Review of the Role of Remote Sensing Applications in Mineral Exploration and Sustainable Development in Oman

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Abstract. Applications of remotely sensed satellite data are wide and unique in the mapping of different lithologies, mineral resources, and ore deposits. Satellite images are capable in discriminating rock types useful for geological applications and significantly used in the identification of mineral resources. The techniques are low-cost and save time in mapping and exploration of such resources and are well-suited and applicable to the arid region. Oman has the potential occurrence of the industrial minerals and ore deposits which mostly occur in inaccessible mountains and desert regions where it is difficult to do conventional geological mapping. Thus, understanding the capability of the techniques to map and explore such potential resources by geologists is highly important. The absorption characters of spectral bands of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and selected imaging processing methods namely decorrelation stretching, band ratios, linear spectral unmixing (LSU), and Mixture Tuned Matched Filtering (MTMF) demonstrates the sensor capability of ASTER to map several mineral deposits and different rock lithologies in Oman, which includes limestone, marl, listwaenites, carbonatites, metamorphic zones, caves, karst, springs, vegetation’s, rock fall and slide, Moho, copper, chromite, awaruite, manganese, and gold deposit in different parts of the Sultanate of Oman. It demonstrates the spectral sensitivity of such rocks for simple interpretation over satellite data and describes and distinguishes them based on the absorptions of hydrous minerals in the spectral bands of ASTER for mapping and exploration studies.

Keywords. mineral exploration, remote sensing, image processing, Sultanate of Oman, arid region.

1. Introduction

Satellite remote sensing images have been widely and successfully used for mineral exploration since the launch of Landsat in 1972. Mineral exploration companies use diverse types of data sets to search for new mineral deposits. Mineral targeting can be done based on multi-evidence maps analysis, either using qualitative or quantitative methods. Nowadays, exploration geologists are increasingly involved in interpreting remotely sensed spaceborne satellite digital images to explore new and more economic mineral deposits. This remote sensing application relies mostly on the capability of the sensor to register spectral signatures and other geological features related to mineral deposits (Drury, 1986). Although it is difficult to identify the economic trace elements (Ni, Au, Ag, Cu, and so on) bearing minerals directly by any remote sensor, such minerals can be detected from the associated altered minerals and altered zones (like clay minerals in the alteration zones) which have diagnostic spectral signatures mostly in the shortwave infrared portion of the electromagnetic spectrum. An example, ferruginous residual deposits (gossans) which overlie mineralized ground can often be identified using spectral signatures and developing color anomalies on en-
hanced false color ratio composites. These signatures can be used to locate sites most favorable to the occurrence of mineral deposits and save the mineral industry a great deal of time and costs in their exploration programs (Abrams et al., 1984).

In mineral exploration, Landsat imagery has been used to provide basic geological maps, to detect hydrothermal alteration associated with mineral deposits, and to produce maps of regional and local fracture patterns, which may have controlled mineralization or hydrocarbon accumulations. Structures seen on Landsat images are faults, fractures, and lineaments of uncertain nature and studies may yield clues to the location of concealed mineral deposits (Abrams et al., 1984; Drury, 1986; Drury, 2001). Recent technological advances now provide high resolution multispectral satellite and airborne digital data. The moderate spatial resolution satellite data have been used successfully to provide regional to sub-regional geologic maps and has played a role in the discovery of new occurrences of oil, minerals and ore deposits, and other resources. Especially, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor covers a wide spectral region with 14 bands from the visible to the thermal infrared parts of the spectrum with relatively high spatial, spectral, and radiometric resolution being used uniquely to explore oil resources, minerals and ore deposits, and to map industrial rock and different lithology (Abrams and Hook, 2002). More details on the sensor and its capability can be referred in Table 1. (Rajendran and Nasir, 2013a; 2013b; 2014a; 2014b; 2015a; 2015b; Rajendran, 2016)

The present study reviews scientific literatures and describes the application of remotely sensed ASTER satellite data for exploration of economic mineral resources, especially to the resources of the Sultanate of Oman for its sustainable development. This study describes the spectral absorption characters of economic minerals, advantages of ASTER data, the simple image processing methods, and their results to understand and use the technique and methods for the exploration geologists, industrialists and mine owners to avoid their ambiguity for more exploration minerals and ore deposits occurred in the arid region.

2. Economic Mineral Resources of Oman

Oman is situated at the eastern boundary of the Late Precambrian Pan-African crystalline metamorphic basement of Arabian Plate near its junction with the Eurasian Plate. The Gulf of Oman is a remnant of the Tethys Sea and overlies a shallow-dipping subduction zone, which extends eastwards below Iran (Searle and Malpas, 1980). The country is rich with occurrences of economic industrial minerals and ore deposits namely chromite, copper, gold, lead, zinc, iron (laterite) coal, magnesite, manganese and silica, barite, clay, dolomite, gypsum, kaolinite, limestone, and marble (Figure 1). Most of these predominantly occur in the convergent margin: parallel to Tethyan Suture Zone especially found in the northern Oman mountains region. These deposits are playing a vital role in sustainable development of the economy of the Sultanate of Oman.

A literature review shows that several studies are available for the occurrence of prospective chrome, nickel, and Cyprus-type volcanogenic massive sulphide (VMS) deposits which are well exposed in the Semail ophiolite belt of Oman that is 800 km long and 5–10 km thick. The VMS copper deposits are hosted in submarine basalts of the Oman ophiolite sequence, a sheet of Cretaceous Tethyan seafloor that was thrust over basement rocks of the Arabian Shield (Close and Gordon, 2003; Partington, 2010). These are found as clusters with pyritic copper-rich mounds with gold bearing gossans overlying lower grade feeder systems within the footwall basalts (Close and Gordon, 2003; Galley and Koski, 1999; Galley et al., 2007; Hayman et al., 2015; Rajendran and Nasir, 2017; Taylor and McLennan, 1985).

1 Table 1:
http://asterweb.jpl.nasa.gov/content/03_data/04_Documents/aster_user_guide_v2.pdf,
Figure 1: Minerals occurrence map of the Sultanate of Oman
Also, the ultramafic rocks forming the Semail massifs of this belt contain widespread chromite mineralization occurring at the Moho transition zone (MTZ) and/or even slightly deeper within the mantle (Close and Gordon, 2003). These deposits occur as individual lenses and vary in texture from podiform to veins. Massive chromite samples of this region have Cr$_2$O$_3$ content ranging from 31.5 to 54.61 wt.% with a Cr:Fe ratio from 1.84:1 to 2.96:1 (Annells, 1989). Research studies were carried out for presence of the base metals namely barium, copper, lead, and zinc in the listwaenites (hydrothermally altered rock) occurred in thrust fault zone of parts of the Semail ophiolite of Oman by Nasir et al. (2007) and Rajendran et al. (2013a). In the NE margin of Oman, there are economic potential of stratiform manganese deposits within the radiolarian cherts of the Wahrah Formation of the Late Jurassic-Cretaceous age. Their occurrences are studied by Kickmaier (1995), Kickmaier and Peters (1990), Peters (1988), and Rajendran and Nasir (2013a).

The occurrence of economically viable industrial rocks, namely limestone, dolomite, marble, clay, gypsum, and kaolinite, are being mined in parts of Oman and are well documented by the Authority of in Oman. The occurrence of limestones and marls in parts of Sultanate of Oman are described in different studies (Beavington Penny et al., 2006; Jones and Desrochers, 1992; Rajendran et al., 2011; Rajendran and Nasir, 2013c; 2014c). The marbles, “the exotic limestone,” of Oman are found in a large number of places as “isolated blocks” within the Hawasina formation. These are used extensively as ornamental stone tiles and slabs in the Oman building industry and are exported to nearby countries (Rajendran et al., 2017; Searle and Graham, 1982; Wilson, 1969). Also, there are small scale occurrences of clay, gypsum, and kaolinite deposits, which need to be mapped and explored for economic exploitation.

### 3. ASTER and Its Applications

As discussed above, the ASTER has improved medium to high-spatial resolution. It measures visible reflected radiation in three spectral bands between 0.52 and 0.86 μm in visible near infrared (VINIR) region (with 15-m spatial resolution), infrared reflected radiation in six spectral bands between 1.6 and 2.43 μm in shortwave infrared (SWIR) region (with 30-m spatial resolution) and thermal infrared radiation in five spectral bands between 8.12 and 11.65 μm in thermal infrared (TIR) region (with 90-m spatial resolution) of the electromagnetic spectrum. An increase of six bands in the SWIR region (one spectral band for Landsat vs. six spectral bands for ASTER) enhances the surface lithological mapping capability related to many silicate, carbonate, hydrate, and hydroxide minerals which can display molecular absorption features by overtones and combination of tones (Hunt, 1977). ASTER data have been used to map silicate and carbonate rocks, as well as for volcanic studies, urban studies, lithological mapping, and monitoring of coastal environments (Yamaguchi et al., 1998). Several research studies proved the capability of the ASTER sensor in discriminating rock types and it is significantly used in identification of above mineral resources (Abdeen et al., 2001; 2002; Alimohammadi et al., 2015; Amer et al., 2010; Azizi et al., 2007; Bedini, 2011; Combe et al., 2006; Corrie et al., 2010; Crosta et al., 2003; Di Tommaso and Rubinstein, 2007; El Janati et al., 2014; Gabr et al., 2010; Hosseinjani Zadeh et al., 2013; 2014a; 2014b; Hosseinjani and Tangestani, 2011; Mars and Rowan, 2003; 2006; 2010; Pour et al., 2011; Pour and Hasim 2012; Rajendran et al., 2011; 2012; 2013a; 2014; 2017; Rajendran, 2016; Rajendran and Nasir, 2013a; 2013b; 2014a; 2014b; 2015a; 2015b; 2017; Tangestani et al., 2011; Zhang et al., 2007). These applications are under consideration of mining companies, exploration geologists, and mine owners for cost-benefit exploration and characterization of such economic important minerals, ore deposits, and rock types.

### 4. Spectral Characteristics of Economic Minerals

Minerals have three types of electronic processes; conduction bands, charge transfer, and crystal field effects. For example, the presence of ferrous iron (Fe$^{2+}$) in weathered surface produces absorptions centered at about 0.45 μm,
1.0–1.1 μm, 1.8–1.9 μm, and 2.2–2.3 μm, depending on its lattice environment. The ferric iron (Fe$^{3+}$) produces absorptions at about 0.65 μm and 0.87 μm. The vibrational processes which cause visible and short-wavelength infrared absorptions are bending and stretching vibrations of bonds within radicals or molecules. On igneous rock surfaces, the most important are due to Al–OH and Mg–OH in micas, amphiboles, and serpentine. Al–OH produces absorptions centered at about 2.2 μm, whereas Mg–OH produces features at about 2.3 μm (Abrams et al., 1988; Rajendran et al., 2011). Abrams et al. (1988) provided the spectra of serpentinite which showed a relatively flat spectral response in which the shallow feature at 0.45 μm is due to ferric iron and the broader absorption centered near 0.9 μm or around 1.0 μm is due to ferrous iron. The rather sharp band at 2.3 μm is due to vibrational processes of Mg–OH, and hydration effects are shown by the absorption near 1.4 μm. The harzburgite spectrum has a broad feature attributable to ferrous iron in pyroxene and olivine minerals, centered near 1.0 μm.

The spectral absorption characters of major economic minerals resources, mineralized zones and associated rocks, carbonate platform, ophiolite sequence, metamorphic sole, and Tertiary and Quaternary formations of Oman have been well described by Rajendran and Nasir (2013a; 2013b; 2014a; 2014b; 2014c; 2015a; 2015b; 2017), Rajendran et al. (2011; 2012; 2013a; 2014; 2017), and Rajendran (2016). Figure 2 shows the lines of spectral absorptions of iron, carbonate, and hydroxyl bearing major economic minerals stacked from the USGS Spectral Library and more descriptions can be referred in Rajendran (2016), Rajendran et al. (2011; 2012; 2013a), and Rajendran and Nasir (2013a; 2013b; 2014a; 2014b; 2014c; 2014d; 2015a; 2015b).

5. Digital Image Processing Methods

Many authors have used different image processing methods such as band rationing, decorrelation stretching, Principal Component Analysis (PCA), and Spectral Angle Mapper (SAM, supervised classification method) to discriminate different lithology, structures, alteration zones, and detecting of minerals using different satellite images of Landsat TM and ETM, ASTER, and hyperspectral sensors and more details on the methods and mapping of resources can be found in, Abdelsalam et al. (2000), Amer et al. (2010), Cle’net et al. (2010), Crosta and Moore (1989), Gabr et al. (2010), Galvao et al. (2005), Ferrier et al. (2002), Khan and Mahmood (2008), Ninomiya and Fu (2002), Rowan et al. (2005; 2006), Rajendran and Nasir (2014c; 2015a; 2015b), Rajendran et al. (2013a), and Tangestani et al. (2008; 2011).

Figure 2: Spectral plot of major economic minerals stacked from the USGS Spectral Library (modified from Rajendran et al., 2013).

The simple methods used in the discrimination of rock types and detecting the minerals and ore deposits using ASTER data in Oman includes (1) band ratios (Rajendran et al., 2012; Rajendran and Nasir 2014a; 2015b), (2) decorrelation stretching (Abrams et al., 1988; Gillespie et al., 1986; Rajendran, 2016; Rajendran and Nasir, 2013b; 2014c; 2015a; Rajendran et al., 2012; Rothery, 1987). (3) false color composites (Rajendran et al., 2013a; 2014; Rajendran and Nasir,
2015a), and (4) principal components analysis (Rajendran 2016; Rajendran and Nasir 2015a; Rajendran et al., 2011; 2012; 2013a; 2014). The other methods which use end members to map minerals such as Spectral Angle Mapper (SAM), Spectral Information Divergence (SID), linear spectral unmixing (LSU), and Mixture Tuned Matched Filtering (MTMF) are adopted by Rajendran (2016), Rajendran and Nasir (2015a; 2015b; 2017) and Rajendran et al. (2013a; 2014) to map the minerals of ophiolite sequence and carbonate rocks.

**Figure 3**: RGB image of PC5, PC4 and PC2 of PCA showing rocks of ophiolite sequence and zone of chromite mineralization. E- Basic extrusives mostly spilites with pillow lava or conglomerate; D- Diabase dyke swarms; G- Gabbro; HGABBroid hypabyssal rocks; PG- Cumulate layered gabbro; P and CD- Sheared serpentinized harzburgite (Rajendran et al., 2012).
Figure 4: Principal Components RGB image (R: PC1, G: PC2 and B: PC3) showing the occurrence of manganese deposits in Ras Al Hadd region, Oman (Qf – Alluvial; Qb- Sabkha; Qe-Aeolian; MF2 - Middle Fars Group (Miocene to Pliocene); MF1 - Lower Fars Group (Miocene to Pliocene); EMD - Dhofar Group (Late Eocene to Early Miocene); EHT3 - Upper Hadhramut Group (Paleocene to Eocene); EHT2 - Middle Hadhramut Group (Paleocene to Eocene); TRKAR - Al Aridh Group; PKHD - Hamrat Duru Group) (Rajendran and Nasir, 2013a)
6. Mapping and Exploration of Economic Minerals, Mineralized Zones and Associated Rock Types of Oman using ASTER Data

As discussed above, Oman is rich with potential economic minerals resources including the major petroleum resources, the minerals and ore deposits such as Cr, Cu, Mn, Au, Ag, Pb, Zn, Ba, and Si, and the industrial rocks namely limestone, dolomite, clay, gypsum, kaolin, magnesite, and marble in different parts of the region. Rajendran (2016), Rajendran and Nasir (2013a; 2013b; 2014a; 2014b; 2014c; 2017) and Rajendran et al. (2012; 2013a; 2014; 2017) and Rajendran (2016) studied spectral absorption characters of minerals of such resources as discussed above and mapped the major economic minerals, mineralized zones, and industrial rocks. They used suitable ASTER spectral bands and selected simple image processing methods to show capability of ASTER spectral bands and potential of image processing methods to map their occurrence and distribution in the interest to explore more deposits in the region of Oman. The results of few studies are given below and more details can be found in Rajendran (2016), Rajendran and Nasir (2013a; 2013b; 2014a; 2014b; 2014c; 2017) and Rajendran et al. (2012; 2013a; 2014; 2017).

i. **Mapping of chromite associated lithology:** In 2012, Rajendran et al., delineated the area of chromite potential mineralized zone and ophiolite sequence rocks occurred in and around of Wadi Fizh region using ASTER data and the decorrelated stretching, different band rationing and principal component analysis image processing methods. They used the band ratios \(((2+4)/3, (5+7)/6, (7+9)/8)\) to discriminate the serpentinized harzburgites from other ophiolite rock units and showed the zone for chromite mineralization (Amer et al., 2010) for detailed mapping. Also, they developed RGB image using principal components PC5, PC4, and PC2 (Figure 3) by PCA in the VNIR-SWIR wavelength regions and successfully showed the sharp contact between the ophiolite sequence rocks and described the chromite occurrence rich mineralized zone.

ii. **Mapping of Manganese associated lithology:** The geological, petrological, and geochemical studies of manganese deposits occurrence of some parts of Oman were studied by Kickmaier (1995), Kickmaier and Peters (1990), and Peters (1988). In 2013a, Rajendran and Nasir studied the 14 spectral bands of ASTER and collected the image spectra over the manganese occurrences (rich in pyrolusite; Kickmaier, 1995; Kickmaier and Peters, 1990; Peters, 1988) of parts of the Sur region. Their study discussed the diagnostic absorption features of the manganese in the 1 to 9 ASTER spectral bands in VNIR-SWIR regions which showed low reflectance value due to the absorption of Mn-O bonds in contrast to 10 to 14 ASTER spectral bands in the TIR region which showed more reflective due to the emission of energy from Mn-O bonds of the manganese occurrences. They found absorption in band 12 in the image due to the contents of silica present in chert which is associated with manganese (Ninomiya, 2004; Ninomiya et al., 2005). Based on the study of spectral absorptions characters of manganese minerals and associated rocks, they processed the 9 VNIR-SWIR spectral bands using the band ratio \(((1 + 3)/2, (3 + 5)/4, (5 + 7)/6)\) and discriminated the occurrences of manganese and associated lithological informations. Further to confirm their occurrences, they used VNIR-SWIR spectral bands and analyzed by PCA and developed RGB image using principal components, the first three high-order principal components (PC3, PC2, and PC1; Figure 4), and showed the occurrence and distribution of manganese deposits of the region.

iii. **Mapping of base metal rich listwaenite and associated mineralized zones:** Listwaenite is a hydrothermally altered carbonated ultramafic rock formed at intermediate-to-low temperature within or near major thrust faults and shear zones. It contains quartz, carbonate minerals (calcite, dolomite, and ankerite), mica such as fuchsite, together with sulfides (pyrite, galena) and oxides (hematite, magnetite), cobalt minerals, and chromite relicts (Kuleshevich, 1984; Kunov et al., 2007; Rajendran et al., 2013a; Nasir et
The rock is extremely important worldwide, because it is potentially associated with economic minerals including gold, nickel, arsenic, cobalt, wolframite, and mercury mineralization (Borojević Šoštarić et al., 2011; Leblanc and Fischer, 1990; Sherlock and Logan, 1995; Tsikouras et al., 2006; Ucurum, 1998; Ucurum and Larson, 1999).

**Figure 5:** ASTER SWIR RGB (PC5, PC3 and PC1) image showing the presence of hydrothermal altered rock (listwaenite in dark red color marked as Li) and mineralized areas in range of colors interpreted along the thrust fault zones (dotted lines in yellow color) of the Fanjah area (Rajendran et al., 2013).
Listwaenite occurrences and their spatial distributions in the Fanjah area, east of Oman, are discriminated and mapped from the associated rocks using ASTER spectral absorption bands 8 (2.295–2.365 μm), 3 (0.78–0.86 μm), and 1 (0.52–0.60 μm) by generation of the simple false color composite (FCC) image by Rajendran et al. (2013a). Also, they studied the spectral absorptions of carbonates and ferro-magnesian silicate minerals and analyzed ASTER VNIR and SWIR spectral bands, using band ratios 9/8, 4/3, and 2/1, and showed clearly the listwaenite. They chose the ratio 9/8 to increase the response of the carbonate mineral bearing rocks, the 4/3 to separate weathered rocks from all the mineralized and unaltered rocks and the 2/1 ratio to make an image for mineralized and the unaltered rock units of the study region. To map the listwaenite-associated mineralized zones, they used the PCA method and applied over 6 SWIR bands and showed which principal component (PC) contains the most information on the mineralized zones. They studied best RGB image derived from the combination of PC5, PC3, and PC1 and discussed that the PC1 enhanced the area of the non-mineralized and unaltered rock units by high reflection and area of weathered, altered and mineralized rocks from strong absorption. Because of good absorption in band 4 and high reflection in band 6, the PC3 component illustrated the weathered and altered mineralized rocks, and because of good absorption in band 8 and good reflection in band 7 and band 9, the PC5 is chosen as a good indicator for discrimination of mineralized zones. The utilized principal components showed the zones of major alterations and mineralization which are mapped along the main thrust and fault zones (dotted line) of the Fanjah area (Figure 5). To confirm the mineralized zones, they used Spectral Angle Mapper (SAM) and identified the minerals and mineralization of the zones (Rajendran et al., 2013).

iv. Mapping of REE rich carbonatite and aillikites lamprophyres: Carbonatites have more than 50% of carbonate minerals (calcite, dolomite, ankerite, sodic/potassic carbonates), with sodic pyroxenes, amphiboles, phlogopite, apatite, olivine, and rare/exotic minerals containing F, Nb, P, Ta, Th, REE, U, V, or Zr (David and Noreen, 2001; Groves and Vielreicher, 2001; Nasir et al., 2011; Mitchell, 2005; Rajendran and Nasir, 2013a; Wall and Mariano, 1996; Zurevinski and Mitchell, 2004). These are an economic important rock, consisting of high REE concentrates occurring as small intrusive bodies (3–5 km in diameter) within larger alkaline complexes characteristics of intraplate margins (Ahijado et al., 2005; Le Roex and Lan-yon, 1998; Nasir et al., 2009; 2011; Tappe et al., 2009; Zaitsev et al., 1998).

To map such economic important carbonatite rock, Rajendran and Nasir (2013b) studied the molecular absorption and emission of carbonate contents and showed the carbonatite as dark due to absorption in the visible and reflected infrared and bright due to emission in the thermal infrared wavelength regions of ASTER and Landsat TM spectral bands. They showed occurrences of carbonatites in the visible ASTER spectral bands (bands 1–3, 15 m spatial resolution) and shortwave infrared bands (bands 4–9, 30 m spatial resolution) NE margin of Oman in dark due to the molecular absorption of energy by carbonate contents. In contrast, the emission of thermal energy recorded in six thermal infrared bands of the ASTER sensor (bands 10–14, 90 m spatial resolution) did not showed the occurrence of carbonatites and appeared with bright pixels due to emitted energy by the carbonates of carbonatites. They also analyzed the ASTER bands by PCA and developed the RGB images by using (1) the PC5, PC3, and PC1 to map the carbonatites and (2) the PC3, PC2, and PC6 image to map aillikites in the region. The presence of carbonate minerals of the rocks is studied using SAM method (Figure 6).
Figure 6: Threshold images of the SAM Target Detection Wizard showing the occurrences of a. carbonates (green color) and b. dolomite (blue color) minerals of the carbonatite dyke and c. calcite (green color) minerals rich in the ancient alluvial terraces over ASTER image (Rajendran and Nasir, 2013b).
v. **Mapping of limestone formations:** As discussed above, the limestones are mostly formed by calcite and dolomite minerals. Rajendran and Nasir (2013b) studied the ASTER spectral sensitivity of carbonate rocks and showed the significant spectral absorption characters of such rocks. In 2014, Rajendran and Nasir used the ASTER spectral bands 8, 3, and 1 and discriminated well the limestone formations and associated lithology of parts of Oman by decorrelation stretching image processing method (2014b, 2014c). They chose the band 8 response to the presence of carbonate and hydroxyl bearing minerals of the limestone formations. Band 3 serves to characterize the general albedo of the materials to highlight certain silicate minerals associated with the formations and band 1 contains information relating to the presence of iron minerals associated with the formations or tectonized harzburgite. The mapped formations are well correlatable with the available geological maps. They stated that the image processing method applied on ASTER spectral bands (8, 3, and 1) are proved beneficial to discriminate limestone formations of the study sites (Figure 7).

vi. **Mapping of Ni-magnesioferrite–magnetite–awaruite bearing hydrothermal altered serpentinized zone:** Ultramafic rocks host significant metal ore deposits such as Cr, Fe, Ni, Cu, Co, Au sulfides, and Platinum Group Elements (PGE), and ore minerals namely magnesioferrite, magnetite, and awaruite which potentially occur in the hydrothermal altered serpentinized rocks (Ahmed and Hall, 1982; Bradshaw, 2008; Gargiulo et al., 2013; Loferski and Lipin, 1983; Page et al., 1979; Rajabzadeh and Moosavinasab, 2013; Staples et al., 2011). The magnesioferrite and awaruite (Ni$_3$Fe alloy mineral; Krishna Rao,
1964) are the economic important minerals developed under reducing environment at an early stage of hydrothermal serpentinization and occur naturally in serpentinized harzburgites of ophiolite sequence (Gargiulo et al., 2013; Klein and Bach, 2009). Several studies describe the economic occurrence of nickel–iron alloys and nickel sulfides, the co-product of serpentinization distributed in serpentinized ultramafics, namely in Quebec (Staples et al., 2011), in British Columbia (Bradshaw, 2008), and in New Zealand (Ulrich, 1980). Understanding the economic importance of magnesioferrite and awaruite minerals, Rajendran and Nasir (2014a) used ASTER VNIR–SWIR spectral bands and image processing methods to map the occurrences of Ni-magnesioferrite–magnetite–awaruite bearing hydrothermal altered serpentinized harzburgites of Wadi Hibi region of Northern Oman. They studied the spectral absorption of OH and Mg–OH molecules that occurred in the serpentine minerals and developed color composite RGB image using ASTER spectral bands 8, 4, and 1 and successfully showed the occurrence of weathered peridotites and delineated the hydrothermally altered serpentinized rocks. Here, they selected the band 1 to show the weathered iron minerals (mainly olivine and pyroxene) rich peridotites surface, band 4 to show the occurrence of water and hydroxyl molecules bearing serpentine minerals in serpentinized harzburgites/peridotites, and the band 8 to improve the pixel’s information on the occurrences of Mg\OH molecules bearing minerals and carbonates in the peridotites/serpentinized harzburgites. They also discriminated more clearly the hydrothermal mineralized areas using band ratios 4/7, 4/1, and 2/3 × 4/3 RGB image (Figure 8).

Figure 8: ASTER RGB band ratios (4/7, 4/1, 2/3*4/3) image (Rajendran and Nasir, 2014a) showing the hydrothermally altered serpentinized peridotites of study area. T – Tertiary formations; E- Basic extrusives mostly spilites with pillow lava; D- Diabase dyke swarms; HG- Gabbroid hypabyssal rocks; G- Gabbro; Pg- Peridotites with gabbro intrusions; P – Peridotites partly serpentinized; P’ - strongly sheared serpentinized harzburgite, Ha- Halîw Formation; OM- Oman Melange; and HD – Hamrat Duru Formations.
vii. Mapping of Neoproterozoic source rocks of the Huqf Supergroup: The Neoproterozoic Huqf Supergroup formations of the Oman Salt Basins have been the target for oil exploration. Study of source rocks, responsible for oil occurrences, exposed on the surface is an analogue for understanding more about the characters of subsurface source rocks and a key to target for future oil exploration. Studying the importance, recently, Rajendran (2016) mapped the surficial exposure of formations of the Huqf Supergroup in and around Khufai Dome of the Huqf area in the Sultanate of Oman using ASTER satellite data and image processing methods such as decorrelation stretching, principal component analysis (PCA), and
spectral angle mapper (SAM). In this research, he studied the ASTER spectral bands 8, 3, and 1 by decorrelation stretching and well-discriminated the Masirah Bay, the Khufai, the Shuram, and the Buah Formations of the Nafun Group, the source rocks of Huqf Supergroup with the Quaternary deposits. He analyzed the visible and near infrared–shortwave infrared spectral bands of ASTER by PCA and showed the occurrence and spatial distribution of such formations in the RGB principal component images (Figure 10; R: PC1, G: PC2, B: PC3). He also used the SAM and ASTER indices to confirm the minerals of the formations (Figure 11).

Figure 10: ASTER RGB image of PC1, PC2 and PC3 showing the occurrence of Huqf Super Group formations (Masirah Bay – Mf; Khufai – Khf; Shuram – Shm; Buah – Bu; Silicified breccias - Sb), the Haima Super Group formation (Thumaylah – Th) and the Quaternary formations (Qes, Qcy-z, Qpy-z, Qtz) in and around the Khufai Dome (Rajendran, 2016).
Figure 11: ASTER TIR minerals indices RGB color composite image (R = QI, G = CI, and B = MI) showing the quartz-rich silicate formations of Masirah Bay in red orange, the carbonates of Khufai and Buah Formations in the range of blue and the silty shale of Shuram Formation in cyan and the Quaternary deposits in mixed purple in and around of the Khufai Dome (Masirah Bay – Mf; Khufai – Khf; Shuram – Shm; Buah – Bu; Silicified breccias - Sb, Thumaylah – Th; Quaternary formations – Qes, Qcy-z, Qpy-z, Qtz; Rajendran, 2016).

viii. Mapping of marble and dimension stones: Marble and dimension stones play vital role in sustaining the economy of the Sultanate of Oman. Rajendran et al. (2017) attempted to map such industrial rocks in several of part of the Sultanate of Oman in the vision to use the remote sensing technique by the exploration and mining geologists, and potential investors to explore more such economic valuable resources in this region. They studied the spectral absorptions of calcite minerals of the marble occurrences in detail and characterized their absorptions at 1.752, 1.875, 1.992, 2.154, 2.341, and 2.491 μm in the SWIR region by measuring spectra at 7 nm spectral resolution and distinguished them from other carbonate minerals (e.g., dolomite). Based on that, they processed the ASTER spectral bands by a simple decorrelation image processing method and showed that the band 8 is characteristic to calcite absorption. Their results showed distinctive tonal variation on the image for the marble occurrences (Figure
They also compared the study with the spectral band 7 of Landsat 7 (ETM+) which resulted that the difference in energy absorption in the wide sensor band width is not that much efficient to discriminate the marble from associated carbonate formations. They demonstrated the capability of the satellite sensor and the potential of the image processing method to map such economic industrial rock to the Sultanate of Oman.

ix. **Mapping of Hydrothermal altered minerals and VMS deposit zone:** Hydrothermal alteration minerals have diagnostic spectral absorptions characters in the visible and near infrared through the shortwave length infrared regions and can be mapped using multispectral and hyperspectral satellite data as a tool for the initial stages exploration of porphyry copper and epithermal gold deposits (Bedini et al., 2009; Carranza and Hall, 2002; Di Tommaso and Rubinstein, 2007; Gabr et al., 2010; Kruse et al., 2003; Mars and Rowan, 2006; Moore et al., 2008; Perry, 2004; Pour et al., 2011; Tangestani and Moore, 2002; Tangestani et al., 2008; Yujun et al., 2007; Zhang et al., 2007). Azizi et al. (2007) used SWIR bands of ASTER and interpreted the image for presence of hydrothermal altered minerals in propylitic and phyllic alteration zone to the exploration of copper and gold mineralization occurred to the SE of Sanandaj city situated in Kurdistan Province, west of Iran. They studied the images of band ratios and PCA, and described the propylitic zone rich in chlorite and epidote minerals, and phyllic zone rich in white mica and kaolinite minerals. Mapping of hydrothermally altered rocks using ASTER data and different image processing methods are well reviewed by Pour and Hasim (2012) and the recent studies include the works of Pour and Hasim (2015), Rajendran and Nasir (2014), and Rajendran et al. (2013a, b; Figure 13).

Recently, Alimohammadi et al. (2015) used the ASTER data to for the mapping of hydrothermal alterations associated with porphyry copper deposits occurred in parts of Daraloo–Sarmeshk area, southern part of the Kerman copper belt of Iran. Rajendran and Nasir (2017) used the nine VNIR-SWIR spectral bands of ASTER and image processing methods namely decorrelation stretching, band ratios, ASTER indices, linear spectral unmixing (LSU), and mixture tuned matched filtering (MTMF) and demonstrated the technique and methods to discriminate host rock of the VMS deposits, to delineate the hydrothermal altered mineralized zone and to detect and map the minerals of the different hydrothermal altered zones namely the oxidized, propylitic, argillic, and phyllic zones of the Volcanogenic Massive Sulphide (VMS) deposits occurred between Sohar-Shinas region of Al-Batina coast of the Sultanate of Oman. The results of study showed that the decorrelation of ASTER spectral bands 3, 6, and 8 well-discriminated extrusive basalts, and the host lithology of altered zones and ASTER band ratios the (5/3+1/2) used for iron oxidized zone, the (4+6)/5 for the argillic zone and the (5+7)/6 for the phyllic zone delineated the mineralized zone. They used ASTER indices of OH bearing altered minerals, kaolin, and alunite indices which are all confirmed the presence of alterations in the mineralized zone. Further, they used the end members derived based on the spectral angle mapper (SAM) method in the linear spectral unmixing (LSU) method to detect the different alteration zones and showed the occurrences of the oxidized, propylitic, argillaceous, and phyllic zones. They compared the LSU results with the results of the mixture tuned matched filtering (MTMF) method.

7. Mapping of Different Lithology of Oman using ASTER Data

In the Sultanate of Oman, the major economic minerals resources and mineralized zones are associated with the carbonate platform, ophiolite sequence, and metamorphic sole, and Tertiary and Quaternary formations. Mapping of these rock types/ formations and understanding their occurrence and distributions are important to explore more economic minerals and ore deposits and the plate tectonism of this region.
**Figure 12:** Decorrelated image of ASTER spectral bands 8, 3, 1 showing the occurrence of marble (Oman Exotic) in bright yellow near Al Hamra region, Oman. (TH – Tectonized Harzburgite; D-Dunite; Jmb2- Qfy – Quaternary deposits).
Figure 13: RGB image of band ratios (R: (b1+b2)/b3; G: (b2+b4)/b5; B: (b4+b6)/b5) showing the VMS mineralized zone and dashed line is the recommended zone for exploration (SE1 and SE2 are extrusives and * Cu occurrences; Rajendran et al., 2013b).
Figure 14: RGB color composite (R = PC5, G = PC3, B = PC2) showing the discrimination of quartz-rich silicates (blue), carbonates (purple) and mafic-rich ophiolite (light green) rock formations. (quartz-rich silicates (blue; Sc), carbonates (purple; Cs and CsD), mafic-rich ophiolite (light green; Mc), Layered Gabbro (Gb), Sheeted dykes (SD) and biocalst and limestone rich sands (Ty). (Rajendran et al., 2011)
The spectral absorption characters of minerals of such rock types are well described and studied by Rajendran (2016), Rajendran and Nasir (2013a; 2014b; 2014a; 2014b; 2014c; 2015a; 2015b; 2017), and Rajendran et al. (2011; 2012; 2013a; 2013b; 2014; 2017) A few more examples follow, showing the capability of ASTER data to map such rock types.

i. **Mapping of ophiolites lithology:** Discrimination of carbonate rocks from mafic and ultramafic ophiolite sequence rocks of Oman are carried out by Abrams et al. (1988), Combe et al. (2006), Corrie et al. (2010), Gillespie et al. (1986), and Rothery (1987). In 2011, Rajendran et al. used the relative band-depth images contain major absorption features of minerals and rocks such as, limestone [(band 7 + band 9)/band 8] and dolomite [(band 6 + band 8)/band 7] for carbonates and mafic ophiolites (band 2/band 1) and mapped the respective rocks in different parts of Oman. Also, they developed RGB color composite image developing band ratio of 9/7 for the carbonates (limestone and dolomite), 6/8 for quartz-rich silicates (shale, schist, sandstone, gray-wackes), and the band ratio 1/2 for mafic ophiolite (harzburgite, harzburgite with dunite) rocks. Their study to discriminate such rocks using SWIR spectral bands by PCA and TIR spectral bands by ASTER spectral indices such as carbonates (carbonate index, CI), silica rich (quartz index, QI), and mafic rich (mafic index, MI) are well-discriminated in their occurrences and distributions (Figure 14).

ii. **Mapping of metamorphic rocks:** Gad and Kusky (2007) studied the ASTER band-ratio (4/7, 4/6, 4/10) image for lithological mapping of the Arabian–Nubian shield, the Neoproterozoic Wadi Kid area, Sinai, Egypt, and discriminated the major rock types namely gneiss and migmatite, amphibolite, volcanogenic sediments with banded iron formation, meta-pelites, talc schist, metapsammites, meta-acidic volcanics, meta-pyroclastics volcanioclastics, albitites, and granitic rocks. In 2015, Rajendran and Nasir mapped the metamorphic zone of the As Sifah region, northeast of Oman. They studied the VNIR-SWIR spectral bands of ASTER and well-known image processing methods such as image decorrelation, Principal Component Analysis (PCA), and Spectral Angel Mapper (SAM). The study delineated the region of metamorphic zone and discriminated the different metamorphic and carbonate rocks of the region characterized by hydroxyl (OH) and carbonate bearing minerals. Also, they studied bright reflections and dark absorptions of individual component of PCA of the region (Rajendran et al., 2011; 2012) and chose the principal components of PC4, PC3, and PC2 and discriminated the metamorphic rocks of the region (Figure 15). Apart from the delineation of metamorphic zone and the discrimination of metamorphic rocks, the occurrence of metamorphic minerals of the rocks of the region are studied using the supervised classification method called Spectral Angle Mapper (SAM).

iii. **Mapping of Moho and Moho Transition zone (MTZ):** Mapping of Moho and MTZ, and discriminating them in between the mafic crustal rocks and ultramafic mantle rocks in ophiolite sequence are more significant and important to the scientific community to understand more about the global tectonism. Moho and Moho Transition Zone (MTZ) of the Samail ophiolite of Sultanate of Oman are also characteristic to potential occurrences of chromite deposit, hydrothermal mineralization, and serpentinization. Recently, Rajendran and Nasir (2015b) described the remote sensing spectral characters of minerals and rocks of the Moho and MTZ and discriminated the Moho of Wadi Al Abyad of Nakhl massif, and Wadi Nidab and Wadi Abda regions of Semail massif in the visible and near infrared (VNIR), and short wavelength infrared (SWIR) spectral regions using ASTER data.
Figure 15: ASTER RGB image of principal components PC4, PC3 and PC2 showing the occurrence and spatial distribution of hydroxyl bearing metamorphic rocks and carbonate formations in the As Sifah region, Oman (Rajendran and Nasir, 2015a).
**Figure 16:** ASTER RGB images of band ratios A) \((4/8, 4/1, 3/2 \times 4/3)\) of Wadi Al Abyad region of the Nakhl massif showing the thin Moho (dashed line) in between the mantle (harzburgite) and crustal (gabbro) rocks (Hz – Harzburgite, LG – Lower Gabbro, UG – Upper Gabbro, Qtz – Recent Wadi Alluvium) and B) the of Wadi Nidab and Wadi Abda of the Sumail massif show the occurrence of thick Moho Transition Zone (Hz - harzburgite, MTZ - Moho Transition Zone, CT – crust, US - Undifferentiated Sediments) (Rajendran and Nasir, 2015 b).
The study shows that the red–green–blue (RGB) color composite images of ASTER spectral bands 8, 3, and 1, and 8, 7, and 4 are able to delineate the Moho and MTZ of the regions. The RGB images of ASTER band ratios (4/8, 4/1, 3/2 * 4/3 [Figure 16]) and ([1 + 3]/2, (4 + 6)*5, (7 + 9)/8) are capable to discriminate the mantle material (ultramafic harzburgites) and crustal rocks (mafic gabbros). The occurrence of such rock types is demonstrated by detection of their minerals using Spectral Angle Mapper (SAM) image processing method in their study.

iv. Mapping of Tertiary and Quaternary formations and Marine Terraces: The occurrence and distribution of different types of limestones, dolomites, marls bearing limestones, sandstones, and wadi alluvial deposits belong to the Tertiary and Quaternary age of different parts of Oman are studied and well-discriminated by Rajendran (2016), Rajendran et al. (2011; 2013a), and Rajendran and Nasir (2013a; 2013b; 2014a; 2014b; 2014c; 2015a) during their work on the above mapping of minerals, ores, and rock types (Figures 4, 6–12, 14–15). In 2016, Yuan et al. studied the Tertiary and Quaternary Marine Terraces and Planation Surfaces of Northern Oman. They used the ASTER data and PCA image processing method and discriminated the terraces and related sedimentary formations of the study region.

8. Accuracy Assessment

Apart from the mapping of different minerals, ore deposits and associate rock types, satellite data have also been used to calculate the area of occurrences and distributions of these rocks and deposits (Bedini, 2011; Chen and Reed, 1987; Congalton, 1991; El Janati et al., 2014; Hosseinjani and Tangestani, 2011; Jia and Richards, 1994; Sabol et al., 1992; Van Der Meer, 1995; Zhang et al., 2007). These studies were able to compare their results of mapping with satellite data with other techniques and showed that mapping of mineral resources with the satellite data could be highly accurate. However, the results of these studies mainly depend on the spatial, radiometric, and spectral resolutions of the satellite data and the spectral information's provided to the method/s. Rajendran (2016), Rajendran and Nasir (2014a; 2015a; 2017) and Rajendran et al. (2013a) used the parallelepiped, spectral angle mapper (SAM), spectral information divergence (SID), linear spectral unmixing (LSU), linear square-fit (LSF), and mixture tuned matched filtering (MTMF) methods to detect minerals and bearing rocks such as ophiolite, metamorphic, and carbonate rocks, and also showed their accuracy to use the method/s for mapping of such resources. Recently, Rajendran (2016) mapped the Neoproterozoic source rocks of the Huqf Supergroup occurred in the Khufai dome region of the Sultanate of Oman using ASTER data and assessed accuracy by confusion matrix using maximum likelihood (ML), spectral angle mapper (SAM) and spectral information divergence (SID) algorithms for their distributions. The matrix of ML algorithm has provided the best overall accuracy of 92.93% and kappa coefficient of 0.92 to map the mineral resources of region.

9. Validation of Research Studies

In the Sultanate of Oman, research studies were carried out and mapped the major minerals and ore deposits and different rock types and formations using various satellite data and suitable simple image processing method (by Abrams et al. (1988), Combe et al. (2006), Corrie et al. (2010), Gillespie et al. (1986), Rajendran, (2016), Rajendran et al. (2017), Rajendran and Nasir (2013a; 2013b; 2014a; 2014b; 2014c; 2015a; 2015b; 2017), and Rothery (1987). The results of image analyses, interpretations, and outcomes of all research studies carried out in the different scale in the several parts of the Sultanate of Oman were always checked, verified, and evaluated either in the field by collecting data and field samples using available geological maps or in the laboratory by analyzing field samples to validate and confirm such results. The capability of sensor/s and potential of the image processing method/s to map such minerals resources were documented in the vision to use
them by the exploration geologists, and mine owners toward exploration of such deposits in parts of Oman and to the similar deposits occurred in the arid region (Rajendran, 2016; Rajendran et al., 2013a; 2014; Rajendran and Nasir, 2014; 2015).

10. Conclusion

This study emphasizes the importance of remote sensing technique to map economically important minerals and ore deposits and industrial rocks by using the spectral absorption characters of minerals and simple image processing methods for such economic resources. This review showed that the remotely sensed ASTER data is capable in detecting mineral resources and discriminating the mineralized zones. The simple image processing methods have potential to show the occurrence and spatial distribution of such economic resources. The satellite data and image processing methods used are good in the mapping of mineral resources of the Oman and therefore it is recommended to use the data and methods to explore more mineral resources in the country and similar deposits occurred in other arid regions of the world.

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