Delineation of Igneous Rocks on Western Axel Heiberg Island Using Geopotential Data and Satellite Imagery

Mosstajiri, Tina

http://hdl.handle.net/11023/706
master thesis

University of Calgary graduate students retain copyright ownership and moral rights for their thesis. You may use this material in any way that is permitted by the Copyright Act or through licensing that has been assigned to the document. For uses that are not allowable under copyright legislation or licensing, you are required to seek permission.

Downloaded from PRISM: https://prism.ucalgary.ca
Delineation of Igneous Rocks on Western Axel Heiberg Island Using Geopotential Data and Satellite Imagery

by

Tina Mosstajiri

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOMATICS ENGINEERING
CALGARY, ALBERTA
April, 2013

© Tina Mosstajiri 2013
Abstract

Remote predictive mapping can provide a base for geological mapping. This thesis investigates different methods for remotely mapping the igneous rocks and their host sedimentary rocks on Axel Heiberg Island, using the already available data sets. Axel Heiberg Island has been chosen as the platform for establishing the most suitable method of mapping igneous rocks and other geological features in the Canadian Arctic Archipelago. The igneous rocks on Axel Heiberg Island are important to understand and study because of their impact on the petroleum system and energy resources that they may contain, and because of the possibility of unravelling the debatable tectonic history of Canadian Arctic Archipelago.

To identify the geological information of the study area three remote predictive mapping approaches have been studied. The first remote predictive approach uses remote sensing techniques such as color composite and band ratio to highlight the igneous rocks on Axel Heiberg Island. The satellite sensors that have been employed to analyse the geological information on the surface of the study area are: ASTER and LANDAST satellite images. Spectral correlation technique is employed for the second and third approach. For the second mapping approach gravity and magnetic field anomalies are spectrally correlated and filtered. The filtered gravity and magnetic field anomalies provided key constrains on analysis of geological features, especially igneous rocks and salt domes. The same procedure has been used to spectrally correlate magnetic field anomalies and silica weight percentage of surface rocks derived from ASTER thermal bands.

The first remote predictive mapping technique proved to be an effective technique for initial assessment of the study area and highlighting the target geological features. Using color composite technique it was inferred that the igneous rocks in the study area have the highest
reflectance in Landsat band3 and ASTER band2. The results in the second approach were constrained by low resolution of gravity data; however the thickness trend of igneous rocks and salt domes were revealed. The third approach proved to be the most effective among the other two approaches, where result map matched well with the only available accurate geological map of the study area.
Acknowledgements

I would like to express my sincere gratitude to my supervisors, Dr. Jeong Woo Kim and Dr. Keith Dewing for their indefinite support and guidance throughout this research. I have been very fortunate to work with very considerate and knowledgeable professors.

I wish to also sincerely thank Dr. John Harper and Dr. Hamed Sanei for their remarkable support, encouragement and guidance.

I would also like to acknowledge Geological Survey of Canada (GSC) for providing me the research opportunity and funding. I also acknowledge Geomatics Engineering Department of University of Calgary for allowing me to conduct this research under Dr. Jeong Woo Kim supervision.

I am grateful for valuable lessons and knowledge I learned from Dr. Quazi K. Hassan.
Dedication

I dedicate this thesis:

To my smart, kind and strong dad for his unlimited encouragement throughout every step of my life.

To my beautiful and determined mom for her unconditional love and support.

To my supportive and lovely brother.

And

To my lovely husband for making my life more colorful with his smiles, care and love. Thank you for teaching me to think more like a scientist.
Table of Contents

Abstract ................................................................................................................................. ii
Acknowledgements ................................................................................................................ iv
Dedication ............................................................................................................................... v
Table of Contents .................................................................................................................. vi
List of Figures and Illustrations ............................................................................................ x

CHAPTER 1 ............................................................................................................................. 1

INTRODUCTION .................................................................................................................. 1

1.1 Background and problem statement ........................................................................... 1
1.2 Significance ................................................................................................................... 3
1.3 Objective of the research ............................................................................................. 4
1.4 Research methodology ................................................................................................. 5
1.5 Scope and limitations .................................................................................................... 7
1.6 Thesis organization ...................................................................................................... 8

CHAPTER 2 ........................................................................................................................... 9

GEOLOGICAL SETTING ........................................................................................................ 9

2.1 Topography, Climate and Sediment Vegetation of Sverdrup Basin Islands .............. 9
2.1.1 Climate ..................................................................................................................... 9
2.1.2 Mountains and Uplands ......................................................................................... 9
2.1.3 Vegetation ............................................................................................................... 10
2.2 Tectonic history of Arctic Canada .............................................................................. 11
2.2.1 Rifting to passive margin of Franklinian Margin ............................................... 11
2.2.2 Sverdrup Basin ..................................................................................................... 12
2.2.3 Rifting, movement and collision of Greenland (Eurekan Orogeny) ..................... 15
2.3 Geology of western Axel Heiberg Island ................................................................... 16
2.3.1 Stratigraphy of western Axel Heiberg Island ......................................................... 17

CHAPTER 3 .......................................................................................................................... 22

IGNEOUS ROCKS AND PETROLEUM SYSTEM .................................................................. 22

3.1 Mineralogy and petrography of igneous rocks ............................................................ 23
3.2 Petroleum system ......................................................................................................... 28
3.2.1 Source Rocks ....................................................................................................... 29
3.2.2 Reservoir Units .................................................................................................... 31
3.2.3 Time and Depth of Burial (Maximum burial and thermal maturity) .................. 31
3.2.4 Time of Structures ............................................................................................... 33
3.3 Impact of Igneous Rocks ............................................................................................ 33

CHAPTER 4 .......................................................................................................................... 35
List of Tables

CHAPTER 3

Table 3.2(a): 1-Twisted Ridge, location displayed on Figure 3.3(Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files) ................................. 26

Table 3.2(b): 3-Bastion Ridge, location displayed on Figure 3.3(Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files). ................................. 27

Table 3.3(c): 9-Glacier Fiord Syncline, location displayed on Figure 3.3(Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files) ................................. 27

CHAPTER 4

Table 4.1: A summary of the characteristics of the LANDSAT 7 ETM+ and ASTER satellite sensors ......................................................................................................................... 37

Table 4.2: Acquired ASTER satellite images for the study area ........................................................................................................................................ 39

Table 4.3: The spectral reflectance of study area’s common rock types including: sandstone, shale, basalt and gabbro igneous rocks; common feldspars; common micas; common clays; calcite, dolomite, quartz .................................................................................. 42

Table 4.4: Correlation matrix of VNIR and SWIR Landsat bands ........................................................................................................................................ 51

Table 4.5: Correlation matrix of VNIR and SWIR ASTER bands ........................................................................................................................................ 52

Table 4.6: Correlation matrix of ASTER TIR bands ................................................................................................................................................ 52

Table 4.7: Optimum index factor (OIF) of twenty possible RGB color composite of Landsat bands ............................................................................................................. 63

Table 4.8: Optimum index factor (OIF) of eighty four possible RGB color composite of VNIR and SWIR ASTER bands ............................................................................. 64

Table 4.9: Optimum index factor (OIF) of ten possible RGB color composite of TIR ASTER bands ............................................................................................................. 65

Table 4.10: Commonly used ASTER band raios ................................................................................................................................................ 85

Table 4.11: Rock types and their SiO$_2$ content ........................................................................................................................................ 89
CHAPTER 5

Table 5.1: Generalized lithologic correlation model in terms of gravity and magnetic anamolies .................................................. 95

CHAPTER 6

Table 6.1: Generalized lithologic correlation model between magnetic susceptibility and SiO$_2$ weight % ................................................................. 116
List of Figures and Illustrations

CHAPTER 1

Figure 1.1: (a) Sverdrup Basin (Dewing & Obermajer 2011) shown as grey (b) Geology map of the study area produced by Harrison 2008, Western Axel Heiberg Island (Harrison 2008) pink polygons represent igneous rocks............................................................... 3

CHAPTER 3

Figure 3.1: Histogram of silica content of127 samples of Isachsen Formation, with average of 49.6% (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)........................................................................................................... 24

Figure 3.2 Histogram of silica content of 112 samples of Strand Fiord Formation, with average of 50.0% (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)........................................................................................................... 25

Figure 3.3: Strand Fiord Formation sampled during the 1983 field season. 1: Twisted Ridge; 3: Bastion Ridge; 9a: Glacier Fiord Syncline East; 9b: Glacier Fiord Syncline West (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files) ........................................................................................................... 26

Figure 3.4: Histogram of silica content weight percentage of 183 samples of Queen Elizabeth dyke swarm samples, NE Sverdrup Basin, with average of 48.7% (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)......... 28

CHAPTER 4

Figure 4.2: Spectral reflectance of sandstone, shale and igneous rocks (gabbro and basalt) in ASTER and Landsat bands (data obtained from USG and NASA spectral library) 8........... 43

Figure 4.2: Spectral reflectance of common feldspars and its chemical gradations(data obtained from USG and NASA spectral library)9 ........................................................................................................ 44

Figure 4.3: Spectral reflectance of common mica (data obtained from USG and NASA spectral library)10 ......................................................................................................................... 45

Figure 4.4: Spectral reflectance of common clay (data obtained from USG and NASA spectral library)11 ......................................................................................................................... 46

Figure 4.5: Spectral reflectance augite pyroxene, olivine, magnetite (data obtained from USG and NASA spectral library)12 ........................................................................................................ 47

Figure 4.6: Display of study area by VNIR and SWIR bands of Landsat color composite of RGB 751 13 ......................................................................................................................... 53
Figure 4.7: Display of study area by VNIR and SWIR bands of Landsat color composite RGB 73114 .......................................................... 54

Figure 4.8: Display of study area by VNIR and SWIR bands of Landsat color composite RGB 53115 .......................................................... 55

Figure 4.9: Display of study area by VNIR and SWIR bands of ASTER color composite RGB 86216 .................................................................. 56

Figure 4.10: Display of study area by VNIR and SWIR bands of ASTER color composite RGB 83217 .................................................................. 57

Figure 4.11: Display of study area by SWIR and VNIR bands of ASTER color composite RGB 62118 .................................................................. 58

Figure 4.12: Display of study area by TIR bands of ASTER color composite RGB 14-11-1019 .................................................................. 59

Figure 4.13: Display of the study area by TIR of ASTER color composite RGB 14-12-1120 ......................................................... 60

Figure 4.14: Display of the study area by Landsat color composite RGB 754 21 ............................................. 66

Figure 4.15: Display of the study area by Landsat color composite RGB 54122 ............................................. 67

Figure 4.16: Display of the study area by ASTER color composite RGB 32123 ............................................. 68

Figure 4.17: Display of the study area by ASTER color composite RGB 42124 ............................................. 69

Figure 4.18: Display of the study area by TIR ASTER color composite RGB 14-13-1225 ............................................. 70

Figure 4.19: Display of the study area by TIR ASTER color composite RGB 14-13-1126 ............................................. 71

Figure 4.20: Display of the study area by TIR ASTER color composite RGB 14-13-10 27 ............................................. 72

Figure 4.21: Display of the study area by TIR ASTER color composite RGB 12-11-1028 ............................................. 75

Figure 4.22: Display of the study area by Landsat band ratio 5/333 .......................................................... 81

\[
DNI_{\text{igneousrocks}} = \frac{(b5 - b3)}{(b5 + b3)} \]

Figure 4.23: Display of the study area by Landsat ................................................................................................. 82

Figure 4.24: Display of the study area ASTER band ratio 4/2 35 .......................................................... 83

Figure 4.25: Display of the study area ASTER \( DNI_{\text{igneousrocks}} = \frac{(b4 - b2)}{(b4 + b2)} \) 36 .......................................................... 84

Figure 4.26: Display of study area using Landsat color composite ratio RGB (5-3)/(5+3), 1, 3/138 ................................................................................................. 87
Figure 4.27: Display of study area using ASTER color composite ratio RGB (4-2)/(4+2), 3, 2/139 ................................................................. 88

Figure 4.28: SiO$_2$ weight percentages of the surface rocks of the study area estimated based on the MMAJ (2000) derived empirical model37 ................................................................. 91

Figure 4.6.11: Estimated SiO$_2$ content of Basalt Igneous Rocks53................................................................. 93

CHAPTER 5

Figure 5.2: Poisson’s theorem, in order to relate magnetic and gravity anomalies over the same point regardless of their size and shape, magnetic has to be reduced to the pole (RTP) and gravity has to be converted to first vertical derivative (FVD) 54 .................... 101

Figure 5.3: The left y-axis represents the standard deviation of gravity and magnetic anomalies after each step of filtering from 0.0 to 1 against the filter number values incrementing from 0.0 to 1; the right y-axis represents the correlation coefficient of the gravity and magnetic anomalies after each step of filtering from 0.0 to 1 against the filter number values incrementing from 0.0 to 1 55 ............................................................................. 104

Figure 5.5: a) Positive gravity and positive magnetic anomalies b) Negative gravity and negative magnetic anomalies c) Positive gravity and negative magnetic anomaliesd) Negative magnetic and positive gravity anomalies56............................................................................. 107

Figure 5.6: Gridded map of magnetic components that are negatively correlated with gravity anomalies57 ......................................................................................... 108

Figure 5.7: a) Magnetic components that are positively correlated with gravity anomalies b) Magnetic components that are positively correlated with gravity anomalies which are overlaid by outline of igneous rocks and evaporates that are outlined from Harrison’s map’s 58 ................................................................................................. 109

Figure 5.8: a) Strong magnetic anomalies that are positively correlated with gravity anomalies; overlaid by igneous rocks (red and yellow outlines) and evaporate (cyan outlines) from Harrison’s map59 ........................................................................................................ 111

Figure 5.8: b) Strong magnetic anomalies that are negatively correlated with gravity anomalies; which are overlaid by igneous rocks (red and yellow outlines) and evaporate (cyan outlines) from Harrison’s map 60 ........................................................................................................ 112

Figure 5.9: a) Positive features from gravity and magnetic components that are positively correlated, SLFI > 063 ........................................................................................................ 113

Figure 5.9: b) Negative features from gravity and magnetic components that are positively correlated, SLFI < 0 64 ........................................................................................................ 113
CHAPTER 6

Figure 6.2: The left y-axis is the standard deviation of magnetic anomalies and SiO$_2$ estimate of surface rocks after each step of filtering from 0.0 to -1 against the filter number values incrementing from 0.0 to -1; the right y-axis is the correlation coefficient of the magnetic anomalies and SiO$_2$ estimate after each step of filtering from 0.0 to -1 against the filter number values incrementing from 0.0 to -1 65 ................................................................. 118

Figure 6.3: (a) Silica weight percentage of the surface rocks that are negatively correlated with magnetic anomalies (b) Magnetic anomalies that are negatively correlated with silica weight percentage of the surface rocks66............................... 119

Figure 6.4: Positive features from the differenced local favorability indices of magnetic anomalies and silica weight percentage of surface rocks that are inversely correlated with each other, DLFI > 0 67................................................................. 120

Figure 6.5: (a) Co-registered gridded silica weight percentage of surface rocks and magnetic anomalies every 90 m68 ........................................................................ 121

Figure 6.5: (b) Normalized (to common standard deviation) silica weight percentage of surface rocks and magnetic anomalies 69.................................................................................. 121

Figure 6.5: (c) Silica weight percentage of surface rocks and magnetic anomalies after inverse correlated data filtered (0 to -1)70................................................................. 122

Figure 6.5: (d) This map represents the features that have high magnetic content and low silica content, DLFI map71................................................................. 122

Figure 6.3.7: DLFI Map with inferred unmapped igneous rocks indicated in red boxes79 ...... 124
## List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tcf</td>
<td>Trillion Cubic Feet</td>
</tr>
<tr>
<td>Landsat</td>
<td>Land Remote-Sensing Satellite</td>
</tr>
<tr>
<td>ETM</td>
<td>Enhanced Thematic Mapper</td>
</tr>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
</tr>
<tr>
<td>Ma</td>
<td>Million Years Ago</td>
</tr>
<tr>
<td>SWIR</td>
<td>Short Wave Infrared</td>
</tr>
<tr>
<td>VNIR</td>
<td>Visible Near Infrared</td>
</tr>
<tr>
<td>TIR</td>
<td>Thermal Infrared</td>
</tr>
<tr>
<td>OIF</td>
<td>Optimom Index Factor</td>
</tr>
<tr>
<td>DN</td>
<td>Digital Number</td>
</tr>
<tr>
<td>NDSI</td>
<td>Normalized Difference Snow Index</td>
</tr>
<tr>
<td>FLAASH</td>
<td>Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes</td>
</tr>
<tr>
<td>FCC</td>
<td>False Color Composite</td>
</tr>
<tr>
<td>R</td>
<td>red</td>
</tr>
<tr>
<td>G</td>
<td>green</td>
</tr>
<tr>
<td>B</td>
<td>blue</td>
</tr>
<tr>
<td>correlation coefficient</td>
<td>CC</td>
</tr>
<tr>
<td>Optimum index factor</td>
<td>OIF</td>
</tr>
<tr>
<td>RTP</td>
<td>Reduced to The Pole</td>
</tr>
<tr>
<td>FVD</td>
<td>First Vertical Derivative</td>
</tr>
<tr>
<td>NF</td>
<td>Normalization Factor</td>
</tr>
<tr>
<td>SLFI</td>
<td>Local Favorability Indices</td>
</tr>
<tr>
<td>DLF1</td>
<td>Differenced Local Favorability Indices</td>
</tr>
</tbody>
</table>
“A good decision is based on knowledge not numbers” Plato
CHAPTER 1
INTRODUCTION

1.1 Background and problem statement

The Canadian Arctic Archipelago, with a land area of 780,000 km² including much of the Northwest Territories and Nunavut, is known to be one of the most prospective frontier regions for natural resources in Canada. These islands contain many areas that have a high mineral and petroleum potential, however, the mineral and petroleum exploration in this area is hindered by lack of insufficient geological mapping, high costs and short mapping seasons (Dewing et al. 2007).

The Canadian Arctic Archipelago are underlain by two sedimentary basins; the Cambrian-Devonian Franlinian basin and by the Mississipian-Tertiary Sverdrup successor basin. Exploration for petroleum in the Sverdrup Basin started in 1968 which lead to discovery of major gas fields between north-eastern Melville Island and western Ellef Ringnes Island. The last well was drilled in 1986 and after that the exploration in the area came to an end due to the collapse of the oil price. More than 140 wells have been drilled for hydrocarbons which resulted in discovery of 12.0 Tcf of recoverable gas as well as small amount of oil. The Sverdrup Basin also contains seams of coal; so far no economic resources have been discovered (Rayer 1981, Embry & Beauchamp 2008).

The Geological Survey of Canada intends to update the maps of the Arctic using modern geological and mapping concepts to identify the potential for energy and mineral resources. Given the enormous area of the Arctic, only a small part can be mapped on the ground. The resulting maps from these areas are meant to provide a base for remote predictive mapping the
geological features in other parts of the High Arctic Islands. Even though ground truthing is the
best method for mapping geological features, this method is not always feasible for remote areas.
Remote predictive mapping, especially if different data sources are used, provides an effective
alternative for geological mapping.

In this thesis different remote predictive mapping techniques using available geopotential
field (gravity and magnetic) and satellite imagery (Landsat and ASTER) data sources to map the
igneous rocks on western Axel Heiberg Island. The igneous rocks are one of the most important
geological features to map because they represent the tectonic development and evolution of a
region and are known to have impact on energy and mineral resources. Despite their importance
and abundance, the igneous rocks on Arctic Islands were not systematically mapped by the
Geological Survey of Canada in the 1960s and 1970s. Igneous rocks were viewed at that time as
a later alteration rather than a primary rock type.

Western Axel Heiberg Island, presented in Figure 1.1, was chosen as the study area for
establishing the most suitable method of mapping igneous rocks and other geological features in
the Canadian Arctic Archipelago. Western Axel Heiberg Island has very complex geology: the
thickest Mesozoic section in Sverdrup Basin, salt diapirs, dyke swarms emplaced in several
directions, extrusive basalt, and sills, and a range of sedimentary rock types.

Because the geology of this region is so interesting, it is among the few regions in High
Arctic that has a detailed geological map against which the remote predictive map can be
checked.
Remote Predictive mapping provides an opportunity to analyze and interpret the geological feature in the high Arctic without the problems that are associated with the field work: high cost, remoteness, lack of infrastructure, environmental sensitivity, and short mapping season. A remote predictive map is an estimate of geological features of an area.

Scarce attention has been paid to the igneous rocks on western Axel Heiberg Island; however, mapping these geological features is important because of the possibility of unravelling the tectonic history of Arctic region and their effect on petroleum systems.

Igneous rocks are related to the initial and subsequent rifting events in the basin’s history. Learning more about them will provide an opportunity to solve a number of controversial aspects.
about the history of continental drift and the interaction of associated tectonic plates in the Arctic region (Ricketts et al. 1985).

The igneous rocks could impact the petroleum system in the Arctic region. The presence of sills and dykes are usually considered as either harmful to preservation of oil and gas or useful for indication of existence of oil and gas. In general igneous rocks are perceived as detrimental to the petroleum system. The high temperature associated with them will cause the organic matter in potential source rocks to be destroyed (Harrison 1995). Gentzis and Goodarzi (1993) observed on Drake Field on Melville Island, that the sill that intruded van Hauen formation caused the source rock to be cooked (Gentzis & Goodarzi 1993).

Conversely, igneous rocks sometimes help in generation of oil and gas. The thermal effect resulting from the igneous activity can cause organic rich sediments to generate hydrocarbons or in some cases transform oil to gaseous hydrocarbons. In some cases they can act as unconventional oil and gas reservoirs due to the rupture and porosity of their host rock (Delpino & Bermudex 2009).

In general igneous rocks are known to be more harmful than helpful to the petroleum system. However, mapping these geological features will help geologists to further explore these features and have a better understanding of the ones that are valuable for the petroleum system.

1.3 Objective of the research

The main objective of this study is to estimate the spatial distribution of different igneous rock types that intruded in the Early Cretaceous time (125 to 90 Ma) on Western Axel Heiberg Island using geopotential field datasets and satellite imagery.
In this study the ability of two different geopotential datasets and satellite imagery to detect igneous rocks is investigated. ASTER and LandSat 7+ satellite imagery are used for discriminating the geological features on the surface of the study area; and gravity and magnetic data are used for measuring the subsurface characteristics of rocks. The following questions are going to be answered in this study.

1. Surface analysis using satellite imagery:
   I. What pre-processing techniques need to be employed for Landsat and ASTER satellite imagery in this project’s study area?
   II. Can Landsat and ASTER satellite imagery detect different geological features and different minerals?
   III. 2. Subsurface analysis using geopotential field data sets:
       I. What pre-processing techniques need to be employed for magnetic and gravity data sets in this project’s study area?

3. Spectral Correlation:
   I. How well can spectral correlation of gravity and magnetic data detect the geological features of the area?
   II. How well can the spectral correlation of satellite images and magnetic data detect the geological features of the area?

1.4 Research methodology
ASTER and Landsat satellite imagery were employed for this study. Before using the satellite images for analysis, it is required to pre-process them to correct for any errors that are associated
with the satellite sensors, atmospheric errors and converting the digital numbers (DN) to reflectance.

In this study, color composite and band ratio techniques are utilized based on the study area’s geological features and igneous rock spectral reflectance properties. Before applying remote sensing techniques, it is important to examine the general spectral reflectance of geological features and the igneous rocks.

Gravity and magnetic data was obtained from the government of Canada’s Geoscience Data Repository website, which is free to public for download. These datasets were examined to ensure that required corrections have been applied.

Magnetics data represents the susceptibility characteristics of a rock, which determines how magnetized that body can become in the presence of an external field. Gravity dataset determines the variation in the density of a rock. In order to discriminate the igneous rocks from host rocks it is important to recognize the susceptibility and gravity characteristics of the rocks in the study area, especially the igneous rocks and their host rocks.

After analysing the satellite imagery and geo-potential field maps, the gravity and magnetic field anomalies were co-registered, normalized and then spectrally correlated to better distinguish the igneous rocks. The anomalies that have direct and inverse correlation are separated by filters in the frequency domain of the data sets. The datasets that are directly correlated are then standardized and summed together and the datasets that are inversely correlated are differentiated to emphasize the recognition of the geological features.

The satellite imagery and the magnetic data are then spectrally correlated. The same procedure for spectral correlation analysis of magnetic and gravity are applied for spectral correlation between magnetic and estimated silica content of surface rocks based on ASTER
Thermal bands. The datasets that are inversely correlated are summed together to segregate the igneous rocks.

1.5 Scope and limitations

The aim of this project is to present the most appropriate method for mapping the geological feature on the Arctic Islands using the available data sources. However, in this project the scope of research has been narrowed down to igneous rocks on western Axel Heiberg Island.

One of the reasons that Western Axel Heiberg Island was chosen as the study area is that there is an accurate geological map of this area available for validation. One of the limitations of this research is that only one detailed geological map, produced by Harrison 2008, is available to compare this research’s results with. Some of the results show differences from the available geological map, however, this project was limited to only one geological map for validation and ground truthing was not an option due to the constrains that are associated with the field work in remote areas.

This research was also faced with a few limitations that were associated with the datasets. One of these limitations was in regards to ASTER satellite images, the six bands in the short wave infrared (SWIR). Some of the ASTER satellite images that were available with good quality in our study area were acquired after April 2008; which meant that the ASTER SWIR was missing from the data because the SWIR detectors stopped functioning after this date. This study was limited to work with only ASTER satellite thermal bands (TIR) and visible and near infrared (VNIR) on the parts of the study area that SWIR bands were not available.

Another data limitation in this project is associated with the gravity and magnetic datasets. Neither one of these datasets have a suitable resolution for detecting dykes and sills that
are thin. Magnetic data in our study area were gridded into grid cell size of every 200 m and gravity data was gridded to every 2 km. Even though magnetic had a better resolution than gravity, overall it could not detect thinner igneous rocks.

1.6 Thesis organization

Chapter two provides an overview of Sverdrup Basin’s geological setting of Sverdrup Basin. Chapter three discusses different types of igneous rocks in the study area and mineralogy of sampled igneous rocks from the study area. Chapter four starts with a brief overview of Landsat and ASTER satellite characteristics and the general reflectance properties of the study area’s rock types in Landsat and ASTER bands. In this chapter different remote sensing techniques (Color composite and Band ratio) are applied and evaluated based on their ability to distinguish igneous rocks. Chapter five discusses available geo-potential datasets (magnetic and gravity data) of study area and applies spectral correlation and filtering approach to separate igneous rocks in the study area. Chapter six uses the same approach to spectrally correlate silica surface content derived from ASTER thermal band and magnetic. Chapter seven concludes this project and provides a summary of this thesis and future works related to this project.
CHAPTER 2
GEOLOGICAL SETTING

2.1 Topography, Climate and Sediment Vegetation of Sverdrup Basin Islands

To understand the surface geology of Sverdrup Basin Islands using remote sensing, it is important to know about its climate, topography and vegetation.

2.1.1 Climate

Rain and snow fall have strong influence on weathering and overall geology of a region (Benedict 2008). So far, there has not been adequate hydrologic information of Queen Elizabeth Islands of Canada, since only four weather stations and one stream-flow recording station is active in this region (Woo 1983).

Weather observations made at Eureka on Ellesmere Island, which is one of the closest weather stations to western Axel Heiberg Island, is archived since 1953. Based on an investigation conducted in 1973, the mean annual precipitation, at Eureka weather station (in 23 years of record), is 58.4 mm (Graham Cogley & McCann 1976).

2.1.2 Mountains and Uplands

Mountains and plateaus are found in the eastern part of the Canadian Arctic Archipelago (Baffin, Devon, Ellesmere and Axel Heiberg islands). These formed in response to the rifting and collision of Greenland (Eurekan Orogeny). Most of the glaciers and ice caps are in this mountainous eastern part of the archipelago. The largest ice caps in the Canadian Arctic are
Devon Ice Cap (14,000 km²) on Devon Island and the Agassiz Ice Cap (17,300 km²) on Ellesmere Island (Dowdewell 2002). Glaciers also cover most of central Axel Heiberg Island.

Topography of the Canadian Arctic Archipelago is also affected by glacioisostatic recovery corresponding to the removal of the load imposed by the former thickness of the Pleistocene Innuitian Ice Sheet. The northwest Queen Elizabeth Islands have been affected by the Innuitian uplift, including western Axel Heiberg which is estimated to have risen 123 m in the last 10000 years (Atkinson & England 2004).

Anhydrite diapirs are common along the axis of the Sverdrup Basin on Axel Heiberg Island and northwestern Ellesmere Island. The size of these diapirs ranges from about 1 km diameter to topographic features such as the South Fiord Diapir, which is about 8 km in diameter and towers some 500 m above the surrounding countryside. These diapirs are sourced from the Otto Fiord Formation and they are three principal kinds of diapirs. A) diapiric dome, which are generally large and round. They are common in western region of the Sverdrup Basin such as Ellef Ringnes and Melville Island. B) Diapiric anticline, which are found in the axial region of anticlines. C) Fault diaper associated with both gravity and thrust faults; they are generally smaller than the diapric dome and occur in the more intensely deformed terrains of Axel Heiberg Island and northwestern Ellesmere Island (Thorsteinsson 1974).

2.1.3 Vegetation

The health and extent of vegetation in a given area is dependent on the type of bedrock and climate. Some formations and climate conditions support a good vegetation cover. Also, it can be observed from the Harrison’s (2008) field photos that there are scarce vegetation covers on Axel Heiberg Island.
2.2 Tectonic history of Arctic Canada

Sverdrup Basin is located in the north of the Canadian Arctic. Carboniferous to Paleogene strata fills this basin with up to 13 km of strata. The area of this basin is about 300,000 km$^2$ (50% land) and it extends from Ellesmere Island in the northeast to Prince Patrick Island in the southwest. It underlies most of the Queen Elizabeth Islands (Embry and Beauchamp 2008).

The Sverdrup basin overlies the lower Paleozoic Franklinian Basin. The summary of Franklinian Basin development is followed by a review of tectonic events that affected the evolution of Sverdrup Basin.

2.2.1 Rifting to passive margin of Franklinian Margin

Rodinia supercontinent broke apart during Neoproterozoic to Early Cambrian time due to a series of super-plume events (Harlan & Heaman 2003). The core of Rodinia supercontinent was Laurentia craton (most of current North America) surrounded by other cratonic blocks (Li et al. 2008). The exact configuration and timing of Rodinia's break up is still a subject of debate. However, the occurrence of 723 Ma Franklin magmatic event in northern Laurentia is speculated to be related to the continental rifting in north of Laurentia (Pelechaty 1996 referred Heaman, L.M., LeCheminant & Rainbird 1992 and Codie & Rosen 1994). Following rifting, the Franklinian Basin was developed north of Greenland, northeast corner of Laurentia, and it extends from northern Ellesmere Island to Melville Island.

Franklinian Basin deposition started as a passive margin. From late Proterozoic to Early Silurian there were no dramatic changes in the development of the Franklinian Basin. Early Cambrian strata are dominantly siliciclastic, but Middle Cambrian to Silurian strata is mainly carbonate.
Mid-Silurian continental collision between Laurentia and Baltica lead to Caledonian orogenesis. The Caledonian orogenic belt is located in East of Greenland (Strachan 1994). The Franklinian Basin was filled rapidly with the sedimentation from the Caledonian Mountain chain in East Greenland followed by sinking of the platform. This stage is associated with major deposition of turbidites sourced from Caledonian mountain belt to the east and the basin expanded southward. The thick sequences of turbidites caused down flexing and widespread deepening of the carbonate platform By Early Devonian much of the Franklinian Basin was either a shallow water carbonate shelf or a deep basin.

Middle and Late Devonian collision of Laurentia with a continent, known as Crockerland, led to the Ellesmerian orogeny. The Ellesmerian orogeny brought carbonate sedimentation in the Franklinian Basin to an end (Higgins et al. 2003). From the Mid to Late Devonian the basin filled from, the northeast as part of a foreland basin. By Mid Devonian the deltaic-marine shelf extended as far as eastern Melville Island (Embry & Klovan 1976). Collision culminated in extensive folding of the strata in the Franklinian Basin.

2.2.2 Sverdrup Basin

Sverdrup Basin opened when Crockerland began to rift away from the Arctic margin of Laurentia (Scotese & Mckerrow 1990). The Sverdrup Basin developed over the Ellesmerian Orogen as and the older thrust faults in the Franklinian Basement were reactivated as normal faults (Harrison 1995). The Sverdrup Basin is a fault-bounded rift that extends for at least 1,300 km from Prince Patrick Island in the southwest to Ellesmere Island in the northeast, and it reaches a maximum width of about 350 km (Davies & Nassichuk 1975).

During Carboniferous time there were three distinct phases of crustal extension, growth faulting and block rotation. By Late Carboniferous three sub-basins existed. These sub-basins
were characterized by evaporites and submarine fan deposits. The largest and central sub-basin was located on western Axel Heiberg Island (Axel Heiberg Basin); and the smallest one was located in the west, central north of Sabine Peninsula (Barrow Basin) and the third one was on northeastern Ellesmere Island (Mayr 1992). Evaporite rocks of these basins are mostly gypsum, anhydrite, and salt (Otto Fiord Formation) (Randell et al. 1992). These were later reactivated and they pierce Mesozoic and Cenozoic rocks in form of diapirs in the axial part of the basin (Sweeney 1976).

Angular unconformities, broad folding, local thrusting and half-graben inversions in latest Carboniferous-Early Permian indicate tectonic compression (Beauchamp 2001). The series of compression events are termed "Melvillian Disturbance". The Melvillian Disturbance is associated with normal and reverse motion along the previous created faults. Many late Paleozoic half-grabens were reactivated. The sandstone and chert limestone-pebble conglomerate started to accumulate. The Melvillian Disturbance is also associated with short-lived volcanism (Esayoo Formation) (Beauchamp 2001, Beaucham et al. 1989, Embry and Beauchamp 2008).

By mid-Permian the tectonic activity was replaced by thermal subsidence and rapid rise in relative sea level led to an increase in sediment supply rate (Beauchamp 2001, Embry and Beauchamp 2008). By the end of Permian the deposition of evaporites and carbonates ceased and Sverdrup Basin became a major site of clastic sedimentation on the northern margin of the continent (Balkwill & Fox1882). The Permian time was ended with a significant drop of base level due to erosion and contemporaneous progradation of the shallow chert facies (Embry and Beauchamp 2008).

The Mesozoic Era started with a major sea level rise, which drowned the shelf areas in earliest Triassic and thermal subsidence continued to earliest Cretaceous. The Early Triassic was
dominated by high rates of deltaic sedimentation. At the same time (Early Triassic) the salt from the Carboniferous started to form circular diapirs, long linear ridges, salt-cored anticlines, and lag domes and deform the Mesozoic succession. By Middle Triassic the sediment influx decreased and organic-rich outer shelf mud and silt accumulated.

In latest Triassic to Early Jurassic the sedimentation rate became very high and sand dominated deltaic system prograded across the eastern and central portions of the basin (Trettin 1991). By late Early Jurassic most of the Sverdrup Basin was occupied with an offshore marine shelf environment that deposited mud. The sediment supply remained low from Mid Jurassic to Early Cretaceous.

Continental rifting beginning in the early Middle Jurassic led to the counterclockwise rotation of northern Alaska and adjacent northern Siberia away from the Canadian Arctic. The rifting in the Canada Basin caused minor crustal extension in the Sverdrup basin, which is evident from the numerous normal faults that are parallel to the Amerasian margin in the Prince Patrick Island area (Embry & Dixon 1992). Sea-floor spreading in the Canada Basin likely began in Early Cretaceous (Embry & Dixon 1992) (Trettin 1991). The opening of the Canada Basin created a rift shoulder called the Sverdrup Rim (Embry and Beauchamp 2008).

In the Early Cretaceous sediment supply increased enormously and a fluvial-dominated deltaic system prograded across the basin away from the rift shoulder. At the same time basalt flows extruded onto the deltaic plain in the northeastern portion of the Sverdrup basin. Hybasssal intrusive sheets and dykes were emplaced in the east-central part of the Sverdrup Basin (Villeneuve and Williamson 2003). The Early Cretaceous volcanism is interpreted to be related to the opening of the adjacent Amerasian Basin (Trettin 1991). In late Early Cretaceous there was a
major transgression and the Sverdrup basin was dominated by thick mudstone deposited on a marine shelf environment.

By early Late Cretaceous there was a regression and deltaic sediments prograded across the Sverdrup Basin. This was followed by deposition of a thick mudstone unit. At the same time, two pulses of basaltic volcanism occurred in the northeastern part of the basin (Trettin 1991) (Embry & Dixon 1992).

The three phases of basaltic volcanism correlate with similar igneous units on Svalbard and Franz Joseph Land. Collectively these form an Arctic Large Igneous Province (Tarduno, 1998) and represent the cratonward extension of the Alpha Ridge (Ricketts et al. 1985). Alpha Ridge is a volcanic ridge that has been active during the formation of Amerasian Basin (Ricketts et al. 1985). Alpha Ridge plume-related volcanism caused regional uplift in the north of the Sverdrup Basin. Dyke swarms intruded much of the Sverdrup Basin which coincided with a maximum horizontal paleostress trending either ENE or N (Jackson & Harrison 2006).

2.2.3 Rifting, movement and collision of Greenland (Eurekan Orogeny)

During the Late Cretaceous and Early Tertiary the sea-floor spreading in the Labrador Sea and Baffin Bay led to counter-clockwise rotation of Greenland relative to North America. The Eurekan Orogeny was formed due to the collision between Greenland and Canadian Arctic Archipelago, mainly on Ellesmere and Axel Heiberg Island and northern Greenland (Lepvrier, van Berkel & Schwerdtner 1996).

This collision caused the pre-existing folds and faults associated with the Late Palaeozoic rifting of the Sverdrup Basin to be reactivated. Also, regional uplifts, thrusts, salt-anhydrite diapiric intrusions along the reverse faults were the result of Eurekan tectonism (Lepvrier et al. 1996). Based on kinematic investigations of Lepvrier (Lepvrier et al. 1996) there are two distinct
periods of deformation in Eastern Sverdrup Basin Eurekan structures; a) Middle Eocene, strike-slip transgression with ENE to NE direction, b) Middle Eocene and possibly until the Early Oligocene NNW-SSE to WNW-ESE compression. Middle Eocene the deformation climaxed and it is evident from the age of the highest stratigraphic unit of the Eureka Sound Group on Axel Heiberg Island (Embry and Beauchamp 2008, Lepvrier et al. 1996). Volcanic units dated about 56 Ma occur on northern Ellesmere Island and Greenland. These are chemically distinct from the older Cretaceous igneous units and seem to be related to rifting.

2.3 Geology of western Axel Heiberg Island

At least 60 evaporite diapirs are known in the Sverdrup Basin, 46 of which are on Axel Heiberg Island (Thorsteinsson, 1974; Jackson and Harrison, 2006). The diapirs on surface consist of anhydrite and gypsum, minor carbonate, and gabbro. Anhydrite is dense so it is suspected that low-density halite is present in the deeper parts of the diapir (Schwerdtner and van Kranendonk, 1984; Davies and Nassichuk, 1991).

The study area on west Axel Heiberg Island includes a cluster of diapirs. These have ‘‘wall-and-basin structure’’ (van Berkel et al. 1984) that is characterized by long, folds often with a wall of evaporite in their core, some more circular diapirs, and complex stratigraphic and structural relationships. Folds on western Axel Heiberg are unlike other areas of Eurekan folding in that they are shorter wavelength (10 km rather than 20+ km), and have two trends (NNW and WNW) rather than the regional NNW trend.

Harrison and Jackson (2006) and Harrison (open file) explained the geology of the western Axel Heiberg region by invoking a salt canopy. Salt canopies form when salt sheets come out of diapirs and spread across the land. They are then covered by younger sediments and preserved in the rock. On western Axel Heiberg, Jackson and Harrison propose that a salt
canopies formed by coalescence salt sheets from active diapirs in the Early Cretaceous. The canopy was then buried by younger sediments. Once buried, the salt canopy acted as a source for a younger (Eocene) generation of diapirs.

2.3.1 Stratigraphy of western Axel Heiberg Island

This section discusses the strata and their lithology that occur on western Axel Heiberg from oldest to youngest.

Otto Fiord Formation formed along the axis of the Sverdrup Basin. It extends from northeasterly across central Axel Heiberg Island into northwestern Ellesmere Island, and ends at northeast of the head of Hare Fiord (Thorsteinsson 1974). It is about 400 m thick. Eighty percent of its thickness is composed of anhydrite and the remaining twenty percent consists of dark grey limestone of relatively shallow water origin and shale

Otto Fiord rocks form the evaporite cores of diapirs on Axel Heiberg Island (Chen et al. 1986). In these diapirs, limestone, dark grey crystalline dolostone, quartz sandstone, dark calcareous mudrock, bedded gypsum and anhydrite and gabbro intrusive rocks can be found (Harrison 1995).

The oldest formation exposed on western Axel Heiberg is Triassic shale of the Blind Fiord formation that was deposited in the deep central part of the Sverdrup Basin. Blind Fiord Formation is composed of grey shale and siltstone and is about 600 m thick (Harrison 1995). Blind Fiord Formation lies on older basinal shales of the upper Paleozoic Hare Fiord, Trappers Cove and van Hauen formations. The Blind Fiord is overlain by Middle and Upper Triassic shale of the Blaa Mountain group (dark grey shale and siltstone, about 700 m). All the shale units tend to be easily eroded and recessive.
The Heiberg Formation is deltaic sandstone with some shale, coal and ironstone and it is widespread throughout the Arctic Islands. This formation is mainly of non-marine deposits, however thin beds with marine fossils occur in the lower part. On western Axel Heiberg, the Heiberg Formation consists of fine to medium grained sandstone in the upper part and some siltstone and shale in the lower part. It is between 215 and 1250 m thick. (Harrison 1995, Tozer and Thorsteinsson 1964).

Overlying the Heiberg Formation are formations associated with the onset of continental rifting in early Middle Jurassic and they are all transgressive (Tozer & Thorsteinsson 1964). These units are referred to the “Savik Beds” or Wilkie Point Group and consist of three formations. The lowest and oldest formation is Jameson Bay Formation which is composed of 50 m of recessive, greenish grey mudrock, siltstone, and glauconitic sandstone. Jameson Bay Formation contains two marker beds, the lower marker, a horizon of oolitic ironstone and phosphatic nodules and the upper marker is ledge-forming ironstone. The Sandy Point Formation is composed of burrowed, glauconitic and ferruginous quartz sandstone. McConnell Island Formation lies on top of the Sandy Point Formation and it has two members. The lower member is composed of sandstone and mudrock and the upper member is composed of recessive, brownish grey, bioturbated mudrock (Harrison 1995, Tozer and Thorsteinsson 1964). These units are 0 to 800 m thick, recessive and mapped together with the overlying Ringnes Formation (Harrison map).

Mould Bay Group lies conformably on top of the Wilkie Point Group. It comprises three formations, Ringnes, Awingak and Deer Bay formations. The Ringnes Formation has thickness of 30 m and is composed of black, recessive, carbonaceous, micaceous shale, and calcite cemented siltstone. It is Upper Jurassic age. The Awingak formation which is up to 490 m thick comprises
of yellow weathering, fine grained, compacted or selectively cemented quartzose sandstone. The Awingak Formation also is Upper Jurassic (Harrison 1995, Tozer & Thorsteinsson 1964). The upper formation of the Mould Bay Group is the Deer Bay Formation. This consists of up to 1000 m of dark grey shale with common ironstone concretions.

The Isachsen Formation is the first unit associated with continental rifting and counterclockwise rotation of northern Alaska and adjacent northern Siberia away from the Canadian Arctic. Sediment supply increased dramatically off the rift shoulder. The Isachsen Formation lies on top of the Mould Bay Formation and is non-marine. There is a major disconformity at the base of this formation in the Sverdrup Basin. Isachsen Formation is composed of three members, a) Paterson Island Member which is composed of white weathering coarse grained sandstone with clast-supported chert pebble conglomerate at the base. b) Rondon Member comprises siltstone and mudrock and c) the Walker Island Member which is composed of fine to medium grained sandstone, carbonaceous sandstone and minor coal. Minor diabase sills, flows, breccias occur in the Isachsen Formation in this area. The Rondon Member is thin and is not mapped separately on western Axel Heiberg Island. The age of Isachsen Formation ranges from late Valanginian to early Albian (Early Cretaceous) (Harrison 1995, Tozer and Thorsteinsson 1964).

Christopher Formation is marine shale that lies between the non-marine Isachsen and Hassel formations. It has two members. The lower Invincible Point Member consists of dark grey to black shale with two sandstone marker beds, one locally developed close to diapirs, the other at the top of the member. The invincible Point Member thickness is up to 1580 m with the sandstones about 60 m thick. Their age is Albian. The upper Mcdougall Point Member is
The Hassel Formation is composed of recessive black and dark grey weathering mudrocks, minor siltstone and sandstone. The upper member is 100 to 560 m thick (Harrison 1995, Tozer and Thorsteinsson 1964).

The Hassel Formation thickness ranges from 105 to 510 m and gradationally overlies on the Christopher Formation. It is non marine and is composed of recessive, loosely compacted, but uncemented, medium and fine grained quartzose sandstone. Its age ranges from late Albian to Cenomanian. The Hassel Formation is overlain by siltstone and mudstone of the Bastion Ridge Formation (5 to 240 m thick) or by basalt flows of the Strand Fiord Formation. The Bastion Ridge and Strand Fiord are in part time equivalent and interfinger. They are Albian to Turonian in age.

The Kanguk Formation is a marine Upper Cretaceous shale and is comprised of two members, the lower is composed of grey weathering, platy, siliceous shale with intercalcted fissile chert. The upper member is composed of upper dark grey, brownish grey and greenish grey fissile mudrock unit with numerous yellow interbeds of bentonitic clay. Kanguk Formation age ranges from Coniacian to Campanian (Harrison 1995, Tozer and Thorsteinsson 1964). On western Axel Heiberg the Kanguk is 30 to 850 m thick.

The Kanguk is overlain by Upper Cretaceous to Tertiary non-marine sandstone and shale of the Eureka Sound Group. These sediments are related to the collision of Greenland and were shed from the Eurekan Orogeny. They may be as much as 1800 m thick. Expedition Formation is the lowest formation of the group and is composed of white weathering quartzose sandstone with common wood. Expedition formation lies below the Strand Bay Formation and Iceberg Bay Formation. Strand Bay Formation is composed of regressive marine shale and siltstone and Iceberg Bay Formation is composed of mostly sand, coastal to fluvial deposits with abundant coal. Buchanan Lake Formation is the upper most formation of the group and it is composed of
conglomerates up to 1 km thick (Harrison 1995, Tozer and Thorsteinsson 1964, Embry and Beauchamp 2008, Miall 1986).

Quaternary units are post-orogenic cover which is composed of modern and ancient fluvial and deltaic deposits, marine sediments and marine-modified bedrocks on raised beach terraces, weathered bedrock as colluvium, talus fans and felsenmeer, varved marine or laustrine silt, till, and peat. Its age is speculated to be Early and/or Middle Pleistocene to Recent (Harrison 1995).
Crystallized magma is known as igneous rock. Magma is primarily composed of O, Si, Al, Fe, Ca, Mg, Na, and K and considerable amounts of H₂O and CO₂ as well as lesser gaseous components such as H₂S, HCl, CH₄, and CO. Igneous rocks are categorized into two types, extrusive and intrusive. Extrusive igneous rocks are those that reach the Earth’s surface in a molten or partly molten state. Intrusive or plutonic rocks are the crystallized magma that did not reach the Earth’s surface and they form as either sill or dyke. Sills are magma intrusive that are concordant to their host rocks have larger grain size than dykes that are discordant magma intrusive. Intrusive igneous rocks have larger grain size than extrusive igneous rocks, since they are buried in the earth’s crust and generally cool slowly and have time to grow in size (Klein et al. 1998).

Volcanism and intrusion in the Sverdrup Basin has occurred at numerous different times in evolution of the basin: Late Carboniferous, Early Permian, Early Cretaceous, Late Cretaceous and Tertiary. These igneous activities seem to be related to the initial and subsequent rifting events of the Sverdrup Basin (Ricketts et al. 1985). The igneous rocks in Sverdrup are generally gabbroic and basaltic composition (Harrison 1995); however, most of these igneous rocks in the Sverdrup Basin have had little petrographical or chemical investigation.

Based on Harrison’s map (Figure 1.1 b), there are three types of igneous rocks present in the study area, flows and sills in the Isachsen Formation, Strand Fiord Formation olivine basalt, and diabase and gabbro dykes and sills of the Queen Elizabeth and Surprise swarms (Harrison & Jackson 2008).
3.1 Mineralogy and petrography of igneous rocks

Gabbro rocks are formed from magma that is rich in iron and magnesium and poor in silica (quartz), in other words they are mafic rocks. In general, gabbro is dark green to almost black with creamy white patches, and usually has little quartz (Williamson 1988 reports less than 10% quartz in all cases). Normal gabbroic rocks contain 35-65% mafic minerals their grain size is coarse, usually a few millimeters in size. Their mineral content is plagioclase feldspar, augite pyroxene, olivine, and sometimes magnetite. Basalt igneous rocks are the same as gabbro igneous rocks in term of color and mineral content their only difference is that basalt rocks are much finer grained (Grice 2010)

Composition of flows in the Isachsen Formation from across the northeastern Sverdrup Basin is reported in M.-C. Williamson, 1988; S. Estrada and F. Henjes-Kunst (2003) and unpublished GSC files. Based on 127 analyses, the average silica (SiO₂) content is 49.6%; the histogram of silica content of these samples is presented in Figure 3.1.
Strand Fiord Formation is the youngest suite of volcanic strata in the Sverdrup Basin. It consists of basalt, olivine tholeiite, vesicular and amygdaloidal flows. The formation thins to the east and south of Axel Heiberg Island (Ricketts et al. 1985). The Strand Fiord Formation igneous rocks are fine grained and consist mainly of plagioclase and clinopyroxene and very small amount of olivine and glass (Estrada and Henjes-Kunst 2003). The histogram of silica content of 112 samples collected at Strand Fiord Formation during the 1983 field season with average of 50.04%, presented in Figure 3.2. Table 3.1 is the chemical analyses of the sample rocks that were collected by Marie-Claude Williamson in August 1984 (Williamson, 1988). The locations that these samples were collected from are presented in Figure 3.3.
Figure 03.2 Histogram of silica content of 112 samples of Strand Fiord Formation, with average of 50.0% (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)
Figure 3.3: Strand Fiord Formation sampled during the 1983 field season. 1: Twisted Ridge; 3: Bastion Ridge; 9a: Glacier Fiord Syncline East; 9b: Glacier Fiord Syncline West (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)

Table 3.1(a): 1-Twisted Ridge, location displayed on Figure 3.3 (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)
<table>
<thead>
<tr>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>FeO (calc)</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>98.00</td>
<td>14.17</td>
<td>1.91</td>
<td>10.77</td>
<td>5.69</td>
<td>10.22</td>
<td>3.04</td>
<td>0.81</td>
<td>2.04</td>
<td>0.00</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>51.40</td>
<td>14.72</td>
<td>1.58</td>
<td>8.94</td>
<td>4.88</td>
<td>18.86</td>
<td>3.12</td>
<td>0.87</td>
<td>2.10</td>
<td>0.00</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>50.04</td>
<td>13.15</td>
<td>2.33</td>
<td>13.16</td>
<td>4.44</td>
<td>8.85</td>
<td>3.44</td>
<td>0.42</td>
<td>2.77</td>
<td>0.13</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>51.68</td>
<td>14.09</td>
<td>1.94</td>
<td>10.97</td>
<td>5.29</td>
<td>10.36</td>
<td>3.07</td>
<td>0.51</td>
<td>2.03</td>
<td>0.07</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>51.43</td>
<td>14.00</td>
<td>1.87</td>
<td>10.55</td>
<td>5.37</td>
<td>10.48</td>
<td>2.91</td>
<td>0.51</td>
<td>1.99</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>51.26</td>
<td>14.04</td>
<td>1.86</td>
<td>10.53</td>
<td>5.33</td>
<td>10.46</td>
<td>2.89</td>
<td>0.54</td>
<td>1.97</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>50.64</td>
<td>13.96</td>
<td>2.05</td>
<td>11.59</td>
<td>5.14</td>
<td>9.90</td>
<td>3.04</td>
<td>0.88</td>
<td>2.46</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>51.56</td>
<td>14.21</td>
<td>1.91</td>
<td>10.81</td>
<td>5.37</td>
<td>10.55</td>
<td>2.78</td>
<td>0.65</td>
<td>2.07</td>
<td>0.00</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>51.53</td>
<td>14.13</td>
<td>1.92</td>
<td>10.83</td>
<td>5.00</td>
<td>10.40</td>
<td>2.94</td>
<td>0.85</td>
<td>1.96</td>
<td>0.00</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>50.27</td>
<td>14.69</td>
<td>2.04</td>
<td>11.53</td>
<td>5.34</td>
<td>8.39</td>
<td>4.20</td>
<td>1.13</td>
<td>2.07</td>
<td>0.00</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>49.67</td>
<td>12.98</td>
<td>2.51</td>
<td>14.18</td>
<td>4.37</td>
<td>8.84</td>
<td>3.18</td>
<td>0.52</td>
<td>2.90</td>
<td>0.12</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>52.28</td>
<td>14.21</td>
<td>1.91</td>
<td>10.81</td>
<td>5.19</td>
<td>10.47</td>
<td>3.04</td>
<td>0.48</td>
<td>1.99</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>51.73</td>
<td>14.16</td>
<td>1.92</td>
<td>10.86</td>
<td>5.28</td>
<td>10.61</td>
<td>3.04</td>
<td>0.55</td>
<td>2.01</td>
<td>0.13</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>51.29</td>
<td>14.18</td>
<td>1.96</td>
<td>11.02</td>
<td>5.11</td>
<td>10.21</td>
<td>2.97</td>
<td>0.44</td>
<td>2.06</td>
<td>0.04</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>52.63</td>
<td>14.31</td>
<td>1.96</td>
<td>11.10</td>
<td>5.22</td>
<td>10.88</td>
<td>2.62</td>
<td>0.40</td>
<td>2.05</td>
<td>0.00</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>49.62</td>
<td>13.85</td>
<td>13.12</td>
<td>12.37</td>
<td>8.58</td>
<td>4.62</td>
<td>10.33</td>
<td>2.93</td>
<td>0.52</td>
<td>2.09</td>
<td>0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>49.30</td>
<td>14.24</td>
<td>13.57</td>
<td>14.09</td>
<td>9.00</td>
<td>4.76</td>
<td>9.93</td>
<td>2.79</td>
<td>0.44</td>
<td>2.07</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>48.71</td>
<td>14.02</td>
<td>13.77</td>
<td>9.62</td>
<td>9.17</td>
<td>4.32</td>
<td>10.16</td>
<td>2.65</td>
<td>0.72</td>
<td>2.08</td>
<td>0.23</td>
<td>0.19</td>
</tr>
<tr>
<td>49.56</td>
<td>13.97</td>
<td>13.86</td>
<td>10.32</td>
<td>9.23</td>
<td>5.13</td>
<td>10.17</td>
<td>2.74</td>
<td>0.48</td>
<td>2.10</td>
<td>0.23</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 2.2(b): 3-Bastion Ridge, location displayed on Figure 3.3 (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)

<table>
<thead>
<tr>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.47</td>
<td>14.04</td>
<td>2.07</td>
<td>13.60</td>
<td>5.17</td>
<td>10.08</td>
<td>3.63</td>
<td>0.25</td>
<td>2.35</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>50.49</td>
<td>14.18</td>
<td>2.01</td>
<td>11.37</td>
<td>5.12</td>
<td>10.14</td>
<td>3.52</td>
<td>0.40</td>
<td>2.39</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>51.42</td>
<td>14.35</td>
<td>1.98</td>
<td>11.19</td>
<td>4.72</td>
<td>10.15</td>
<td>3.47</td>
<td>0.77</td>
<td>2.31</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 3.3(c): 9-Glacier Fiord Syncline, location displayed on Figure 3.3 (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)

Queen Elizabeth and Surprise Fiord swarms are diabase and gabbro sills and dykes intruding Strand Fiord Formation and all older strata. These dykes and sills are associated to the volcanic rocks, dyke swarms and sills of Cretaceous age that are widely scattered across high Arctic. These dykes and sills are speculated to be due to the Alpha Ridge which source from the oceanic plateau (Buchan and 2006). Queen Elizabeth Island swarms and Surprise Fiord dykes
have different trending; however, these dykes and sills have not been distinguished in the study area. Based on 183 analyses, the average silica content is 48.2% and their histogram is presented in Figure 3.4. The Surprise Fiord swarms have not been chemically analyzed (Buchan and Ernst 2006).

![Histogram of silica content weight percentage](image)

**Figure 3.4:** Histogram of silica content weight percentage of 183 samples of Queen Elizabeth dyke swarm samples, NE Sverdrup Basin, with average of 48.7% (Williamson 1988; Estrada and Henjes-Kunst 2003; unpublished GSC files)

### 3.2 Petroleum system

Oil exploration in the Sverdrup basin started in 1968 and 120 wells were drilled between 1969 and 1986. Exploration resulted in discovery of 18 fields in a broad fairway extending from western Ellef Ringnes Island southwestward to northeastern Melville Island. Natural gas was the primary hydrocarbon discovered. Exploration ceased due to the collapse of the oil prices in 1986.
From the available surface and subsurface data it can be inferred that there is reduced petroleum potential in eastern Sverdrup Basin, especially in Axel Heiberg and Ellesmere islands. This is because the eastern part of the Sverdrup Basin was affected by Mesozoic magmatism and has been deformed and eroded due to the Eurekan orogeny. Therefore, the rocks in eastern part of Sverdrup Basin have poor reservoir characteristics and a complex thermal history (Chen et al. 1986).

3.2.1 Source Rocks

Source rocks are rocks that have been the source for migrated oil or gas. They must contain a suitable organic matter type at the correct level of maturation. The criteria that have been used for determining the presence of potential source rocks are high content of organic matter, high atomic hydrogen to carbon ratios of kerogen, and high pyrolysis yield (Gentzis 1996).

No wells have been drilled targeting Tertiary strata in the Sverdrup Basin. Tertiary deposits are about 3 km thick in the eastern part of the basin. There is poor petroleum potential for Tertiary strata due to immaturity and speculation that freshwater have flushed the potential reservoirs (Chen et al. 1986).

Most of the hydrocarbons discoveries occur in the Mesozoic succession (Chen et al. 1986). Starting from the youngest formations, Kanguk Formation contains rich hydrocarbon-prone organic matter and would likely be an excellent source rock if it were mature. Isachsen Formation contains excellent reservoir potential. These formations have undergone insufficient thermal diagenesis for significant hydrocarbon generation. This group of sediments would have to undergo considerable burial and diagenesis before hydrocarbon generation could take place (Gentzis 1996).
Awingak and Wilkie Point formations are composed of mainly sandstones whereas the Deer Bay is a thick grey to black marine shale. The Deer Bay-Ringnes-McConnell Island formations are largely immature to marginally mature in the western Sverdrup Basin. Northeast of central Ellef Ringnes Island these units may enter the oil window due to burial, and igneous intrusions in one of the well samples has been sufficient to raise the level of thermal digenesis of the Deer Bay Formation to the over mature stage. In general Deer Bay Formation may have gas potential particularly in the northeast Sverdrup Basin.

The Heiberg Formation is sandstone underlying the Jurassic shale succession. Samples of this formation range from under mature rocks at the basin margin to over mature rocks in certain wells on Ellef Ringnes. In general, the hydrocarbon yields are low at less than 30 mg per gram organic carbon. The carbon content is much higher in the southeastern part of the basin, reflecting the presence of coal seams and carbonaceous stringers within the Heiberg Formation.

Schei Point and Blaa Mountain formations were deposited at the same time. Schei Point formation is composed of shale interbedded with sandstone and limestone. The Blaa Mountain formation is the basinal shale equivalent. Generally Schei Point Formation has a substantial total organic carbon, the kerogen is type II (oil prone) and the content of wet gas is relatively high. The Blaa Mountain Formation is encountered in the subsurface east of Lougheed Island and is commonly intruded by sills and dykes which cause transformation to the over mature facies in many places. Gas source rocks with minor oil potential are encountered where the Blaa Mountain is penetrated by dykes and sills.

Bjorne Formation is composed of mainly quartzose and commonly crossbedded sandstone with conglomeratic interbeds. Blind Fiord Formation is a fine-grained equivalent consisting of red and green silty shales. These formations are encountered in the subsurface west
of Lougheed Island and at the basin margins. The sample evaluations show that these formations do not have source potential.

No hydrocarbon discoveries have been made in the Upper Paleozoic strata of the Sverdrup Basin. However, they have been identified as good shows of oil and gas have been identified. Oil has been discovered in Canyon Fiord Formation on the southeastern basin margin and Belcher Channel Formation on Sabine Peninsula, Melville Island.

Hare Fiord and Van Hauen formations have been identified as oil-prone source rocks. Also, in the Emma Fiord Formation on Grinnell Peninsula oil shales with organic carbon contents up to 50% have been discovered. The Upper Paleozoic strata of Sverdrup Basin in its central portion are identified as over matures and along the margins of the basin mature zone (Embry 1991).

3.2.2 Reservoir Units

Porous sandstone covered by shale make a suitable reservoir rock, reservoir units in the Sverdrup Basin are the three main prograding delta units, the Triassic Bjorne Formation overlain the shaley Schei Point Formation, the Triassic-Jurassic Heiberg Formation overlain by the Jameson Bay Formation, the Jurassic Awingak Formation overlain by the Deer Bay Formation, and the Cretaceous Isachsen Formation overlain by the Christopher Formation. The Heiberg is the reservoir of most of the oil and gas discovered in the Sverdrup Basin, with lesser amounts in the Awingak and Isachsen formations (Chen, 2000). The younger reservoirs are often filled from oil or gas leaking from a reservoir in the Heiberg Formation below (Waylett and Embry, 1992).

3.2.3 Time and Depth of Burial (Maximum burial and thermal maturity)

Thermal maturity data provide constraints on the maximum depth of burial and paleogeothermal gradient of a rock (Dewing and Sanei 2007). Thermal maturities of Mesozoic sediments in the
Sverdrup Basin are mainly a function of burial depth. However, other factors such as thermal subsidence, uplift, erosion and heat associated with periods of diapiric and igneous intrusions may have been responsible for the thermal maturity pattern (Gentzis and Goodarzi. 1993).

Sverdrup Basin experiences two main phases of burial and three thermal events. The first burial is associated with the opening of the Sverdrup Basin and thick accumulation of strata, in the Carboniferous to Cretaceous. The second burial event is where the sedimentation progressed and reached its maximum in Eocene time before the Eurekan Orogeny (Dewing and Sanei 2007).

The first thermal event was during the rifting of the Sverdrup Basin, Permian to Jurassic. The second thermal event was during the opening of the Amerasian Basin which is associated with the spreading of the Arctic Ocean in Mid Jurassic and Early Cretaceous. The third thermal event was during the widespread igneous activity in the Early to Late Cretaceous which is associated with spreading of the Alpha Ridge (Dewing and Sanei 2007).

Gentzis and Goodarzi (1993) studied the thermal maturity of the organic matter of the Mesozoic formations in the southern Sverdrup Basin, Melville Island, using organic petrology and Rock-Eval pyrolysis. Based on the vitrinite reflectance they noticed an overall increase of thermal maturity with depth of burial. They noticed that the thermal maturity of Mesozoic sediments increases towards the centre (N-NE direction). However, there are some anomalous zones of high geothermal gradient, which could be due to the igneous intrusions. Generally, the depth of burial of the Triassic source rocks in the NE Sverdrup Basin is in the range of gas generation or over matures with respect to gas. Thermal constraints on younger source rocks are too few to evaluate the hydrocarbon potential, in large part due to the uncertain distribution of igneous rocks.
3.2.4 Time of Structures

The western Sverdrup Basin structure has very good conditions for petroleum occurrence. However, not all of the structures are economical and contain petroleum. The high amplitude (King Christian, Skate, and Jackson Bay) structures are under-filled; this could be due to the lack of seal and fractures over the structures (Waylett and Embry 1992). Also, they were at least partly formed during the Eurekan Orogeny, which is after the maximum burial and hydrocarbon generation. The low amplitude structures (Drake, Hecla, and Whitefish) are full and it is speculated that they were formed before the hydrocarbone generation (Dewing and Obermajer 2011).

3.3 Impact of Igneous Rocks

Murchinson (1989) has investigated the effect of igneous intrusions on organic matter in Scotland, and postulate that the lithology of the host rock, the temperature of the magma, the level of maturity prior to sill emplacement, the volume of pore water in the sediments, and the thermal conductivity of the sediments are important factors that influence effects of intrusion on organic matter. Based on the Gentzis and Goodarzi (1993) observations on Drake Field, which is located between 107° Longitudes to 109° Latitude, the sill that intruded van Hauen Formation caused the source rock to be cooked. Volcanic and igneous intrusions have been perceived by hydrocarbon exploration as detrimental on the petroleum system (Rohrman 2007). However, Jones (Jones et al. 2007) uses 1D numerical modeling for a well near the Eureka Sound, Axel Heiberg Island to demonstrate the contrary in Sverdrup Basin. The result of the model shows that the hydrocarbon generation in Hare Fiord and van Hauen formations was ceased before the igneous activity in Sverdrup Basin. In the case of younger and shallower strata such as Blaa
Mountain Formation the results show that the emplacement of the sills increased the hydrocarbon generation rates which lead to production of gas rather than oil.
CHAPTER 4

SURFACE ANALYSIS OF STUDY AREA USING SATELLITE IMAGERY

Electro-magnetic radiation energy from the Sun to the Earth’s surface is either reflected as it is for visible wavelengths (V), near-infrared (NIR), and short-wave infrared (SWIR), absorbed and then re-emitted as it is for thermal infrared (TIR) wavelengths. The reflected or emitted electromagnetic depends on the nature of the interaction between the incident radiation and the earth’s surface material.

The optical remote sensing images are based on the reflected and emitted solar energy. The remote sensing images are in digital format and are presented as raster images. The individual elements of the raster image are called pixels, which are recorded in digital numbers (DN) (Sabins 1987).

There are different optical sensors that are available for geological mapping. In this study two satellite-based sensors, LANDSAT 7 ETM+ and ASTER, have been chosen for surface analysis of the study area using two remote sensing techniques, color composite and band ratioing. Acquiring data from the satellite-based sensor are more feasible and less expensive than airborne sensors, especially for remote areas. These two satellites sensors have been widely used for geological mapping; they both have good spatial and spectral resolution suitable for geological mapping.

Generally satellites are characterized based on their spectral, spatial, radiometric, and temporal resolution, which defines their ability to map and discriminate surface material. Spatial resolution indicates the pixel size of satellite images. Spectral resolution refers to the wavelength interval size and number of the intervals that the sensor is measuring. Radiometric resolution is defined as the number of bits (each bit records an exponent of power 2) used for coding numbers.
in binary format, in other words number of greyscale levels. Temporal resolution defines the frequency of a satellite sensor re-imaging same location (Sabins 1987). A summary of the characteristics of the LANDSAT 7 ETM+ and ASTER sensor is provided in Table 4.1.

LANDSAT 7 ETM+ images are the most widely used images and have been used for mapping and structural analysis in geological studies (Kalelioglu et al. 2009). They are freely available and have good spectral resolution with seven bands. Landsat was launched on April 15, 1999 with swath width of 180 km, an altitude of 705 km and orbit inclination of 98.2 +/- 0.15. Bands 1-4 are visible bands in the spectrum of blue, green, and red, bands 5 and 7 are Shortwave Infrared (SWIR) with 30 m spatial resolution and band 6 is a thermal infrared (TIR) channel with 60 m spatial resolution (NASA 2012).

ASTER images have been effective in mapping different rocks and minerals (Massironi et al. 2008). ASTER has better spectral and spatial resolution than Landsat which provides better results for discriminating different minerals. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was launched on December 18, 1999 with swath width of 60 km, an altitude of 705 km and orbit inclination of 98.3 degrees. This instrument consists of three separate instrument subsystems, bands 1-3 are Visible Near Infrared (VNIR) with 15 m spatial resolution, bands 5-9 Shortwave Infrared (SWIR) with 30 m spatial resolution and Thermal Infrared (TIR) bands 10-14 with 90 m spatial resolution (NASA 2004).
### Table 4.1: A summary of the characteristics of the LANDSAT 7 ETM+ and ASTER satellite sensors

<table>
<thead>
<tr>
<th>ASTER</th>
<th>Landsat ETM+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band #</td>
<td>Spectral range (µm)</td>
</tr>
<tr>
<td>1</td>
<td>0.520-0.600</td>
</tr>
<tr>
<td>2</td>
<td>0.630-0.690</td>
</tr>
<tr>
<td>3N</td>
<td>0.760-0.860</td>
</tr>
<tr>
<td>3B</td>
<td>0.760-0.860</td>
</tr>
<tr>
<td>4</td>
<td>1.600-1.700</td>
</tr>
<tr>
<td>5</td>
<td>2.145-2.185</td>
</tr>
<tr>
<td>6</td>
<td>2.185-2.225</td>
</tr>
<tr>
<td>7</td>
<td>2.235-2.285</td>
</tr>
<tr>
<td>8</td>
<td>2.295-2.365</td>
</tr>
<tr>
<td>9</td>
<td>2.360-2.430</td>
</tr>
<tr>
<td>10</td>
<td>8.125-8.475</td>
</tr>
<tr>
<td>11</td>
<td>8.475-8.825</td>
</tr>
<tr>
<td>12</td>
<td>8.925-9.275</td>
</tr>
<tr>
<td>13</td>
<td>10.25-10.95</td>
</tr>
<tr>
<td>14</td>
<td>10.95-11.65</td>
</tr>
</tbody>
</table>

**Temporal Resolution:** 16 days (sun-synchronous)

**Temporal Resolution:** 16 days (sun-synchronous)

### 4.1 Data acquisition and preprocessing

All satellite data, including Landsat and ASTER, have errors related to their sensors or platforms, which need to be corrected for before spectral mapping and analysis. They also have errors related to atmosphere as the incoming light and radiation could be affected by particles and gases in the atmosphere. These errors can be minimized using available atmospheric correction techniques. For image pre-processing and visual analysis of applied remote sensing techniques, ENVI 4.8 image processing software has been used.
The Landsat images that were used in this study were acquired on July 22, 1999. Band six has been exempt from this study due to its low spatial resolution. The originator of these images, is Geomatic Canada, Centre for Topographic Information and they are distributed by Geological Survey of Canada. These images were acquired in summer so there would be less snow on the ground and the ones with cloud percent of less than 10% were chosen. The sizes of these images are 8,752 pixels by 8,682 lines.

The Landsat satellite images have already been geometrically corrected. Non geological sources such as glacier and water bodies have been masked and removed from analysis; so they would not interfere with geological analysis based on the culture data of Canada provided by the government. The vegetation density of the study area is low; therefore the vegetation in the study was determined to not be a barrier for geological mapping. To remove snow, normalized difference snow index has been used (NDSI equation 4.1) with threshold of 0.3 (Riggs et al. 1994).

\[ NDSI = \frac{(TM2 - TM5)}{(TM2 + TM5)} \] (4.1)

To correct for the atmospheric effects “Dark Subtraction” method has been utilized. The satellite data were then converted to radiance and from radiance to reflectance data (please refer to APPENDIX I).

ASTER L1B data are unprocessed raw radiance at sensor data that has been radiometrically calibrated and geometrically co-registered. Six ASTER Level1B images have been utilized for this study, the acquired date; granule ID and cloud coverage of these images are provided in Table 4.2. Only one of the images, ASTL1B 0607282017011102150024, has been
used for VNIR and SWIR analysis, since the other images are missing SWIR bands (ASTER’s SWIR sensor stopped working after year 2006).

<table>
<thead>
<tr>
<th>Granule ID</th>
<th>Acquisition Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTL1B 0607282017101102150025</td>
<td>28 August, 2007</td>
</tr>
<tr>
<td>ASTL1B 1008161928071102150037</td>
<td>16 August, 2010</td>
</tr>
<tr>
<td>ASTL1B 0607282017011102150024</td>
<td>28 July, 2006</td>
</tr>
<tr>
<td>ASTL1B 1008161928161102150035</td>
<td>16 August, 2010</td>
</tr>
<tr>
<td>ASTL1B 1008161927591102150036</td>
<td>16 August, 2010</td>
</tr>
<tr>
<td>ASTL1B 0607091946311102150022</td>
<td>09 July, 2006</td>
</tr>
<tr>
<td>ASTL1B 0607282017181102160027</td>
<td>28 July, 2006</td>
</tr>
</tbody>
</table>

Table 4.2: Acquired ASTER satellite images for the study area

ASTER L1B contains some errors which should be corrected for before using the data for spectral interpretation and geological mapping. These images were first corrected for crosstalk effect. Crosstalk effect is an offset or additive radiance error due to the leakage of photons from one detector element to another. This leakage is more distinct from band 4 to band 5 and 9; however, it affects all SWIR bands (Hewson et al. 2005). To correct for this error, crosstalk correction software has been employed and applied for Level 1B ASTER data; this software can be downloaded from: “http://gds.aster.ersdac.jspacesystems.or.jp/gds_www2002/service_e/a.tools_e/a.tools1_e.html”.

ASTER Level1B data are delivered in units of digital number (DN) and are converted to radiance (W/m²/str/µm) by ENVI 4.8 software, using unit conversion coefficients. This study also uses ENVI 4.8 software for processing the images which automatically applies the unit conversion coefficients and converts the data in radiance units (Wickert et al. 2008).

Non geological sources such as glacier and water bodies have also been masked and removed from analysis for ASTER satellite images. To remove snow, the snow normalized difference index has been used, equation 4.2. The normalized difference snow index (NDSI) to
identify snow in the ASTER images of this study area was created based on the Keshri et al. (2009) reflectance curves for snow, where snow has highest reflectance in ASTER band 1 and lowest in ASTER band 4 (Keshri et al. 2009). Threshold value that has been determined appropriate for this study is 0.9 of the normalized difference snow index image; and it was used to create a mask to remove snow from the VNIR and SWIR ASTER data.

\[
NDSI = \frac{(b_1 - b_4)}{(b_1 + b_4)}
\]  
(4.2)

To correct for atmospheric errors and conversion of the data from at-sensor radiance to at-surface reflectance, FLAASH (Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes) based on atmospheric correction algorithm MODTRAN4 has been used (Anderson et al. 2002). The VNIR bands were co-registered with the six SWIR bands to spatially resample the 30m resolution SWIR data to match the 15 m resolution VNIR data.

ENVI’s thermal atmospheric correction has been applied to the ASTER TIR bands. ASTER TIR is useful for classifying the rock types based on silicate minerals. Thermal infrared region is affected by the thermal emission from the land surface which is a valuable data in evaluating minerals and igneous rocks.

4.2 Spectral reflectance analysis of study area’s surface rocks

Before applying image enhancement techniques, it is important to examine the spectral reflectance of the target features and their surroundings material. The spectral reflectance of the same type of rock could vary at different areas. Generally the reflectance spectrum of a rock depends on its mineral composition, weathering minerals and vegetation covers. The particle size could also impact the reflectance properties of a rock as generally the reflectance increased with decrease of particle size (Ross et al. 1968). Therefore, it is important to use the spectral
reflectance characteristics of these rocks as only a reference and employ different image enhancement techniques for geological analysis.

The spectral reflectance properties of the rock type that occur in the study area and their minerals were obtained from USGS and NASA spectral library. USGS measured the spectral reflectance of a wide range of minerals in the spectroscopy lab and compiled them in a spectral library obtained from: “http://speclab.cr.usgs.gov/spectral.lib06/”. NASA ASTER spectral library includes three spectral library datasets, the Johns Hopkins University (JHU) Spectral Library the Jet Propulsion Laboratory (JPL) spectral Library, and the United States Geological Survey (USGS-Restone) Spectral Library; they are distributed through NASA Spectral Library obtained from: “http://speclib.jpl.nasa.gov/search-1” (Baldridge et al. 2009).

The study area is mostly composed of shale, sandstone, and igneous rocks (basalt and gabbro), Table 4.3 provides a summary of these rock types and their common minerals. The spectral reflectance of the sandstone, shale, basalt and gabbro igneous rocks; common feldspars; common micas; common clays; calcite, dolomite, quartz; in ASTER and Landsat VNIR and SWIR bands are graphed (based on NASA and USGS spectral library) in Figure 4.1, Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5, and Figure 4.6.
<table>
<thead>
<tr>
<th></th>
<th>quartz</th>
<th>Potassium feldspars</th>
<th>Microcline Sanidine Orthoclase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>feldspar</td>
<td>Plagioclase feldspars</td>
<td>Albite Oligoclase Andesine Labradorite Bytownite Anorthite</td>
</tr>
<tr>
<td></td>
<td>mica</td>
<td></td>
<td>Muscovite Biotite phlogopite</td>
</tr>
<tr>
<td></td>
<td>clay</td>
<td></td>
<td>Kaolinite Montmorillonite Illite</td>
</tr>
<tr>
<td></td>
<td>calcite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>dolomite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>quartz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale</td>
<td>feldspar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potassium feldspars</td>
<td>Microcline Sanidine Orthoclase Albite Oligoclase Andesine Labradorite Bytownite Anorthite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plagioclase feldspars</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Igneous rocks</td>
<td>Plagioclase feldspar</td>
<td></td>
<td>Albite</td>
</tr>
<tr>
<td>(Gabbro and Baslat)</td>
<td></td>
<td></td>
<td>Oligoclase Andesine Labradorite Bytownite Anorthite</td>
</tr>
<tr>
<td></td>
<td>augite pyroxene</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>olivine</td>
<td></td>
<td>magnesium iron silicate</td>
</tr>
<tr>
<td></td>
<td>magnetite</td>
<td></td>
<td>Iron oxide</td>
</tr>
</tbody>
</table>

Table 4.3: The spectral reflectance of study area’s common rock types including: sandstone, shale, basalt and gabbro igneous rocks; common feldspars; common micas; common clays; calcite, dolomite, quartz
Figure 4.2: Spectral reflectance of sandstone, shale and igneous rocks (gabbro and basalt) in ASTER and Landsat bands (data obtained from USG and NASA spectral library)
Figure 4.2: Spectral reflectance of common feldspars and its chemical gradations (data obtained from USG and NASA spectral library)
Figure 4.3: Spectral reflectance of common mica (data obtained from USG and NASA spectral library)
Figure 4.4: Spectral reflectance of common clay (data obtained from USG and NASA spectral library)
Figure 4.5: Spectral reflectance augite pyroxene, olivine, magnetite (data obtained from USG and NASA spectral library)
4.3 False color composite (FCC)

False color composite, displays a color image which is suitable for geological analysis. Three bands are required to assign to fundamental colours Red (R), Green (G), and Blue (B). The best band combinations are those that delineate the desired geological features (Sabins 1987). There are twenty possible band combinations from the six bands of Landsat, eighty-four possible band combination from the nine VNIR and SWIR of ASTER bands, and ten possible band combination from the TIR ASTER bands.

To determine the most suitable color composite for overall geological mapping of the study area, statistical techniques such as correlation coefficient (CC) and optimum index factor (OIF) are employed to determine the most suitable color composite.

4.3.1 Literature review of false color composite

This technique is relatively easy and fast to display geological features and it has been widely used among geologists. Numerous studies have used Landsat band combination of RGB 742 for geological mapping and regional lineaments. Ramadan and Fattah (2010) uses Landsat color composite of RGB 742 for regional geologic mapping of Garin Hawal area in northwest of Nigeria. Sakem et. al. (2011) also use color composite of Landsat RGB 742 to highlight the geological features southern Sinai, Egypt.

Harding (1989) recognizes band combination technique as one of the most adequate and easy techniques to distinguish the Alaskan ophiolites including a gabbro complex and mafic (e.g basalt) sheeted dykes. He claims that Landsat RGB 731, 541, and 321 are the most useful band combination for visually displaying different ophiolites rock types in Alaska.

Kalelioglu et al. (2009) finds that lithological boundaries between ophiolite rocks, dyke complexes and the volcano-sedimentary sequence are best visible in Landsat RGB 731 color
composite. Schetselaar (2008) states that Landsat band combination of RGB 731 and 732 delineate the iron-oxide and carbonate and mica-rich rocks.

Mshiu (2011) uses Landsat remote sensing data and color composite RGB 741 and 754 to discriminate individual lithological units in Rungwe volcanic province southwestern Tanzania. They were able to differentiate individual intrusions such as gabbros and extrusions such as basalts. Some scientist have used statistical techniques such as correlation coefficient method to determine the best possible Landsat color composite that highlights different geological features. For example Dwivedi and Rao (1990) successfully use correlation coefficient method to determine the best possible band combination for delineating salt-affected soils.

VNIR and SWIR ASTER color composites are also known to be very effective for geological interpretation. Massironi et al. (2008) use color composite RGB 731 and observe that plutons in their study area have variety of reddish colors which could be related to variations in the content of mafic minerals and altered feldspars. Qari et al. (2008) evaluate different ASTER band combinations and find out that RGB 457 is the best band combination for lithological discrimination especially the post-tectonic granite and its joint systems. Khan and Mahmood (2008) use ASTER SWIR color composite RGB 458 to discriminate lothologies of Muslim Bagh in Blaocistan. Diabase dykes/sills are highlighted as dark grey to greenish grey. Mars and Rowan (2011) use color composite image RGB 631 for mapping the Khanneshin carbonatite volcano, Afghanistan. Using this band combination they were able to discriminate the quartz-rich sands, which were displayed in red.

TIR ASTER bands are known to be the most suitable for identifying granitoid rocks (Massironi 2008). Watanabe and Matsuo (2003) use ASTER band combinations BGR 10, 12, and 13 or 14 to classify the rock type; and notice that the area will appear reddish hue as the SiO₂
increases in the rock. In color composite BGR 10, 12, 14 coarser silica rocks appear more reddish hue whereas finer rocks appear more whitish hue. In this color composite the igneous rocks appear in bluish to magenta hue. For igneous rocks abundant in pyroxene they would be appeared in magenta to purple hue. When they applied BGR 11, 12, 13 the alkaline rich rocks appear in bluish and the alkaline poor rocks such as basalt appear greenish hue. Aboelkhair et al. (2010) also uses band combination RGB 14, 12, 10 and 12, 13, 11 for mapping granite in the central eastern desert of Egypt. The granite were shown as light brownish yellow in RGB 14,12, 10 and light greenish in RGB 12,13, 11. Massironi et al. (2008) apply de-correlation stretch technique followed by color composite technique. They use RGB 14, 13, 10 to highlight the Arharhiz granite, which are highlighted as orange-yellowish colors.

### 4.3.2 Correlation coefficients (CC)

One of the statistical based techniques to determine the most suitable color composition is correlation coefficient method for regional geological mapping (Benomar 2005). The correlation coefficient determines the distribution of pixel values between the two bands, the expression for the correlation coefficient of two variables, x and y is presented in equation 4.3. Where \( \sigma_{xy}^2 \) is the covariance of x and y and \( \sigma_x \) and \( \sigma_y \) are the standard deviations of the variables (Ross et al.1968).

\[
\rho = \frac{\sigma_{xy}^2}{\sigma_x \sigma_y} \quad (4.3)
\]

If two images have high correlation value (close to +1) it means that when the spectral values in one band are high the spectral value in the correlated band is high as well. For color composite the features are highlighted best when the two bands have low correlation, since they
contain independent information. Correlation matrix helps to determine the least correlated bands (Benomar 2005).

The calculated correlation matrix for the reflective bands of Landsat, (VNIR, SWIR) and TIR ASTER data are shown in Table 4.4, Table 4.5, and Table 4.6 respectively. Based on the correlation matrix of Landsat data, bands that have relatively low correlation coefficient are 1, 5, 7 and 3. Therefore, it is speculated that Landsat band color combination of RGB 751, 731, and 531 are suitable to map the geological features of the study area. Landsat color composite of RGB 751, Figure 4.6, highlights the geological features in the study area the best. The igneous rocks are highlighted in as dark green and dark blue, shale are highlighted as purple and light green, sandstones are highlighted as yellow and white colors, and evaporates are highlighted as cyan. However, in Landsat color composite RGB 731 and 531, Figure 4.7 and Figure 4.8, the igneous rocks which are highlighted as green are more noticeable; since, there is a better contrast between the igneous rocks and the surrounding rocks.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
<th>Band 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 2</td>
<td>0.994</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 3</td>
<td>0.980</td>
<td>0.996</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 4</td>
<td>0.977</td>
<td>0.987</td>
<td>0.986</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 5</td>
<td>0.956</td>
<td>0.968</td>
<td>0.971</td>
<td>0.985</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Band 7</td>
<td>0.955</td>
<td>0.971</td>
<td>0.977</td>
<td>0.978</td>
<td>0.995</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.4: Correlation matrix of VNIR and SWIR Landsat bands,
Table 4.5: Correlation matrix of VNIR and SWIR ASTER bands

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
<th>Band 6</th>
<th>Band 7</th>
<th>Band 8</th>
<th>Band 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 2</td>
<td>0.987</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 3</td>
<td>0.978</td>
<td>0.985</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 4</td>
<td>0.785</td>
<td>0.747</td>
<td>0.797</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 5</td>
<td>0.780</td>
<td>0.743</td>
<td>0.786</td>
<td>0.992</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 6</td>
<td>0.778</td>
<td>0.743</td>
<td>0.787</td>
<td>0.992</td>
<td>0.997</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 7</td>
<td>0.786</td>
<td>0.753</td>
<td>0.794</td>
<td>0.990</td>
<td>0.995</td>
<td>0.995</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 8</td>
<td>0.772</td>
<td>0.739</td>
<td>0.779</td>
<td>0.987</td>
<td>0.994</td>
<td>0.993</td>
<td>0.996</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Band 9</td>
<td>0.781</td>
<td>0.746</td>
<td>0.785</td>
<td>0.986</td>
<td>0.994</td>
<td>0.992</td>
<td>0.995</td>
<td>0.995</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.6: Correlation matrix of ASTER TIR bands

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Band 10</th>
<th>Band 11</th>
<th>Band 12</th>
<th>Band 13</th>
<th>Band 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 10</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 11</td>
<td>0.9998</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 12</td>
<td>0.9996</td>
<td>0.9998</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 13</td>
<td>0.9992</td>
<td>0.9993</td>
<td>0.9988</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Band 14</td>
<td>0.9935</td>
<td>0.9937</td>
<td>0.9931</td>
<td>0.9943</td>
<td>1</td>
</tr>
</tbody>
</table>

VNIR and SWIR ASTER bands of 1, 8, 2, 5, 6, and 3 have relatively low correlation coefficient. Consequently, band combination of RGB 862, 832 and 621 were evaluated for their ability to discriminate geological features of the study area. Color composite RGB 862 and 832, Figure 4.9 and Figure 4.10, highlight different geological features. Color composite RGB 832 creates a good color contrast between different geological features, where sandstone is highlighted in yellow and light red, shale is highlighted in green and grey, igneous rocks are highlighted as brown and dark blue, and evaporates are highlighted as cyan. The igneous rocks in color composite RGB 621, Figure 4.11, are clearly visible as green color.
ASTER TIR bands are highly correlated, however bands 10, 14, 11, and 12 are least correlated and consequently band combination of RGB 14, 11, 10, Figure 4.12, and 14, 12, 11, Figure 4.13 are speculated to display the geological features of the study area using ASTER TIR bands. Both of these color composite images highlight the geological features the same, the sandstone is highlighted as red, shale as yellow, igneous rocks as white and evaporates as pink.

Figure 4.6: Display of study area by VNIR and SWIR bands of Landsat color composite of RGB 751
Figure 4.7: Display of study area by VNIR and SWIR bands of Landsat color composite RGB 731
Figure 4.8: Display of study area by VNIR and SWIR bands of Landsat color composite RGB 531
Figure 4.9: Display of study area by VNIR and SWIR bands of ASTER color composite RGB 862
Figure 4.10: Display of study area by VNIR and SWIR bands of ASTER color composite RGB 832
Figure 4.11: Display of study area by SWIR and VNIR bands of ASTER color composite RGB 621
Figure 4.12: Display of study area by TIR bands of ASTER color composite RGB 14-11-10
Figure 4.13: Display of the study area by TIR of ASTER color composite RGB 14-12-11
4.3.2 Optimum index factor (OIF)

Optimum index factor (OIF) is another technique, introduced by Chavez (1984), for the selection of the best possible three band combination for separating geological features. This method is based on the total variance and correlation between various bands. The three bands that have high total variance within bands and low correlation coefficient between bands will have high OIF. High value of OIF indicates that the bands contain much information and little redundancy between the bands. The following algorithm, equation 4.4, has been used to calculate OIF of the twenty possible band combinations (Benomar 2005).

\[
OIF = \frac{\sum_{k=1}^{3} S_k}{\sum_{j=1}^{3} |r_j|} \quad (4.4)
\]

\(S_k\) is the standard deviation of band \(k\) after atmospheric correction and converted to radiance

\(r_j\) is the correlation coefficient between any two or three bands being evaluated

Table 4.7, Table 4.8, and Table 4.9 lists the OIF for Landsat, VNIR, SWIR, and TIR ASTER bands respectively; and they are ranked from the highest OIF to the lowest. The band combinations with rank 1, 2 and 3 of each of the data sets have been chosen, i.e. Landsat band combinations of RGB 754, 751, and 541. Landsat color composite RGB 751 has also been recognized as good color composite in correlation coefficient method. The geological features in color composite RGB 754 image, Figure 4.14 have almost the same characteristics as color composite RGB 751 image. Landsat color composite RGB 541, Figure 4.15 also clearly
distinguishes the geological features of the study area, this image creates a better contrast between the shale and sandstone, where shale is displayed as blue and light green and sandstone is displayed as light brown and yellow colors. The igneous rocks are displayed as dark green color. Evaporates are not clearly highlighted as the other two color composite images.

The top three ranked OIF of VNIR and SWIR ASTER are band combinations of RGB 321, 421 and 621. Color composite image RGB 621 has already been evaluated. Color composite image RGB 321, Figure 4.16 seems useful for distinguishing some of the igneous rocks where they are highlighted as dark green and brown, sandstone is highlighted mostly as grey and in some areas they are highlighted as brown which makes it difficult to distinguish them from igneous rocks; and shale is highlighted as red, evaporates are not clearly highlighted. ASTER color composite RGB 421, Figure 4.17 highlights the igneous rocks and delineates different geological features better than color composite ASTER band image RGB 321.

Based on the OIF rank of TIR ASTER bands, color combination of RGB 14-13-12, 14-13-11, and 14-13-10 , Figure 4.18, Figure 4.19, and Figure 4.20 respectably, their ability to discriminate different geological features were evaluated. These color composite images do not clearly discriminate different geological features and the color characteristics of the geological features in the study area are all the same. The sandstone are shown in dark yellow, shale is highlighted as pale yellow and igneous rocks are shown as white. The darkness of the color yellow decreases from color composite image RGB 14-13-10 to color composite RGB 14-13-11-12; the igneous rocks are highlighted best in color composite image RGB 14-13-10 where shale, sandstone are highlighted in color yellow and igneous rocks as white color.
| RGB  | $\sum_{k=1}^{3} S_k$ | $\sum_{j=1}^{1} |r_j|$ | OIF  | Rank |
|------|----------------------|-----------------|------|------|
| 754  | 0.24899              | 2.95803         | 0.08417 | 1    |
| 751  | 0.23668              | 2.92855         | 0.08082 | 2    |
| 541  | 0.23529              | 2.91765         | 0.08064 | 3    |
| 753  | 0.23302              | 2.94313         | 0.07917 | 4    |
| 752  | 0.23198              | 2.93459         | 0.07905 | 5    |
| 543  | 0.23163              | 2.94235         | 0.07872 | 6    |
| 542  | 0.23059              | 2.94044         | 0.07842 | 7    |
| 521  | 0.21828              | 2.91734         | 0.07482 | 8    |
| 741  | 0.21372              | 2.91045         | 0.07343 | 9    |
| 532  | 0.21462              | 2.93503         | 0.07313 | 10   |
| 743  | 0.21006              | 2.94182         | 0.0714  | 11   |
| 742  | 0.20902              | 2.93689         | 0.07117 | 12   |
| 531  | 0.19775              | 2.90646         | 0.06804 | 13   |
| 731  | 0.19775              | 2.9122          | 0.06791 | 14   |
| 721  | 0.19671              | 2.92006         | 0.06736 | 15   |
| 431  | 0.19637              | 2.94334         | 0.06672 | 16   |
| 421  | 0.19532              | 2.95784         | 0.06604 | 17   |
| 732  | 0.19305              | 2.94442         | 0.06556 | 18   |
| 432  | 0.191664             | 2.939374        | 0.065206 | 19     |
| 321  | 0.17936              | 2.96907         | 0.06041 | 20   |

Table 4.7: Optimum index factor (OIF) of twenty possible RGB color composite of Landsat bands
| RGB | $\sum_{k=1}^{3} S_k$ | $\sum_{j=1}^{1} |r_j|$ | OIF | Rank | RGB | $\sum_{k=1}^{3} S_k$ | $\sum_{j=1}^{1} |r_j|$ | OIF | Rank | RGB | $\sum_{k=1}^{3} S_k$ | $\sum_{j=1}^{1} |r_j|$ | OIF | Rank |
|-----|----------------|----------------|-----|-----|-----|----------------|----------------|-----|-----|-----|----------------|----------------|-----|-----|
| 421 | 43.761 | 2.519 | 17.373 | 2 | 871 | 23.822 | 2.554 | 9.327 | 30 | 853 | 15.328 | 2.559 | 5.990 | 58 |
| 621 | 41.699 | 2.508 | 16.627 | 3 | 961 | 23.726 | 2.552 | 9.298 | 31 | 863 | 15.312 | 2.560 | 5.982 | 59 |
| 921 | 41.265 | 2.514 | 16.412 | 7 | 542 | 21.687 | 2.482 | 8.737 | 35 | 973 | 15.074 | 2.573 | 5.859 | 63 |
| 931 | 37.236 | 2.544 | 14.637 | 13 | 752 | 19.553 | 2.491 | 7.850 | 41 | 864 | 3.865 | 2.972 | 1.300 | 69 |
| 432 | 35.181 | 2.530 | 13.907 | 14 | 762 | 19.537 | 2.490 | 7.845 | 42 | 874 | 3.794 | 2.973 | 1.276 | 70 |
| 832 | 32.851 | 2.504 | 13.120 | 16 | 862 | 19.341 | 2.476 | 7.812 | 44 | 964 | 3.698 | 2.971 | 1.245 | 72 |
| 532 | 33.134 | 2.530 | 13.098 | 17 | 872 | 19.270 | 2.489 | 7.743 | 45 | 974 | 3.627 | 2.971 | 1.221 | 73 |
| 732 | 33.047 | 2.532 | 13.052 | 18 | 952 | 19.190 | 2.483 | 7.729 | 46 | 984 | 3.431 | 2.968 | 1.156 | 74 |
| 932 | 32.684 | 2.516 | 12.992 | 19 | 962 | 19.174 | 2.481 | 7.728 | 47 | 765 | 2.015 | 2.987 | 0.675 | 75 |
| 541 | 26.239 | 2.556 | 10.264 | 20 | 972 | 19.103 | 2.493 | 7.663 | 48 | 865 | 1.818 | 2.984 | 0.609 | 76 |
| 641 | 26.223 | 2.555 | 10.263 | 21 | 982 | 18.907 | 2.516 | 7.514 | 49 | 875 | 1.748 | 2.985 | 0.585 | 77 |
| 741 | 26.152 | 2.561 | 10.211 | 22 | 543 | 17.658 | 2.576 | 6.856 | 50 | 876 | 1.732 | 2.982 | 0.581 | 78 |
| 841 | 25.956 | 2.543 | 10.205 | 23 | 643 | 17.642 | 2.577 | 6.846 | 51 | 965 | 1.652 | 2.983 | 0.554 | 79 |
| 941 | 25.799 | 2.553 | 10.103 | 24 | 743 | 17.571 | 2.581 | 6.807 | 52 | 975 | 1.581 | 2.983 | 0.530 | 80 |
| 651 | 24.176 | 2.555 | 9.463 | 25 | 843 | 17.375 | 2.563 | 6.779 | 53 | 976 | 1.565 | 2.982 | 0.525 | 81 |
| 761 | 24.089 | 2.558 | 9.415 | 26 | 943 | 17.208 | 2.568 | 6.701 | 54 | 985 | 1.385 | 2.983 | 0.464 | 82 |
| 751 | 24.105 | 2.561 | 9.414 | 27 | 653 | 15.595 | 2.571 | 6.066 | 55 | 986 | 1.369 | 2.981 | 0.459 | 83 |
| 861 | 23.893 | 2.543 | 9.396 | 28 | 753 | 15.524 | 2.575 | 6.028 | 56 | 987 | 1.298 | 2.986 | 0.435 | 84 |

Table 4.8: Optimum index factor (OIF) of eighty four possible RGB color composite of VNIR and SWIR ASTER bands

64
| RGB     | $\sum_{j=1}^{3} | r_j |$ | $\sum_{k=1}^{3} S_k$ | OIF  | Rank |
|---------|----------------|----------------|-------|------|------|
| 14-13-12 | 9.344          | 2.986          | 3.129 | 1    |
| 14-13-11 | 9.232          | 2.987          | 3.090 | 2    |
| 14-13-10 | 9.060          | 2.987          | 3.033 | 3    |
| 13-12-11 | 9.028          | 2.998          | 3.011 | 4    |
| 14-12-11 | 8.942          | 2.986          | 2.994 | 5    |
| 13-12-10 | 8.856          | 2.998          | 2.954 | 6    |
| 14-12-10 | 8.771          | 2.986          | 2.937 | 7    |
| 13-11-10 | 8.744          | 2.998          | 2.916 | 8    |
| 12-11-10 | 8.659          | 2.987          | 2.899 | 9    |
| 14-11-11 | 8.455          | 2.999          | 2.819 | 10   |

Table 4.9: Optimum index factor (OIF) of ten possible RGB color composite of TIR ASTER bands
Figure 4.14: Display of the study area by Landsat color composite RGB 754
Figure 4.15: Display of the study area by Landsat color composite RGB 541
Figure 4.16: Display of the study area by ASTER color composite RGB 321
Figure 4.17: Display of the study area by ASTER color composite RGB 421
Figure 4.18: Display of the study area by TIR ASTER color composite RGB 14-13-12
Figure 4.19: Display of the study area by TIR ASTER color composite RGB 14-13-11
Figure 4.20: Display of the study area by TIR ASTER color composite RGB 14-13-10
4.3.3 Experimentation with different color composites

All the possible band color compositions of Landsat, VNIR, SWIR, and TIR ASTER data have been evaluated; the color composite image that creates the best color contrast between the igneous rocks and its surrounding materials were chosen as an appropriate band composite for this study area.

By visually inspecting all the possible Landsat band color composites, color composites of RGB 731 and 531 clearly highlighted the igneous rocks. It was noticeable that color composite of VNIR and SWIR ASTER RGB 421 and 621 are the best color composite for delineating the igneous rocks for that sensor array.

From all the possible Landsat and VNIR and SWIR ASTER color composite images, it was noticeable that igneous rocks are prominent when Landsat band 3 and ASTER band 2 is assigned as one of the fundamental colors. It can be inferred that igneous rocks have high reflectance in Landsat band 3 and ASTER band 2 (0.630-0.690 μm).

To determine which minerals cause the high reflectance in wavelength range of 0.630-0.690 μm, the spectral reflectance graphs (section 3.2) of minerals that generally compose igneous rocks were examined. Olivine, augite pyroxene and magnetite have highest reflectance in SWIR bands and lowest in NIR. The spectral reflectance of plagioclase feldspars (except anorthite) seems to increase in Landsat band 3 and ASTER band 2 (0.630-0.690 μm) starts to decrease in SWIR bands (ASTER band 6 and Landsat band 7). Consequently it is speculated that plagioclase feldspar crystals have high impact on the reflectance characteristics of igneous rocks.

Based on the visual evaluation of all the possible ASTER TIR color composite bands, color composite RGB 12-11-10, Figure 4.21, seems to be the best color composite combination to discriminate igneous rocks and other geological features. In this image the sandstone are
highlighted in dark brown and dark green colors, shale as yellow, igneous rocks as white and evaporates are highlighted as light pink.

Experimentation with different color composites, especially for satellites that have high spectral resolution, could be a tedious and time consuming task. The statistical techniques that were used in this study (Correlation Coefficient and Optimum Index Factor) proved to be useful for determining the best color composite images using VNIR and SWIR ASTER and Landsat bands. However, the statistical techniques were not as useful for TIR ASTER bands.

In general color composite is a simple and fast method to distinguish different rock types. This technique is especially useful for areas that not a lot of geological information is available. There may be some slight differences between different interpreters; since, the human eyes are not equally sensitive throughout the spectrum. However, to better understand and verify the results more rigorous methods and techniques need to be employed.
Figure 4.21: Display of the study area by TIR ASTER color composite RGB 12-11-10

4.4 Band ratio

Band ratio technique divides pixel values of one band with another band, to emphasize differences in the spectral reflectance of materials. Band ratio technique is useful for reducing the effect of illumination direct from the sun, topographic slope and shadows. The bands to be ratioed are determined based on the reflectance and absorption properties of the desired geological features. This method creates a greater contrast between the units, which will mitigate
the feature recognition (Sabins 1987). This technique has been widely used for mineral exploration.

To determine the best band ratio for delineating a geological feature, it is important to select bands in which the target geological feature has high value or vice versa, relative to their surrounding features. However, it is almost impossible to achieve this, especially in low spectral resolution satellite images, because of the spectral reflectance correlation of other minerals. Therefore it is important to examine different possible band ratios.

4.4.1 Literature review of band ratio

Numerous studies have verified the usefulness of ASTER to discriminate minerals and geological features. To delineate argillic and phyllic minerals using SWIR ASTER data Rowan and Mars (2003) developed band index of \((b4+b6)/b5\) and \((b4+b7)/b6\); Mars and Rowan use this index to map phyllic and argillic-altered rocks in the Zagros magmatic arc of Iran. Qari et al. (2008) use ASTER band ratio 4/8 and noticed that post-tectonic granite has a dark grey image signature and diorite has a bright image signature. They also use ASTER band ratio 6/8 and noticed that post-tectonic granites and acidic dykes have a dark image signature. Khan and Mahmood (2008) use OH bearing altered minerals index \((b7/b6) \times (b4/b6)\), developed by Ninomiya (2003), to discriminate solid rock components of ophiolite complexes and their structural relationship. ASTER satellite’s high spectral resolution provides a good opportunity for scientists to develop band ratios associated with discriminating different minerals. Some commonly used ASTER band ratios are summarized in Table 4.10.

Landsat band ratio technique has proven to be useful for discriminating different minerals and geological features. The most commonly used band ratios are Landsat band ratio of 3/1 and 5/7, which is utilized for hydrothermal altered rocks (e.g. Yazdi et al. 2010 and Sabins 1987).
Landsat band ratio 5/7 is a common ratio that is used for discriminating hydrothermal altered rocks. Clay/hydroxyl minerals have high reflectance in Landsat band 5 and absorption in band 7 (Mshiuh 2011). Sultan et al. (1987) uses this band ratio and notices that rocks such as coarse and fine grained granite and granite gneiss (mineral content similar to basalt and gabbro igneous rocks such as feldspar and pyroxene) have low value in the Landsat band ratio 5/7 image. Boettinger et al. (2008) uses normalized difference ratio of (5-2) / (5+2) Landsat bands and successfully distinguishes sedimentary rocks from igneous rocks.

Landsat band ratio 3/1 delineates the iron rich rocks, since iron minerals have maximum reflectance in Landsat band 3 (visible red light) and minimum reflectance in Landsat band 1 (visible blue light) (Rowan et al. 1977). Consequently, band ratio 3/1 can be used to map the iron altered minerals. This band ratio has been widely used for detecting iron altered zones. Yazdi et al. (2010) use Landsat band ratio of 3/1 to differentiate between iron alteration zones and those of unaltered rocks in the Siyah Bisheh area located in central part of Alborz zone. Elnaggar and Noller (2010) use Landsat band ration of 3/1 to distinguish iron altered zones from saline soils.

ASTER band ratio 2/1 is commonly used to delineate iron oxide bearing minerals. Shi et al. (2012) uses ASTER band ratio 2/1 to discriminate the iron oxide-rich rocks which showed high values in Kuga foreland basin, south Tian Shan. ASTER band ratio 2/1 was initially developed by Rowan and Mars (2003) to delineate ferric iron in Mountain Pass, California. Rajendran et al. (2011) also uses band ratio 2/1 to identify mafic-rich (Fe$^{3+}$) rocks formations of eastern mountain region (Saith Hatat window) of Sultanate of Oman.

Iron oxide-bearing minerals could help to delineate weathered pyroxene-bearing basalt rocks, since surface weathering on pyroxene-bearing basalt causes the formation of iron oxide-bearing minerals (Harding 1989).
Gabbro and basalt igneous rocks are categorized as mafic rocks. Generally mafic rocks have lower spectral reflectance than acidic, intermediate and ultramafic rocks; since, they have relatively high abundance of opaque minerals such as magnetite. Materials that have abundant opaque minerals should have high absorption in band 5 and high reflectance in band 1 (Sultan et al. 1987). This band ratio has also been used to highlight mafic igneous rocks for geological interpretations of central Madagascar (Inzana et al. 2003). Ninomiya et al (2005) develop indices for minerals related to volcanic rocks such as mafic index (MI) which uses ASTER TIR band ratio 12/13. Rajendran et al. (2011) uses MI index and notice that the ratio of the two bands increases as the rock type moves from a felsic to an ultramafic rock.

Most of the ratio images are used in as color composite ratio images for better display of target features. One of the most commonly used color composite ratio images is Landsat RGB 3/1, 5/7, and 5/4, this color composite ratio image is popular because they are known to be sensitive to lithologic variable and the band have least redundancy; they also best to discriminate the hydrothermally altered rocks.


Kusky et al. (2011) use ratio band combination of Landsat RGB 5/7, 3/1, 4/3 and 5/7, 5/1, 4 to delineate different rock types in northwestern desert of Egypt using Landsat bands. The color composite ratio images of Landsat RGB 5/7:5/1:4 have also been used by Kalelioglu et al. (2009) to identify compositionally different dykes in Central Anatolia, Turkey.
Aboelkhair et al. (2010) uses ASTER color composite ratio image of RGB b12/b13, b11/b12, b14/b13 separated albite granite in Central Eastern Desert of Egypt as pinkish magenta. van Der Meer et al. (2012) uses color composite ratio RGB (1+3)/2,(3+5)/4,(5+7)/6 to separate magnetite quartzite and associated lithologies of garnet-ferrous pyroxene granulite, hornblende biotite gneiss, amphibolites, dunite and pegmatite which showed good absorption features in ASTER bands 1,3,5, and 7.

Rajendran et al. (2011) use color composite ratio ASTER RGB 9/7 which highlights carbonates, 6/8 for quartz-rich silicates and band ratio 1/2 for mafic ophiolites; where the mafic-rich rocks were shown in purple.

4.4.2 Difference normalized index (DNI)

Based on the experimentation with different color composite and color composite statistical techniques used earlier in this study, it has been inferred that the igneous rocks of the study area have high reflectance in band 3 (0.630-0.690 µm) of Landsat and band 2 (0.630-0.690 µm) of ASTER.

It is speculated that the igneous rocks will have high value (bright signature) in Landsat band ratio of 3/5 and 3/7 and low value (dark signature) in Landsat band ratio of 5/3 and 7/3. After examining these band ratios it was determined that the igneous rocks are best discriminated in band ratio 5/3, Figure 4.22, where they have low value and dark signature. It can be inferred that study area’s igneous rocks have higher absorption in band 5 than band 7. To better highlight the igneous rocks, difference normalized index (DNI) has been developed using Landsat bands 5 and 3, equation 4.5, shown in Figure 4.23.

\[
DNI_{\text{igneourock}} = \frac{(b5 - b3)}{(b5 + b3)} \tag{4.5}
\]
Based on the above observations, study area’s igneous rocks have high reflectance in ASTER band 2 and low reflection in Landsat band 5 (1.550-1.750 μm). Landsat band 5 is between ASTER band 3 (0.760-0.860 μm) and ASTER band 4 (1.60-1.70 μm), therefore, ASTER band ratios 3/2 and 4/2 has been examined. Between the two igneous rocks band ratio 4/2, Figure 4.24, was determined to be a better band ratio image for discriminating igneous rocks. This band ratio creates a good contrast between the igneous rocks and its surrounding rocks; where, the igneous rocks have low values (dark signature). To better highlight the igneous rocks, difference normalized index (DNI) has been developed using ASTER bands 4 and 2, equation 4.6, shown in Figure 4.25.

\[
DNI_{\text{igneousrocks}} = \frac{(b4 - b2)}{(b4 + b2)}
\]  

(4.6)
Figure 4.22: Display of the study area by Landsat band ratio 5/3
Figure 4.23: Display of the study area by Landsat

$$DNI_{\text{igneous rocks}} = \frac{(b5 - b3)}{(b5 + b3)}$$
Figure 4.24: Display of the study area ASTER band ratio 4/2
Figure 4.25: Display of the study area ASTER $DNI_{\text{igneousrocks}} = \frac{(b4 - b2)}{(b4 + b2)}$
<table>
<thead>
<tr>
<th>Feature</th>
<th>Band ratio</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Iron</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferric iron, Fe3+</td>
<td>2/1</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Ferrous iron, Fe2+</td>
<td>5/3+1/2</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td>Laterite</td>
<td>4/5</td>
<td>Bierwith (2002)</td>
</tr>
<tr>
<td>Gossan</td>
<td>4/2</td>
<td>Volesky et al. (2003)</td>
</tr>
<tr>
<td>Ferric oxides</td>
<td>4/3</td>
<td></td>
</tr>
<tr>
<td><strong>Carbonates-mafic minerals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonate-chlorite-epidote</td>
<td>(7+9)/8</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td>Epidote-chlorite-amphibole</td>
<td>(6+9)/(7+8)</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Amphibole-MgOH</td>
<td>(6+9)/8</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Amphibole-MgOH</td>
<td>6/8</td>
<td>Bierwith (2002)</td>
</tr>
<tr>
<td>Dolomite</td>
<td>(6+8)/7</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td>Carbonate</td>
<td>13/14</td>
<td>Bierwith (2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ninomiya (2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td><strong>Silicates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sericite-muscovite-illite-smectite</td>
<td>(5+7)/6</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Alunite-kaolinite-pyrophyllite</td>
<td>(5+6)/5</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td>Phengite</td>
<td>5/6</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Muscovite</td>
<td>7/6</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>7/5</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Clay</td>
<td>(5×7)/6^2</td>
<td>Bierwith (2002)</td>
</tr>
<tr>
<td>Alteration</td>
<td>4/5</td>
<td>Volesky et al. (2003)</td>
</tr>
<tr>
<td>Host rock</td>
<td>5/6</td>
<td>Volesky et al. (2003)</td>
</tr>
<tr>
<td><strong>Silica</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz-rich rocks</td>
<td>14/12</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td>Basic degree index (garnet, clinopyroxene, epidote, chlorite)</td>
<td>12/13</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>SiO2</td>
<td>13/12</td>
<td>Rowan and Mars (2003)</td>
</tr>
<tr>
<td>SiO2</td>
<td>12/13</td>
<td>Ninomiya (2002)</td>
</tr>
<tr>
<td>Silica</td>
<td>11/10</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Silica</td>
<td>11/12</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
<tr>
<td>Silica</td>
<td>13/10</td>
<td>Hewson et al. (2001) (2004a)</td>
</tr>
</tbody>
</table>

Table 4.10: Commonly used ASTER band ratios
4.4.3 Color composite ratio (CCR)

Color Composite Ratio (CCR) is a technique that is used widely to better distinguish and analyse the ratio images. Color composite ratio images are produced by combining three ratioed images in blue, green, and red (Sabins 1987). This technique is commonly used after appropriate band ratios for delineating target features have been chosen.

The effectiveness of Landsat color composite ratio images to discriminate igneous rocks was examined. The Landsat normalized index which was developed to discriminate igneous rocks, equation 4.5, was used as one of the fundamental colors. The most useful color composite ratio for discriminating different igneous rocks and other geological features is color composite ratio image RGB (5-3) / (5+3), 1, 3/1, Figure 4.26. The sandstone is shown as light yellow, shale is highlighted as dark red and green, igneous rocks are shown in magenta color, and evaporates are highlighted as cyan to light green colors.

The ASTER normalized index for discriminating igneous rocks, equation 4.6, has been used as one of the fundamental colors. Also band ratio 2/1 used for highlighting the iron oxide bearing rocks were used as one of the fundamental colors of ASTER color composite image ratio. After experimenting with different possible color composite band ratios and ASTER bands; ASTER color composite ratio RGB (4-5) / (4+2), 3, 2/1, Figure 4.27 proved to be most appropriate for delineating different geological features such as igneous rocks. The sandstone is highlighted in light blue, shale is highlighted in orange and grey color and igneous rocks are highlighted as magenta and purple colors.

Color composite band ratio technique proved to be useful for reducing the effect of illumination direct from the sun, topographic slope and shadows. This technique also is useful for examining the mineralogy of the study area. However, to successfully use this technique for
discriminating different minerals, it is important to have a good knowledge of the study area’s mineralogy and their reflectance properties.

Figure 4.26: Display of study area using Landsat color composite ratio RGB (5-3)/(5+3), 1, 3/1
4.4.3 Estimate of SiO₂ weight percentage of the surface rocks

Changes in silicate minerals of rocks are useful for geological mapping, they can be used to classify and interpret igneous, sedimentary and metamorphic rocks. Various studies have illustrated that SiO₂ structure has a strong signature in thermal infrared (TIR) atmospheric
window (8-12 μm) (e.g. Watanabe and Matsuo, 2003; Ninomiya et al., 2005). For silicate minerals and rocks, the emissivity at band 12 to 13 for silicate rocks increases as the SiO₂ content decreases (Aaboelkhair et al. 2010). The relative SiO₂ content of various igneous rocks is displayed in Table 4.11 (Ninomiya and Fu 2010). Some scientists such as Ninomiya and Fu (2010) use mafic index (MI), ASTER TIR band ratio 12/13 index, to measure SiO₂ content of the minerals because of the inverse correlation of MI rocks with SiO₂, as MI increases, the silica content decreases and vice versa.

Metal Mining Agency of Japan (MMAJ, 2000) has proposed an equation 4.4.3 for estimating the SiO₂ weight percentage content of surface rocks using satellite images. This equation has been successfully used by many researchers (e.g. Watanabe and Matsuo, 2003; Keshri et al. 2008). SiO₂ content factor (K-value, equation 4.7) was first developed by MMAJ (2000) which was derived based on the empirical approach on a laboratory work on 194 samples including fresh and weathered rocks, and minerals. Then they found a good linear approximation between K-value and SiO₂ content of the sample rocks.

\[
SiO₂(\text{wt} \%) = 57.11 + 286.88 \times K
\]  

(4.7)

\[
K = -\log \left( \frac{E10 + E11 + E12}{3} \right) \frac{1}{E13}
\]  

(4.8)

Where, E10, E11, E12 and E13 is the emissivity for ASTER bands 10, 11, 12, and 13.

<table>
<thead>
<tr>
<th>Rock Category</th>
<th>Example rock type</th>
<th>SiO₂ Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felsic</td>
<td>Granite</td>
<td>High</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Diorite</td>
<td></td>
</tr>
<tr>
<td>Mafic</td>
<td>Gabbro</td>
<td></td>
</tr>
<tr>
<td>Ultramafic</td>
<td>Peridotite</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 4.11: Rock types and their SiO₂ content
The SiO$_2$ weight percentage of the surface rocks in the study area were measured using equation 4.8 and which is displayed on Figure 4.28. In this image the igneous rocks have dark signature, which means that they have low silica values relative to the sandstone and shale. By visually inspecting the image, it can be inferred that there is a clear distinction between different rock types of the study area. The sandstone has the lightest signatures in agreement with them having the highest SiO$_2$ weight percentage, shale is intermediate and igneous rocks have lowest SiO$_2$ weight percentage (dark signature).
Figure 4.28: SiO$_2$ weight percentages of the surface rocks of the study area estimated based on the MMAJ (2000) derived empirical model

4.6 Results and Analysis

By investigating the color composite and color composite ratio images, it can be inferred that the sun illumination effect and the shadow effect has been reduced using band ratioing technique. Color composite ratio technique using TIR ASTER bands was not as effective in reducing the
shadow and illumination effect compared to color composite using VNIR and SWIR bands of ASTER and Landsat.

ASTER proved to be more useful than Landsat in mapping surface minerals using band ratio technique. ASTER satellite thermal bands were especially effective for mapping the SiO$_2$ weight percentage of the surface rocks, which will help to determine the rock types based on their SiO$_2$ weight percentage.

In this study area, it is speculated that there are unmapped igneous rocks. These areas can be characterized as igneous rocks because they are in vicinity of other igneous rocks and have the same spectral characteristics as the mapped igneous rocks in all the remote sensing maps. The locations of these areas are illustrated in APPENDIX II.

Measurement of SiO$_2$ weight percentage of the surface rocks using TIR ASTER bands was determined to be an effective technique for delineating igneous rocks. The dominant chemical composition of most common rocks in the study area such as shale, sandstone and igneous rocks is SiO$_2$. The average SiO$_2$ composition of gabbro igneous rocks is 48.4%, the average composition of sandstone is 78.3% and average chemical composition of shale is 58.1% (Hurlbut and Klein 1993). By investigating the SiO$_2$ weight percentage images it can be concluded that the igneous rocks have the darkest signature (in other words, lowest values SiO$_2$ values).

To validate the effectiveness of the employed method for estimating the SiO$_2$ weight percentage of the basalt igneous rocks from the ASTER data, the average estimated SiO$_2$ weight percentage of all the basalt igneous rocks were compared with average calculated SiO$_2$ weight percentage of the SiO$_2$ from the study area.
The SiO$_2$ weight percentage of the basalt igneous rocks as calculated from the ASTER thermal bands tends to overestimate SiO$_2$ content of the basalt igneous rocks (by about 10%). The over estimation of SiO$_2$ weight percentage is consistent over the entire study area, where the SiO$_2$ weight percentage of the surface rocks increase from igneous rocks to shales and sandstone. A histogram of the estimated SiO$_2$ for basalt olivine is presented in Figure 4.6.11.

Figure 4.6.11: Estimated SiO$_2$ content of Basalt Igneous Rocks
CHAPTER 5
SPECTRAL CORRELATION OF GRAVITY AND MAGNETIC ANAMOLIES

Gravity and magnetic data have proven to be useful for mapping geological features, especially igneous rocks. Magnetic measures the susceptibility characteristics of a rock, which determines how magnetized that body can become in the presence of an external field. Gravity measures the variation in the density of a rock, which determines the gravity characteristics of that body. In order to discriminate an intrusive rock from its host rock using gravity and magnetic anomaly data, there should be an appropriate density and susceptibility contrast between the igneous rocks and their host rock (Pilkington et al. 2008).

Magnetic measurements, contrary to some other remotely sensed data, are less affected by surface materials such as water, ice and vegetation. Conversely, gravity measurements could be affected by surface materials such as ice, if they are thick enough, which could be corrected by simple correction (Pilkington and Keating 2009). The gravity and magnetic anomalies for Canada are freely available in gridded format for most of Canada (Pilkington et al. 2008).

Magnetic anomaly by itself is considered not accurate enough for mapping rock types. This is because surface magnetic anomaly provides information about the magnetic mineral concentration of surface rocks, but magnetic minerals are accessory composition of a rock and not used for lithologic classification. In addition, magnetic anomalies are highly sensitive to the underlying magnetic source distribution (Pilkington et al. 2008). The available gravity anomaly does not have a good survey resolution compared to magnetic data. In an attempt to minimize the limitations associated with gravity and magnetic data, they are often used in conjunction with each other.
Different approaches are utilized for interpretation of potential field data (gravity and magnetic). In this study, to remotely investigate the distribution of igneous rocks on western Axel Heiberg Island, spectral correlation of gravity and magnetic anomalies are evaluated. The intrusive rocks in Axel Heiberg Island mostly intrude shale, sandstone or occur in vicinity of salt domes. The exact density and susceptibility characteristics of these rocks in this study area are undetermined. However, to create a generalized lithologic correlation model an approximate average susceptibility and density of the shale, sandstone, salt and igneous rocks (gabbro and basalt) has been used which are presented in Table 5.1(Kearey et al. 2002 and Reynolds 1997).

**Table 5.1: Generalized lithologic correlation model in terms of gravity and magnetic anomalies**
5.1 Literature review

Yushan et al. (2011) use gravity and magnetic anomalies to delineate the magmatic intrusions in the Carboniferous strata of the Qinggelidi area, north-eastern Junggar Basin. They were able to map twenty three anomalies as basalts, diabases and andesite which had high density and strong magnetization. Shu-Ling et al. (2010) use gravity and magnetic data to map the distribution of igneous rocks in the South China Sea. They map the igneous rocks in the South China because they are known to have broad prospects for oil and gas exploration. Wang et al. (2011) apply high-pass filter technique to process gravity and aeromagnetic data and were able to differentiate granite intrusions, in southeastern Yunnan District, China, from surrounding geological bodies based on their variations in geophysical properties.

5.2 Data acquisition and processing

Gravity and magnetic anomalies for Canada are accessible for free on internet using the Geoscience Data Repository (GDR) from the website (http://gdr.nrcan.gc.ca). More information on the study area’s gravity and magnetic data and applied corrections are discussed in the following paragraph; which, is based on the metadata and information provided by the GDR (Pilkington et al. 2008).

5.2.1 Gravity data

Government of Canada started systematic gravity mapping in 1944 with data spacing of 1 km to over 20 km. In this study area the survey started in 1960-11-10 and lasted in 1987-07-31. Gravity data was acquired using relative gravimeters that measure changes in gravity from one place to another. This method was conducted with knowledge of the start and end point of gravity of a series of observations. The start and end points (the base stations) were established from the International Gravity Standardization Network 1971(IGSN71). Least squares adjustment to the
control stations were used to convert gravimeter readings to gravity observations. The datum that was used is NAD83 (Geological Survey of Canada, 2007).

The gravity data has been gridded by Government of Canada into data spacing of every 2 km. There are also several corrections that have to be taken into account for analysis. These corrections have been done by government of Canada which are as following:

*Theoretical Correction:*

The Earth is not a perfect sphere and it is about 20 km smaller from pole to pole than through the equator. Therefore, the force of gravity increases as it gets closer to the pole. The theoretical correction corrects for the lateral variation in density within the Earth using the following formula, equation 5.1.

\[
g_r = 978032.7(1.0 + 0.0053024\sin^2(\theta) - 0.0000058\sin^2(2\theta))
\]

where \(\theta\) is the latitude in degrees of the observation point and the effect of latitude is removed by subtracting the theoretical value of gravity from the observed values. The theoretical gravity is in milliGals \((10^{-5}\text{m}\cdot\text{s}^{-2})\) which is calculated from the Geodetic Reference System 1967 (GRS67).

*Bouguer and Free Air Correction:*

To correct for the mass and lateral variations in density on gravity, gravitational attraction of the slab of material between the observation point and the mean sea level is corrected as following formula, equation 5.2:
\[ BA = g_o - g_t + \left( \frac{\partial g}{\partial z} - 2\pi G \rho_c \right) h \]  
(5.2)

where \( g_o \) is observed gravity; and \( g_t \) is the theoretical gravity at the surface of the reference ellipsoid; and \( \frac{\partial g}{\partial z} \) is the average vertical gradient of gravity (0.3086 mGal·m\(^{-1}\)); and \( G \) is the gravitational constant 6.672 x 10\(^{-11}\) m\(^3\)·kg\(^{-1}\)·s\(^{-2}\) or 6.672 x 10\(^{-6}\) m\(^2\)·kg\(^{-1}\)·mGal; and \( \rho_c \) is the density of crustal rock 2670 kg m\(^{-3}\); and \( h \) is the elevation above sea level (m).

### 5.2.2 Magnetic data

Magnetic data has been collected through aeromagnetic surveys. The magnetic survey of Canada started in 1947 with a flight-line spacing of 800 m. However, in the areas of deep sedimentary basins, the flight-line spacing increased to more than 1600 m. Flight altitude of the aeromagnetic was 305 m above the ground and over mountainous areas the surveys were flown at a constant barometric altitude. They flowed an electrical current over the survey area which orbital of electrons in atoms create magnetic dipole, ancillary field proceed by aligned dipoles, \( M \), augments the magnetizing field, \( H \). \( M \) and \( H \) are related based on formula, \( M = kH \) where \( k \) is the magnetic susceptibility which is the measurement of how magnetized the body can become in the presence of an external field (Geological Survey of Canada, 2007).

In the study area the survey was conducted on 1970-01-01 and was finished on 1971-12-31 with a constant barometric altitude at flying height of 2743.0 m and control line spacing of 4828 m and traverse line spacing of 1609 m. The magnetic sensitivity of the instrument was at 0.0100 nT with visual navigation system. They acquired their data on NAD27 datum. Then the
survey data were re-gridded into finer grid cell size of 200 m and the following correction has been applied:

*Removed core field:*

Earth’s magnetic consists of core field, induced field and remanent field. Where core fields is generated by the dynamo effect of electric currents flowing in the Earth’s liquid core; induced magnetic field is magnetic susceptibility of the underlying rocks and remanent magnetization is a property of crustal rocks which produces a magnetic field. To obtain physical properties of the underlying rocks, the core field is removed by subtracting the international Geomagnetic Reference Field model from the core field.

*Reduced to the Pole (RTP):*

In general if the magnetic anomalies are not reduced to the pole (unless they are located at the pole) they tend to produce a “skewed” magnetic anomaly. To transform dipolar magnetic anomalies to monopolar anomalies centered over their contributory bodies. The reduced to the pole correction was applied to these data using the method described by Blakely (1995).

**5.3 Spectral correlation of gravity and magnetic anomalies**

Based on the lithological correlation model presented on Table 5.1, there is a close correlation between gravity and magnetic anomalies for different rock types. According to von Frese et al. (1997b) magnetization and density tend to increase as rocks become more mafic (iron-rich). In general, to obtain the correlation coefficient between two data \((X, Y)\) sets the following formula, equation 5.3, is used.

\[
CC(X,Y) = \frac{\sigma_{x,y}^2}{\sqrt{\sigma_x^2 \sigma_y^2}} \quad (5.3)
\]
\( \sigma_{x,y}^2 \) is the covariance between the two data sets.

The closer the value of CC is to 1 the more directly (positively) the two data sets are correlated; and the closer the CC value is to -1 the more inversely (or negatively) the two data sets are correlated. In data domain, when CC value is close to 0 it means that there is no correlation between the two data sets; however, this is not unique in terms of the feature correlations between data sets. CC value close to zero could mean that the variation in one signal is not matched by variations in the other signal (von Frese et al., 1997b, Bevington, 1969; Davis, 1986).

If each wave number is compared individually there could be correlation between the two individual wave numbers. In this study gravity and magnetic data sets are spectrally correlated to obtain better and more unique results.

von Frese et al. (1997b) proved the effectiveness of employed approach to analyse the spectral correlation of gravity and magnetic using three examples. The same approach has been used by von Frese et al. (1997b) to map out the possible dyke complex in northwestern Ohio. Ritis et al. (2010) uses the employed approach for spectral correlation analyses to map out the volcanic structures and intrusive bodies of the Sardinia eastern margin of the Tyrrhenian Sea.

Possoin’s theorem, equation 5.4, has been adopted for this study Figure 5.2. Possoin’s theorem uses the relationship between the first vertical derivatives of gravity data and reduced to the pole magnetic data, independent of the shape and position of the source, to calculate one correlation value sets (Chandler et al., 1981). Accordingly, FVD of gravity anomalies are correlated with RTP magnetic anomalies in this study.
The relationship between the first vertical derivative of the gravity ($\partial g/\partial z$) and reduced to the pole magnetic ($T_z$) potentials arising from a common, isolated source is shown by Poisson to be:

$$T_z = \frac{1}{G} \frac{\Delta m \partial g}{\Delta \sigma \partial z}$$  \hspace{1cm} (5.4)

where $G$ is universal gravitational constant, $\Delta m$ is the induced magnetization contrast of the source and $\Delta \sigma$ is the density contrast of the source (Chandler et al., 1981).

In order to make this approach effective it is required that the data sets to be estimated at common observation points (von Frese et al., 1997b and Ritis, 2010). First Vertical Derivative (FVD) of Gravity and Reduced to the Pole (RTP) of magnetic were co-registered at common grid coordinates.
To enhance the graphical presentation of the data sets and to facilitate the visual correlation analysis, the magnetic and gravity anomalies were normalized into the common mean and standard deviation (eg. von Frese et al. 1997b and Ritis 2010). The following formula, equation 5.5, is used to normalize the data into the same plotting parameters:

$$z_i(X) = \sigma_z \left( \frac{x_i - \mu_x}{\sigma_x} \right) + \mu_z$$  \hspace{1cm} (5.5)

where $z_i$ is the normalized data set; and $\mu_x$ and $\sigma_x$ are the mean and standard deviation of data set $X$ (it this study either gravity or magnetic), respectively and $X_i$ is the gridded amplitude. The $\mu_z$ and $\sigma_z$, can be specified by user, in this project the mean value was set to zero and standard deviation was set to ten; and to transfer the normalized data back into the original data set it is multiplied by normalization factor, equation 5.6.

$$NF = \left( \frac{\sigma_x}{\sigma_z} \right)$$  \hspace{1cm} (5.6)

To spectrally correlate the two data sets, correlation coefficient of the wavenumber of the two data sets is estimated. First they are converted into polar coordinate system using the equation 5.7 and equation 5.8:

$$\bar{X}(k) = |X(k)| \exp(-j \theta_{\bar{x}(k)})$$  \hspace{1cm} (5.7)

$$\bar{Y}(k) = |Y(k)| \exp(-j \theta_{\bar{y}(k)})$$  \hspace{1cm} (5.8)
where \( k \) is the wavenumber of FVD (X) and RTP magnetic anomalies (Y); and \( |X(k)| \) and \( |Y(k)| \) are magnitudes (amplitudes); and \( \theta_{F(k)} \) and \( \theta_{x(k)} \) are phase angles with phase difference of \( \Delta \theta_k = (\theta_{F(k)} - \theta_{x(k)}) \); and \( j = \sqrt{-1} \). Therefore their correlation spectrum is, equation 5.9:

\[
CC(k) = \cos(\Delta \theta_k)
\]  
(5.9)

In the spectral correlation, to decide which wavenumber to keep and which one to reject, correlation of the two data sets after filtering and standard deviation of each data set has been determined and graphed, Figure 5.3. First the positively and negatively correlated anomaly features are separated, by setting the filter values between 0.0 to 1.0 and 0.0 to -1.0 respectively. Then the minimum filter value increases by a value of 0.1 for positively correlated features and decreased the minimum filter value by same value for negatively correlated features.

By investigating the graph in Figure 5.3 it was noticeable that as the minimum value increases from 0.0 to 1.0 for the positively correlated features the correlation between the two data sets increases. However, when the filter value gets larger than 0.3, the standard deviation of the two data set start to decrease drastically. Same trend can be seen from the negatively correlated features. To not lose data and at the same time to keep the wave number correlation coefficients that have high correlation, it was decided to keep all the wavenumber correlated coefficients that are between 0.3 and 1.0 (for strongly positive correlated features) and -0.3 and -1.0 (for strongly negative correlated features).

As the results of the above procedures, four maps are produced, positively correlated gravity anomaly map Figure 5.4(a), positively correlated magnetic anomaly map, Figure 5.4(b),
negatively correlated gravity map Figure 5.4(c) and negatively correlated magnetic map Figure 5.4(d).

Figure 5.3: The left y-axis represents the standard deviation of gravity and magnetic anomalies after each step of filtering from 0.0 to 1 against the filter number values incrementing from 0.0 to 1; the right y-axis represents the correlation coefficient of the gravity and magnetic anomalies after each step of filtering from 0.0 to 1 against the filter number values incrementing from 0.0 to 1.
Figure 5.4: a) Gravity components that are positively correlated with magnetic anomalies 
b) Gravity components that are negatively correlated with magnetic anomalies 
c) Magnetic components that are positively correlated with gravity anomalies 
d) Magnetic components that are negatively correlated with gravity anomalies
To map out the positively correlated features the normalized outputs of the FVD gravity anomalies (X) and RTP magnetic anomalies (Y) were added point by point, which will result in summed local favorability indices (SLFI) in equation 5.10.

\[
SLFI_i = \frac{z_i(X) - \mu_X}{\sigma_X} + \frac{z_i(Y) - \mu_Y}{\sigma_Y} \quad \forall i = 1, 2, ..., m...
\] (5.10)

Generally when SLFI\_i is greater than zero, positive features between the two data sets that are correlative are mapped out, Figure 5.5(a), and when SLFI\_i is less than zero negative features that are correlative are mapped out Figure 5.5(b).

To map out the negative correlated features the normalized data sets are subtracted point-by-point according to the following formulas which will result in differenced local favorability indices (DLFI) equation 5.11:

\[
DLFI_i = \frac{z_i(X) - \mu_X}{\sigma_X} + \frac{z_i(Y) - \mu_Y}{\sigma_Y} \quad \forall i = 1, 2, ..., m...
\] (5.11)

Overall, when DLFI\_i is greater than zero, it means that features in first vertical gravity data (X) are positive and features in reduced to the pole magnetic (Y) are negative 5.5(c); and when DLFI\_i is less than zero, it means that features in reduced to the pole magnetic (Y) are positive and features in first vertical gravity (X) are negative Figure 5.5 (d).
Figure 5.5: a) Positive gravity and positive magnetic anomalies b) Negative gravity and negative magnetic anomalies c) Positive gravity and negative magnetic anomalies d) Negative magnetic and positive gravity anomalies
5.4 Results and analysis

The four filtered maps have been investigated and compared with the available geology map of the west of Axel Heiberg Island. Unfortunately, due to the poor resolution of the gravity data from this study area, the igneous rocks were not distinguishable using positively and negatively correlated gravity maps.

A pattern of positive and negative anomalies can be observed from the filtered inverse correlation of magnetic data with gravity map, Figure 5.6. It is speculated that this pattern is related to Sverdrup Basin.

Figure 5.6: Gridded map of magnetic components that are negatively correlated with gravity anomalies
Some of the igneous rocks were delineated using positively correlated magnetic map.

Figure 5.7(a) is the positively correlated magnetic map and the black polygons are the igneous rocks Figure 5.7(b).

Figure 5.7: a) Magnetic components that are positively correlated with gravity anomalies b) Magnetic components that are positively correlated with gravity anomalies which are overlaid by outline of igneous rocks and evaporates that are outlined from Harrison’s map’s
To separate the igneous rocks, using filtered (Correlation coefficient of 0.3-1) magnetic features that are directly correlated with gravity, strong positive features and strong negative features are separated and displayed in Figure 5.8(a) and Figure 5.8(b) respectively. In these maps the basalt igneous rocks are displayed in red outline, gabbro diabase igneous rocks are displayed in yellow outline and the evaporates are displayed in cyan color. In general the basalt igneous rocks are more likely to be detected, since they are thicker and the resolutions of the data sets are not coarse enough for thinner igneous rocks. By observing these maps it can be seen that some of the basalt igneous rocks are highlighted as positive features and some as negative features. It can also be observed that these anomalies do not show the exact shape of the igneous rocks and there is about 1 km offset with the outlined igneous rocks.

Most of the igneous rocks in the study area are surrounded by surface and subsurface evaporates. According to the correlation model Table 5.1 salt have low magnetic and low gravity characteristic. Therefore, it can be concluded that evaporates around the igneous rocks affected both gravity and magnetic data; and in some cases they cause the igneous rocks to be highlighted as negative magnetic features.

To separate igneous rocks from salt domes, the SLFI maps are used to separate positive and negative features that are positively correlated, Figure 5.9(a) and Figure 5.9(b) respectively. The thicker basalt igneous rocks are visible when SLFI is greater than zero, there are some areas which are highlighted as positive features and they are speculated to be unmapped igneous rocks.
Figure 5.8: a) Strong magnetic anomalies that are positively correlated with gravity anomalies; overlaid by igneous rocks (red and yellow outlines) and evaporate (cyan outlines) from Harrison’s map
Figure 5.8: b) Strong magnetic anomalies that are negatively correlated with gravity anomalies; which are overlaid by igneous rocks (red and yellow outlines) and evaporate (cyan outlines) from Harrison’s map

Some of the negative features present on SLFI map, Figure 5.9(b) includes the highlighted igneous rocks which could be because of the interference of evaporates with the potential data sets. Also there are negative features which are more pronounced on east of the study area and they are located mostly on the vicinity of the salt domes.

Overall some of the igneous rocks could be detected using the applied approach. The result maps were constrained by the low resolution of the gravity data. However, the general trend of where the igneous rocks get thinner and the salt becomes thicker can be observed from the Harrison’s cross section map, Figure 5.10.
Figure 5.9: a) Positive features from gravity and magnetic components that are positively correlated, SLFI $> 0$

Figure 5.9: b) Negative features from gravity and magnetic components that are positively correlated, SLFI $< 0$
CHAPTER 6

SPECTRAL CORRELATION OF MAGNETIC AND SILICA DATASETS

Integration of different data sources has proven to be an effective method for geological interpretation. The most effective data integration approach is using data sources that are independent yet able to some extent complete each other’s limitations. There are numerous data sources that are used in conjunction with each other for geological interpretation. For example, in the previous chapter gravity and magnetic anomalies have been used to delineate igneous rocks. In this chapter, correlation of magnetic and ASTER satellite imagery is employed to highlight the igneous rocks.

Magnetic data and employed satellite images, to some extent, can complete each other’s limitations. Magnetic anomalies, in contrary to satellite images, are not affected by surface materials such as water, ice and vegetation. On the other hand, combination of SiO$_2$ weight percentage from ASTER thermal bands and magnetic data can be effective, since lithological classifications are mainly based on silica composition of a rock (Pilkington et al. 2008).

Spectral correlation of magnetic anomalies and surface rock’s SiO$_2$ weight percentage has been employed to separate igneous rocks. The exact susceptibility and SiO$_2$ weight percentage characteristics of the study area’s rocks are undetermined. However, to create a generalized lithologic correlation model an approximate average susceptibility and SiO$_2$ weight percentage of the shale, sandstone, salt and igneous rocks (gabbro and basalt) has been used which are presented in Table 6.1 (Kearey et al. 2002, Reynolds 1997 and Hurlbut Jr. and C. Klein 1993).

In this study, estimated silica weight percentage of surface rocks using ASTER thermal bands and potential data are employed to separate geological features. Satellite imagery analyses
are often affected by surface cover, therefore geological features that are located in shadows, under vegetation and snow are not distinguishable. Potential data have also their own limitations; gravity data available for this study has a very low resolution and are insufficient for many analyses. Magnetic data provides information about the magnetic minerals concentration of surface rocks. Magnetic minerals are considered to be accessory minerals and not useful for lithological classification.

Table 6.1: Generalized lithologic correlation model between magnetic susceptibility and SiO₂ weight %

6.1 Literature review

Franklin (1988) proposed that remote sensing imagery analysis can be improved using ancillary digital data, such as magnetic anomaly and digital elevation model. To prove the effectiveness of data integration, Franklin presented two examples from vegetated and boreal areas for ecological
mapping and geological analysis. He was able to verify that classifying and interpretation of remote sensing imagery using ancillary data is more successful in geological mapping than analysis of remote sensing data sets alone.

Integration of ASTER images, Landsat images and magnetic data proves to be useful in identifying new kimberlite pipes in the Northern Cape Province of South Africa (Tessema et al. 2011). Schetselaar et al. (2000) stated that Landsat satellite images are insufficient to discriminate granite-gneiss terrain in areas with high vegetation cover. Therefore, they employ airborne gamma ray spectrometry and magnetic data to better classify the lithology. These data sets are chosen because they are not affected by surface cover. Integration of these datasets proved to improve lithological classification. Markandeyulu (2012) finds that integration of aeromagnetic and satellite imagery data helped analysis of structural fabric of the Gwalior Basin and delineating favourable loci of uranium mineralization.

6.2 Data acquisition and processing

Please refer to Chapter 5.2.2 for acquisition and preprocessing of magnetic data; and refer to Chapter 4.1 for ASTER thermal band data acquisition, preprocessing and also equation used for estimation of SiO$_2$ weight percentage of surface rock.

6.3 Spectral correlation of potential data

Based on the lithological correlation model presented on Table 6.1, there is an inverse correlation between magnetic data and SiO$_2$ weight percentage of surface rocks. The same approach that was used for spectral correlation analysis of gravity and magnetic is used for spectral correlation of magnetic and SiO$_2$ weight percentage of surface rocks.

First the data sets are co-registered and gridded to every 90 m, using minimum curvature gridding technique. Then to enhance the graphical presentation of the data sets and facilitate the
visual correlation analysis, the two data sets were normalized into the common mean and standard deviation. The same formulas and procedures have been applied for normalization of the two datasets.

To choose the right wavenumber correlation coefficients to filter, correlation of the two data sets after filtering and standard deviation of each data set has been determined and graphed and displayed in Figure 6.2. In this study, because there is an inverse correlation between the silica and magnetic of igneous rocks, negatively correlated anomaly features are separated, by setting the filter values between 0.0 to -1.0. Then the minimum filter value decreased by a value of 0.1.

![Figure 6.2](image)

**Figure 6.2**: The left y-axis is the standard deviation of magnetic anomalies and SiO₂ estimate of surface rocks after each step of filtering from 0.0 to -1 against the filter number values incrementing from 0.0 to -1; the right y-axis is the correlation coefficient of the magnetic anomalies and SiO₂ estimate after each step of filtering from 0.0 to -1 against the filter number values incrementing from 0.0 to -1

By examining the graph of Figure 6.2, it can be observed that there is no drastic change in correlation value as the filter value gets closer to -1.0. Therefore, no filter values were chosen
and the values between 0.0 and -1.0 are mapped. As a result two maps are produced, negative correlation silica map, Figure 6.3(a) and negatively correlation magnetic map Figure 6.3 (b).

Figure 6.3: (a) Silica weight percentage of the surface rocks that are negatively correlated with magnetic anomalies (b) Magnetic anomalies that are negatively correlated with silica weight percentage of the surface rocks
Same approach as chapter 5 is employed for separating the negative correlated features using differenced local favorability indices (DLFI). In this study because magnetic is high and silica weight percentage of the surface rocks is low for igneous rocks, when DLFI is greater than zero it means that features in magnetic are positive and features in silica are negative, which is presented in Figure 6.4.

![Figure 6.4: Positive features from the differenced local favorability indices of magnetic anomalies and silica weight percentage of surface rocks that are inversely correlated with each other, DLFI > 0](image)

6.3 Results and Analyses

Figure 6.5 summarizes the maps used for separating igneous rocks, using spectral correlation technique. Figure 6.5(a) displays the original data co-registered and gridded to every 90m. Figure 6.5(b) represents the normalized silica and magnetic data followed by Figure 6.5(c) which shows the filtered inverse correlated magnetic data and inverse correlated silica data. Figure 6.5(d) is the final map which segregated igneous rocks using DLFI equation.
Figure 6.5: (a) Co-registered gridded silica weight percentage of surface rocks and magnetic anomalies every 90 m

Figure 6.5: (b) Normalized (to common standard deviation) silica weight percentage of surface rocks and magnetic anomalies
Figure 6.5: (c) Silica weight percentage of surface rocks and magnetic anomalies after inverse correlated data filtered (0 to -1)

Figure 6.5: (d) This map represents the features that have high magnetic content and low silica content, DLFI map
Due to the low resolution of the input data (every 90 m for silica and every 200m for magnetic) only thicker igneous rocks specially the basalt olivine could be mapped. Most of the diabase and gabbro sills are not thick enough to be detected.

Using remote sensing techniques, it was inferred that there are five unmapped igneous rocks in the study area. Figure 6.6 displays the final produced map of igneous rocks derived from DLFI map; areas that are speculated to be unmapped igneous rocks and have not been noticeably highlighted in the satellite image are indicated by a red box. This map is same as Figure 6.5(d); however for better visualization the color scale has been changed.
Figure 6.3.7: DLFI Map with inferred unmapped igneous rocks indicated in red boxes
CHAPTER 7
CONCLUSION

7.0 Summary
In this study, image analysis techniques such as color composition and band ratio are employed to better interpret the geological features (mainly igneous rocks) and their mineralogy. These image analysis techniques were conducted using ArcGIS and ENVI software.

Color composite technique is a fast and easy technique for highlighting different geological features. The most appropriate bands to assign to RGB color composite image are chosen based on the bands in which the target geological feature (in this case igneous rocks) has the highest and lowest reflectance in.

The general reflectance properties of geological features are easily accessible online and are available at USGS (http://speclab.cr.usgs.gov/spectral-lib.html) and ASTER spectral library (http://speclib.jpl.nasa.gov/). The spectral reflectance property of a rock depends on its mineralogy, weathering, vegetation, and grain size, so the reflectance properties of the same rock type may not always be the same. Consequently, using the general reflectance of the same igneous rock types in the study area, was not very effective.

Statistical techniques such as correlation coefficient and optimum index factor (OIF) proved to be an effective technique for choosing suitable bands to map igneous rocks using color composite technique. Based on the experimentation with different possible band combination, it became apparent that the igneous rocks have the highest reflectance in Landsat band 3 and ASTER band 2. Band combinations of Landsat RGB 532 and ASTER RGB 421 were used to map the igneous rocks which were highlighted as green to dark green colors.
Band ratio technique minimizes the shadow and the effect of illumination from the sun. This technique is also useful for analyses of different mineralogy of the surface rocks of the study area. Different band ratios that are commonly used for highlighting minerals using ASTER and Landsat bands have been investigated. Since ASTER satellite has higher spectral resolution than Landsat, more band ratios are available for mineralogy mapping using ASTER bands.

Based on the earlier postulation, that study area’s igneous rocks have highest reflectance in Landsat band 3 and ASTER band 2, to better distinguish igneous rocks, difference normalized index (DNI) were developed. Igneous rocks, relative to the earlier adopted band ratios, were highlighted well using developed DNI for both ASTER and Landsat.

Using DNI and band ratios Landsat 3/1 and 2/1 result maps proved to be effective for color composite ratio maps. ASTER color composite ratio RGB (4-5) / (4+2), 3, 2/1 and Landsat color composite ratio image RGB (5-3) / (5+3), 1, 3/, highlight the igneous rocks as magenta color and reduced the shadow and illumination effect.

Metal Mining Agency of Japan (2000) developed an equation for estimating the SiO$_2$ weight percentage of the surface rocks, using ASTER thermal bands. In this study this equation has been adopted for estimating the SiO$_2$ weight percentage of the surface rocks of the study area. This equation classifies different rock types based on their silica content. However, based on the comparison of the estimated SiO$_2$ and measured rocks samples, the silica content of the rocks are over estimated by about 10%.

Using introduced image enhancement techniques, five unmapped areas of igneous rocks were mapped using the employed image enhancement techniques. To better analyse and
introduce more robust technique for separating igneous rocks, potential data (magnetic and gravity) have been employed.

This study also evaluated the possibility of mapping the igneous rocks using potential data. Spectral correlation approach has been taken, since it is considered to be more precise in identifying the correlation between the two data sets. This technique was constrained by the low resolution of the gravity data (every 2km). However, this approached revealed the trend of the thickness of igneous rocks over the study area.

Magnetic data reveals the magnetite content of a rock, which is one of the limitations associated with using magnetic data alone for lithological classification. Therefore, this project proposed the technique of spectrally correlating estimated silica content of surface rocks using ASTER satellite thermal band and magnetic data. This technique proved to be more effective than remote sensing technique and spectral correlation of gravity and magnetic.

7.2 Future work

Proposed remote predicting mapping techniques can be used to map other unmapped igneous rocks of high Arctic and improve the available geological maps. The existing geological maps did not map the distribution of igneous rocks. This hampers the understanding of the geological history and petroleum prospectively of the area. One of the limitations associated with this project is that not all the utilized remote predictive mapping techniques were able to delineate the smaller sized igneous rocks. For future work, the input data resolution could be improved using data fusion to improve the resolution of the data. It is speculated that improving the resolution of the input data sets can improve the accuracy of the result maps. Other possible techniques that can be applied is to spectrally correlate DEM values with magnetic anomalies, since Igneous rocks are located at higher elevations.
It is speculated that the result maps from the inverse correlated magnetic data with gravity showing the rift axis of Sverdrup basin. To further investigate and prove the speculation that the filtered spectral magnetic anomalies that are inversely correlated with gravity, can detect the rift axis of Sverdrup basin the spectral correlated approach should be applied over other areas of Sverdrup basin.

The data sets can be used for further analyse the geological features, for example other ASTER band ratios can be applied for more mineralogical analysis of surface rocks. The available data sets can be used for other geological analysis such as how far the igneous rocks are transferred relative to their original source.

One of the major limitations with of this thesis is that, we did not have an accurate data to evaluate the exact accuracy of our results. The purpose of this project was to evaluate the available datasets and techniques to map the igneous rocks on Axel Heiberg Island. For future work it is required to travel to Axel Heiberg Island and gather the location (latitude, longitude, and elevation), mineral content, weather condition of sample igneous rocks on.

7.3 Conclusion
Using statistical techniques such as correlation coefficient and optimum index factor proved to be effective to highlight the igneous rocks on Axel Heiberg Island. From the experimentation with different color combination, it was inferred that the study area’s igneous rocks have highest reflectance in Landsat band 3 and ASTER band 2.

By visually inspecting the igneous rocks in the study area it can be inferred that not all the igneous rocks have the same mineralogy. Also it was revealed that some smaller sized igneous rocks have not been mapped.
Band ratioing proved to be an effective technique for reducing the shadow and illumination effect and better highlighting the igneous rocks. An equation for estimating silica content of the surface rocks developed by Metal Mining Agency of Japan (2000) proved to be effective for classifying igneous rocks. However because of the low resolution it failed to detect thinner and smaller igneous rocks.

Spectral correlation of gravity and magnetic data was not very useful for separating igneous rocks, however under surface thickness trend of igneous rocks and salt domes was revealed using this technique. It was concluded that the igneous rocks in the study get thinner towards east.

Spectral correlation of satellite image and potential data reduces the ambiguities that are associated with each data set. The magnetic data and silica content of surface rock were spectrally correlated and proved to improve to be more effective than remote sensing techniques and spectral correlation of gravity and magnetic for delineating the igneous rocks.

Overall Landsat and ASTER satellite both were useful for mapping igneous rocks. Landsat is useful for visual interpretation of geological features and ASTER is useful for mineralogy mapping.

The available gravity data (with resolution of every 2 km) is not useful for regional mapping. However, magnetic data in correlation with satellite image proved to be useful for mapping igneous rocks.
REFERENCES


Embry, A.F. & Klovan, J.E. 1976. The Middle-Upper Devonian Clastic Wedge of the

Volcanism, Queen Charlotte Islands, Arctic Archipelago. *Canadian Journal of Earth
Sciences*, 25: 1209-1219


of geology of Innuitian Orogen and Arctic Platform of Canada and Greenland h.p. Trettin


Gentzis, T. & Goodarzi, F. 1993. Thermal Maturity and Source-Rock Potential of the
Sedimentary Succession from the Drake Field, Sverdrup Basin, Arctic Canada. *Journal of
Petroleum Geology*, 16(1): 33-54


Koerner R.M. 1979, Accumulation, Ablation, and Oxygen Isotope Variations on the Queen Elizabeth Islands Ice Caps, Canada. *Journal of Glaciology*, 22(86):25-41


Metal Mining Agency of Japan, 2000. Annual report


Ninomiya, Y. & Fu, B. 2008. Regional Scale Lithologic Mapping in Western Tibet Using ASTER Thermal Infrared Multispectral data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science, 38:454-458*


Springer, Berlin, p. 363


Ross, H.P., Adler, J.E.M. & Hunt G.R. 1969. A Statistical Analysis of the Reflectance of Igneous Rocks from 0.2 to 2.65 µm. ICARIS, 11:46-54


