Evaluating the effectiveness of multi-spectral remote sensing data for lithological mapping in arid regions: a quantitative approach with examples from the Makkah Neoproterozoic region, Saudi Arabia

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EVALUATING THE EFFECTIVENESS OF MULTI-SPECTRAL REMOTE SENSING DATA FOR LITHOLOGICAL MAPPING IN ARID REGIONS: A QUANTITATIVE APPROACH WITH EXAMPLES FROM THE MAKKAH NEOPROTEROZOIC REGION, SAUDI ARABIA

By

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Approved by

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Dr. John Hogan
ABSTRACT

This work quantitatively evaluates the effectiveness of multi-spectral remote sensing data for geological mapping in arid regions. For this, Landsat Thematic Mapper (TM) data covering part of the Neoproterozoic Arabian Shield around the Makkah region in Saudi Arabia are used. The Makkah region is dominated by a variety of layered and intrusive rocks covered by unconsolidated sediments. The Landsat TM data have six spectral bands in the visible and near infrared (VNIR) and shortwave infrared (SWIR) with thirty meters spatial resolution.

The Optimum Index Factor (OIF) has been computed to determine the best Red-Green-Blue (RGB) band combination emerging from the six spectral bands, the six corresponding Principal Components (PCs), and selected band-ratio images. Results of the OIF analysis showed that the RGB color combination 3-5-7 is the best among all twenty possible RGB color combinations obtained from the six Landsat TM bands. Also, the OIF analysis pointed to that the PC RGB color combination 2-4-5 have the highest spectral information among all twenty RGB color combinations obtained from the six PCs. As well, the modified band-ratio RGB color combination 5/7-5/4-3/1 has the highest OIF compared to other band-ratio Landsat TM images that have been previously used for lithological mapping in arid regions.

Subsequently, in order to quantify the effectiveness of the Landsat TM data for lithological mapping, the Maximum Likelihood supervised classification is implemented. Results of the classification are evaluated in relation to previously published geological map using the Error Matrix and Kappa hat image classification accuracy assessment methods. These results show variation in accuracy between different lithological units, with an overall accuracy of 66.25% and Kappa hat of 56.98%. Part of this error is attributed to the presence of the unconsolidated sediments which are highly heterogeneous.
ACKNOWLEDGEMENTS

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Thanks also go to the Remote Sensing lab colleagues who have taught me most of the remote sensing digital image processing and Geospatial Information System (GIS) tricks. These colleagues include, bt not limited to Elamin Ismail, Ahmed Elsheikh, David Bridges, Hanadi Al-Doukhi Carrie Bender, Leslie Lansbery, and Tom Jerris.

Finally, my gratitude to my friends and colleagues at King Abdul Aziz University in Jeddah, Saudi Arabia.
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1. INTRODUCTION

1.1. BACKGROUND AND OBJECTIVES

1.1.1. Background. Multi-spectral remote sensing data such as Landsat Thematic Mapper (TM) have been widely used for lithological mapping in arid regions since the mid 1980s (e.g. Sultan et al., 1986, 1987; Abdelsalam et al., 2000; Ramadan et al., 2001; Abdeen et al., 2002; Elnagdy and Abdelsalam, 2006; Qiu et al., 2006; Gad and Kusky, 2007; Amer et al., 2010). These data have been used to create Red-Green-Blue (RGB) color combination images from individual bands, or manipulating the data through Principal Component Analysis (PCA) (Ren and Abdelsalam, 2006) or band ratios (Sultan et al., 1986, 1987; 2002; Amer et al., 2010). Visual interpretation of the color variation reflected in these images manifesting different lithological units is used to general lithological maps at different scales. However, the accuracy of such remote sensing studies for lithological mapping has not been quantitatively evaluated. Rather, many of these studies relied on a more qualitative approach for evaluating results of image processing and interpretation.

1.1.2. Objectives. The objective of this study is to quantitatively evaluate the accuracy of multi-spectral remote sensing data for lithological mapping in arid regions. For this, Landsat TM data covering the Makkah region (which exposed a variety of Neoportozoic layered and intrusive rocks) are used to: (1) Produce images from individual bands for all possible RGB color combinations (Total = 20). (2) Produce Principal Components (PCs) from the original Landsat TM bands (Total = 6) and produce PC images for all possible RBG color combinations (Total = 20). (3) Produce selected band-ratio images from the Landsat TM bands. (4) Evaluate the effectiveness of these images in extracting the optimum spectral information by utilizing the Optimum Index factor (OIF) statistical approach. (5) Perform supervised classification based on the spectral bands of the Landsat TM data. (6) Evaluate the accuracy of the supervised classification through the Error Matrix and Kappa hat accuracy assessment.

1.2. TECTONIC SETTING OF THE STUDY AREA

The study area is situated within the Arabian Plate which is also is known as the Arabian Peninsula (Figure 1.1). The Arabian Peninsula is bordered by the Red Sea and the Aqaba transform fault in the west and northwest, the Bitlis and Zagros orogenic belt in the north and northeast, and the Gulf of Aden in the south (Figure 1; Stern and Johnson, 2010).
Saudi Arabia, which dominates much of the Arabian Peninsula, has a variable of geological terrains. These geological terrains can be divided into four different regions. (1) The Arabian Shield (Johnson et al., 2011) which is dominantly Neoproterozoic in age, comprising metamorphosed volcano-sedimentary successions and ophiolites intruded by a variety of granitoids ranging in composition from granite to gabbro. The Arabian Shield is separated from the Nubian Shield by the Red Sea (Figure 1.2). (2) The Arabian platform which Phanerozoic in age, consisting of clastic, calcareous, and evaporitic successions dipping gently eastward away from the Arabian Shield. (3) The Neogene-aged Harrats constituting extensive basalt lava flows developed in association which different phases of the opening of the Red Sea (Pallister, 1988; Bosworth et al., 2005) and covers many parts of the Arabian Shield. (4) The Red Sea coastal plain which is dominated by Neogene to Quaternary sedimentary rocks and coral reefs.

The study area falls within the Arabian Shield (Figure 1.2) which was formed through the accretion of island-arc, back-arc and micro-continent terranes representing an orogenic event that spanned much of the Neoproterozoic era. The collision between different terranes resulted in the formation of ophiolite-decorated suture zones of different orientation. The study area falls with the 870-760 Ma old Jeddah terrane which is bounded in the north by the NE-trending Bir Umq stuture and in the south by the NE-trending Afaf Belt.

1.3. GEOLOGY OF THE MAKKAH AREA

This study focuses on a portion of the Makkah quadrangle which was mapped by Moore and Al-Rehaili (1989) with scale of 1:250,000. This part of the quadrangle is dominated by a NE-trending fold and thrust belt that exposes low-grade greenschist facies metamorphic rocks intruded by granitic bodies ranging in composition from granodiorite to tonalite.

Six Neoproterozoic formations are present in the study area: (1) Madiq formation which is made-up of meta-basalt and volcani-clastic rocks. In this study this formation will be referred to as "metabasalt" (Map 1.1). (2) Jumum formation which constitutes hornblende quartz-feldspar schist locally intercalated with biotite and garnet and banded amphibolites. This will be referred as in this study as “hornblende schist”. (3) Bahrah formation which is dominantly chlorite sericite schist with sub-
ordinate quartz-feldspathic schist. This will be referred to as “Chlorite schist”. (4) Tonalite to quartz diorite. This is referred to in this study as "Tonalite I". (5) Ju’ranah complex which is made-up of hornblende tonalite and tonalite to granodiorite. This will be referred to as "Tonalite II". (6) Samd Tonalite which is made-up of hornblende-biotite tonalite. This will be referred to as "Tonalite III". (7) In addition, these rocks are partially covered with unconsolidated sediments, dominantly sand.

Figure 1.1: Tectonic setting of Arabian Plate (After Stern and Johnson, 2010)
Figure 1.2: The study area (red rectangle) within the Arabian-Nubian Shield (After Johnson et al, 2011).
Map 1.1: lithological map of the study area. Simplified from Moore and Al-Rehaili (1989)
2. DATA, METHODS AND RESULTS

2.1. LANDSAT THEMATIC MAPPER (TM) DATA

The Landsat TM is a satellite-borne multi-spectral discrete detector and scanning mirror sensor that record energy in seven bands within the visible and near infrared (VNIR, four bands), shortwave infrared (SWIR, two bands) and thermal infrared (TIR, one band) regions of the electromagnetic spectrum. The spatial resolution of Landsat TM is thirty meters for the VNIR and SWIR bands and one-handed and twenty meters for the TIR bands. This work focuses on the VNIR and SWIR bands only since the TIR band have a lower spatial resolution and it measures emissivity rather than reflectivity. The Landsat TM sensor has sixteen days temporal resolution and the data are collected at an altitude of 705 km. The swath width is one-handed eighty five kilometers with an orbital inclination of 98.2°. The Landsat TM data has an 8-bit radiometric resolution (Digital Number (DN) ranges between 0 and 255).

The VNIR portion of the Landsat TM data has four bands including: (1) Band 1 (visible blue) which has a wavelength ranging between 0.45 and 0.52 µm. This band generally suffers from atmospheric scattering and has not been widely used for the generation of RGB color combination images form individual bands. However, this band has been used for the generation of band-ratios such as 3/1 (Abrams et al., 1983) and 5/1 (Sultan et al., 1986, 1987) because iron oxide minerals have absorption feature within the visible blue. (2) Band 2 (visible green) has a wavelength ranging between 0.52 and 0.60 µm. This band which has been widely used for mapping vegetation has also been included in RGB color combinations such as 7-4-2 (ARAMCO combination) for lithological mapping in arid regions since these regions lack vegetation cover. (3) Band 3 (visible red) has a wavelength ranging between 0.63 and 0.69 µm. This band has been used for the generation of band-ratio such as 3/1 (Abrams et al., 1983) because iron oxides have reflection feature in this band. (4) Band 4 (NIR) has a wavelength ranging between 0.76 and 0.90 µm and this band is usually utilized for mapping biomass of vegetation. In addition, it has been used for RGB color combinations of individual bands such as 7-4-2 and band ratios such as 4/5 (Abrams et al., 1983), 3/4 and 5/4 because hydroxyl minerals have absorption feature in the NIR portion of electromagnetic spectrum.
The SWIR of Landsat TM has 2 bands. These are band 5 which has a wavelength ranging between 1.55 and 1.75 µm and band 7 which has a wavelength ranging between 2.08 and 2.35 µm. Both bands are important for discriminating between different rock and soil types because all clay minerals have reflection features in band 5 and absorption feature in band 7.

The six bands (Band 1-5 and 7) used in this study are shown in Appendix 1. All of the bands are displayed with 8 bit radiometric resolution in which the spectral information are shown within 256 shades of grey. Generally, these bands are characterized by a wide dynamic range (between 0 and 150) except band 1 (visible blue) which has a narrow dynamic range (between 50 and 115 DN) because of the atmospheric scattering (Figure 2.1).


The visible bands (band 1-3) are highly-correlated as indicated by their high correlation coefficients (Table 2.1). Differently, there are low correlations between the visible, the NIR and the SWIR bands (Table 2.1)
Table 2.1: Initial statistics of the six Landsat TM bands used in this study.

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2.2. METHODS AND ANALYSIS

2.2.1. Red-Green-Blue (RGB) Color Combinations. The six Landsat TM bands allow for one-hundred twenty different RGB color combinations if the order of placing the three bands in the RGB color space is observed. Nevertheless, in this work only twenty color combinations are considered because the work relies on statistical analysis rather than visual evaluation. Hence, the statistics of the RGB color combination 1-2-3 = 1-3-2 = 2-1-3 = 2-3-1 = 3-1-2 = 3-2-1. All twenty RGB color combinations are shown in appendix 2. Generally, RGB color combinations that use bands with low correlation coefficients between them are expected to give better results for lithological mapping because of the spectral diversity in these bands. Also, bands with high standard deviation are expected to be better than bands with low standard deviation because bands that have high standard deviation have higher level of seperability between different lithological units compared to bands that have low standard deviation.

2.2.2. Principal Component Analysis (PCA). Principal component analysis (PCA) is an approach used in remote sensing digital image processing to de-correlate the highly spectrally-dependent multi-spectral remote sensing data (Ready and Wintz, 1973; Richards and Jia, 1999; Ren and Abdelsalam, 2006). This analysis involves mathematical computation of the variance-covariance matrix to translate and rotate
the principal axis to new origins and orientations to maximize de-correlation between bands.

The PCA was applied to the six Landsat TM bands covering the study area using the 6X6 variance-covariance matrix to produce six new Principal Components (PCs). Generally, the highest level PCs are the one that are expected to have the maximum amount of spectral information (Figure 2.2). PC1 is expected to have ~87% of the spectral information, PC2 will have ~12% and PC3 will have ~1% of the spectral information. However, Ren and Abdelsalam (2006) observed from PCA work in the Eastern Desert of Egypt that PC5 might be the most useful component for the analysis of geological structures and lithological mapping in arid regions. Ren and Abdelsalam (2006) explained this as due to that this low PC is effective in imaging the long wavelength geological features by reducing the masking effect of the higher PCs due to the richness of the spectral information in them.

The PC1 covering the study area is characterized by the highest dynamic range followed by PC2 and PC3 (Figure 2.3; Table 2.2). Other PCs are characterized by very narrow dynamic range (Figure 2.3; Table 2.2). all twenty RGB PC images resulting from the six PCs are shown in Appendix 2.

Figure 2.2: Eigen number (the rank of the principal component) - Eigen value (amount of spectral information) of the 6 Principal Components computed for the Landsat TM data covering the study area
Figure 2.3: Histograms of the six Landsat TM PCs used in this study. PC 1 (visible blue) = White. PC 2 (visible green) = Red. PC 3 (visible red) = Green. PC 4 (NIR) = Blue. PC 5 (SWIR) = Yellow. PC 6 (SWIR) = Cyan

Table 2.2: Initial statistics of the six Landsat TM Principal Components used in this study

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2.2.3. Band-ratio Images. Landsat TM band-ratio images have been widely used for lithological mapping and mineral exploration in arid regions. The Abrams-type and Sultan-type band-ratio images have been widely used in lithological mapping in the Arabian-Nubian Shield. In this work Abrams-type and Sultan-type images are used (Appendix 3). In addition, a modified Abrams-type band-ratio image is introduced (Appendix 3). The histograms of the band-ratios used in these images are shown in
figure 2.4. These histograms are characterized by dynamic range ranging between 0.5 and 2.5 (Figure 2.4).

The RGB color combination that produces Abrams-type image (Abrams et al., 1983) uses band-ratios 5/7 as red, 4/5 as green, and 3/1 as blue. These band-ratios (5/7, 4/5, and 3/1) are produced by dividing the digital number (DN) of one band (bands 5, 4, and 3) by another (bands 7, 5, and 1, respectively) to yield an image that enhances spectral differences between different lithological units and reduce the morphology effect. Additionally, these band-ratios usually results in new bands that have low correlation coefficients between them. The Landsat TM band-ratio 5/7 has been favored because all clay minerals have a significant reflection spectral feature in band 5 (short SWIR) and a significant absorption spectral feature in band 7 (long SWIR). Similarly, the landsat TM band-ratio 3/1 is selected because all iron oxide minerals have a reflection spectral feature in band 3 and an absorption spectral feature in band 1 (Sabins, 1997). Landsat TM band-ratio 4/5 is used because it emphasizes silicates minerals compared to FeO-rich minerals (Abrams et al., 1983).

![Figure 2.4: Histograms of the six Landsat TM band-ratios used in this study.](image)

In this work, the Abrams-type band ratio image is modified by using band-ratio 5/4 instead of 4/5. This is because such a modification optimizes the spectral information in the image as will be discussed later.
Sultan-type images (Sultan et al., 1986; Sultan et al., 1987) use band-ratio 5/7 as red, 5/1 as green, and 3/4*5/4 as blue. These are referred to as 5/7-5/1-3/4*5/4 Landsat TM images. Sultan et al. (1986; 1987) used the 5/7-5/1-5/4*3/4 Landsat TM images to map different lithologies in the Eastern Desert of Egypt and found them useful for identifying ultra-mafic rocks. Landsat TM band-ratio 5/1 is used because magnetite and other opaque minerals have reflectance feature in band 5 and absorption feature in band 1 (Sultan et al., 1987). This is similar to the Landsat TM band-ratio 3/1 used in the Abrams-type images (Abrams et al., 1983). FeO-rich alumina-silicate minerals have reflectance features at bands 3 and 5 and absorption feature at band 4. Hence, band-ratios 3/4 and 5/4 results in high DN values in pixels dominated by FeO-rich alumina-silicates minerals. Multiplying 5/4 by 3/4 to yield 5/4*3/4 results in even higher DN values, hence better definition of these minerals (Sultan et al., 1987).

Table 2.3 Initial statistics of the six Landsat TM band-ratio used in this study

<table>
<thead>
<tr>
<th>Basic Stats</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Stdev</th>
<th>Num</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4*5/4</td>
<td>0.37294</td>
<td>2.779412</td>
<td>1.805611</td>
<td>0.18022</td>
<td>1</td>
</tr>
<tr>
<td>5/7</td>
<td>0.894737</td>
<td>1.774194</td>
<td>1.109544</td>
<td>0.0493</td>
<td>2</td>
</tr>
<tr>
<td>4/5</td>
<td>0.509615</td>
<td>1.510638</td>
<td>0.750616</td>
<td>0.06211</td>
<td>3</td>
</tr>
<tr>
<td>3/1</td>
<td>0.615385</td>
<td>1.535354</td>
<td>1.099381</td>
<td>0.12363</td>
<td>4</td>
</tr>
<tr>
<td>5/1</td>
<td>0.407407</td>
<td>1.858974</td>
<td>1.09912</td>
<td>0.16219</td>
<td>5</td>
</tr>
<tr>
<td>5/4</td>
<td>0.661972</td>
<td>1.962264</td>
<td>1.341625</td>
<td>0.11455</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Correlation</th>
<th>3/4*5/4</th>
<th>5/7</th>
<th>4/5</th>
<th>3/1</th>
<th>5/1</th>
<th>5/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4*5/4</td>
<td>1</td>
<td>-0.06389</td>
<td>-0.903503</td>
<td>-0.167429</td>
<td>0.217154</td>
<td>0.915702</td>
</tr>
<tr>
<td>5/7</td>
<td>-0.06389</td>
<td>1</td>
<td>-0.089658</td>
<td>0.179565</td>
<td>0.269469</td>
<td>0.07582</td>
</tr>
<tr>
<td>4/5</td>
<td>-0.09035</td>
<td>-0.089658</td>
<td>1</td>
<td>-0.020442</td>
<td>-0.50236</td>
<td>-0.990271</td>
</tr>
<tr>
<td>3/1</td>
<td>-0.167429</td>
<td>0.179565</td>
<td>-0.020442</td>
<td>1</td>
<td>0.831273</td>
<td>-0.033738</td>
</tr>
<tr>
<td>5/1</td>
<td>0.217154</td>
<td>0.269469</td>
<td>-0.50236</td>
<td>0.831273</td>
<td>1</td>
<td>0.464889</td>
</tr>
<tr>
<td>5/4</td>
<td>0.915702</td>
<td>0.07582</td>
<td>-0.990271</td>
<td>-0.033738</td>
<td>0.464889</td>
<td>1</td>
</tr>
</tbody>
</table>

2.2.4. Optimum Index Factor (OIF). The optimum index factor (OIF) analysis (Chavez, et al., 1982; Chavez, et al., 1984) is a statistical approach to rank all possible RGB color combinations of multi-spectral remote sensing data on the basis of total variance within bands and correlation coefficient between bands. Hence, the OIF can be expressed as:
\[ OIF = \frac{\sigma_K + \sigma_L + \sigma_M}{|r_{KL}| + |r_{KM}| + |r_{LM}|} \]

Where:

\( \sigma_K, \sigma_L, \text{and} \sigma_M = \) Standard deviation of bands K, L, and M, respectively;

\[ |r_{KL}|, |r_{KM}|, \text{and} |r_{LM}| = \) Absolute value of the correlation coefficients between bands K and L; K and M; and L and M, respectively.

The OIF is calculated for all twenty RGD color-combinations of the Landsat TM data covering the study area (Table 2.4; Figure 2.5) as well as all twenty PC images (Table 2.4; Figure 2.6) and the three band-ratio images (Table 2.4; Figure 2.7). For the Landsat TM images of the study area, the OIF calculation indicates that the RGB color combination 3-5-7, PC 2-4-5 and band-ratios 5/7-5/4-3/1 are the ones with the highest spectral information. This is supported by the scatter graph of the bands, PCs and band-ratios used in this combination which shows them with the least correlation coefficient between them (Figure 2.8, 2.9 and 2.10).

Table 2.4: OIF values of bands, PCs and band-ratio images

<table>
<thead>
<tr>
<th>All possible 20 combinations</th>
<th>Band Comb OIF</th>
<th>PC OIF</th>
<th>band ratio</th>
<th>OIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>13.66217256</td>
<td>155.37504</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>124</td>
<td>12.50467595</td>
<td>192.56278</td>
<td>5/7-4/5-3/1</td>
<td>0.8</td>
</tr>
<tr>
<td>125</td>
<td>14.7854162</td>
<td>168.13044</td>
<td>5/7-5/1-3/4*5/4</td>
<td>0.7</td>
</tr>
<tr>
<td>127</td>
<td>13.91727696</td>
<td>153.01691</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>134</td>
<td>14.62599675</td>
<td>176.87366</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>135</td>
<td>17.00065206</td>
<td>156.10534</td>
<td>5/7-5/1-3/4*5/4</td>
<td>0.7</td>
</tr>
<tr>
<td>137</td>
<td>16.14355413</td>
<td>143.03195</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>145</td>
<td>15.75544443</td>
<td>193.72236</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>147</td>
<td>14.93550803</td>
<td>173.7291</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>157</td>
<td>16.86166814</td>
<td>153.72133</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>234</td>
<td>15.56521632</td>
<td>494.15109</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>235</td>
<td>17.91651618</td>
<td>267.99501</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>237</td>
<td>17.0771268</td>
<td>225.45981</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>245</td>
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<td>591.84907</td>
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<td>1.17</td>
</tr>
<tr>
<td>247</td>
<td>15.90101136</td>
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<td>1.17</td>
</tr>
<tr>
<td>257</td>
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<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>345</td>
<td>18.76100538</td>
<td>444.03396</td>
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<td>1.17</td>
</tr>
<tr>
<td>347</td>
<td>17.98385411</td>
<td>280.00953</td>
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<td>1.17</td>
</tr>
<tr>
<td>357</td>
<td>19.89241379</td>
<td>207.25784</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
<tr>
<td>457</td>
<td>18.65099154</td>
<td>391.08026</td>
<td>5/7-5/4-3/1</td>
<td>1.17</td>
</tr>
</tbody>
</table>
Figure 2.5: OIF of the twenty Landsat TM RGB band combinations used in the study area

Figure 2.6: OIF of the twenty Landsat TM RGB PC combinations used in the study area

Figure 2.7: OIF of the tree Landsat TM RGB band-ratio combinations used in the study area
Figure 2.8: The Landsat TM RGB band combination (3-5-7) with the best OIF (19.89)
Figure 2.9: Scatter plots of the three bands resulting in the best OIF Landsat TM data used in the study area
Figure 2.10: The Landsat TM RGB PC combination (2-4-5) with the best OIF (591.85)
Figure 2.11: Scatter plots of the three PC resulting in the best OIF of Landsat TM data used in the study area
Figure 2.12: The Landsat TM RGB band-ratio combination (5/7-5/4-3/1) with the best OIF (1.17)
Figure 2.13: Scatter plots of the three band-ratios resulting in the best OIF of Landsat TM data used in the study area
2.2.5. Supervised Classification. To evaluate the effectiveness of multispectral remote sensing data in lithological mapping in arid regions Maximum Likelihood supervised classification is applied to the Landsat TM data processed above. This algorithm classifies any pixel in the remote sensing data based on its spectral distance from the mean of the training sites or the regions of interest and probability (Jensen, 2005). The pixel is assigned to the class that has the highest probability with it. Hence, the supervised classification has been implemented as follows:

(1) Seven regions of interest were selected that are likely reflecting the seven lithological units that dominate the study area. These are: (A) Meta-basalt represented by a purple region of interest constituting four-hundred forty five pixels. (B) Hornblende schist represented by green region of interest constituting six-hundred forty six pixels. (C) Chlorite schist represented by cyan region of interest constituting two-hundred thirty nine pixels. (D) Tonalite I represented by blue region of interest with three-hundred eighty nine pixels. (E) Tonalite II represented by red region of interest constituting one thousand four-hundred forty three pixels. (F) Tonalite III represented by yellow region of interest constituting two thousand two-hundred and six pixels. (G) Unconsolidated sediments represented by white region of interest constituting eighty three pixels. The colors are chosen to match those used in the geological map in Figure 1.3.

(2) The Maximum Likelihood supervised classification was applied using the seven classes with a probability threshold set to a single value and a scale factor of 0-255. Results of the supervised classification are shown in Figure 2.14.

2.2.6. Accuracy Assessment. Accuracy assessment of the Maximum Likelihood classification results were evaluated using the error matrix and the kappa hat approach (Congalton and Mead, 1981, Feinstein, 1998; Foody, 2002). For this, regular spaced systematic sampling was used to select reference points from the geological map shown in Figure 1.3. Subsequently, these points were used to calculate the overall accuracy, commission error (classification of a pixel a class that it does not belong to), omission error (omitting the classification of a pixel to a class that it belongs to), and Kappa hat. Results of the accuracy assessment are shown below.
Figure 2.14: Results of the maximum Likelihood supervised classification. Meta-basalt = Purple. Hornblende schist = Green. Chlorite schist = Cyan. Tonalite I = Blue. Tonalite II = Red. Tonalite III = Yellow. Unconsolidated sediments = White
Table 2.5: Error matrix of the Maximum Likelihood supervised classification. TII Ref = Reference Tonalite II. MB Ref = Reference Meta-basalt. HS Ref = Reference Hornblende schist. TI Ref = Reference TonaliteI. CS Ref = Reference Chlorite schist. TIII Ref = Reference Tonalite III. US Ref = Reference unconsolidated sediments.

<table>
<thead>
<tr>
<th></th>
<th>TII Ref</th>
<th>MB Ref</th>
<th>HS Ref</th>
<th>TI Ref</th>
<th>CS Ref</th>
<th>TIII Ref</th>
<th>US Ref</th>
<th>Row Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TII</td>
<td>94</td>
<td>26</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>138</td>
</tr>
<tr>
<td>MB</td>
<td>26</td>
<td>50</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>79</td>
</tr>
<tr>
<td>HS</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>TI</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>23</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>CS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>67</td>
<td>0</td>
<td>34</td>
<td>101</td>
</tr>
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<td>TII</td>
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<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>9</td>
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<tr>
<td>US</td>
<td>7</td>
<td>5</td>
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<td>1</td>
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<td>24</td>
<td>26</td>
<td>74</td>
<td>8</td>
<td>57</td>
<td>397</td>
</tr>
<tr>
<td>Column Total</td>
<td>263 =</td>
<td>127</td>
<td>81</td>
<td>24</td>
<td>26</td>
<td>74</td>
<td>8</td>
<td>57 =</td>
</tr>
</tbody>
</table>

OVERALL ACCURACY % \( \frac{263}{397} = 66.24685139 \)

<table>
<thead>
<tr>
<th>Producer's Accuracy (Omission Error)</th>
<th>94/127=</th>
<th>74.01574803</th>
<th>25.98425197</th>
<th>% omission error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50/81=</td>
<td>61.72839506</td>
<td>38.27160494</td>
<td>% omission error</td>
</tr>
<tr>
<td></td>
<td>11/24=</td>
<td>45.833333333</td>
<td>54.16666667</td>
<td>% omission error</td>
</tr>
<tr>
<td></td>
<td>23/26=</td>
<td>88.46153846</td>
<td>11.53846154</td>
<td>% omission error</td>
</tr>
<tr>
<td></td>
<td>67/74=</td>
<td>90.54054054</td>
<td>9.459459459</td>
<td>% omission error</td>
</tr>
<tr>
<td></td>
<td>8/8.=}</td>
<td>100</td>
<td>0</td>
<td>% omission error</td>
</tr>
<tr>
<td></td>
<td>10/57=</td>
<td>17.54385965</td>
<td>82.45614035</td>
<td>% omission error</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>User's Accuracy (Commission Error)</th>
<th>94/138=</th>
<th>68.11594203</th>
<th>31.88405797</th>
<th>% commission error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50/79=</td>
<td>63.29113924</td>
<td>36.70886076</td>
<td>% commission error</td>
</tr>
<tr>
<td></td>
<td>11/12=</td>
<td>91.66666667</td>
<td>8.333333333</td>
<td>% commission error</td>
</tr>
<tr>
<td></td>
<td>23/28=</td>
<td>82.14285714</td>
<td>17.85714286</td>
<td>% commission error</td>
</tr>
<tr>
<td></td>
<td>67/101=</td>
<td>66.33663366</td>
<td>33.66336634</td>
<td>% commission error</td>
</tr>
<tr>
<td></td>
<td>8/9=</td>
<td>88.88888889</td>
<td>11.11111111</td>
<td>% commission error</td>
</tr>
<tr>
<td></td>
<td>10/30=</td>
<td>33.33333333</td>
<td>66.66666667</td>
<td>% commission error</td>
</tr>
</tbody>
</table>
The computation of Khat Coefficient of Agreement as follows:

\[
K = \frac{\sum_{i=1}^{k} x_{ii} - \sum_{i=1}^{k} (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{k} (x_{i+} \times x_{+i})}
\]

Where \( N=397 \)

\[
\sum_{i=1}^{k} x_{ii} = (94 + 50 + 11 + 23 + 67 + 8 + 10) = 263
\]

\[
\sum_{i=1}^{k} (x_{i+} \times x_{+i}) = (127 \times 138) + (81 \times 79) + (24 \times 12) + (26 \times 28) + (74 \times 101) + (8 \times 9) + (57 \times 30)
\]

\[
= 17526 + 6399 + 288 + 728 + 7474 + 72 + 1710
\]

\[
= 34197
\]

\[
\hat{\kappa} = \frac{(397)(263) - 34197}{(397)^2 - 34197} = \frac{104411 - 34197}{157609 - 34197} = \frac{70214}{123412} = 56.98\%
\]

The accuracy assessment points to an overall accuracy in the range of 66.25% and Kappa hat of 56.98%. However, the commission and omission error vary significantly from one rock type to another. This will be discussed below.
3. DISCUSSION

Results obtained from the use of individual bands of landsat TM data points to that the multi-spectral remote sensing data is most effective in lithological mapping when bands from different portions of the electromagnetic spectrum (such as combining the VNIR and SWIR bands) are used in a single RGB color combination. The OIF analysis of all possible twenty combinations obtained from the six Landsat TM bands show the RGG combination 3-5-7 as being the one with the highest OIF value. This is because one visible (band 3, visible red) and two SWIR (bands 5 and 7) are used in the RGB color combination. These bands ensure that there are enough spectral diversity in the RGB color combination and avoids spectral redundancy.

Traditionally, it has been recommended that the upper level PCs (PC1, PC2, and PC3) are the ones that should be used in any RGB color combination since these have the highest amount of spectral information. However, results of this work show that PCs other than the upper level ones can equally be effective in lithological mapping in arid regions. The OIF calculation for all twenty RGB combinations emerging from the six PCs of the six Landsat TM data showed that the RGB color combination PC2-PC4-PC5 is one with the highest OIF value. Visual evaluation of this image shows that this combination is effective in discriminating between the layered rocks (meta-basalt, chlorite schist and hornblende schist) on one hand and the intrusive rocks (tonalities) on the other hand. Additionally, this image shows that it is possible to distinguish between different layered rocks. However, it is not possible to differentiate between different tonalities in the study area. The effectiveness of the PC2-PC4-PC5 RGB color combination in this regard is attributed to that this combination emphasize the long wavelength feature (e.g. gross spectral characteristics of geological material) as compared to PC RGB combinations where the higher level PCs are used. These observation is in good agreement with conclusions made by Ren and Abdelsalam (2006) in which they have shown that PC5 is most effective in structural mapping in the Eastern desert of Egypt. These higher level PC RGB color combinations bring overwhelming spectral details to the image. Geological materials are usually not homogeneous even within specific rock units; hence “spectral generalization” that is brought through using low order PCs might be desired.
Multi-spectral band-ratio images such as those used for Landsat TM data (e.g. Abrams et al., 1983 and Sultan et al., 1986, 1987) have proven to be effective in lithological mapping in arid regions. In this work a modified Abrams-type band ratio image (5/7-5/4-3/1) is introduced and this proved to have a higher level of spectral information compared to the original combination as indicated by its higher OIF value. This might be due to that the original Abrams-type band-ratio combinations have used the band-ratio 4/5 to emphasize silicate minerals. However, silicate minerals are not uniform in there spectral signature in the electromagnetic radiation region defined by Landsat TM 4 and 5. Some silicate minerals have reflectivity in band 4 and absorption in band 5 whereas others show a reversed pattern. Even some silicate minerals show flat reflectance spectra in both Landsat TM 4 and 5. Hence, it seems that the rocks dominating the study area contains silicate minerals that have reflectivity in band 5 and absorption features in band 4, hence the band-ratio 5/4 became more effective than the 4/5 band-ratio.

Results obtained from the supervised classification results are acceptable given the heterogeneous nature of lithological mapping. The Maximum Likelihood supervised classifications effectively differentiate between the three types of Tonalite rocks. These rock types have the lowest omission and commission error value because they are relatively homogeneity. On the contrary, supervised classification results of the unconsolidated sediments are vastly erroneous because these unconsolidated sediments comprise heterogeneous mixture of weathering products coming from the surrounded rocks and maybe from other places such as eolian sand brought to the region through winds. As a result, these unconsolidated sediments have the highest omission and commission error value.
4. CONCLUSIONS

Quantitative evaluation of the effectiveness of multi-spectral remote sensing data (Landsat TM in this study) for lithological mapping in arid regions using examples from the Neoproterozoic region of the Makkah region showed the following:

(1) Individual bands of Landsat TM data are most effective in lithological mapping in arid regions when different portions of the electromagnetic radiation are used in the RGB color combination. Hence, mixing bands from the VNIR and SWIR in a single RGB color combination is most effective because these bands have low spectra redundancy and high spectral diversity. The Landsat TM 3-5-7 appears to be the most effective RGB color combination as indicated by its highest OIF value compared to all other twenty RGB color combinations.

(2) Lower order Principal Components (PCs), might be equally effective in lithological mapping in arid regions. This is attributed to that these lower order PCs emphasis the general spectral character of the heterogeneous geological materials rather than the spectral details of individual unit constituting the geological formation. Results of this study show the Landsat TM PC2-PC4-PC5 RGB color combination image as the best one to be use in lithological mapping in arid regions. This is indicated by its highest OIF value compared to all other twenty RGB combination emerging from the six PCs of the Landsat TM data..

(3) The modified Abrams-type Landsat TM band-ratio image 5/7-5/4-3/1, which is introduced for the first time in this study, proved to be more effective in lithological mapping in arid region compared to other traditional Landsat TM band-ratio images such as Abrams-type and Sultan-type. This is supported by OIF analysis which showed that the modified Abrams-type image have the highest OIF value compared to other Landsat TM band-ratio images.

(4) evaluating the accuracy of supervised classification results of Landsat TM data through Error Matrix and Kappa Hat showed that this remote sensing digital image processing technique can have moderate to high level of effectiveness in lithological mapping in arid regions. The accuracy of this technique is highly dependent on the homogeneity of the lithological units.
Homogeneous geological materials will have high level of accuracy of supervised classification results whereas heterogeneous geological materials will have low level of accuracy.
APPENDIX A:

THE SIX LANDSAT TM BANDS USED IN THIS STUDY.
Band 7
APPENDIX B:

THE SIX LANDSAT TM PC BANDS USED IN THIS STUDY.
APPENDIX C:

ALL TWENTY RGB COLOR COMBINATIONS OF THE LANDSAT TM OF THE STUDY AREA.
Bands 1-2-4
Bands 1-2-5
Bands 1-4-7
Bands 2-3-4
Bands 2-3-5
Bands 2-3-7
Bands 2-4-5
Bands 2-5-7
Bands 3-4-7
Bands 3-5-7 (best OIF)
APPENDIX D:

ALL TWENTY RGB COLOR COMBINATIONS OF THE LANDSAT TM PRINCIPAL COMPONENT (PC) OF THE STUDY AREA.
APPENDIX E:

ABRAMS-TYPE, SULTAN-TYPE AND MODIFIED ABRAMS-TYPE LANDSAT TM BAND-RATIO IMAGES OF THE STUDY AREA.
REFERENCES


VITA

Nawwaf Awad Al Munshry was born in Jeddah, Saudi Arabia. He got his B.S in Engineering Geology from King Abdulaziz University (KAU), Jeddah, Saudi Arabia. Having graduated he worked as an engineering geologist with the Soil and Foundation Company (SAFCO) in Saudi Arabia. He joined the Ministry of Education in Saudi Arabia as geology teacher. Following that he joined KAU as a demonstrator. In 2009 he got an academic scholarship from the King Abdulaziz University to study abroad. He traveled to the United State of America pursue his graduate studies (master’s and doctoral degree).