (61-74 Mw/m^2). The basement of these cratons ranges in age from 3.5 to 2.7 Ga (Mahadevan, 1994).

The Dharwar has a basement of 350,000 km^2 and occupies the southern peninsular region (Haggerty and Brikett, 2004). The Dharwar craton is divided into Western and Eastern craton and separated by the Chitradurga boundary fault, which is parallel and adjacent to the contacts in the west of the Closepet Granite (Ravindra and Ranganathan, 1994; Haggerty and Brikett, 2004). Intensely exploring kimberlite and lamproite led to the finding of 55 kimberlite bodies and nine lamproite intrusions in the Western Dharwar Craton region (Haggerty and Brikett, 2004).

The Wajrakarur kimberlite field (WKF) in the Eastern Dharwar Craton is the centre of the study, which lies in the Anantapur district, Andhra Pradesh, India. The WKF contains 31 kimberlite intrusions discovered by the Geological Survey of India (Rao and Phadtre, 1996). Kimberlites of WKF are poor in diamond-bearing. Kimberlites in the study area consist of granites and gneisses of the Eastern Dharwar Craton (Neelkantam, 2001). The kimberlites of the WKF are of middle to late Proterozoic age, ranging from 840 to 1,153 Ma. They are overlaid by a 0.5 to 1.5-meter-thick calcrete layer (Chalapathi Rao et al., 1996).

The formation of serpentine in kimberlite is caused by hydrothermal or meteoric water. If the external fluid contains silica and mixes with kimberlite magma during diapiric extrusion, the serpentine content can increase from 25% to approximately 75% by volume. Parent magma fluid precipitates in kimberlites, which leads to the intrusion of carbonate minerals such as calcite and dolomite (Gaffey, 1986; Schumacher, 2012; Baranval et al., 2022).

ASTER data has become more popular in mineral prospecting due to its vast coverage, relatively inexpensive cost, and unique integral bands particularly sensitive to alteration minerals (i.e., minerals known to surround target minerals). Serpentine and carbonates are associated with Kimberlites, so mapping those minerals will help determine possible kimberlite locations (Pour et al., 2010). The possible kimberlite exploration zone was recently determined using the spectral bands of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which is based on the convergence of lithological, structural, and geomorphic controls of kimberlite emplacement. A potential zone for in-depth investigation was found by combining these geological themes with the surface alteration map and geophysical information (Guha, 2018). The Advanced Visible Infrared Imaging Spectroradiometer Next Generation (AVIRIS-NG) sensor's high spectral and low spatial resolution makes it well-suited for identifying subtle surface anomalies of kimberlite by leveraging the enhanced spectral contrast between kimberlite pipes and surrounding rocks in AVIRIS-NG images (Patel et al., 2019; Baranwal et al., 2022). Utilizing airborne hyperspectral data during optimal seasons with minimal surface cover and high radiant energy can significantly enhance the detection of new surface anomalies linked to kimberlite (Guha, 2023). The AVIRIS's high spectral resolution allows for detecting subtle radiometric variations, ultimately leading to improved identification of the spatially restricted kimberlite pipes. (Baranwal et al., 2022).

The advanced capabilities of the high-resolution AVIRIS-NG sensor, coupled with its extensive spectral bands, have enabled the identification and delineation of all lineaments and lithological features within the study area. A noteworthy observation is that known kimberlite points tend to appear either in proximity to the boundary between two distinct lithological units or near prominent lineaments. Identifying altered minerals, such as carbonates and serpentines, has been made feasible using ASTER data (Guha et al., 2021).

Geographical location and geologic setting of the study area

The research site lies within the Wajrakarur region of the Eastern Dharwar Craton in Anantapur, Andhra Pradesh, at 15.0266° N and longitude 77.3839° E (Fig. 1).

Greenstone belts with intrusive granitoids that range in age from 3.4 to 2.7 Ga make up the Archean Dharwar Craton of Peninsular India. The Closepet granite, which is dated 2518 Ma, has split this craton into Western Dharwar craton (WDC) and Eastern Dharwar Craton (EDC) (Manikyamba and Kerrich, 2012). The Eastern and Western Dharwar craton are separated through the Chitradurga Fault, a boundary Fault. Within the EDC, there are four kimberlite fields: Wajrakarur Kimberlite Field (WKF), Narayanpet Kimberlite Field (NKF), Raichur Kimberlite Field (RKF), and Tungabhadra Kimberlite Field (TKF). Additionally, there are three lamproite fields in the EDC: Krishna Lamproite Field (KLF), Nallamalai Lamproite Field (NLF), and Ramadugu Lamproite Field (RLF) (Kaur et al., 2013).

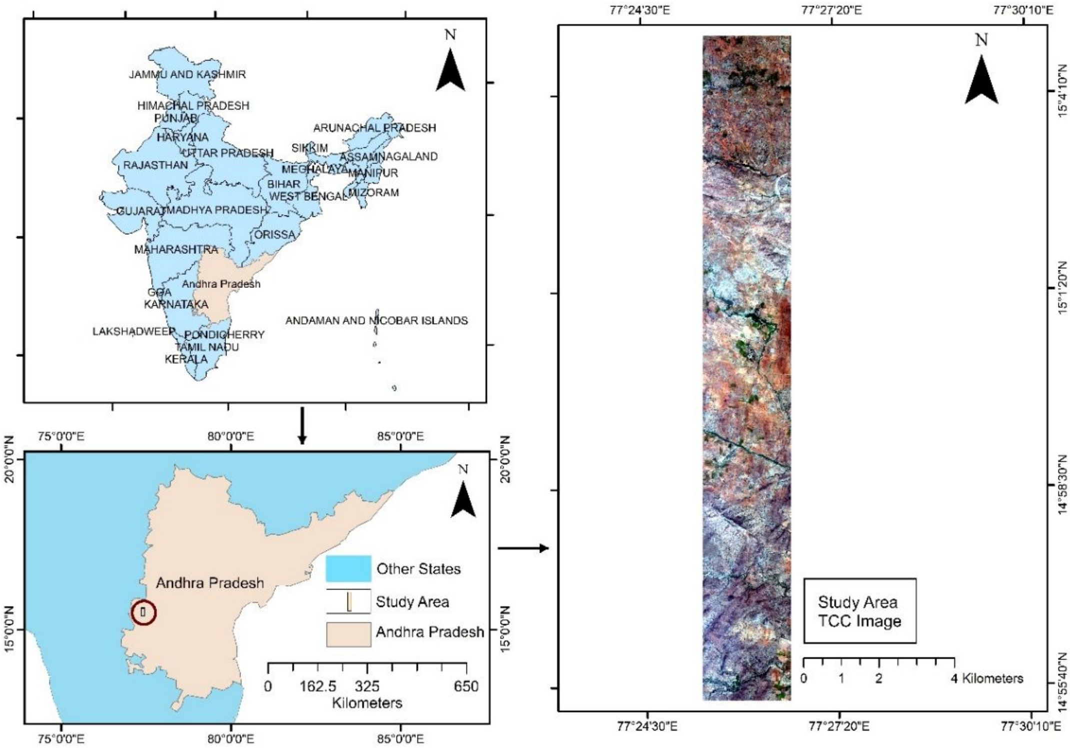

Fig. 1. AVIRIS True color composite image of the study area (own processing based on AVIRIS data)

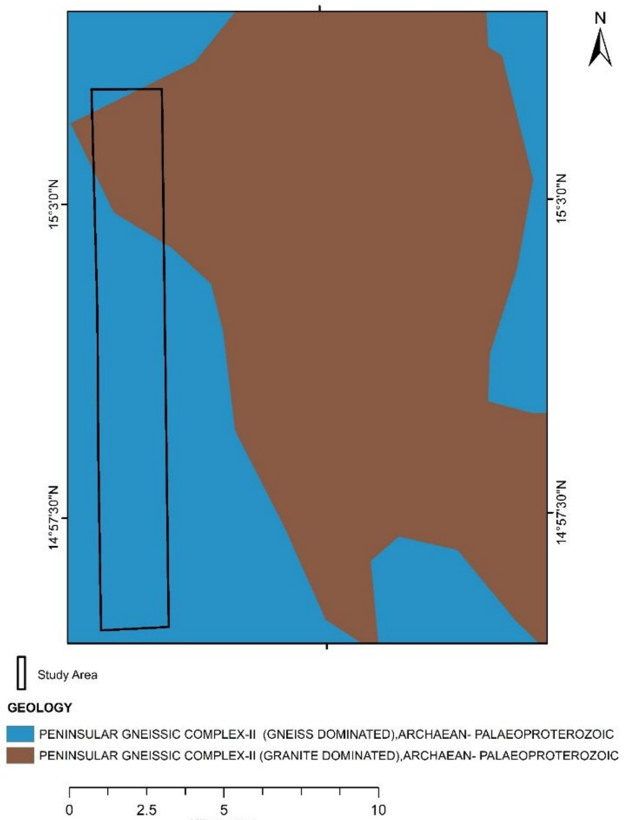

Fig. 2. Geological map of the study area (Source: Geology of Anantapur district, Andhra Pradesh, Geological Survey of India, Government of India, Bhukosh portal: https://bhukosh.gsi.gov.in/Bhukosh/Public)

The WKF region is characterized by an Archaean Granite-Greenstone terrain, as described by (Murthy et al., 1987; Nayak et al., 1999). The intrusion of quartz reefs, dikes, and granites marks this terrain. Multiple faults dissect the landscape, and the litho-units exhibit a series of culminations and depressions due to deformation. The dominant dykes in this region are primarily composed of dolerites and gabbro. The majority of kimberlites within WKF are characterized by low diamond content. These kimberlites are situated within the granitic and gneissic rocks of the EDC (Rao, 1996). A distinctive feature characterizes the kimberlites of the WKF: they are capped by a layer of calcrete, ranging in thickness from 0.5 to 1.5 meters. Additionally, these kimberlites date back to the middle to late Proterozoic era, spanning approximately 840 to 1,153 million years ago (Kaur et al., 2013).

The geological map from Bhukosh GSI depicts that the predominance of Granite and Gneissic complexes characterizes the study area. Granite is a coarse or medium-grained intrusive igneous rock. Quartz and feldspar are dominant in Granite. It is formed by the cooling of magma at greater depths and is the most common plutonic rock in the Earth's crust. Granite in Wajrakarur is estimated to have formed between 2500 and 4000 Ma, respectively (Reddy and Kumar, 1987).

Data and Methodology

Data

Airborne Visible InfraRed Imaging Spectrometer- surface reflectance data (acquisition date 28-01-2006) has been downloaded from the AVIRIS data portal of NASA Jet Propulsion Laboratory. The site is in Wajrakarur, India, and covers an area of 53.085 sq. km. AVIRIS measures the wavelength range from 380 nm to 2510 nm with a spatial resolution of 20 m, having 425 spectral bands ranging from Visible to SWIR wavelengths and a spectral resolution of 5 nm ± 0.5 nm (www1)

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) L1 Surface Radiance VNIR and Crosstalk Corrected SWIR V003 (acquisition date 02-04-2006) has been downloaded from the NASA EARTHDATA from the data portal of NASA Jet Propulsion Laboratory under favourable conditions of cloud cover <10 %. The total number of bands is 14, of which 3 are VNIR, 6 are SWIR bands, and 5 are TIR bands. The L1T radiance data was downloaded, and the image was radiometrically calibrated and atmospherically corrected.

Methodology

The methodology flow chart is shown in (Fig. 3). The lithological map of the research site was downloaded from the Bhukosh GSI data portal, and the known kimberlite body was analyzed. The lithological map is depicted in (Fig. 4). AVIRIS False colour composite image was used to delineate the pure spectra of kimberlites from the known kimberlite location reported by GSI. The diagnostic absorption features in the SWIR range are ideal for delineating serpentine and carbonate minerals, which are associated with kimberlites (Baranval et al., 2022). Minimum Noise Fraction (MNF) was carried out, and the noise-free bands in the SWIR range of AVIRIS data were selected. The pure spectra of the known kimberlite body (shown in Fig. 4) were used as reference spectra to find the unknown kimberlite bodies in the area. Matched Filtering (MF) and Adaptive Coherence Estimator (ACE) algorithms were employed by importing the known spectra of kimberlite to find the matching pixels and locating the unknown kimberlite bodies.

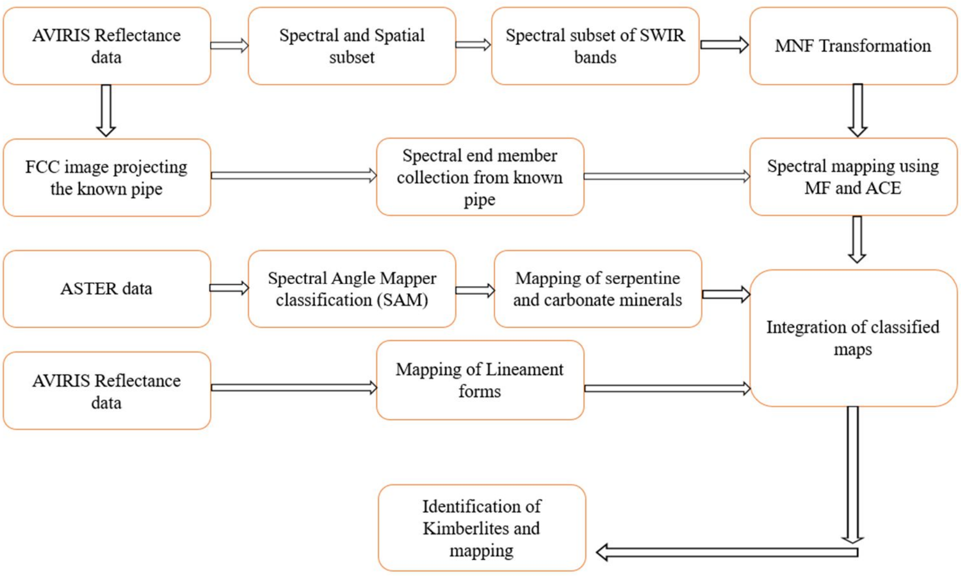

Fig. 3. Methodology Flowchart (Source: Baranval et al., 2022)

Spectral Angle Mapper classification was employed to find the presence of serpentine and carbonate minerals in the ASTER images. The reference spectra for identifying these minerals' presence were extracted from ENVI's spectral library.

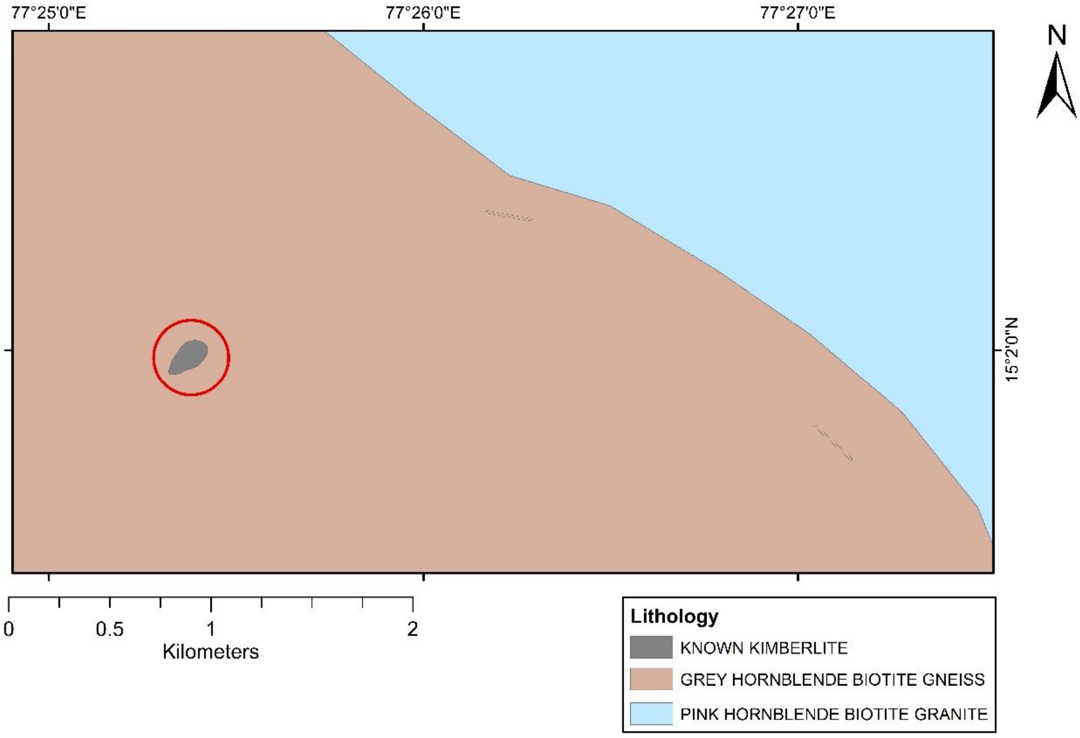

Fig. 4. Lithological map of Wajrakarur site depicting known kimberlite body. (Source: Lithology of Anantapur district, Andhra Pradesh, Geological Survey of India, Government of India, Bhukosh portal: https://bhukosh.gsi.gov.in/Bhukosh/Public).

AVIRIS data processing

A false colour composite image was used to trace the pure spectra of kimberlite. The image was prepared using the AVIRIS bands 98, 56, and 36 (Fig. 5). Kimberlite's known body was identified by analyzing the Bhukosh map that was downloaded from the Bhukosh GSI data portal (Fig. 4). Spectral bands in the SWIR range were used to identify the pure spectra of the known kimberlite body between wavelengths of 2000 nm and 2400 nm. The process of MNF was performed for the SWIR bands to extract the noise-redundant bands and to reduce the data dimensionality. SWIR noise reductant bands were utilized for Matched Filtering and Adaptive Coherence Estimator algorithms, as serpentine and carbonates show characteristic absorption features in the SWIR range. MNF transformation is a 2-step process used to estimate the spectral dimensionality and reduce the noise in the data. Forward MNF can select the noise-free bands based on eigenvalues generated during the process. Bands with high eigenvalues are noise-free, but those with values close to 1 are considered bad bands. These noise-free bands were spectrally resized. The reverse MNF procedure was performed with noise-free bands.

Matched Filtering (MF) is a partial unmixing method used to enhance the response of the known end member and to suppress the response of the unknown background composite by using the known image spectra of kimberlite (Bogliolo et al., 2004). Adaptive Coherence Estimator (ACE) is a classification algorithm in which the threshold is defined beforehand, and the background is separated against the targets. Information on all the end members from the image is not necessary for this algorithm (Baranval et al., 202; Rowan et al., 2005; Pour et al., 2012). The pure spectra of the known kimberlite are used as a reference to identify the rest of the information from the image scene. MF and ACE output maps were integrated to calculate the dot product (Fig. 7).

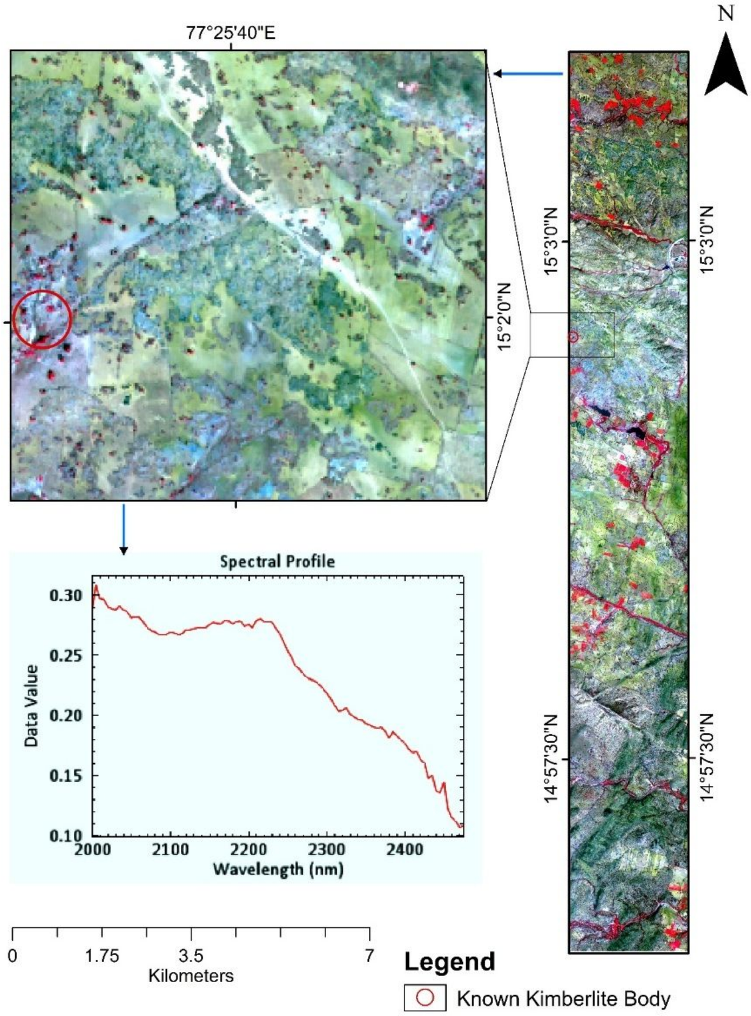

Fig. 5. Pure spectra of the known kimberlite pipe (own processing using SWIR band range of AVIRIS data)

ASTER data processing

The L1A radiance image was downloaded from the NASA Jet Propulsion Laboratory for further classification and analysis. The radiance image was then radiometrically calibrated using the ENVI software. The FLAASH atmospheric correction process was applied to the radiometrically corrected image. Pure spectra of serpentine and carbonate minerals were used as reference spectra from the ENVI spectral library. SAM classification was employed to visualize and analyze the spatial distribution of serpentine and carbonate minerals in the image.

Results and Discussion

Integrated maps of two classified outputs (MF and ACE**)** better interpreted the unknown kimberlite bodies. MF and ACE are two classification algorithms that highlight areas based on the imported reference spectra and suppress or darken the response of unknown background composite. Spectral signatures of the known and unknown kimberlite bodies were compared, similar absorption anomalies were detected, and distinct absorption characteristics were identified at 2230 nm. A similar absorption feature of serpentine was identified with the help of the ENVI spectral library. A comparison of spectral curves between the known and unknown kimberlite bodies is depicted in (Fig. 6). Fig. 6 shows absorption characteristics at a wavelength of 2300 nm, which is similar to the absorption characteristics of serpentine and carbonate minerals such as calcite and dolomite. It can be concluded from (Fig. 6) that the WKF consists of serpentine and carbonate-rich kimberlite due to similar absorption anomalies (Guha et al., 2021). "Lineaments" refer to the geological features beneath the surface, such as faults, folds, fractures, joints, and other similar formations. They are major topographical features for the detection of a mineral. Lineaments can be easily detected using a geological map or aerial photograph. Mapping of lineaments helps to determine the trends of faults, folds, joints, and topographical features like mountains and streams or other similar formations (Bishal et al., 2020). Drainage patterns of the study area were identified, which helped to provide an overview of the topographical trend of the surface. AVIRIS and ASTER data were used to mark all the lineaments in the study area. After selecting noise-free bands from both images, various band combinations were considered to avoid missing lineament features. Lineaments are trending in NE-SW, N-S, and E-W directions.

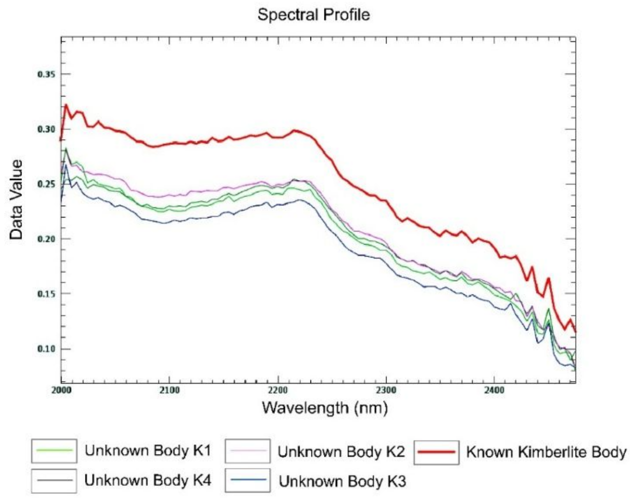

Fig. 6. Comparison of pure spectra of known and unknown kimberlite bodies (own processing using AVIRIS data)

After performing MNF on the selected SWIR bands of AVIRIS data, classification was done using MF and ACE algorithms in the ENVI platform. Lineaments marked manually with ASTER and AVIRIS data using different band combinations were linked to those lineaments downloaded from the Bhukosh GSI data portal to avoid missing lineament features. Pure spectra of the known kimberlite body were used to perform MF and ACE classification algorithms. Both classified outputs were integrated to obtain the dot product of maps (Fig.7). The area was analyzed and visualized using integrated maps. Circular anomalies are found in some parts of the area. Spectral signatures obtained from these anomalies match the pure spectra of known kimberlite bodies, as shown in (Fig. 6). Lineaments were overlapped with the integrated map of MF and ACE to determine if they are associated with the kimberlite bodies. Four kimberlite bodies were identified. The dot product of the MF and ACE classification algorithm is depicted in (Fig. 7).

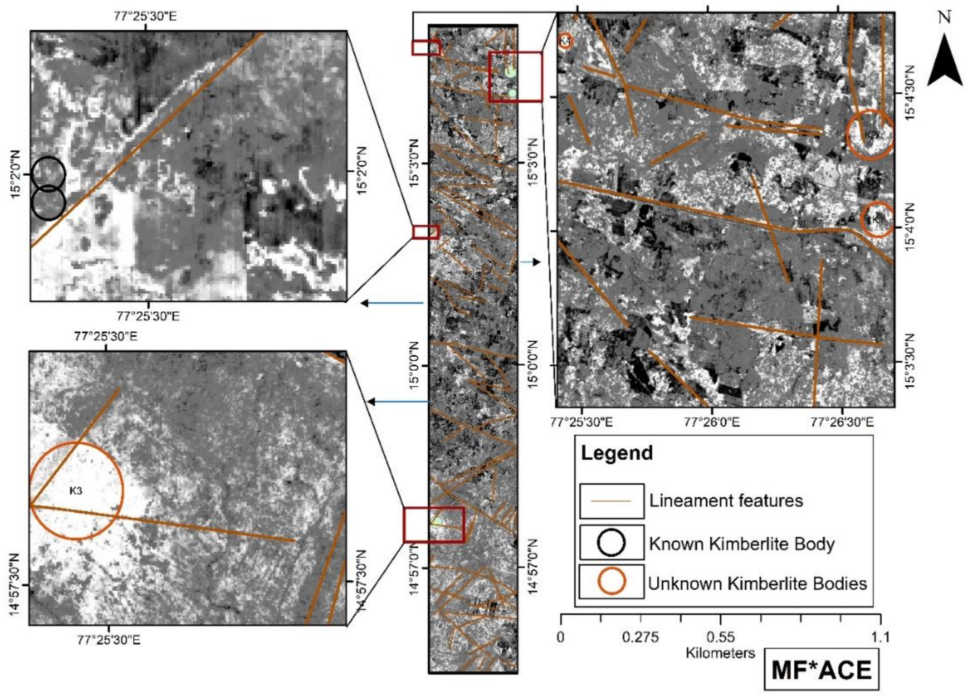

Fig. 7. Map depicting unknown kimberlite bodies' locations with lineaments overlapped to the classified output (own processing using classification methods of matched filtering and adaptive coherence estimator algorithms)

Spectral signatures of these unknown locations are shown in (Fig. 6). Unknown kimberlite bodies are named K1, K2, K3, and K4, respectively. Interpretation of these unknown kimberlite bodies reveals their characteristic circular features and association with lineaments aided in accurate interpretation. The locations of these unknown bodies are depicted in the table below. These locations are extracted by analyzing the integrated output of MF and ACE.

Table 1. Locations of unknown kimberlite bodies based on the analysis from MF and ACE (using ENVI)

Unknown Kimberlite Body	*Latitude*	*Longitude*
K1	*15.06782222*	*77.44420000*
K2	*15.07263056*	*77.44270556*
K3	*14.96226389*	*77.42437500*
K4	*15.07857778*	*77.42414722*

ASTER images were radiometrically and atmospherically corrected. SAM classifier was performed with the reference spectra of serpentine and carbonate minerals (Fig. 8).

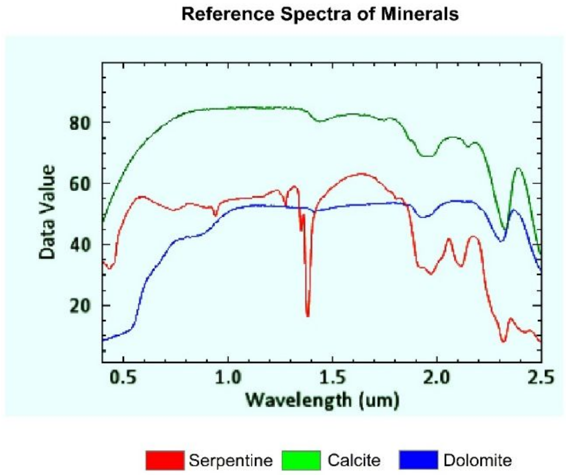

Fig. 8. Reference spectra of serpentine, calcite, and dolomite used for SAM classification (Source: ENVI spectral library)

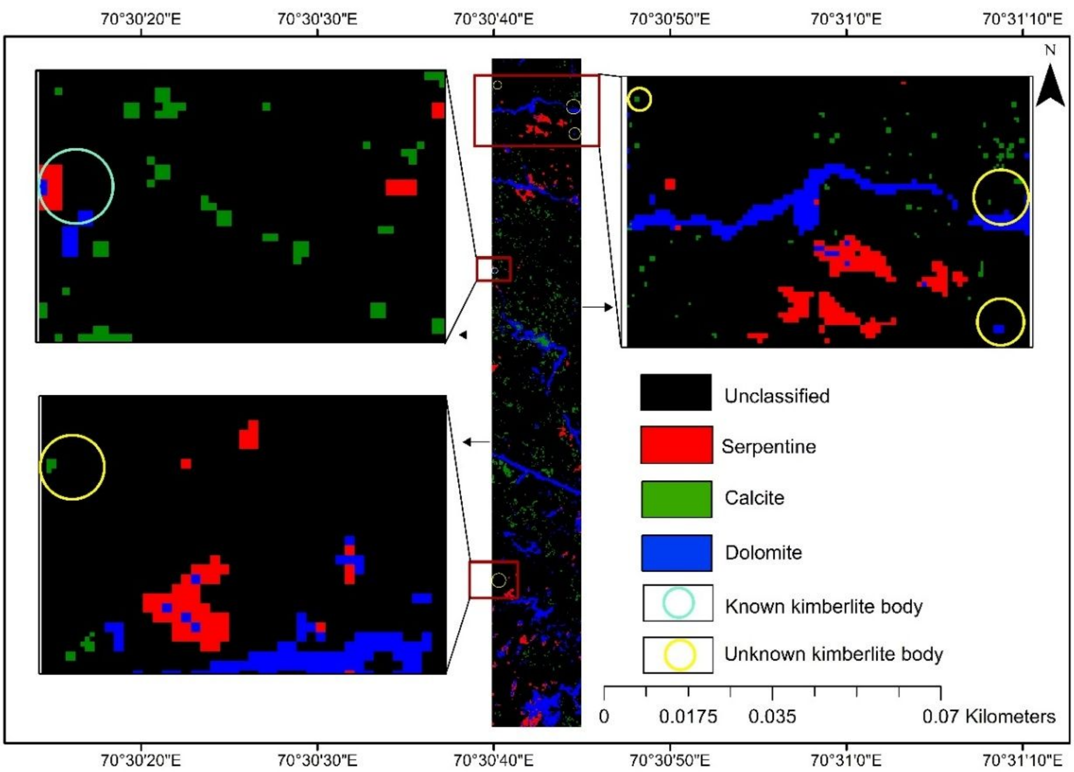

Fig. 9. Spectral Angle Mapper (SAM) classified output (own processing using ASTER image)

The SAM is an algorithm that can quickly map the spectral similarity between the spectra of an image and a reference. The reference spectra are obtained directly from the image. The SAM classifier compares the two spectra by treating them as vectors in a space with dimensions equal to the number of bands. It determines their spectral similarity (Qasim et al., 2022). For performing SAM classification, spectral signatures of serpentine and carbonate minerals are extracted from the ENVI spectral library. The output of the SAM classification algorithm is depicted in (Fig. 9). SAM output shows that the Wajrakarur kimberlite location contains serpentine and high levels of carbonate. The known kimberlite body is rich in serpentine, and all the unknown bodies we got from MF and ACE classification algorithms are carbonate-rich. Most of the lineaments in the study area are dolomite-induced features according to the SAM classification.

Conclusion

The study conducted in the Wajrakarur area of Anantapur, Andhra Pradesh, in the Eastern Dharwar Craton India, utilized remote sensing AVIRIS and ASTER images. Classification algorithms like MF and ACE were employed to classify and map the kimberlite bodies based on a known kimberlite body and its respective spectral reflectance curve. Kimberlite bodies were delineated using SWIR bands due to the diagnostic spectral absorption in the SWIR range (Baranval et al., 2022). Circular anomalies in the study area resemble known kimberlite bodies. Identifying circular anomalies and lineaments helped to understand the geology and structure of the study area. These anomalies were validated by extracting the pure spectra of the unknown kimberlite bodies. The spectral reflectance curves of the known and unknown kimberlite bodies exhibit a strong similarity, as shown in Fig. 6. SAM classification was performed to identify the presence of serpentine and carbonate minerals in kimberlite bodies. The lineament features were found to be associated with the kimberlites on the dot product of MF and ACE (Fig. 7). The study revealed the importance of lineaments and lithologic contacts in mapping kimberlite. The study also highlighted the effectiveness of AVIRIS hyperspectral data and optical ASTER images in kimberlite detection in the study area.

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