Integration of DEM, ETM+, Geologic, and Magnetic Data for Geological Investigations in the Jifara Plain, Libya

Nureddin M. Saadi, Essam Aboud, and Koichiro Watanabe

Abstract—We used an integrated approach to constrain the geological structure of the Jifara Plain in northwest Libya. The analysis of surface data, including a digital elevation model (DEM), Landsat Enhanced Thematic Mapper Plus images, and geologic maps, was combined with subsurface data, including well logs and magnetic data. The DEM data were used for the identification of geological lineaments in the study area. The interpretation and analysis of the lineaments indicate that the Jifara Plain is controlled by three main fault systems, trending northwest–southeast, east–west, and northeast–southwest. The three trends represent the remnants of reactivated structures that formed under the stress regimes generated during the tectonic evolution of North Africa. The magnetic data reveal three northwest- and northeast-trending sedimentary basins in the study area. The depth of the basement inside the main basin ranges from 1 to 5 km. The results indicate that the Jifara Basin is shallower than the surrounding basins. The integration of the results reflects different periods of tectonic activity in the Jifara Plain and the adjacent Jabal Nafusah.

Index Terms—Digital elevation model (DEM), Enhanced Thematic Mapper Plus (ETM+), integration, Jifara plain, Libya, magnetic.

I. INTRODUCTION

Geological investigations can be efficiently carried out by integrating different data analyses and techniques [1]–[6]. In geological investigations, an understanding of the geomorphology, structure, and geophysical characteristics is required to accurately target areas and reduce the ambiguity of geological interpretations (e.g., [7]–[9]). The Jifara Plain in northwest Libya has been the subject of numerous geological studies by different geologists in the 1940s, 1960s, and 1970s (e.g., [10]–[18]). The origin and structure of the Jifara Plain and the adjacent Jabal Nafusah have been the subject of several different hypotheses. So far, no comprehensive study of all available information that would enable a regional analysis of geological lineaments in the study area. The interpretation and analysis of the extracted lineament lengths and trends based on the age of the geological formations provided information about the tectonic evolution of the study area.

The application of Landsat ETM+ images for regional structural mapping has a long tradition worldwide [25]–[28]. To investigate this area, we overlaid ETM+ images (visible composite) on shaded relief maps, slope maps, and traverse profiles [24]. The identification of geological lineaments was a valuable tool for improving our knowledge of the surface structure of the Jifara Plain. The analysis and interpretation of the extracted lineament lengths and trends based on the age of the geological formations provided information about the tectonic evolution of the study area.

Geophysical data record the physical characteristics of subsurface geological features, allowing subsurface structures to be identified and interpreted [29]–[32]. We used aeromagnetic data to gain a general picture of the subsurface structure in the study area. Horizontal gradient (HG) and analytic signal (AS) filters were used to locate the edges of the subsurface structures [31], [33], [34]. The qualitative interpretation of the magnetic data indicates that the Jifara Plain is characterized by a large NW-trending positive magnetic anomaly. The analysis and interpretation of the aeromagnetic data revealed a main basin that trends northwest–southeast (NW–SE) and two subbasins in the northeast and southwest.

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The integration of all results indicated that five major tectonic episodes have affected the Jifara Plain and the adjacent Jabal Nafusah.

II. GEOLOGICAL SETTING

The study area (Fig. 1) lies in northwestern Libya and is bounded by longitudes $12^\circ10' \text{ E}$ to $13^\circ55' \text{ E}$ and latitudes $31^\circ50' \text{ N}$ to $32^\circ55' \text{ N}$. It covers a surface area of approximately 20000 km$^2$. Three main geomorphological units divide the area: the Jifara Plain, the Scarp, and the Plateau. The Jifara Plain is a low-lying area in northwest Libya. It is bounded to the north by the Mediterranean Sea and to the south by the scarp of Jabal Nafusah [35]. Late Permian–Middle Triassic dextral (clockwise) motion of Africa relative to Eurasia created a westward-narrowing wedge-shaped arm of the paleo-Tethys [36]. This phase of rifting led to the collapse of paleohighs, subsidence, and widespread basin formation in North Africa, particularly around the margins of Tethys [37]. Permian clastic deposition dominated in the Tripolitania Basin and Jifara Plain [38]. The area became a stable platform from the Late Cretaceous to the Miocene. Downwarping in the Miocene resulted in the deposition of Miocene sediments [37].

The Scarp (Jabal Nafusah) runs approximately east–west from the Mediterranean Sea to beyond the Libyan border. It overlooks the Jifara Plain and rises to an elevation of 500 to 700 m above sea level. The Scarp consists of Mesozoic rocks, including limestone, sandstone, clays, and dolomitic limestone [15]. There are two theories for the origin of the Scarp. The first was proposed by Zaccagna in 1919 [39], who believed that the Jabal front is an uplifted marine cliff that was eroded on its northern side by wave action when the Jifara was still submerged. The second theory was described in [10], [15], and [40], who attributed the formation of the scarp to the Al Aziziyah Fault, which was active prior to the Miocene.

The Plateau is a queda made mainly of hard and resistant dolomitic limestone of Upper Cretaceous age. Basalt sheets cover the southeastern area with scattered black hills made of phonolite and basalt [18]. The Plateau has an average elevation of 500 to 800 m.

The study area contains exposures of sedimentary rocks ranging in age from Triassic to Quaternary. The Aziziyah Formation (Middle–Upper Triassic) [41] is widely distributed throughout the central part of the study area. The Abu Shaybah Formation (Upper Triassic) [42] consists of sandstone...
alternating with layers of clays and scattered limey bands [16].
The Abu Ghaylan Formation (Upper Triassic–Middle Jurassic) [13] appears as a narrow limestone ridge in the southern part of the study area [15]. The Bir al Ghanam Formation (Middle Jurassic) [13] is exposed throughout the southwestern part of the study area. It comprises three successive rock units: the Abreghs Gypsum, Bu en Niran Member, and Bir al Ghanam Gypsum [15]. The Takbal Formation (Middle Jurassic) [42] is present in the southwestern part of the study area and consists of limestone with clayey and marly intercalations [11]. The Sidi as Sid Formation (Upper Cretaceous) comprises two successive rock units, which are the Ain Tobi Limestone and Yafirin Marls [13] and [16]. The Nalut Formation (Upper Cretaceous) [39] is widely distributed throughout the area and consists of limestone and dolomitic limestone [17]. The Qasr Tigrinmah Formation (Upper Cretaceous) [12] is exposed in the southern part of the study area. In [15], the Mizdah Formation comprises two members, which are the Mazuzaah Limestone and the Thala Member. The Al Khums Formation (Miocene) is composed of an upper limestone bed underlain by a conglomerate layer [16].

The volcanic rocks (Tertiary–Quaternary) consist of three types: phonolite and trachyte intrusions, basalt cones, and basalt flows [17], [18]. Piccoli [43] interpreted the age of the basalt sheet as early Eocene to Pliocene, whereas Christie [13] interpreted the age of the basalt as early Quaternary. The produced DEM was not validated against SRTM or ASTER data.

Several image processes were applied to the digital elevation data to create shaded relief maps, slope maps, and transverse profiles to identify geological lineaments in the Jifara Plain.

A. Shaded Relief Maps

The ability to illuminate topography from any angle is an advantage of shaded relief maps. Conversely, the major limitation of aerial photographs and satellite images is their dependence on natural east–west solar illumination paths that highlight north–south linear features that are perpendicular to the solar illumination [48]. Smith and Clark [24] suggested that some linear landforms are less visible when shaded from certain azimuths and become more visible through a small change in the azimuth of the light source. In [49], the dominant trend of glacial lineaments in the image was toward the east–northeast (ENE) and north-northeast (NNE). They used incoming illumination from the northwest to avoid azimuth-biasing effects [50], [51]. In this paper, we experimented with the evaluation of an incoming illumination that is perpendicular to the prevailing trend of lineaments in the study area. According to the geologic map of the investigated area, the prevailing lineaments trend in the NW–SE directions [52]–[55]. Therefore, low incoming solar radiation from the NE–NNE was tested to mitigate azimuth-biasing effects and enhance the visual detection of linear features in the dominant trend. Four azimuth angles of simulated sun illumination (NE–NNE, NW–NNW, NW–WWN, and N) were tested to prevent azimuth-biasing effects [51]. A low sun-elevation angle (20° to 30°) was used for lineament detection in all directions. Lineaments represented by boundaries between light and dark tones in the shaded relief maps indicate slope changes. Since the locations of shading change with illumination azimuth and inclination, lineament identification was improved by the overlay of elevation contour maps and drainage pattern maps showing the exact locations of valleys, ridges, and slope breaks. Lineaments of tectonic origin are often associated with characteristic geomorphologic features, such as linear valleys, ridgelines, and slope breaks that can be identified as lineaments in the DEM. The ability to zoom in introduced more flexibility to the visual interpretation and correlation between many linear features in the study area. All lineaments observed within the four shaded maps were manually mapped through on-screen digitizing using ER Mapper 7. The resulting four lineament maps were combined into one map. Simple lines were used for digitizing linear features (lines) on the surface of the study area.

Four Landsat ETM+ images (acquired on January 25, 2001; January 23, 2000; June 11, 2001; and March 4, 2000) with the band combination red, green, and blue 321 (visible composite) were overlain on the DEM to study geomorphological units in the study area and their relationship to subsurface structures (Fig. 2).

B. Slope Maps

A slope is used for the identification of features with topographic expression. Slope is a measure of the steepness of the terrain or the rate of change in elevation at a given part of the topographic surface. ER Mapper 7 calculated slope using
Fig. 2. Oblique view of Landsat ETM+ images (visible composite) overlain on shaded relief maps showing the main topographic features in the study area.

Fig. 3. Slope map. Areas in white are the steepest slopes; areas in black are the gentlest slopes.

a quadratic fitted to a $3 \times 3$ kernel. This $3 \times 3$ filter is written in C code and does not use a weighted convolution array.

This slope filter generates data values in degrees from horizontal. The output image contains slope values that range from $0^\circ$ (flat terrain) to $90^\circ$ (vertical terrain). It is visualized as an 8-b panchromatic image (Fig. 3), in which white areas are the steepest slopes and black areas are the gentlest ones. This is fundamentally different from shaded relief maps, in which topography is artificially illuminated from specific direction and angle. Topographic lineaments can be distinguished by their elevation difference from the surrounding terrain. These elevation changes can be represented as changes in grayscale color in the slope map (Fig. 3). The brightness of each pixel in the slope map is related to the slope angle; white areas are steep, and black areas are flat. Although the slope map is not illuminated, the results are similar to those of shaded relief maps.

C. Traverse Profiles

A traverse profile is a line that displays the amplitude or change in elevation underneath the traverse line. We applied this technique to the DEM to create elevation profiles across topographic anomalies of interest. In this paper, the traverse profiles were used to locate significant breaks in slope, measure escarpment heights, and display how topography varies along the profiles. This assisted our identification of geological lineaments in the study area. We selected eight profiles along lines close to the scarp to interpret topographic forms that may have been affected by fault interaction (Fig. 4). The extracted profiles are reasonable and can be compared to profiles calculated from the published geological maps [52]–[55].

The lineaments extracted from the DEM were divided into six groups based on the age of the geological formations (Fig. 5). The analysis and interpretation of these lineaments were based on the principle of crosscutting relationships [56], [57].

IV. MAGNETIC DATA ANALYSIS

The study area was investigated using an aeromagnetic survey conducted by the Libyan Petroleum Institute. The aeromagnetic survey data had corrections applied, including the International Geomagnetic Reference Field. The final product is a total magnetic intensity (TMI) map. Fig. 6 shows the TMI map for the Jifara area.

Qualitative interpretation requires an interpreter experienced in working with magnetic data. Experienced interpreters can usually interpret a geological structure by looking at a magnetic map, much as one can visualize surface features from the contours of a topographic map [58]. The qualitative interpretation of the magnetic data in the Jifara area (Fig. 6) indicates that the area is characterized by a large positive anomaly (80 km long by 45 km wide) at the center of the area (reddish-pink color), which we refer to as the Jifara magnetic anomaly (JMA). The JMA trends NW–SE with a maximum value of $\sim 230$ nT at the center and values of $\sim 80$ nT on the troughs. This trend does not occur at random but is aligned along definite and preferred axes that can be used to define magnetic provinces [59], [60].

Filtering the magnetic data enhances and sharpens the anomalies and edges that directly relate to the structure. We used two filters to locate the edges of the structure: the HG and AS filters [61], [62]. The most important advantage of the HG and AS filters is that they highlight the maxima of the anomalies at the edges (faults/borders) of the main structure. They are referred to as edge detection filters. Once the maxima are located, other methods can be applied to these HG and AS maps in order to estimate the depths and trends of these borders.

A. Background of the Methods

The AS technique is applied directly to the magnetic data, while the HG method requires the magnetic data to be converted to pseudogravity data in order to obtain accurate results [63]. The AS can be easily estimated from the horizontal and vertical derivatives of the total magnetic field, as shown in

$$|A(x, y)| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2}$$

where $T$ is the anomalous magnetic field, $dT/dx$ and $dT/dy$ are the horizontal derivatives, and $dT/dz$ is the vertical derivative of the total field $T$. 

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The most important advantage of the AS is that it does not depend on the inclination of the magnetic field, which means that there is no need to reduce the data to the magnetic pole [reduced to pole (RTP)].

The HG filter uses the derivatives of the field in the $x$ and $y$ directions. These can be estimated by

$$|H(x, y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2} \quad (2)$$

where $M$ is either the RTP magnetic field or the pseudogravity transformation of the magnetic field.

The two methods use a common approach to determine the horizontal locations and depths of contacts. For gridded data (Jifara area), we used the approach of [64] to locate local maxima within a $(3 \times 3)$ window. If at least two internal maxima are found, the local strike direction is estimated by searching for additional local maxima around the periphery of the $(3 \times 3)$ window or within a larger $(5 \times 5)$ window, then fitting a least squares line to the internal and peripheral maxima.
Fig. 5. Geological formations by age, showing lineaments extracted from the DEM. Rose diagrams are also shown.

Fig. 6. TMI map. C.I. = 10 nT. Grid cell size = 500 m. Red lines represent the traced geologic faults [Industrial Research Center (I.R.C.), Libya, 1975a, b; 1977a, b]. Fine black lines represent the lineaments interpreted from the DEM.

The data in the window (including any estimated maxima) are extracted within a belt perpendicular to the strike direction, and the squared depths are estimated by a least squares method.

B. Applications of the Methods

The magnetic data were gridded with a 500-m grid cell size (Fig. 6), and then, (1) was applied to the gridded magnetic data in order to obtain the AS map (Fig. 7).

In order to generate the HG map of the study area, we first converted the data to a pseudomagnetic map using the geomagnetic specifications (Total field = 42 000 nT, Inclination = 45°, and Declination = 1.5°) and then used (2) to create the HG map. Fig. 8 shows the output of the HG map.

We applied a depth estimation method to the output of the AS and HG data in order to image the subsurface structure and further analyze the JMA. Fig. 9 shows the depth maps from the AS and HG data.

V. RESULTS

In agreement with the published geological maps, the faults trend predominantly NW–SE, with secondary NE–SW and...
E–W trends. The NW–SE trending faults are characterized by large throws and long strike lengths (1–10 km). The E–W faults are interpreted mainly from subsurface data and are represented by the Al Aziziyah and Coastal Faults [65]. Remarkably, the Jurassic rocks are present in the east and are entirely absent in the west. The Quaternary sediments fill the area from the scarp to the Mediterranean Sea in the north.

The DEM data identified 645 geological lineaments, of which 437 had NE–NNE azimuth angles and 208 had other azimuth angles (NW–NNW, NW–WWN, and N). In particular, the NW–NNW illumination azimuth angle was very useful for extracting lineaments, particularly those that trend in an NE–SW direction. In agreement with [49]–[51], we found that a low illumination angle was most suitable for detecting lineaments. Lineaments extracted from the DEM have different trends, but the main trend is NW–SE, which is parallel to the main tectonic line of the Jabal Uplift and characterized by the Uplift’s long extent (3–7 km). The NE–SW lineaments represent a secondary trend (2–4 km). Another significant direction is E–W (1–2 km). The remaining directions are statistically unimportant. We divided the lineaments extracted from the DEM into six groups on the basis of the ages of the surrounding geological formations. Lineaments in Upper Triassic rocks trend dominantly NW–SE, with subordinate E–W and NE–SW structures. Lineaments in Upper Triassic–Middle Jurassic rocks trend dominantly NW–SE, with subordinate E–W and NE–SW trends. The prevailing trend of the Middle Jurassic rock lineaments is NE–SW, and the second dominant trend is NW–SE. Lineaments in Upper Cretaceous rocks are dominantly NW–SE, with the NE–SW direction being subordinate. Lineaments are entirely absent in Miocene rocks. Lineaments in Tertiary rocks are mostly NW–SE, with the NE–SW direction being subordinate. Lineaments in Quaternary sedimentary units trend dominantly NW–SE.

ETM+ (visible composite) images overlaid on shaded relief maps indicate two geomorphological units trending E–W, which probably reveal the Al Aziziyah and Coastal Faults. Three other NW–SE trending geomorphological units were identified in the southern part of the Jifara Plain.

The interpretation and study of the magnetic data indicate that the Jifara Plain is characterized by two magnetic anomalies: low magnetic anomalies in the northeast and southwest regions, and high magnetic anomalies at the central part of the Plain. The high positive magnetic anomaly at the central part is divided into offshore and onshore regions, although these regions are connected. The magnetic data reveal two features with different trends in the Jifara Plain: an NW trend in the central and southeastern parts and an NE trend in the northeastern part. The magnetic source depths calculated from the AS and HG methods indicate the existence of a main basin that trends NW–SE and two subbasins in the northeast and southwest. The main basin is located beneath the JMA, and its depth increases toward the coastline.
and then decreases to the north offshore. The depth to the basement inside the basin varies from shallow (1 km at the center) to deep (5 km at the troughs). The abrupt change in the magnetic anomaly reflects a basement fault, which separates the main basin from the two subbasins. Surprisingly, the magnetic intensity map does not show a basalt intrusion beneath Jabal Nafusah, while an extrusive basalt flow covers the southeastern part of the Plateau.

The study area is characterized by many fault zones belonging to different fault systems. We recognized and mapped three main fault trends in the study area (NW–SE, NE–SW, and E–W).

VI. DISCUSSION

Based on the geological maps, the analysis and interpretation of the frequency and lengths of the NW–SE faults in the Upper Triassic and Upper Cretaceous rocks indicate reactivated faulting.

The analysis and interpretation of the DEM results indicate that the different lengths of the NW–SE lineaments in the Upper Cretaceous rocks probably indicate reactivated faulting. Lineaments are entirely absent in Miocene rocks in the northeastern part of the study area, which confirms that this region is slightly tectonically deformed, as indicated by Desio et al. [42]. Variations in lineament trends can be explained by gentle anticlinal or broad synclinal forms. Lithologically, the arrangement of phonolite hills and basalt cones in lines parallel to the dominant lineament trends (NW–SE) indicates that the volcanic activity is related to the tectonic activity of the Jabal Uplift.

The analysis of the magnetic data raises the question of how the magnetic source exists in the basin. There are two possible explanations. First, the basement rocks in the area could be uplifted and are highly magnetic, which causes the JMA. Second, the presence of an igneous intrusive body may cause the high magnetic anomaly in the basin. Unpublished hydrogeological log data (wells: RDH7 and 222/76) were obtained from the General Water Authority, Libya, which proved the existence of igneous rocks beneath the surface of the Jifara Plain. Well RDH7 showed rhyolitic rock at different depths from 76 to 550 m, while well 222/76 showed igneous rocks at depths from 500 to 925 m, which makes the possibility of the igneous intrusive body more reasonable.

The analysis of the magnetic data also shows that the depth to the basement inside the basin ranges from 1 to 5 km. This indicates that the Jifara Basin has a sediment thickness less than those of the surrounding basins, such as the Ghadames and Sirt Basins. The existence of three sedimentary basins with variations in depth and trend probably indicates renewed tectonic movement along the coast of North Africa. This also indicates that the Jifara Basin was active at several stages, which probably reactivated the Nafusah Arch and introduced a new generation of faulting in the Jifara Basin. The magnetic intensity map does not show basalt intrusion beneath the extrusive basalt flow that covers the southeastern part of the study area.

Two ideas have been advanced to explain this result. First, the basaltic rocks may be hydrothermally altered. Second, the rock may be weakly or reversely magnetized, and consequently, a relatively deep intrusion would be detected on a gravity map but not on a magnetic map. The first conclusion seems more logical.

Our integration of results reflects different periods of tectonic instability in the Jifara Plain. The study area was probably affected by the following five major tectonic episodes:

1) The oldest movement began in the Late Permian–Middle Triassic with dextral motion of Africa relative to Eurasia. This led to the collapse of paleohighs, subsidence, and widespread basin formation in North Africa. The Jifara Plain probably subsided due to this activity.

2) The second episode (Tibesti–Sirte Uplift) began during the Late Silurian Caledonian orogeny, which initially defined the limits of the Paleozoic basins of Libya [66]. This uplift was associated with and followed by an activity on parallel faults trending NE–SW.

3) The third movement started in the Late Triassic. Due to this, the study area was tilted, with its eastern part gradually uplifted and the western part gradually subsiding. This explains the presence of the Jurassic rocks in the west and their absence in the east.

4) The fourth episode, which is at the end of the Cretaceous or in the early Tertiary, was the uplift that resulted in the formation of an NW–SE anticlinal swelling. This was followed by parallel faulting and magmatic activities represented in the study area by intrusive and extrusive volcanic rocks.

5) The fifth movement occurred in the pre-Miocene and was related to the Al Aziziyah and Coastal faults. This activity caused the study area to undergo E–W trending faulting. During the Quaternary period, the Jifara Plain acted as a basin that received mainly continental deposits of sandy silt and gravel formed by the erosion of the older rocks. This explains why the Quaternary sediments filled the Jifara Plain.

VII. CONCLUSION

The integration of remote-sensing and potential field data has the potential to provide valuable information about hitherto unknown areas and reduces the ambiguity of geological interpretations.

In this paper, DEM, ETM+, geologic, and magnetic data were integrated to constrain quantitative details about the origin and development of the Jifara Plain and the adjacent Jabal Nafusah. The DEM and its products (shaded relief maps, slope maps, and traverse profiles) were used to extract geological lineaments because of their efficient observation of the Earth and the freedom to illuminate topography from any angle. The segmentation of the extracted lineaments into groups based on the age of the geological formations was attempted in order to obtain information about the tectonic evolution of the investigated area. Landsat ETM+ images were overlain on shaded relief maps to identify regional landforms in the Jifara Plain. Well logs and magnetic data were used to provide a general picture of the subsurface structure of the study area. HG and AS filters were applied to the magnetic data to highlight the maxima of the anomalies at the edges of the main structure and to estimate the depths of these edges and trends.
Our results indicate that the main trend of the extracted lineaments is parallel to the main tectonic line of the Jabal Uplift (NW–SE). The volcanic activity in the study area is related to the tectonic activity of the Jabal Uplift. Our results also revealed that the Jifara Plain contains three basins separated from one to another: the main basin that trends NW–SE and two subbasins that trend NE–SW. The high magnetic anomaly in the main basin was caused by igneous intrusive body. The results of the integrated analysis indicate that the Jifara Basin was active at several stages. Three main fault trends (NW–SE, NE–SW, and E–W) characterize the study area. The study area was probably affected by five major tectonic episodes that began in the Late Permian–Middle Triassic and continued to the Quaternary.

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