

**BASEMENT CONFIGURATION AND TECTONIC
EVOLUTION IN ABU TUMAYAM TROUGH
WESTERN SIRT BASIN USING INTEGRATED
APPLICATION OF POTENTIAL FIELD AND
SEISMIC DATA**

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by

ESHANIBLI ABDELHAKIM S RAJAB

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LIST OF SYMBOLS

a	acceleration
F	Force
m	mass
°	Degrees for distance measurement (1° ~ 111 km)
P₁, and p₂	Monopoles
r	Distance
R_E	Radius
ρ	Bulk density

LIST OF ABBREVIATIONS

AHAS	Al Haruj al Aswad Sub-volcanic
AHBS	Al Haruj al Abyad Sub-volcanic
AHVP	Al Haruj Volcanic Province
AMMP	African Magnetic Mapping Project
AS	Analytical Signal
CET	Centre for Exploration Targeting
E	East
ED	Edge Detection
ENE	East-North- East
FFT	Fast Fourier Transform
Fm	Formation
GMT	Generic Mapping Tools
GPR	Ground Penetrating Radar
HCG	Hydrocarbon Generated
HD	Horizontal Derivative
HG	Horizontal Gradient
HI	Hydrogen Index
HI _{org}	Hydrogen Index Original
HI _{pr}	Hydrogen Index of Present Day
HZ	Hertz
IGRF	International Geomagnetic Reference Field
IP	Induced Polarization
Km	kilometer

Km ²	Square Kilometer
LGP	Libyan Gravity Project
m	meter
mGal	Milli gal
ms	Milliseconds
my	Million years
N	North
NE	North-East
NNE	North-North-East
NNW	North-North-West
NOC	National Oil Corporation
nT	Nano Tesla
NW	North-West
PRC	Petroleum Research Center
RTP	Reduction to the Pole
S	South
SE	South-East
SEG Y	The Society of Exploration Geophysicist Y Format
SI	Structural Index
SP	Spontaneous Potential
SPI	Source Parameter Imaging
SSE	South-South- East
SSW	South-South- West
SW	South-West
TA	Theta Derivative

TAD	Tilt Angle Derivative
THG	Total Horizontal Gradient
TMI	Total Magnetic Intensity
TOC	Total Organic Content
TR	Transformation Ratio
TVP	Tibesti Volcanic Province
TWT	Tow Way Time
UC	Upward Continuation
UTM	Universal Transverse Mercator
W	West
WGS	World Geodetic System
WSW	West- South- South

**TATARAJAH DASAR DAN EVOLUSI TEKTONIK DI JURANG ABU
TUMAYAM, BAHAGIAN BARAT LEMBANGAN SIRT, MENGGUNAKAN
APLIKASI BERSEPADU KAEDAH MEDAN KEUPAYAAN DAN DATA
SEISMIK**

ABSTRAK

Kawasan kajian ini dikenali sebagai jurang Abu Tumayam di bahagian barat lembangan Sirt, timur laut Libya. Tatarajah dasar dan evolusi tektonik jurang Abu Tumayam telah ditafsirkan menggunakan data medan keupayaan (graviti dan magnetik) serta data seismik 2D untuk menyokong operasi penerokaan. Data graviti dan magnetik telah dianalisis menggunakan penuras laluan tinggi, kecerunan mendatar total, analisis grid CET, terbitan theta, pengimejan parameter sumber (SPI), dekonvolusi Euler, pemodelan songsangan GM-SYS, dan dekonvolusi Werner. Kajian ini menggunakan sismik 2D dan data telaga untuk menjana model subpermukaan yang tepat dan boleh dipercayai. Anomali graviti bouguer dan anomali graviti bouguer sisa di jurang Abu Tumayam menunjukkan kawasan tengah mempunyai nilai anomali graviti yang rendah masing-masing antara -52 hingga -7 mGal dan -26 hingga 18 mGal, manakala keamatan magnetik total (TMI) dan penurunan ke kutub mempunyai nilai anomali tertinggi iaitu 320 nT di pelbagai kawasan. Peta penurunan ke kutub (RTP) mempunyai nilai anomali tertinggi iaitu 405 nT di kawasan timur. Daripada data graviti dan magnetik, kesemua analisis seperti Kecerunan Mendatar Total, analisis grid CET, Terbitan Theta, dan dekonvolusi Euler menunjukkan sesar yang berarah NW-SE, NE-SW, NNW-SSE, ENE-WSW, dan N-S. Kedalaman berbeza dari 350 m hingga lebih 5200 m untuk data graviti dan dari 500 m hingga lebih 6,000 m

untuk data magnetik. Kedalaman dasar jurang Abu Tumayam adalah 5400-5900 m, menurut songsangan SPI dan GM-SYS data graviti dan magnetik. Songsangan data graviti memberikan anggaran ketumpatan yang berbeza bagi deposit klastik pra-Atas Kapur, sedimen peringkat rendah, syal pertengahan, dan tahap sedimen lebih tinggi. Sedimen klastik pada lapisan teratas mempunyai ketumpatan 2.39-2.42 g/cc. Di pusat mendapan jurang Abu Tumayam, sedimen syal pertengahan kaya dengan syal dan mempunyai ketumpatan 2.58 hingga 2.62 g/cc. Lapisan terakhir adalah sedimen klastik atas yang mempunyai ketumpatan 2.42–2.49 g/cc. Anggaran ini merangkumi kedalaman dan ketebalan sedimen klastik pra-Atas Kapur. Sedimen klastik rendah adalah pada 3800-5300 m, syal pertengahan pada 3550-4900 m, dan lebih tinggi pada 3100–4400 m. Lapisan klastik rendah, pertengahan, dan atas adalah masing-masing pada 90-420 m, 110-560 m, dan 130-580 m. Dekonvolusi Werner mendedahkan bahawa intrusi igneus pada kedalaman 5067 m dan 5540 m masing-masing menembusi jurang Abu Tumayam dan Gerad Graben. Profil pemodelan ke hadapan GM-SYS seismik 2D mengesahkan sesar dalam jujukan sedimen. Garis sismik 2D menunjukkan penebalan jujukan pra-Atas Kapur di sekitar pusat mendapan jurang serta lapisan pertumbuhan di sekitar sesar. Pemodelan penilaian laluan layar menunjukkan minyak naik pada sesar jujukan sedimen. Isipadu hidrokarbon dan pengeluaran memberikan rizab 77% dan 1.1 bilion tong hidrokarbon.

**BASEMENT CONFIGURATION AND TECTONIC EVOLUTION IN ABU
TUMAYAM TROUGH WESTERN SIRT BASIN USING INTEGRATED
APPLICATION OF POTENTIAL FIELD AND SEISMIC DATA**

ABSTRACT

The study area is called Abu Tumayam trough in the western Sirt basin, northeastern Libya. The Abu Tumayam Trough's basement configuration and tectonic evolution have been interpreted using potential field (gravity and magnetic) and 2D seismic data to support exploration operations. Gravity and magnetic data have been analysed using high-pass filters, total horizontal gradients, CET grid analysis, theta derivatives, source parameter imaging (SPI), Euler deconvolution, GM-SYS inversion modelling, and Werner deconvolution. This study utilised 2D seismic lines and well data to generate accurate and reliable subsurface models. The bouguer gravity and residual bouguer gravity anomaly of the Abu Tumayam trough show a central region have low gravity anomaly values ranging from -52 to -7 mGal and -26 to 18 mGal, respectively, while the total magnetic intensity (TMI) and reduction to the pole had the highest anomaly value of 320 nT in various regions. The reduction to the pole map (RTP) had the highest anomaly value of 405 nT in the eastern region. According to gravity and magnetic data, the Total Horizontal Gradient, CET grid analysis, Theta Derivative, and Euler deconvolution all show faults trending NW-SE, NE-SW, NNW-SSE, ENE-WSW, and N-S. The depths range from 350 m to over 5200 m for gravity data and from 500 m to over 6,000 m for magnetic data. The Abu Tumayam trough's basement depth is 5400-5900 m, according to SPI and GM-SYS gravity and magnetic data inversions. Gravity data inversions provide different density estimates for pre

Upper Cretaceous clastic deposits, lower, mid-shale, and higher sediment levels. Clastic sediments in the uppermost layer weigh 2.39-2.42 g/cc. In the depocenter of Abu Tumayam trough, mid-shale sediments are shale-rich and weigh 2.58 to 2.62 g/cc. The last layer is 2.42–2.49 g/cc upper clastic sediments. The estimates include pre-Upper Cretaceous clastic sediment depth and thickness. Lower clastic sediments are 3800-5300 m, mid-shale 3550-4900 m, and higher 3100–4400 m. The low, mid, and upper clastic strata are 90-420 m, 110-560 m, and 130-580 m respectively. The Werner deconvolution reveals that 5067 m and 5540 m igneous intrusions penetrated the Abu Tumayam Trough and Gerad Graben, respectively. The GM-SYS 2D seismic forward modelling profile confirmed faults in the sedimentary sequence. The 2D seismic lines show the thickening of the pre-Upper Cretaceous succession around the trough depocenter as well as the growth layers surrounding the faults. Play Fairway Evaluation modelling shows oil rising on sedimentary sequence faults. Hydrocarbon volume and the expulsion production yielded a 77% reserve and 1.1 billion barrels of hydrocarbon.

CHAPTER 1

INTRODUCTION

1.1 Background

The study area is located in the western part of the Sirt basin, which is called Abu Tumayam. The Sirt basin is among the most significant basins in North Africa in terms of hydrocarbon production since the 1950s. To develop the oil and gas sector and its hydrocarbon resources, it is critical to understand the basement configuration, faulting, and tectonic development of the studied area. The basement configuration indicates the structural structure of the crystalline basement rocks underlying the area of study, which is important because it influences the overlying sedimentary strata in which hydrocarbons may be trapped. In addition, the fault system Faults play a key role in hydrocarbon exploration. which can act as conduits for hydrocarbon migration or as traps where hydrocarbons accumulate; for instance, in the Sirt basin, some extensional faults have made structural traps hold vast quantities of hydrocarbons. Furthermore, Tectonic evolution includes continental drift, rifting, and collision, which form the Earth's crust. These processes greatly affect sedimentary basin formation and hydrocarbon potential.

The geophysical method plays an important role to identify the basement configuration, fault system, and tectonic evolution to add more information and understanding these subsurface structures. There are several geophysical approaches that have an 'operative' physical attribute to which the method is sensitive. Gravity, Magnetics, Seismic, Electromagnetics, Electrical Resistivity, Induced Polarization (IP), Spontaneous Potential (SP), and Ground Penetrating Radar (GPR) are some of

the geophysical techniques used to investigate the subsurface. This study has used three types of geophysical methods: gravity, magnetic, and 2D seismic data.

Gravity methods have a wide range of applications and used in numerous studies, including hydrocarbon exploration, detection of subsurface faults, voids, and cavities, locating salt domes, water table levels, buried valleys, determining glacier thickness, tidal oscillations, the shape of the earth and isostatic compensation, and locating geothermal heat sources. Magnetic or geomagnetic methods are used to detect changes in the rocks' magnetic susceptibility (the amount to which they can be magnetised in a magnetic field). It is passive and non-destructive, like the gravity approach. Many research have utilised the magnetic method to investigate the underground metallic items such as pipelines, cables, hazardous waste metal drums, and hidden mineshafts. Gravity and magnetic methods assess Earth's potential fields (gravitational and magnetic). These are the oldest techniques used in subsurface exploration, mining, and environmental investigations. Gravity and magnetic methods are often used in subsurface exploration. Density affects gravity, whereas magnetic susceptibility controls magnetic variation. Magnetic fields are unstable and sensitive to space and time changes, unlike gravitational fields (Pantelis et al., 2016). The densities and susceptibilities of rocks vary (e.g., the order of four or five). Magnetic susceptibility varies between and between rock types. Magnetic techniques are ineffective. Gravity interpretations disclose rock density changes, whereas magnetic interpretations indicate contributing processes. Magnetic anomalies may be induced or remanent.

Seismic surveying is the most significant geophysical exploration tool for identifying large-to small-scale subsurface features. The seismic method uses an

energy source to probe the ground and measures the subsurface reactions to the transmitted energy to estimate the forms and physical features of the Earth's subterranean layers (Mondol, 2010). Reflection seismic is the most commonly employed approach in hydrocarbon exploration. This approach generates 2D or 3D subsurface images (Yilmaz 2001). Subsurface seismic pictures are obtained by analysing the earth's "seismic waves" (Mondol, 2010). Different rock densities and velocities reflect waves, exposing what's underneath (Milligan, 2004). During exploratory surveys, an airgun, vibrator, or dynamite produces seismic pulses. For terrestrial seismic studies, a vibrator and dynamite are used. Site, rock type, imaging depth, and source affect seismic pulse strength (Yilmaz 2001).

Geologically, Libya is situated on the northern edge of the African shield, positioned between the stable craton to the south and the active Mediterranean (formerly Tethys) area to the north. The geological formation of Libya is principally linked to the Paleozoic basins in the central Sahara, despite the substantial influence of the late Mesozoic and Tertiary rifts in the eastern Mediterranean (Klitzsch, 1996). Several significant tectonic events shaped Libya's structural and stratigraphic history, including folding and compaction in the Precambrian, the creation of a NW-SE trending fault system during the Cambrian, and the evolution of regional highs and lows during the Silurian and Devonian. Late Paleozoic and early Mesozoic structural trends shifted WNW-ESE (Thomas, 1995). The Pan-African orogeny transpired during the Proterozoic era, around 650 to 540 million years ago, followed by a thermal sag that remobilised extensive regions of pre-existing crust (Hallett and Clark-Lowes 2016).

The late Pan-African orogeny in Libya created a number of broad NW-SE to N-S troughs and horsts, including the Tripoli-Tibesti Arch, the Murzuq-Jadu Trough, and the Timboka Arch, which affected the depositional system during the early Palaeozoic and later structural development (Gumati and Kanes, 1985). During the upper Silurian, several collision events occurred, such as the Baltica and Laurentia, which generated the Caledonian orogeny (Hammuda et al. 1985). During the mid-Devonian, a small movement occurred within Murzuq Basin (Gumati and Nairn, 1991). Gondwana-Laurussian contact in mid-Carboniferous triggered Hercynian orogeny (Hallett and Clark-Lowes 2016).

In Libya, during the end of the Carboniferous, the Hercynian orogeny introduced E-W and NW-SE structural trends, including prominent arches and troughs (Hallett, 2002). According to Sutcliffe et al. (2000), magmatic evidence in Libya provides some proof of the early Permian period as well as the Mid-late Permian basalts and late Permian granite found offshore and on the Waddan Platform. Triassic rift grabens in Tunisia and Libya, such as the Maragh trough, are filled with Triassic sediments, indicating that the breakup of Pangaea began during this time period (Brenchley et al., 1994). Tensional faults and unconformities in Triassic sequences may indicate the earliest deposits of Syn-rift grabens in north Libya, such as in the eastern Sirt Basin (Hallett and Clark-Lowes 2016). Geophysical and field data show that the upper Mesozoic rifting stage of the North African basement included abortive rifts south of the continental edge (Guiraud and Bosworth, 1999; Craig et al., 2008). Carr (2003) proposed that the Sirt basin collapse was caused by upper Cretaceous regional high subsidence, which can be observed in the Atlas highlands as well as Libya's Ghadames, Murzuq, Tripolitania, and Kufrah basins (Figure 2.3). The Tethys domain, extending from North Libya to the south of the Aegean Sea, began to close in

the mid-Cretaceous due to a shift in the African plate's motion towards Europe (Stampfli, 2000; Zouaghi et al., 2005). This movement is likely due to the operation of various sub-plates within the African domain (Fairhead et al., 2013). According to Hallett (2002), a line of convergence between two sub-plates spans from the Benue Graben within Nigeria to the Tibesti Plateau in Libya.

In Libya, the early Tertiary was characterised by the uplifting and elimination of marine environments in western Libya, as well as light subsidence over older Cretaceous grabens within the Sirt Basin (Dercourt et al. 1986). The direction of movement of the African plate has been briefly changed during the Oligocene, which caused subsidence activity within Libya, such as the subsidence within Hon Graben (Wilson et al. 1998). Libya's major event is the Sirt trans-extensional movement and sub-plate variations related to the African rift system. Subsidence occurred in three primary directions: NNW, NNE, and E, creating significant depocenters such as the Ajdabiya and Abu Tumayam troughs. Libyan basement structures originate from Pan-African and Palaeozoic features that trend NE-SW to ENE-WSW and slope gently to the SE (Coward and Ries, 2003).

The Sirt basin covers around 500,000 km² and has a triple junction rift in northern Africa (Ahlbrandt, 2001). The study region includes two troughs, Zallah trough and the Abu Tumayam trough, both of which are situated in the western Sirt basin. The region has attracted various oil and gas companies, including Waha Oil Company and Harouge Oil Operation, to investigate and drill multiple oil and gas wells for production. The Sirt basin is structurally complex because multiple tectonic events contributed to its development (Finetti, 1985; Hallett, 1996).

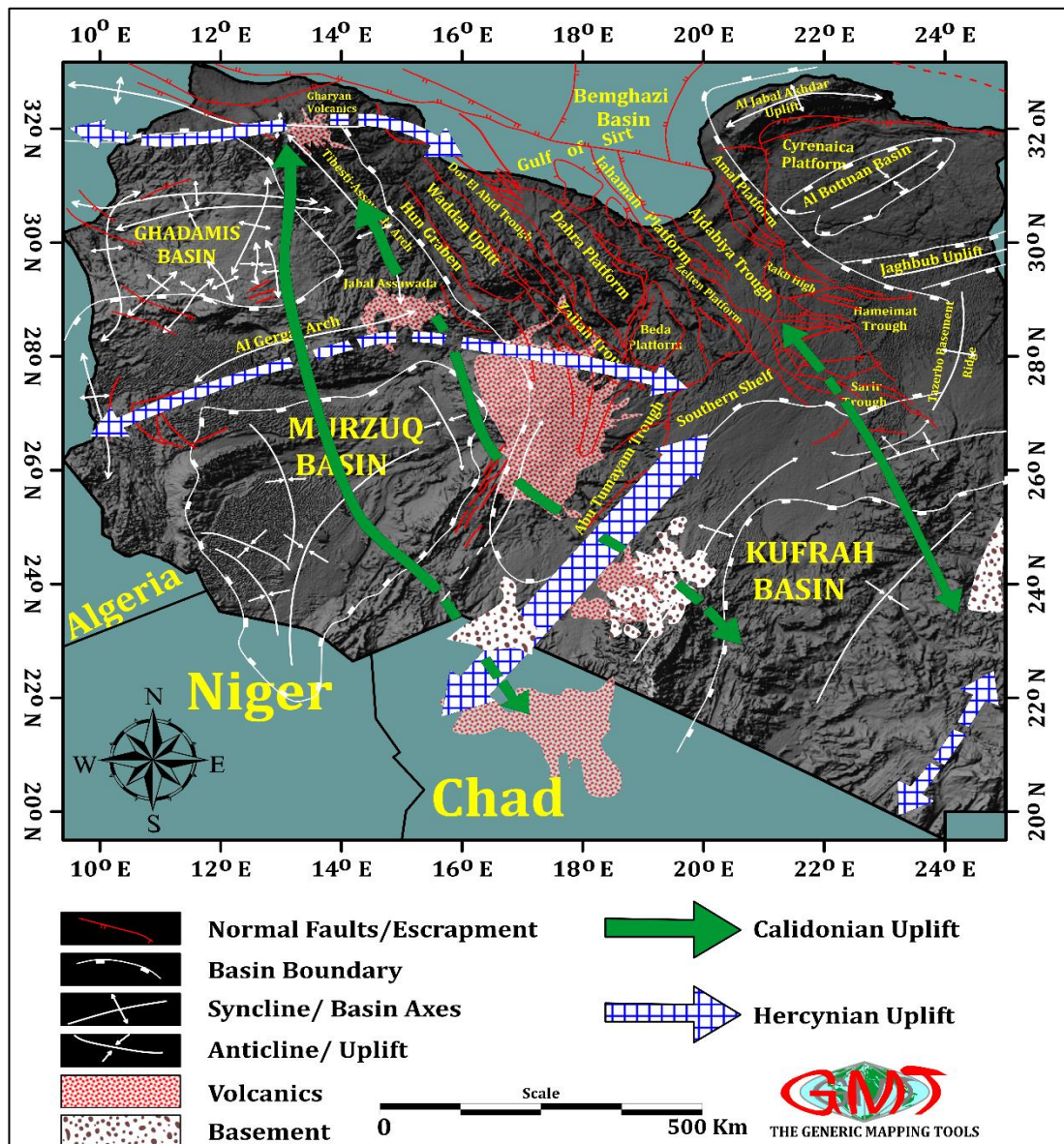


Figure 1.1 Shaded topography map superimposed by tectonic elements that distributed within Libya.

The results of this study will depend on many factors, such as the quality and coverage of the data, as well as the type of the geological structure. Several writers have conducted investigations in the vicinity and surrounding areas.

1.2 Problem statement

The Sirt basin has been an active exploration area for over fifty years, leading to the discovery of numerous oil and gas-producing fields within a sequence of sedimentary layers ranging in age from the lower Cretaceous to the Eocene. These discoveries have presented numerous challenges, such as comprehending the methods of trap formation, their structural and sedimentary nature, and their evolution over the geological age, which spans more than 130 million years.

The prevailing comprehension of the Sirt Basin's structure and stratigraphy mostly relies on disjointed seismic investigations and a restricted quantity of exploratory drilling operations performed inside the basin. The Abu Tumayam trough was poorly explored by National Oil corporation and other international companies due to the complexity of the subsurface structures, basement depth as well as the volcanic intrusions bodies the distributed beneath the trough. The drilling operations have faced some igneous intrusions that caused the pending of the drilling operations.

Furthermore, the drilling and geochemical studies in Gerad Graben, north of the study area, have revealed the presence of complete Lower Cretaceous sequences that are 3000 feet thick, as well as a well-known shale bed from the Mid-Lower Cretaceous (Mid Nubian Shale) that is more than 300 feet thick. Well NTF-51, operated by Harouge Oil Operations Company, was used as a reference point for this study.

1.3 Research objectives

This study will focus on the configuration of deep structures, such as basements and deep fault systems, that arose from several tectonic events in the Sirt basin (pre-

rift, post-rift, and syn-rift). Libya's four producing basins are still in the early phases of exploration owing to (1) low well density in various probable sites and (2) only a few wells having reached credible deep targets in several large regions, often basin centres. The Abu Tumayam troughs are two of these locations of extraordinary promise. Because of its proximity to the Al Haruj Al Swad volcanic mountains, this research will investigate the consequences of volcanic activity in the region. Both extensional and compressional tectonic movements have influenced the region surrounding the Abu Tumayam Troughs; however, it is unknown when or how the tectonic movements affected sedimentation. The thesis will elaborate on these points. Given the aforementioned variables, the study's objectives are as follows:

- I. To characterize the tectonic framework and structural elements of the Abu Tumayam trough, focusing on fault systems, structural settings, and their depths.
- II. To evaluate the depth and morphology of the basement, including the extent of volcanic intrusions, characteristics of sediment infill, extraction of the sediment density boundary of the pre-upper Cretaceous clastic sediments, and mapping the possible deep source rock based on volume estimation and generated expulsion
- III. To construct a comprehensive play fairway and petroleum system model for the Abu Tumayam trough.

1.4 Scope and Limitations of this Research

The general theme of this work is that the Abu Tumayam trough comprise distinct domains of variable tectono-stratigraphic histories. The aim of this work is to

identify and describe the characteristics and histories of these domains. Tectonically, the whole Sirt Basin evolved in the time dimension through a set of stages which are fundamentally different in the northern and southern parts of the basin (Baird et al., 1996).

Within the limits of accessibility to data, this research is restricted to using only the available gravity, magnetic, and 2D seismic data from the Abu Tumayam Trough area. The research is inherently but minimally affected by some of the challenges mentioned in Section 2.3. However, data from the land gravity survey done by the Petroleum Research Center (PRC) while the aero magnetic data from the African Magnetic Mapping Project (AMMP) are expected to be of high quality. As well as the 2D seismic data was provided by Al Harouge Oil Operation Company. The quality and accuracy of the results are expected to improve due to the progress made in software and the introduction of the Global Positioning System (GPS). Recent advances in the techniques of analysing, processing and interpreting these data are expected to increase the reliability of the results.

1.5 Significance of the study

This integrated geological and geophysical study of the Abu Tumayam trough areas provides a new tectonic framework and the best refined depth-to-basement surface, derived from numerous wells, potential field and seismic data, and some geological references. The tectono-stratigraphic understanding of the study area will benefit most by concentrating our study on the Mesozoic-Cenozoic evolution of the troughs, including an assessment of how the deeper, rift-related structures may have influenced the post-rift strata. The main reason for this focus is that the seismic reflection images of the Mesozoic-Cenozoic section are generally of good quality, but

resolution possibly decreases significantly at greater depths because there are few wells that penetrate the Cretaceous and older sections. The results of this study should shed much needed light on the recent structural evolution and on the hydrocarbon exploration history of the western Sirt Basin area.

1.6 Thesis outline

The first chapter introduces the idea of geophysical methods and several techniques for exploring the subsurface, with particular emphasis on gravity, magnetic, and seismic methods. The problem statement is clearly defined, and the objectives are listed. The scope of this study is provided.

Chapter two provides a theory for both potential and seismic methods. Afterward, some previous works have been carried out on the surrounding Libya using potential field and seismic data. In addition to the previous work carried out within the Sirt basin of Libya and surrounding areas. Chapter two discusses the geology of Libya and the study area, in addition to the volcanic history of Al Haruj volcanic province.

Chapter three presents the methodology, which presents the process and analysis of the potential field and seismic data. Both datasets are analyzed using Oasis Montaj, Surfer software, and Petrel Schlumberger software. Oasis Montaj's GM-SYS profile modelling extension created a geologic model of the study region.

In chapter four, the interpreted data is provided. The results are shown in high-resolution images.

Chapter five discusses the findings and concludes this work. Recommendations for future studies in the area are provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Geophysical investigations generally require the measurement of some parameters on the surface of the earth in order to discern the internal distributions of physical properties beneath the earth's surface. These measurements are either of variations in the Earth's natural fields or of the introduction of an artificial source of energy. The gravity and magnetic methods of subsurface investigations are the earliest among the various geophysical methods, while the seismic method is considered one of the most important geophysical methods in oil and gas investigation. The theory of the potential field method is discussed in section 2.2, while section 2.3 attempts to explain the seismic method. 2.4 is described in the section that provides some previous work related to the study area. Finally, a summary of this chapter is provided in section 2.5.

2.2 Potential field methods

Gravity and magnetic fields are two types of potential fields. Hence, the gravity and magnetic geophysics methods may be categorised as potential field methods. In addition, gravity and magnetic methods are considered passive geophysical techniques as they measure the naturally existing potential fields without the need for any applied potential field, energy, or force.

2.2.1 Gravity method

The gravity method investigates the impact of differences in subsurface density on the acceleration of gravity, which is measured on the earth's surface using a gravimeter. By measuring changes in gravitational acceleration caused by gravitational forces, the gravity approach infers alterations in subsurface materials (Nabighian et al., 2005a). The gravity technique is used for geologic or subsurface structural mapping, void identification, mineral prospecting, and estimating the depth of bedrock.

2.2.1(a) Theory of gravity method

The gravity method involves measuring the earth's gravitational field at certain points to set the location of subsurface density variations. These density variations are possibly related to changes in geologic structures such as faults and basin geometry. The gravity method is predicated on two laws developed by *Sir Isaac Newton*. The *Second Law of Motion* which relates force (F) to mass (m) and acceleration (a) of a body (Equation 2.1), and the *Universal Law of Gravitation*, which relates an attractive force that exists between masses (e.g. two masses m_1 and m_2) that have some separation d between them (Equation 2.2). When the acceleration is in a vertical direction, then it is due to gravity and is usually denoted by the symbol (g).

$$F = ma \quad (2.1)$$

$$F = G \frac{m_1 m_2}{d^2} \quad (2.2)$$

where F denotes the gravitational force, G is the universal gravitational constant ($6.673 \times 10^{-11} \text{N(m/kg}^2\text{)}$). For the earth of mass M_E and radius R_E . Some rock with a mass m_r on the surface of the earth will experience a force due to the earth's centre of mass which is R_E away from the rock given by Equation 2.3

$$F = G \frac{M_E m_r}{R_E^2} \quad (2.3)$$

The downward acceleration (g) caused by the Earth is the force per unit mass and it can be obtained from equation (2.3)

$$g = \frac{F}{m_r} = G \frac{M_E}{R_E^2} \quad (2.4)$$

2.2.1(b) Gravity units

The standard unit of gravity measurement is the centimetre per second squared (cm/s^2). This is also referred to as the *Gal* in honour of *Galileo Galilei*, who made the first measurement of the acceleration due to gravity ($1 \text{ Gal} = 1 \text{ cm/s}^2$). The average value of g at the Earth's surface is 980 cm/s^2 . The modern gravimeters are capable of readings with the precision of $1 \times 10^{-3} \text{ mGal} = 1 \times 10^{-6} \text{ cm/s}^2$.

2.2.2 Magnetic method

The magnetic method was one of the first geophysical methods used to map subsurface structures and prospect for minerals. The magnetic survey has been improved by advancements in equipment resulting in increased data resolution, quality, and quantity. The magnetic method can be used to delineate extensive geologic

formations, analyses the composition of underlying rock layers, and carry out research related to the environment (Nabighian et al., 2005b).

2.2.2(a) Theory of magnetic method

The magnetic method is a very common and cheap approach. The basic operation is quite simple. When a ferrous material is put in the Earth's magnetic field, it creates an induced magnetic field. The induced field is put on the Earth's field at that location creating a magnetic anomaly. Detection depends on the quantity of magnetic material existing and its distance from the sensor. Theoretically, If two magnetic monopoles of strength p_1 and p_2 are isolated by a distance r , a force, F , exists between them. If the poles have the same polarity, the force will push the poles apart, and if the poles have opposite polarity, the force is attractive and will draw the poles together. The equation for F is given by Equation 2.5:

$$F = \frac{1}{\mu} \frac{p_1 p_2}{r^2} \quad (2.5)$$

where μ is a constant of proportionality called the *magnetic permeability* of the medium separating the poles; p_1 and p_2 and r the distance between them.

Instruments used to measure the magnetic field are called *magnetometers*. In magnetic methods, the inducing field determines the magnetization of the body, and complex interaction between the inducing field creates the induced field. In many cases, the magnetization of rocks is weak; therefore, a simple approximation can be made to calculate the magnetic anomaly.

2.2.2(b) Magnetic units

The magnetic flow lines between two poles per unit area is the flux density B (and is measured in Weber/m² = Tesla). B , which is also named the “magnetic induction”, is a vector quantity. The unit of Tesla is too large to be workable in geophysical work, so a sub-unit called a nanotesla (1 nT = 10⁻⁹ T) is used instead, where 1 nT is numerically equivalent to 1 gamma in c.g.s. units (1 nT is equivalent to 10⁻⁵ gauss).

2.3 Seismic methods

Seismic reflection method is the most extensively utilized in oil and gas exploration. This Seismic Method uses a mechanical energy source to generate seismic waves above or just below the earth surface, then receiver will record the reflected and refracted waves that arriving at another surface location. Wave travel-time and wave motion-velocity measurements depict underlying geological layer structural variation. The seismic waves can divide in two types is shown in Figure 2-1.

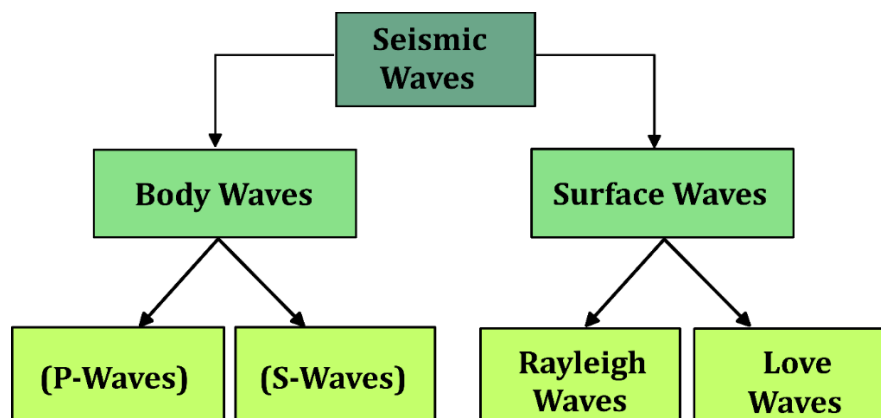


Figure 2.1 Classification of the common seismic waves

Seismic reflection surveying, employed since the 1930s, is the most popular geophysical method. The method has been utilised for investigating hydrocarbon reservoirs above crustal structures within sedimentary basins at several kilometres. Seismic reflection surveys have been extensively researched and developed in the hydrocarbon business, so there is a lot of technical literature about it.

The basic principles involve measuring the time required for a seismic energy source (e.g., vibriosis, air or water gun) to travel from that source at or near the surface, via the earth layers with different densities and velocities, and finally back up to a receiver or a number of receivers (geophone or hydrophone) on the land or sea surface Figure 2-2. The time required for a seismic signal or pulse to travel from the source to the receiver is called two-way travel time (TWTT), milliseconds (ms) are used to measure it. The milliseconds equal to 1×10^{-3} seconds. Seismic processing is an essential stage in the seismic method, which usually requires running gathered seismic data through a number of processing stages or processing sequences to generate a final processed seismic picture. Seismic data processing procedures are utilised to improve the signal quality and reduce the existence of noise in the gathered seismic data. In seismic processing, five primary categories of corrections and adjustments are commonly used: amplitude, time, data compression (deconvolution), frequency-phase content, data compression (deconvolution), and data positioning (migration).

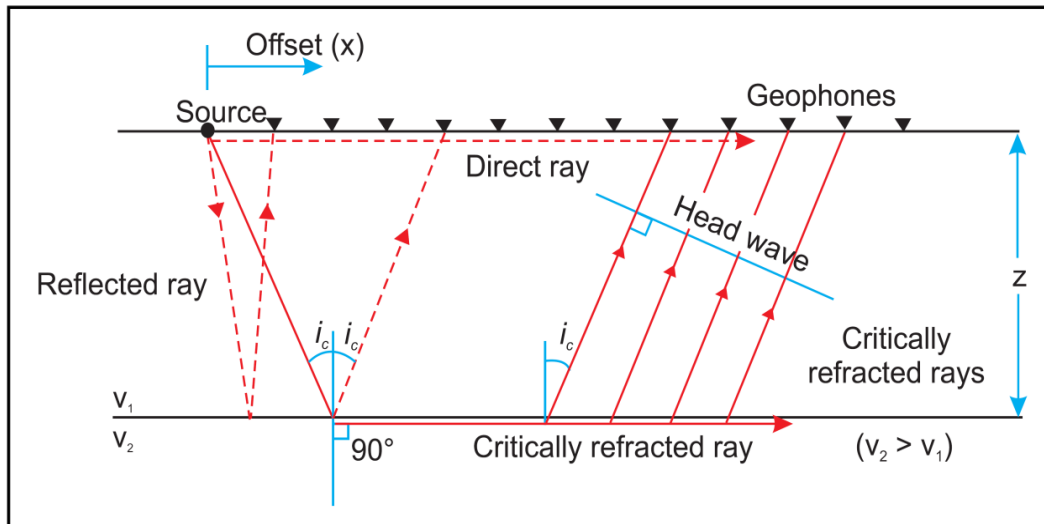


Figure 2.2 Ray path diagram showing a respective diagram for direct paths from source and reflected, rays up to geophones at the surface. The behavior of a wavefront as it meets an interface of two media with contrasting acoustic impedances based on velocities V_1 and V_2 . The angle of the incident wave (i_c) is the same to the reflected wave in an isotropic media. Obtained from Reynolds, (2011)

2.4 Tectonic setting and sequence stratigraphic of the study area

Libya's tectonic evolution has undergone several geological events, leading to the formation of significant basins such as the Sirt basin, Ghadames basin, and Murzuq basin. Most of these mentioned basins are producing oil and gas. The study area is situated within a Sirt basin, which is considered to be a peri-cratonic basin. The current understanding of the Sirt Basin's structure and stratigraphy is mostly based on fragmented seismic studies and a limited number of exploratory drilling activities conducted within the basin.

2.4.1 Tectonic settings of Sirt Basin and Abu Tumayam trough

Libya's oil and gas production originates from the Sirt basin, north Africa's largest sedimentary basin. The Sirt basin borders the Ghadames basin, Tripolitania, and Marzuq basins to the west, the Kufra basin and Tibesti to the south, the Cyrenaica platform to the east, and Sirt offshore to the north. The basin has NW-SE platforms

and troughs (Figure 2-3). Several researchers have studied the tectonic history and framework of the Sirt basin, such as (van der Meer and Cloetingh, 1993; Wilson et al., 1998; Bumby and Guiraud, 2005; Hallett, 2002; Craig et al., 2008; Abadi et al., 2008; Bosworth et al., 2008). The fragmentation of the North African craton was a pivotal tectonic event impacting Libya regionally during the late Precambrian, concurrently with the erosion of a substantial portion of eastern North Africa (Klitzsch and Squyres, 1990). The Sirt Arch emerged in the late Paleozoic era when early Paleozoic tectonic structures were reversed. Extensive erosion obliterated the whole Paleozoic succession (Hercynian unconformity) at the top of the Sirt arch (Hallett, 2002). The first set originated during the early Paleozoic Caledonian Orogeny. As a consequence, multiple NW-SE trending horsts and grabens have formed, while the Hercynian Orogeny formed the second fault series trending NE-SW in the late Palaeozoic (Hallett and Clark-Lowes 2016). A huge E-W trending regional high formed from the late Carboniferous to the early Jurassic. This occurred in a large part of Egypt and a large part of eastern Libya, including the Cyrenaica platform and the eastern parts of the Sirt Basin, which are far to the north.

Post-Hercynian structural reorganisation identified the major depo-centres until Pangea's Jurassic-Cretaceous split (El Hawat and Shelmani, 1993; Klitzsch, 1996). In the middle Cretaceous, sinistral shearing forces and thermal sag caused subsidence and graben floods, which broke up the Northern Tibesti-Sirt Arch into NW-SE horsts and grabens (Hallett, 2002). According to Kingston et al. (1983), a continental block extended to form the Sirt Basin and created the horsts and grabens within the Sirt basin, which trended in NW-SE directions. This tendency resembles East African and Red Sea rift systems (Finetti, 1985; Gras and Thusu, 1998).

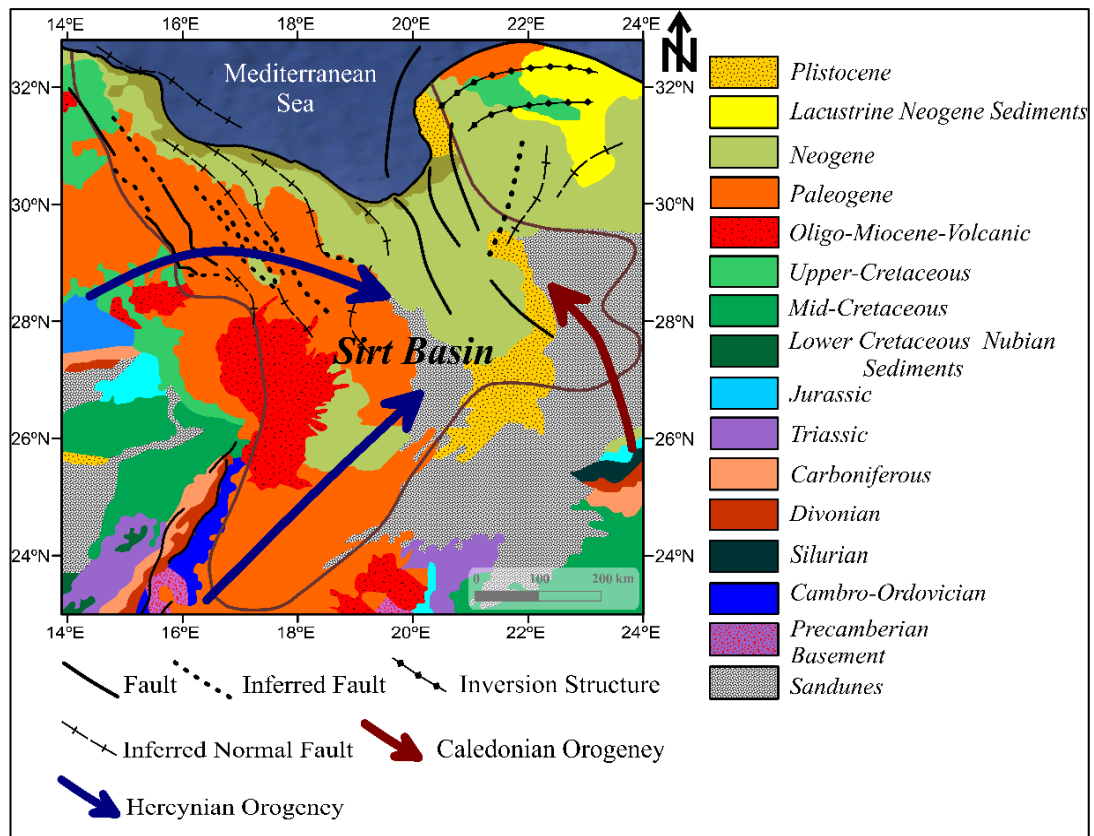


Figure 2.3 A simplified geological map of the Sirt Basin shows the distribution of geological rock units and significant structural elements. The brown line indicates the limit of the Sirt Basin.

Baird et al. (1996) suspected that the rifting started after the mid-Cretaceous. This was followed by the rift-infill episode, which continued until the end of the Cretaceous. The Sirt Basin Grabens may represent a triple junction in the northern African plate's crust; according to Harding (1984), a fragmented western edge of the Sirt Basin overlaps with the Malta Escarpment, which followed the Libyan Pelagian cratonic block northwest. Guiraud and Bosworth, (1999) postulated that the initial episode of rifting in the Sirt basin began in the early to middle Cretaceous and was subsequently followed by crustal extension with block faulting systems. According to Anketell (1996), early Cretaceous rifting exhibited east-west strike-slip faults that significantly influenced clastic sedimentation in eastern Sirt basin portions such as the Sarir arm (Figure 2-4). A second phase of rifting was initiated at the end of the Early

Cretaceous (Early Aptian) as a result of NE-SW crustal extension (Guiraud et al., 1992), while the third phase was characterised by NW-SE horsts and grabens trending (Hallett and El Ghoul, 1996). Crustal extension throughout the Late Cretaceous in the NE-SW orientation resulted in NW-SE structural features within the Sirt basin (Westaway, 1996; Shaaban and Ghoneimi, 2001). The Sirt Basin's post-rift phase started in the upper Eocene and was marked by a graben fill structure. This was caused by thermal subsidence and peripheral sagging (Gumati and Nairn, 1991). Subsidence reached its highest point in many troughs throughout the upper Eocene, notably the Zallah trough, the Abu Tumayam trough, and the Ajdabiya trough (Gumati, 1985).

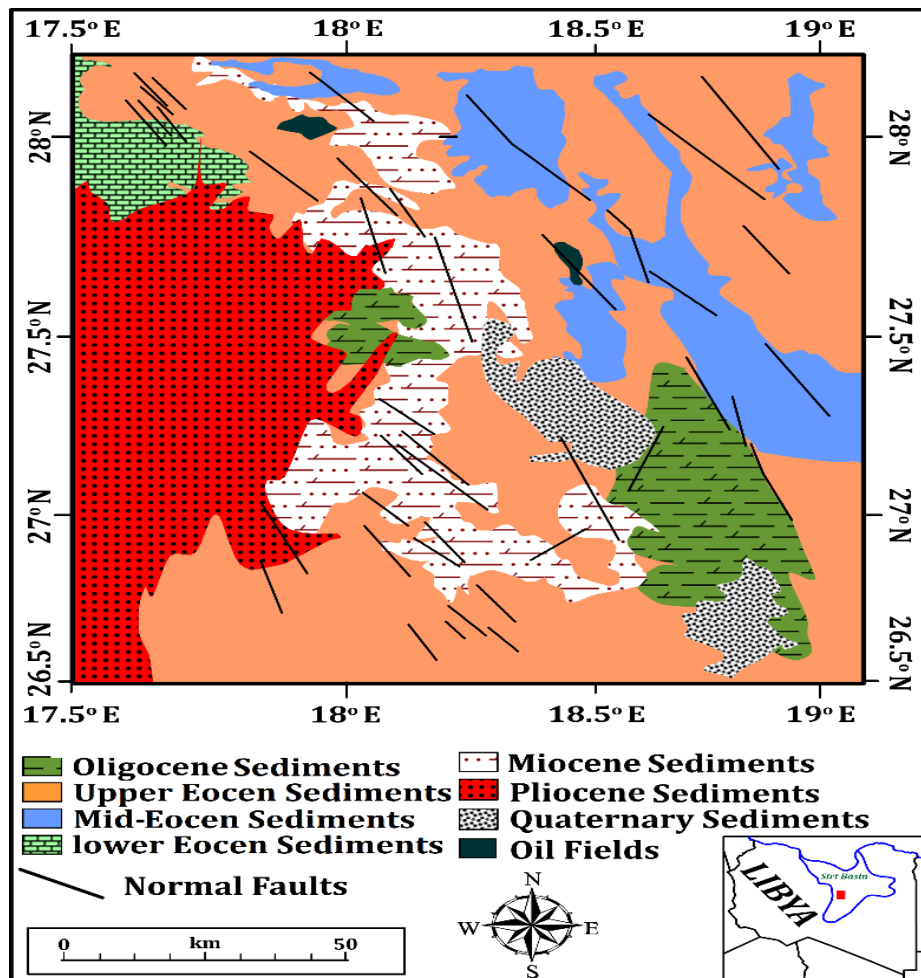


Figure 2.4 Simplified surface geologic map of study area shows the exposed rock units, and oilfields compiled after Anketell and Gumati (1991)

2.4.2 Al Haruj volcanic province (AHVP)

AHVP is the biggest of the five Gharyan-Tibesti volcanic provinces, which are characteristic of Libya (Busrewil and Wadsworth, 1980; Less et al., 2006). The Al Haruj Volcanic Province formed from the end of the Miocene to the Holocene and is associated with the Sirt Basin rifting and tectonic history (Cvetkovic et al., 2010; Busrewil, 2012). The AHVP is comparable to other Libyan mafic volcanic fields but differs from the Tibesti Volcanic Province (TVP) in volcano-tectonic process, volcanic style, and materials (Elshaafi, 2017). Volcanic activity in AHVP began in the Messinian period and persisted until the early Pleistocene, then decreased in volume and number, especially in the middle part of the Pleistocene (Elshaafi and Gudmundsson, 2017). The Al Haruj Volcanic Province covers an area of around 42,000 km² (Figure 2-5) It has two sub-provinces from north to south depending on lava flow shape, age, and thickness (Busrewil and Wadsworth, 1980; Peregi et al., 2003). Al-Hafdh and Elshaafi, 2015 reported that the Al Haruj Volcanic Province was separated into sub-provinces, the youngest of which is known as Al Haruj al Aswad Sub-province (AHAS) and is believed to be younger than the Pliocene, while the southern part of the AHVP is called Al Haruj al Abyad Sub-province (AHAB), which is somewhat extended in an NNW-SSE trending zone. The initial volcanic eruption was what created the vast magma plateau. In addition, magma has poured in liquid form through a number of volcanic fissures, the locations of which are presently unknown because they were obscured by the recent volcanic eruption (Busrewil, 2012). The earliest volcanic stages are heavily eroded, but the latest stages have been beautifully preserved and contain pahoehoe lava flow characteristics, indicating that volcanic activity persisted into the Holocene (Busrewil, 1996). Klitzsch (1968) suggested that Al Haruj volcanic timing is Holocene.

Woller and Fediuk (1980) referred to the structures that affected the Al Haruj volcanic province and concluded that there are two major fault systems: the first one is the NNW-SSE Al Haruj uplift, which has the orientation of the red sea, and the second fault system is the NNE-SSW, which trend parallel to the rift of the African plate. (Vesely, 1985) divided the AHVP lava flow into six stages (I, II, III, IV, V, and VI) Figure 2-5 and believed that volcanic activity in the Al Haruj region began in the late Miocene and continued until pre-historic times, with volcanic stages V and IV being post-Neolithic. This division is basically based on field observations and trace element chemistry.

- i. The initial stage of lava flows (I) dates from the lower to upper Pliocene (5.33-2.59 My) and is exposed throughout the Al Haruj region, with the exception of the more recent main volcanic centres, and trends NW-SE.
- ii. The second stage (II) occurred during the upper Pliocene (3.60-2.58 My), covered the central portion of the Al Haruj al Abyad Sub-province (AHAB), and produced over twenty cones. At this period, the lava flows at this stage were mostly composed of grey flood basalt.
- iii. The third stage (III) occurred during the early Pleistocene (1.81-0.78 My) and was mainly composed of black basaltic lava. This stage produced volcanic cones with 30–50 m craters and less than 1 km in diameter.
- iv. The fourth stage (IV) of lava flows dates from the Lower to Middle Pleistocene (1.80-0.13 My) and covered the Al Haruj al Abyad Sub-province (AHAB). In this stage, vesicular lavas build rough hills with tumuli, ridges, and steep lava scarps in a wadi filled with thin basalt flows 10 meters wide.

- v. The fifth and sixth stages (V&VI) were unconformably covered by Pleistocene sandy-limestone and Quaternary deposits.

Peregi et al., (2003) found that there are numerous basaltic and phonolitic dykes and smaller lava plugs that intersect the current basaltic rocks and/or the Tertiary sediment within surrounding areas. According to Cvetkovic et al. (2010), dykes strike NW-SE and dip NE and SW, whereas the second system may be pinnate systems associated with the end of the Lower Miocene sinistral strike slip activity of NW-SE striking faults with an acute angle to the first system. Al-Hafdh and Elshaafi (2015) concluded that the AHVP is mostly composed of large alkaline basalts, transitional basalts, and minor sub-alkaline basalts, with no more distinguished volcanic rocks. The AHVP field's magmatism is linked to the reactivation of pre-existing structures during post-rifting of the Sirt Basin, likely due to plate convergence since the Jurassic to Holocene (Al-Hafdh and Elshaafi, 2015). According to Abdel-Karim et al. (2013), alkaline magma is what forms phases 3 and 4 basalts, whereas tholeiitic to alkaline magma forms phase 1 basalts.

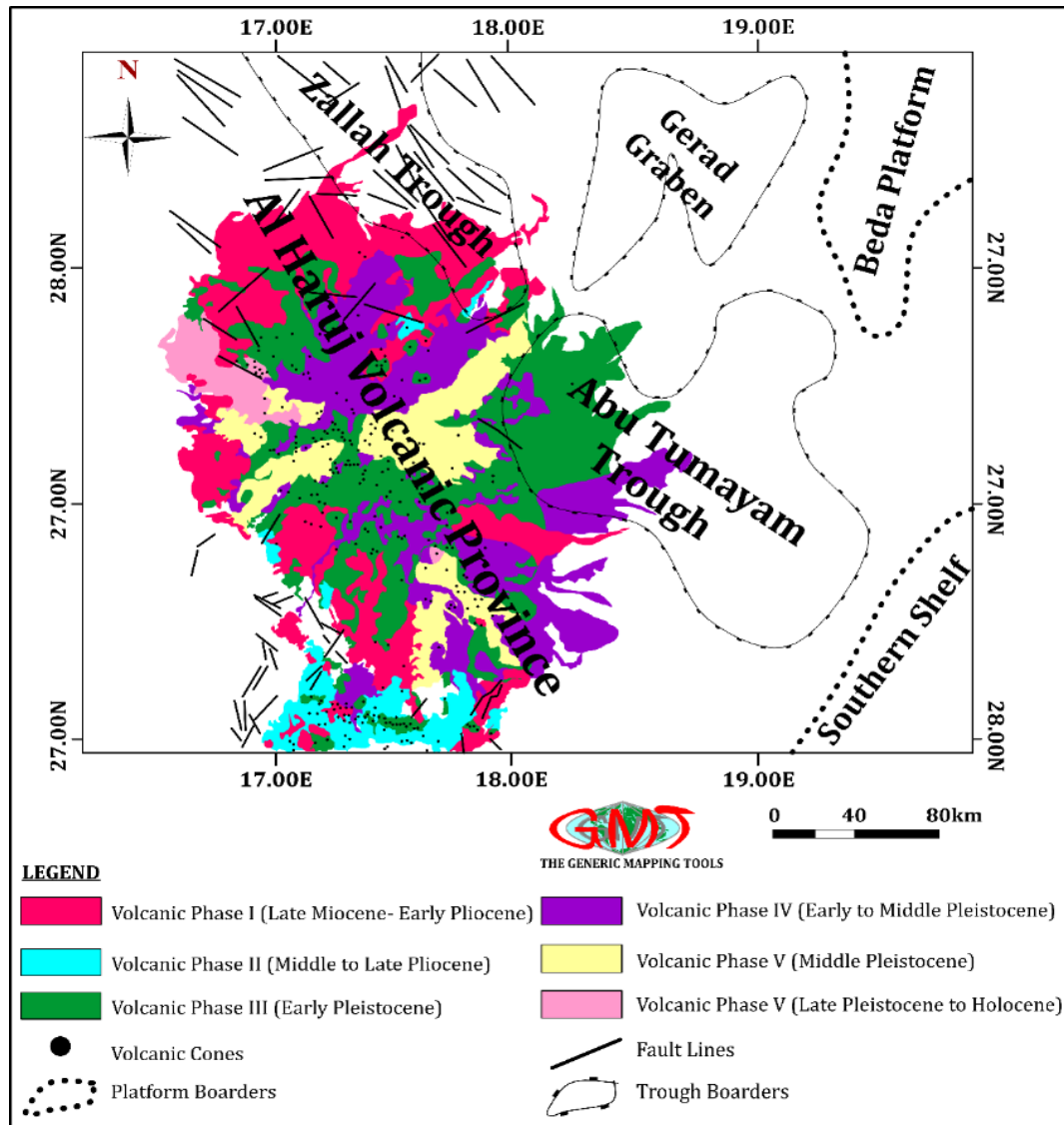


Figure 2.5 The Al Haruj Volcanic Province (AHVP) geological map depicts the distribution of the primary six volcanic stages, volcanoes, and surrounding troughs and structural components determined by merging satellite images with existing geological maps modified from (Less et al., 2006).

2.4.3 Sequence stratigraphy of Abu Tumayam trough

The stratigraphy development of the Abu Tumayam trough started during the early Syn-rift and post-rift periods Figure 3.5, which have been investigated by 2D seismic and well data. In addition to that there is still lack of information beneath the upper cretaceous layers. The stratigraphy of the Abu Tumayam trough has been summarized in Table 2.1.