



New ASTER derived thermal indices to delineate mineralogy of different granitoids of an Archaean Craton and analysis of their potentials with reference to Ninomiya's indices for delineating quartz and mafic minerals of granitoids—An analysis in Dharwar Craton, India

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ABSTRACT

We processed five thermal infrared (TIR) bands of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) "at-sensor radiance" (Level 1B) data to derive few new indices to delineate variation in quartz, feldspar and mafic minerals in three different variants of granitoid; commonly occurring quartz bearing intrusive rock group. In this regard, three indices named as quartz-bearing rock index (QRI), feldspar-bearing rock index (FRI) and mafic-bearing rock index (MRI) were proposed. QRI index was derived using band 10, band 12 and band 13 $((\text{band } 10/\text{band } 12) * (\text{band } 13/\text{band } 12))$ of ASTER radiance image. MRI index was derived using band 12, band 13 and band 14 $((\text{band } 12/\text{band } 13) * (\text{band } 13/\text{band } 14))$ of ASTER radiance bands while band 10, band 11 were combined to derive FRI $((\text{band } 10/\text{band } 11))$ index. Three indices were combined in false colour composite image (FCC) and three-dimensional scatter plot to delineate granite, alkali granite and mafic rich granodioritic gneiss from each other as these granitoids had variable abundances of quartz, feldspar and mafic minerals. QRI and MRI were compared with the corresponding quartz and mafic indices proposed by Ninomiya (2005). It was observed from the respective ratio images and their regression plots that MRI and Ninomiya's mafic index (NMI) were complementary to each other. On the other hand, QRI image was better in enhancing quartz enrichment in alkali granites than Ninomiya's quartz index (NQI). However, QRI index was comparable with the quartz index proposed by Rockwall and Hofstra (2008) in terms of delineating quartz enrichment in alkali granite. Mutual exclusive nature of mafic minerals and quartz in granitoids was also evident from the negative correlation between MRI and QRI indices of the granitoids. On the other hand, FRI and QRI were negatively correlated with low regression value. This was resulted due to the combined effect of inverse relation of abundance of two dominant feldspars with quartz in different granitoids. In granitoids, abundance of plagioclase is known to increase with decreasing quartz content in granodiorite and tonalite although alkali feldspar bearing granites are characterised with high silica content. Results of discrimination of granitoids using proposed indices were validated based on deriving emissivity spectra of rocks and comparing them with ASTER TIR band resampled laboratory spectra of respective granitoids in addition to use geological map of the study area. Emissivity spectra of granitoids were derived from emissivity image (derived using emissivity normalisation method) after geospatially tagging it with QRI–FRI–MRI image composite; which was used to delineate exposures of granitoids. Further, we also found that the QRI, MRI and FRI indices had poor temperature dependence; when these indices were compared with relative surface temperature image derived from radiance bands using emissivity normalisation algorithm. Therefore, proposed indices can be implemented for delineating mineralogical variations of granitoids irrespective of surface temperature condition. Hence, proposed indices may be used successfully to delineate different granitic intrusions and relating their mineralogical variations with metallogeny.

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1. Introduction

The important rock-forming minerals such as quartz and feldspar are not characterised with absorption features in their reflectance spectra collected within the spectral domain of the visible-near-infrared (VNIR) and short wave infrared (SWIR) regions (as it was the case

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for clay minerals, oxides–hydroxides, carbonates etc.) (Lyon, 1972; Salisbury and Walter, 1989). On the other hand, thermal infrared (TIR) region is extremely useful for the spectral discrimination of these minerals based on differences in the emissivity spectra resulted due to variable vibration modes of Si–O bonds of major rock forming silicate minerals (Farmer, 1974; Kahle, 1976; Lyon, 1972). The subtle differences in the bonding of silicates are responsible for shifting of the emissivity minima in the TIR spectra of silicate bearing rocks (Salisbury and Walter, 1989; Salisbury and D'Aria, 1992). Geological mapping is an integral part in many of the geoscientific disciplines like mineral exploration, geo-environment and geo-engineering sciences. In conventional geological mapping, rock types are delineated by integrated analysis of qualitative and quantitative field data with mineralogical data on rock exposures. Mineralogical data are derived from X-ray diffraction (XRD) analysis and petrographical studies of optical thin sections of rock samples. Field data and mineralogical data are also often combined with geochemical data on elemental abundance to delineate intra or inter-rock compositional changes. In this regard, spectroscopic data are often used to identify the minerals present in the rocks of the earth's surface and also in the other planets based on identification of absorption features in the spectral profiles of rocks and minerals. These spectral features are collected within wider wavelength range encompassing VNIR (0.4–1.0 μm), SWIR (1.0–2.5 μm), mid-infrared (MIR) (3–5 μm) and TIR (8–14 μm) electromagnetic domains. Mineralogical dependence of TIR spectroscopy especially, its sensitiveness to silicate structures provides scope for mapping different rock types based on thermal characters of constituent minerals. This is particularly useful for geological mapping and classification of primary rocks, i.e. igneous rocks and also selected metamorphic rocks; which are rich in recrystallised silicate and carbonate minerals. Most rock forming minerals like silicates and carbonates exhibit diagnostic emissivity features in the TIR region. But TIR emissivity spectra are less studied and utilised for spatial delineation of natural targets like rocks in comparison to VNIR–SWIR reflectance spectra. This is due to the fact that very few hyperspectral (spectral observation in contiguous channels) and multispectral space-borne sensors are operative in TIR domain. It is in turn related to poor signal-to-noise (SNR) of data recorded by the thermal channels within TIR domain (Gillespie, 1985). This is another hindrance for using contiguous spectral bands with finer spectral resolution to detect subtle variation in thermal emissivity within the TIR wavelength range.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) launched on board the EOS-Terra satellite, is a multi-spectral sensor system (Abrams, 2000). ASTER has three bands in VNIR domain, six bands in short wave infrared SWIR domain and five bands (band numbers 10 to 12) in TIR domain. ASTER data have been extensively used for mapping few significant types of surface mineralisation signatures associated with hydrothermal alteration zones and oxidation capping of supergene enrichment deposit based on the diagnostic absorption features of different clay, carbonate, aluminium–iron hydroxide minerals in VNIR–SWIR domain (Abrams, 2000; van der Meer et al., 2012; Zhang et al., 2007). Further VNIR–SWIR bands of ASTER were also used for delineating few economic rock types constituted with spectrally sensitive minerals (Abrams, 2000; Guha et al., 2013a,b, 2014; Rajendran et al., 2011a; van der Meer et al., 2012).

In recent times, different thermal false colour composites and thermal band ratio images have been used to delineate rock types (Ding et al., 2014; Gomez et al., 2005; Kalinowski and Oliver, 2004; Matar and Bamousa, 2013; Ninomiya et al., 2005; Rajendran and Nasir, 2014). It is observed that quartzo-feldspathic rocks like granite and silica rich dry river sand appear with reddish colour in the L1B daytime (geo-rectified “at-sensor radiance” data) false colour composite image derived using red, green and blue colour assignment to band 14, band 12 and band 10 of ASTER sensor respectively (Yajima and Yamaguchi, 2013). This is due to the fact that the spectral emissivity of quartz is relatively lower in the 8–9 μm region (band 10 to band 12 of ASTER TIR sensor) than in the 10–12 μm region (band 13 and band 14 of ASTER TIR sensor). Feldspar

also has emissivity minima in band 11 of ASTER sensor. But mafic rocks appear white or bright grey in TIR false colour image prepared using band 12, band 11 and band 10 (first three bands) of ASTER thermal sensor in red–green–blue (RGB) colour space as mafic minerals have relatively higher (in comparison to quartz and feldspar) and similar spectral emissivities in 8–9 μm region (Yajima and Yamaguchi, 2013). Based on analysis of ASTER TIR band based emissivity spectra of rocks, Ninomiya et al. (2005) have proposed few popular spectral indices for the mapping of quartz, carbonate, and mafic rocks using ASTER data. Many important geological units were also mapped using TIR bands of ASTER data using emissivity as a parameter (Bertoldi et al., 2011; Ding et al., 2014; Matar and Bamousa, 2013; Ninomiya et al., 1997, 2005; Rowan et al., 2005). But derivation of multi-channel thermal emissivity from space-borne data is a challenge as contrast in spectral emissivity collected in few thermal bands (operative within specified spectral domain) is very less for commonly occurring terrain elements. Striping noise was also reported in emissivity bands derived from ASTER level 1B data due to poor SNR in multiband emissivity data (Son et al., 2014). However, mineralogically sensitive indices often derived significant results in terms of delineating mineralogical contrast by highlighting variations in thermal emissivity of terrain elements recorded in selected numbers of bands. Utilization of ASTER TIR bands for mapping of different granitoids of Archaean Dharwar Craton is a challenge as each granitoid variant represents specific mineralogy and specific stage of magmatic differentiation of parent magma. The term granitoids include family of felsic igneous rocks viz. alkali granites, granites, granodiorites, tonalities; which are essentially constituted with quartz, varied proportions of alkali feldspar and plagioclase feldspar (Bose, 1997). Alkali feldspar rich granite is characterised with high ratio of alkali feldspar to plagioclase feldspar content whereas the ratio is progressively lower in granodiorite and tonalite (Bose, 1997). Mafic mineral content (biotite, hornblende etc.) is low in granitoids in general. However, mafic mineral abundances are also progressively higher as we go from granite to tonalite in granite–granodiorite–tonalite sequence.

Each granitoid province of Archaean and Proterozoic terrain is known for the presence of different granitoids each of which has specific range of mafic mineral and quartz content. Alkali feldspar to plagioclase feldspar abundance ratio is also distinct in each variant. It is important to enhance some of these mineralogical variations of granitoid using ASTER thermal bands. Delineation of different sub variants of granitoids with varying quartz and alkali feldspar content would provide Precambrian geologists a scope to identify the relative stage of differentiation involved in the evolution of granitoids. This would also help in understanding the different chronological events of granite emplacement and how these granitoids are related to Archaean greenstone rocks (i.e. either intrusive or basement).

In the present study, we have attempted to identify different granitoids by delineating variations in quartz, mafic and feldspar content in these rocks using thermal bands of space borne ASTER sensor. In this regard, we have processed ASTER “at-sensor radiance” thermal bands to delineate mineralogical contrast of granitoids based on derivation of few indices; which are effective in delineating broad mineralogical variations of key minerals like quartz, feldspar and mafic minerals. Multistage enhancements of thermal spectral features based on derivation of indices to understand mineralogical variations of quartz, feldspar and mafic minerals proved important in identifying granitoids and also in sub-categorising them (Ding et al., 2015).

In this regard, researchers also have concluded based on their study that the indices directly derived from ASTER Level-1B radiance data would be more effective and accurate than the indices derived from emissivity image for detection of specific minerals and rocks (Ding et al., 2014). One advantage of using Level 1B data is that lower-level data (i.e. level 1B) are free of functional uncertainties introduced by the atmospheric-correction methods and temperature separation algorithms on spectral emissivity (Ninomiya et al., 2005; Ding et al., 2015). Researchers have demonstrated the utility of ASTER level 1B data in derivation of mineralogically sensitive indices (Chen and Wang, 2007;

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