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Using ASTER Images to Analyze Geologic Linear Features in Wadi Aurnah Basin, Western Saudis Arabia

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Abstract: Remotely sensed data often used to study terrain surface, thus unique geomorphic and geologic features can be identified. The processing of satellite images is successfully utilized in this respect. Therefore, "lineaments" are commonly known among these features. They are observed as linears on satellite images and usually represent fracture traces, faults or lithologic boundaries. These systems are well utilized in the interpretation of several hydrogeological and tectonic criteria. This study introduces the procedure of identifying linear features in Wadi Aurnah basin (3100km^2), of the Arabian Peninsula. Hence, the lineaments map for this catchment was produced. For this purpose, ASTER satellite images were treated using *ENVI4.3* and *ERDAS Imagine* software. Consequently, the obtained map was analyzed using GIS techniques to interpret the behavior of the existing lineaments and their spatial distribution. This will provide valuable information that can be used in several studies related to water resources management in this basin, which is under water stress.

Keywords: lineaments, fracture system, groundwater, ASTER, Saudi Arabia.

1. INTRODUCTION

Recently, new space-based techniques have been involved in different disciplines, notably those related to Earth's surface studies. These techniques can provide numerous aspects of useful data for evaluating terrain characteristics. They either help in monitoring or detection approaches, such as land cover change, coastal pollution and identification of geological features, etc.

One of the most important applications of space-based techniques is for water resources assessment, especially in arid regions like the Arabian Peninsula.

In this view, the development of remote sensing techniques allows detecting remarkable geological features observed in aerial photographs and satellite images. These features encompass a number of shapes, orientations and scales, where each of them is indicative of specific geologic properties, either in lithology or structure.

Among the most observable features on aerial photos and satellite images are the linear shapes, so-called *lineaments*. They appear as straight or curved lines of different lengths. They are often related to fractures and lithologic boundaries and in some cases to geomorphic relief, thus appear on the image with tonal difference (i.e., diversity in the gray scale color of the image features) [1]. Thus their identification is necessary in geological and hydrogeological studies. The extraction of these features from satellite images are commonly undertaken using specialized software that to apply several digital advantages.

The area of Wadi Aurnah catchment is selected in this study. It is a typical coastal basin in the western part of the Arabian Peninsula, which is adjacent to the Red Sea (Fig. **1**). The area is a part of a mega-structure, ascribed as the Arabian Shield.

It contains topography with remarkable geomorphic features as well as a miscellany of rock lithologies that are interrupted by intensive rock deformation. The basin covers an area of about 3100 km^2, and is considered as an area of water-stress. This is especially true in the Holy Muslim city of Makka Al Mukaramah, where millions of people come each year and water demands are great.

The basin Wadi Aurnah is funnel-shaped and lies within the geographic coordinates: 39° 12′ 00" E; 40° 18′ 00" E and 21° 01′ 30" N; 21° 35′ 30" N. The geomorphology of the study area is comprised of an elevated region of mountain chains with altitudes exceeding 2000m to the east, which gradually slope towards the coast of the Red Sea. The area is characterized by complicated geological terrain because of the existing Shield. The Shield was formed during the Late Precambrian from a complex process of terrain accretion [2, 3]. Late Precambrian felsic plutons and batholiths and small patches of layered metamorphic rocks underlie the area of concern. In addition, Tertiary sedimentary rocks and Cenozoic lavas form extensive the fields in the north. The Quaternary surficial deposits cover different parts of the area, but mainly in the coastal plain [4].

According to Moor and Al-Rehaili [5], the area of concern has been subjected to polyphase deformation, including folding, sharing and faulting, but the youngest plutons have been elongated, marginally foliated, sheared and faulted. This intensive rock deformation systems and the existence of different rock types and facies has resulted in a large number

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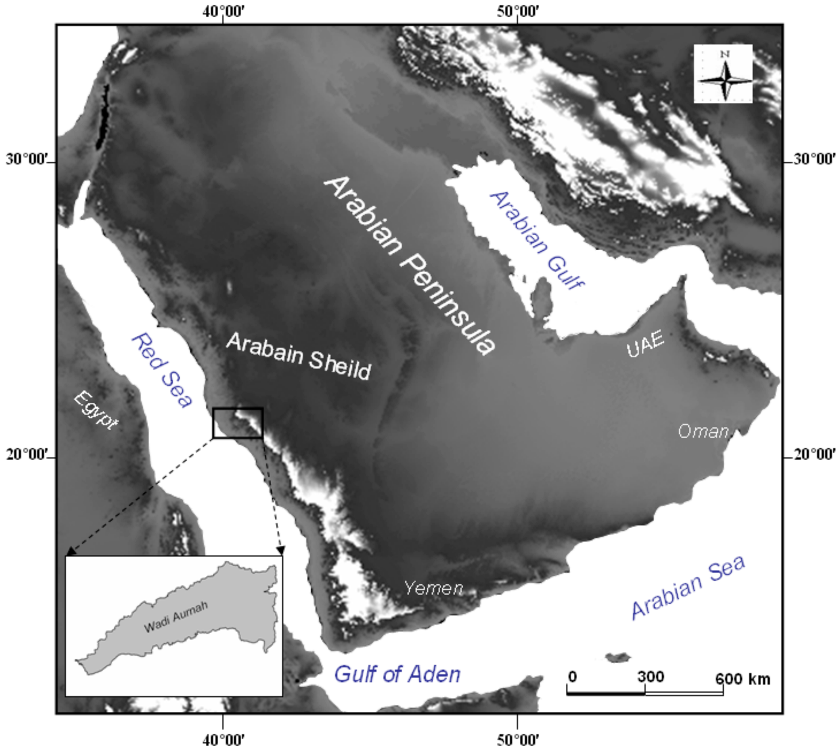

Fig. (1). Location map of the studied area.

of fractures sets that can be clearly observed as lineaments on satellite images.

This study aims to produce a lineament map of Wadi Aurnah basin, thus analyzing these lineaments in terms of density and their relation to each other. This will be achieved using remotely sensed data, more specifically ASTER images, which have a spatial resolution that enables us to extract different linear features. The resulting analyzed data on lineaments can provide supplementary information to be utilized in a variety of studies, but especially those on water resources assessment.

2. CONCEPT OF LINEAMENTS

The term "lineament" is a commonly used term in geological remote sensing. Nevertheless, it is still misleading, since similar features on satellite image or aerial photos exist, which can create confusion between geologic and non-geologic features. There are several definitions for linear features. For example, O'Leary *et al.* [6] defined a "lineament" as a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship. This tends to be the generally accepted definition. Woodruff *et al.* [7] defined lineaments as a feature that: 1) is perceived in an image of a solid planetary body, 2) is linear and continuous, 3) has definable end points and lateral boundaries, 4) has a relatively high length-to-width ratio and hence a discernible azimuth, and 5) is shown or presumed to be correlative related to stratigraphy or geologic structure.

Lineaments can be in some cases as false features. Hence, a "false lineament" is defined as a perceived lineament that meets all but criterion number 5 as described above. Also, it could be cultural manifestations that do not coincide with linear topography, such as fence lines, roads, pipelines, railroads, and animal trails, etc. In addition, lineaments are ambiguous because they cannot always be field-verified, nor are they precisely reproducible [8]. They could be 1) straight stream and valley segments, 2) aligned surface sags and depressions, 3) soil tonal changes revealing variations in soil moisture, 4) alignments in vegetation, 5) vegetation type and height changes, and 6) abrupt topographic changes. All of these phenomena might result from structural phenomena such as faults, joint sets, etc.

Recently, the development of remote sensing techniques has allowed for the easy identification of linear features on satellite images. They appear to be tremendous on hard rock bodies and negligible on soft terrain (Fig. **2**). Linear features, on satellite images and aerial photos, have attracted the attention of hydrogeologists who believe that lineaments perceived in remotely sensed images are attributed to geologic structures. The attribution of linear features to rock fractures was demonstrated in many studies [9-11]. Hence, identification of these features is important in hydrogeological assessments, since they reflect fracture traces and thus may represent zones of higher infiltration and groundwater potential [12-16]. However, field verification is required to confirm their genetic relation with fracture systems.

3. IMAGE ANALYSIS AND INTERPRETATION

In this study, Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) satellite images (*Aster L1A Reconstructed Unprocessed Instrument Data V003*) were processed to obtain the lineament map of Wadi Aurnah basin. ASTER is an advanced multi-spectral sensor [17], with wide electromagnetic spectral region that ranges from visible to thermal infrared with 14 spectral bands, and high spatial, spectral and radiometric resolution (Table **1**). ASTER images are high resolution, with a visible spatial resolution of 15 m. Each scene covers 60 km x 60 km, hence seven image scenes were used to cover the whole Wadi Aurnah basin. The ASTER, abbreviation. For image processing, *ERDAS Imagine-9.1*, *ENVI-4.3* and *PCI's Geomatica* softwares were utilized because of their high accuracy and tremendous digital advantages for image processing.

For digital data, pre-processing procedures are commonly applied. They comprise a series of sequential operations, including but not limited to, atmospheric correction or normalization, image registration, geometric and radiometric corrections. Another pre-processing phase is the linking of the available image scenes, called image mosaicking. This is essential in order to obtain a unique scene from all images and to facilitate further image treatment approaches. For this purpose, all images were primarily saved in *tiff* Format and the linking approach was obtained using the *PCI's Geomatica* software.

In this study, we applied the following approach for digital image processing:

1. Band combination: This allowed for better discrimination of terrain features. The optimum band orders were found to be as follows:
   a. VNIR (15m, 3 bands): bands order as 3-2-1
   b. SWIR (30m, 6 bands): bands order as 7-9-5, 5-7-6 and 8-4-7
   c. TIR (90m, 5 bands): bands order as 14-12-14
2. Enhancement: There are a variety of images enhancement tools available in *ENVI-4.3* and *ERDAS*

Table 1. Main Spectral Characteristics of ASTER Images [17]

System	Band	Spectral Range (*µm*)	Spatial Resolution	Radiometric Resolution
VNIR	1	0.52-0.60	15 m	8 bit
	2	0.63-0.69		
	3	0.78-0.86		
SWIR	4	1.60-1.70	30m	8 bit
	5	2.145-2.185		
	6	2.185-2.225		
	7	2.235-2.285		
	8	2.295-2.365		
	9	2.360-2.430		
TIR	10	8.125-8.475	90m	12 bit
	11	8.475-8.825		
	12	8.925-9.275		
	13	10.25-10.95		
	14	10.95-11.65		

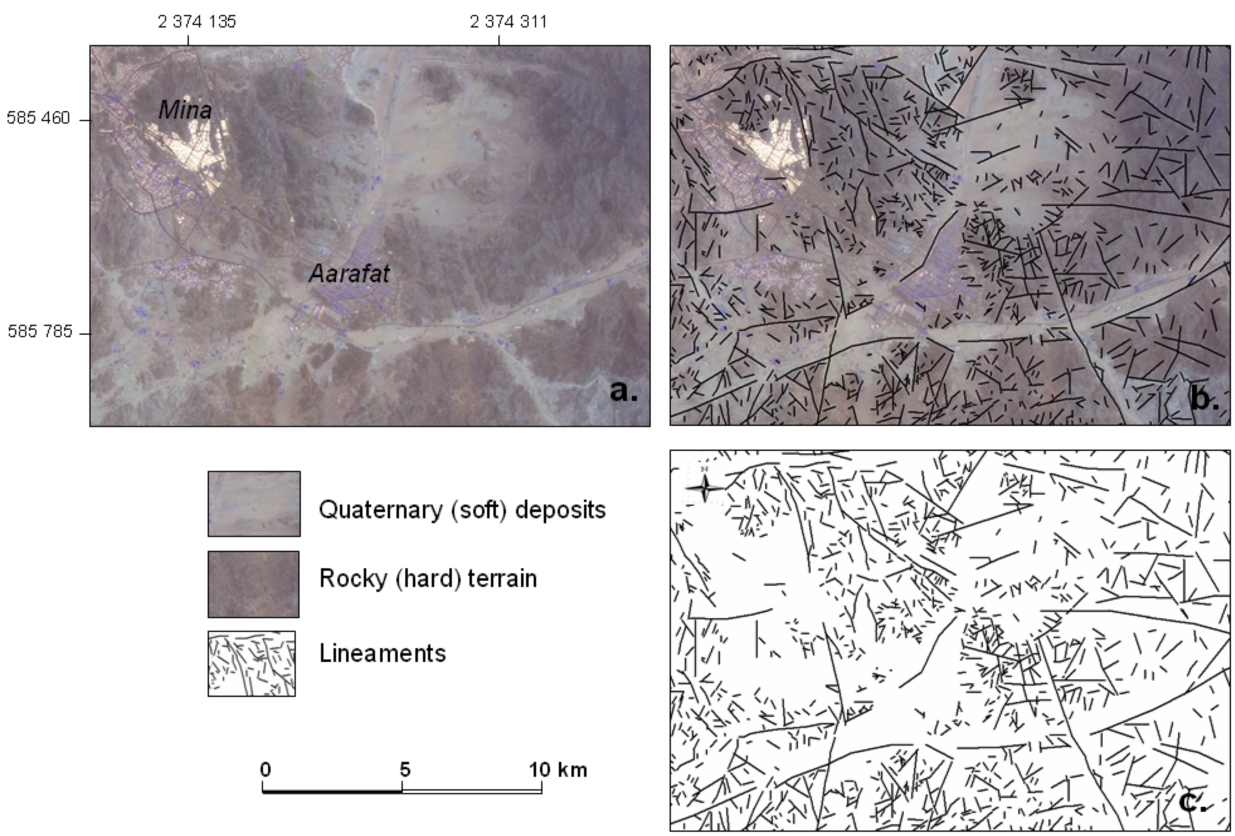

Fig. (2). Example of lineaments in the studied area. (**a**) ASTER Image showing soft and hard rocks, (**b**) plotting lineaments on the image, (**c**) produced lineament map.

Imagine. These are: filtering, and different levels of linear stretching, Gaussian, equalization and square root. Each has different effect on the appearance of the scene after the newly assigned Digital Numbers (*DNs*) are substituted for the original data values. In this study, Gaussian, equalization were the most suitable tools for image enhancement (Fig. **3**),

3. Interactive stretching: This is another tool for image enhancement that uses histograms. The histograms work in parallel with the previous enhancement applications, i.e. linear, Gaussian, etc plus three new tools: Piecewise linear, Arbitrary and User defined LUT. Therefore, in applying the above approaches, the greatest contrast stretch enhancement is applied to the most populated range of *DNs* values in the original image (Fig. **3**),

4. Density slice colouring and contouring: These methods enable classifying the colour of *DNs* that are within the same range.

Thermal interpretation from thermal bands, i.e., bands 10-14 (90m resolution), was also undertaken. It provided optimum information for detecting wet horizons, which would differentiate fracture zones that are moist (wet) from those that are dry.

The application of different digital processing techniques on ASTER images of Wadi Aurnah basin enabled us to extract all linear features. However, there are many linear objects on the terrain surface that are not geologically-related (false lineaments). In order to avoid any conflict between real and false lineaments GIS (Geographic Information System) was utilized, in particular, the *ArcGIS* software. This was done through an overlapping of the detected lineaments with the relevant topographic maps, with special reference to linear objects such as roads, pipelines and terraces. Any coincidence of these objects with our detected lineaments was interpreted as non-geologic features, and was eliminated.

4.. RESULTS AND DISCUSSION

Following the processing methodology outlined in Section 3, a detailed lineament map was produced for Wadi Aurnah basin (Fig. **4**). It shows a variety of aspects with respect to the geographic distribution the existing lineaments, their orientation and even their scale. The length of lineaments ranges from hundreds of meters to several tens of kilometers. Accordingly, short lineaments have more than set of directions even within a small area, while long ones often follow specific orientations according to the affecting tectonic forces.

There are several of approaches to analyzing and interpreting lineaments properties, but all imply defining the behaviour of fracture systems and thus their relation to rock structures. The most effective properties are the length of lineaments, frequency, direction and orientation.

4.1. Lineament Length

In the studied basin, there are 4038 lineaments of different length (as counted using ArcGIS software). There are 3630 lineaments of the short type (< 1km), which is equal to about 90% (per number) of the existing lineaments (Table **2**). The rest are 336 and 72 lineaments for moderate (1-10 km) and long ones (> 1km); respectively. The resulting linea-

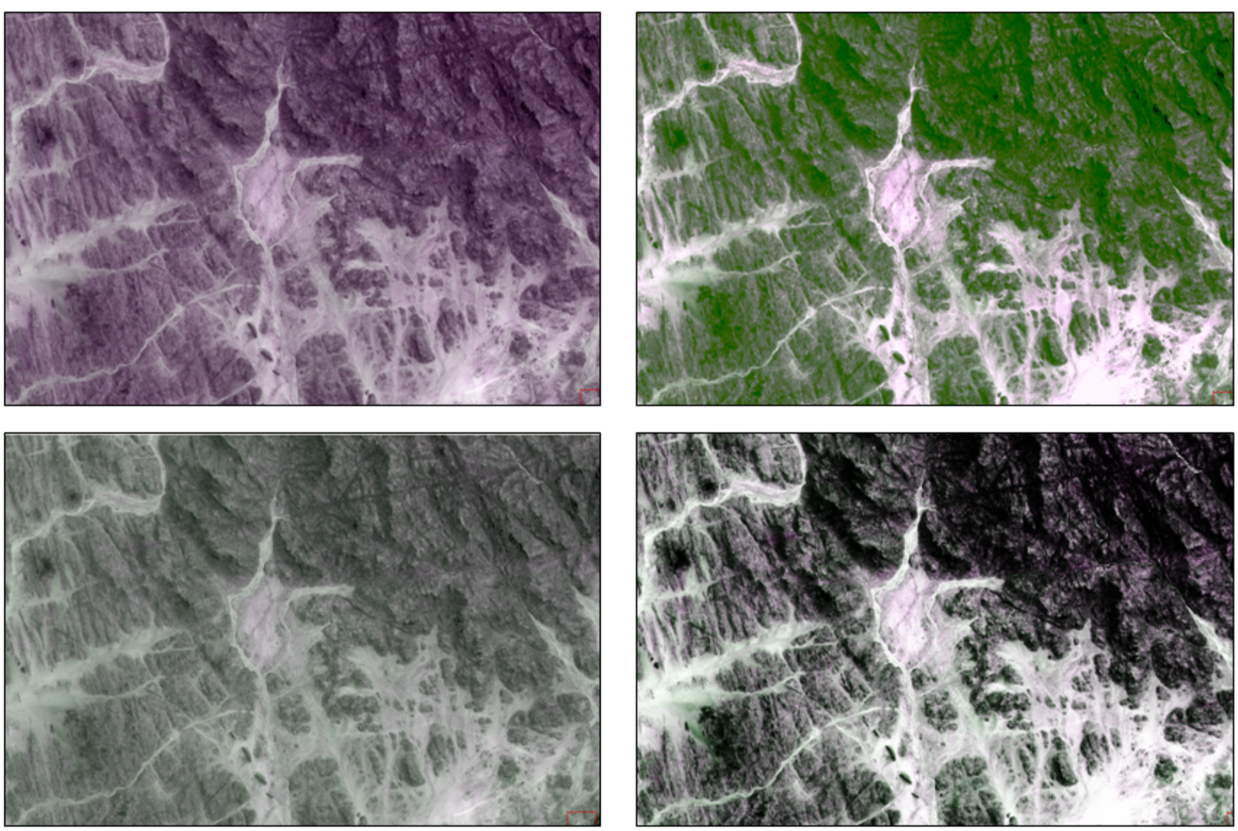

Fig. (3). Examples showing different enhanced ASTER images for the same area.

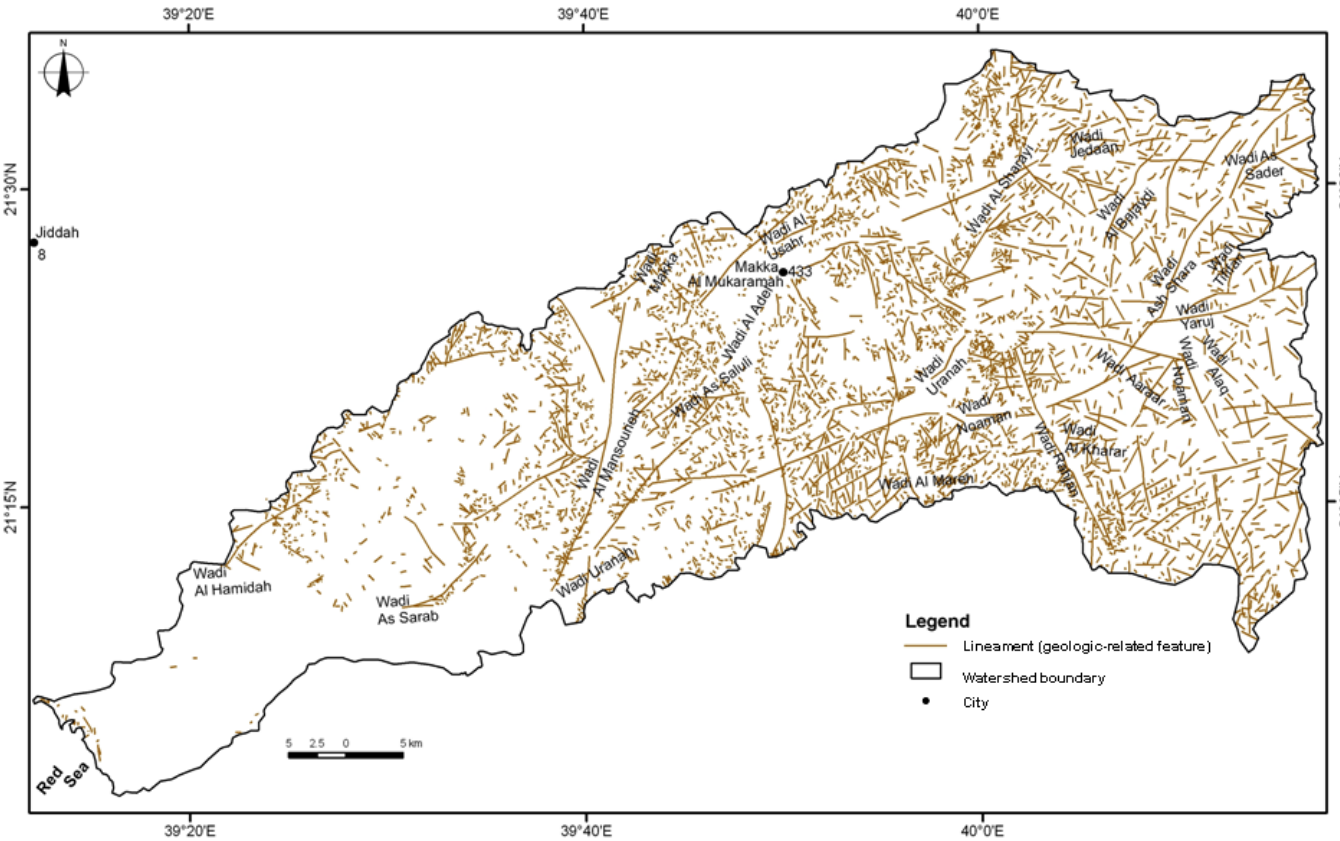

Fig. (4). Lineaments map of Wadi Aurnah basin as adopted from ASTER images.

ments map reveals a range of lengths, which are indicative of several geo-tectonic and geomorphic controls, mainly: the power of the tectonic forces, rock hardness and consolidation, geomorphic setting of terrain where lineaments exist. In the Wadi Aurnah basin, the smallest identified lineament was about 500 m long, whilst the longest one spans more than 35 km, and continues outside the area of study; it may extend some tens of kilometres (Table **2**).

4.2. Lineament Frequency

Many studies, such as Gustafsson [14] and Teeuw [18], estimate the lineament density, which expresses the total length of lineaments per specific area. However, the concentration of lineaments of different lengths within a specific area indicates certain properties of fracture systems. The latter indicator is called lineament frequency and is more useful for describing rock deformation. Greenbaum [19] expressed lineaments frequency (F_L) as the visible number of lineaments per unit area.

$$F_L = \boldsymbol{\Sigma} \mathbf{L}_n \qquad \mathbf{A}$$

For this purpose, lineaments frequency often expressed spatially on geographic distribution basis, which is done through maps. Thus, areas with different lineament frequencies will describe zones with different fracture system properties. This adds valuable information to studies concerned with infiltration and groundwater recharge properties.

In this study a lineament frequency map was produced showing eight frequency intervals (Fig. **5**). The development of this map followed a grid classification approach, in which the basin of Wadi Aurnah was classified into frames of 5km x 5km, thus the number of linears was counted in each frame. Consequently, the resulting values were plotted in the middle of each frame. Accordingly, these values were utilized to draw the contours for the frequency intervals.

Table 2. Lineaments Classification and their Geometric Characteristics in Wadi Aurnah Basin

Lineament Type	**Length**	**Extent Orientation**	**Dominant Geologic Control**	**Existence* (*Per Number*)**
Large-scale lineaments (long)	>10 km	Straight and almost slightly curved	Regional tectonic forces resulting long faults	2%
Moderate-scale lineaments (Moderate)	1 -10 km	Straight and partially curved	Almost due to faulting and sometimes to lithologic contacts	8%
Small-scale lineaments (short)	<1 km	Almost straight	Small-scale faults and sometimes local joints	90%

** Percentage of existence in Wadi Aurnah basin according to the obtained lineament map by the author.*

The lowest number of lineament frequency was less than 60 linears/25km^2, whilst the largest exceeded 420 linears/25km^2. The highest values were concentrated in the middle part of the study area, while the low values were al-

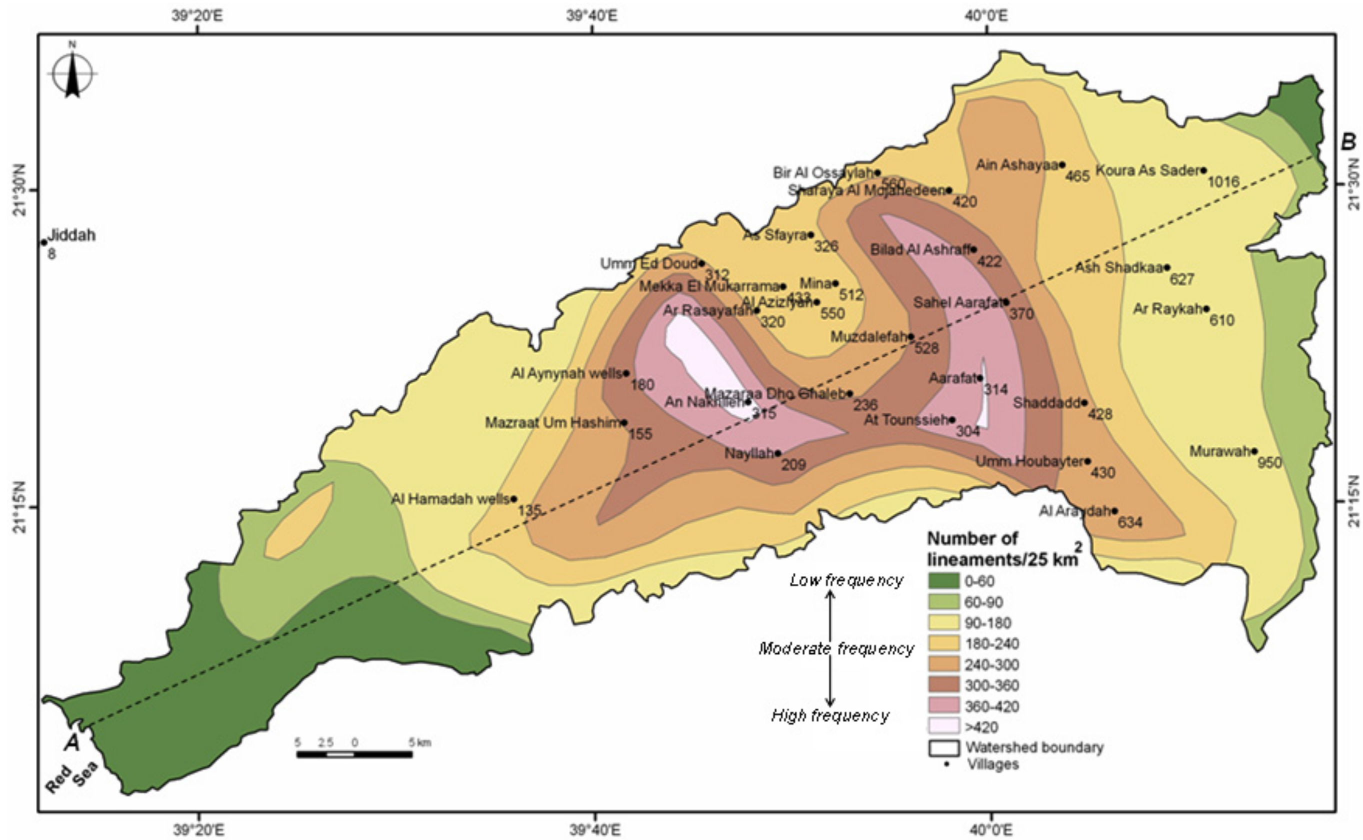

Fig. (5). Lineament frequency map of Wadi Aurnah basin.

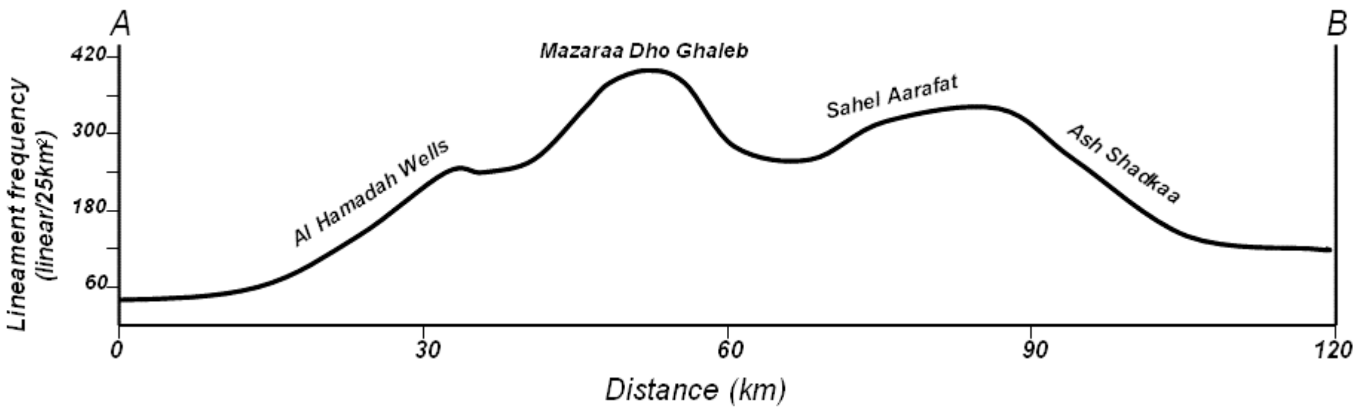

Fig. (6). Simplified cross-section showing lineaments frequency in Wadi Aurnah (AB- section according to Fig. (**5**)).

most all located in the coastal area where Quaternary deposits exist (Fig. **6**).

4.3. Lineaments Direction

The dominant direction of lineaments is indicative to the direction of the generating tectonic forces. However, rock types and their competence also affect the direction of linear features. Our lineament map (Fig. **4**) shows a wide variety number of linear directions. In the study area, three major aspects of lineaments direction were expressed using rose-diagrams, which describe the length and dominant direction of lineaments per number.

a Short-chaotic lineaments direction: This is applied to lineaments with short lengths (< 1km), and in some instances to the moderate ones with are less than 5km length (Table **2**). This type has no specific direction, and multi-direction sets dominate even within a small region (Fig. **7a**). These lineaments are almost always found as clusters and were attributed to local fracture and joint systems,

b Uniform lineament direction: This type always follows certain direction patterns and reflects specified geologic structures (parallel faulting, horst faults, joint systems, etc). Therefore, their direction/or length usually appear as parallel lineament sets (Fig. **7b**),

c. Long-lineaments direction: This type is attributed to the long linear features (>10 km length), which are almost crossing through different rock formations follow (Fig. **7c**). The existence of this type often accompanied with geo.morphological features (e.g., valleys,

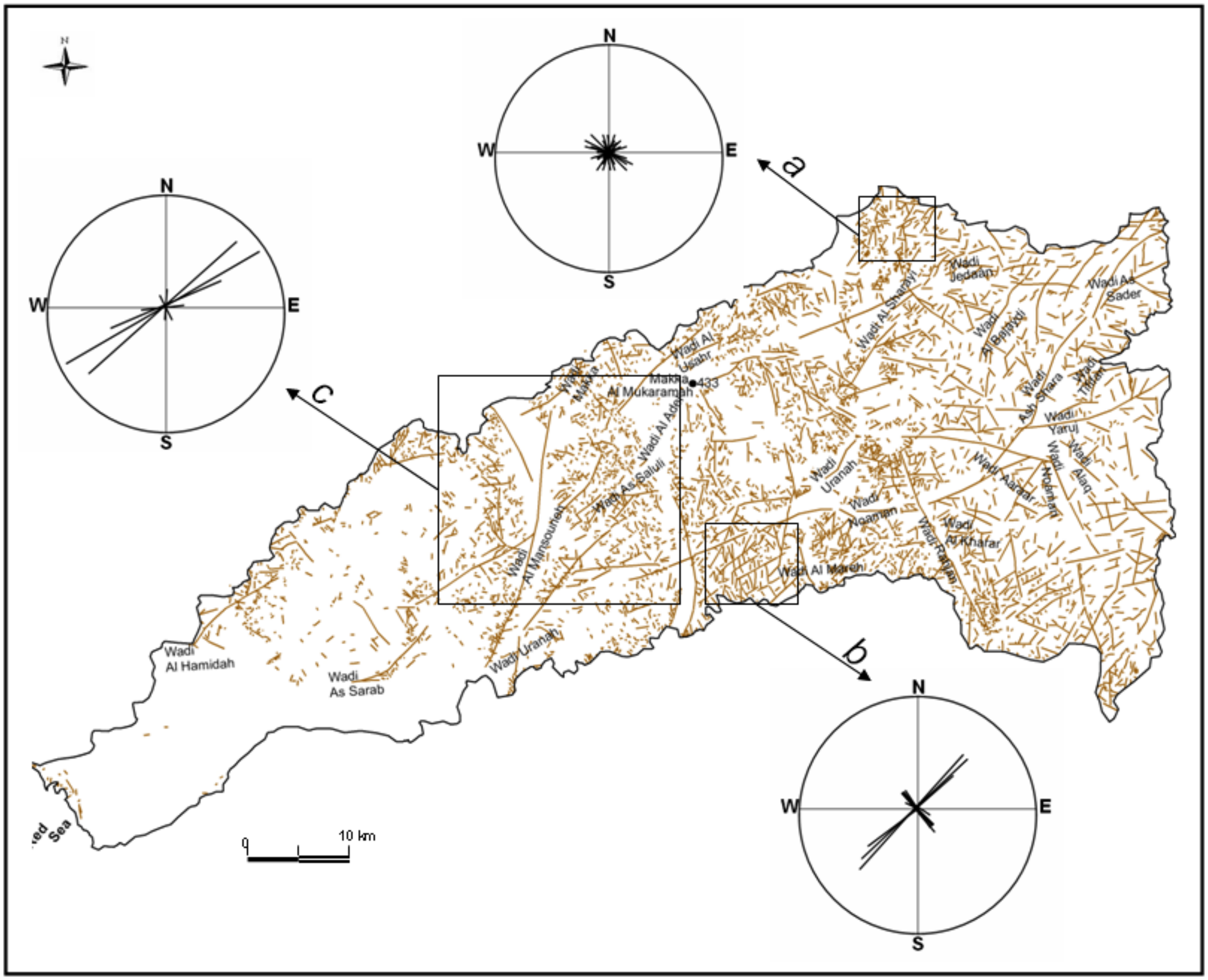

Fig. (7). Rose-diagrams of three areas representing the aspects of lineament directions in Wadi Aurnah basin.

depressions, elevated areas, etc.). This type is common in the Arabian Peninsula and found to control a large number of valleys, thus fault-valleys often exist [20].

In the area of concern, long lineaments are considered to be the major structural controls for many valleys, such as Wadi Al Mansourah, Wadi Al Adel, Wadi Rahjan, Wadi Al Sharayi and many other major valleyes, which are described as fault valleys.

4.4. Lineament Orientation

This property distinguishes a number of lineaments features which results from the morphometric interrelation between different lineament sets rather than from one-set lineament. In other words, the existence of lineaments, of different scales and shapes, adjacent/or intersected with each other creates certain orientations (i.e., patterns).

In the study area, there are a number of lineament orientations; however, the most common were found to be:

a. Rounded orientation: Some of the existing lineaments show circular orientation. This is a common phenomenon in the study area. These circulars often occur with relatively wide diameter (i.e., several kilometres). They almost always reflect the existence of geomorphic ring structures (Fig. **8**),

b. One-side lineament orientation: This type of represents dense clusters of short lineaments on one side of a long lineament (Fig. **8**). It indicates lithologic diversity between the two sides of the long lineament, where the latter must be a fault system along which different lithologies have resulted,

c. Parallel orientation: This type exposes a uniform parallelism of lineament of moderate and long type (Fig. **8**). They represent horst faults and grabens, thus depression exists, which were found to be filled with Quaternary deposits.

d. V-shape orientation: This is a simplified orientation, in which two lineaments, often moderate and long ones, are intersected at acute angle (Fig. **8**). The intersection usually terminates the shorter lineament, whilst longer one spans for longer distance. This re-

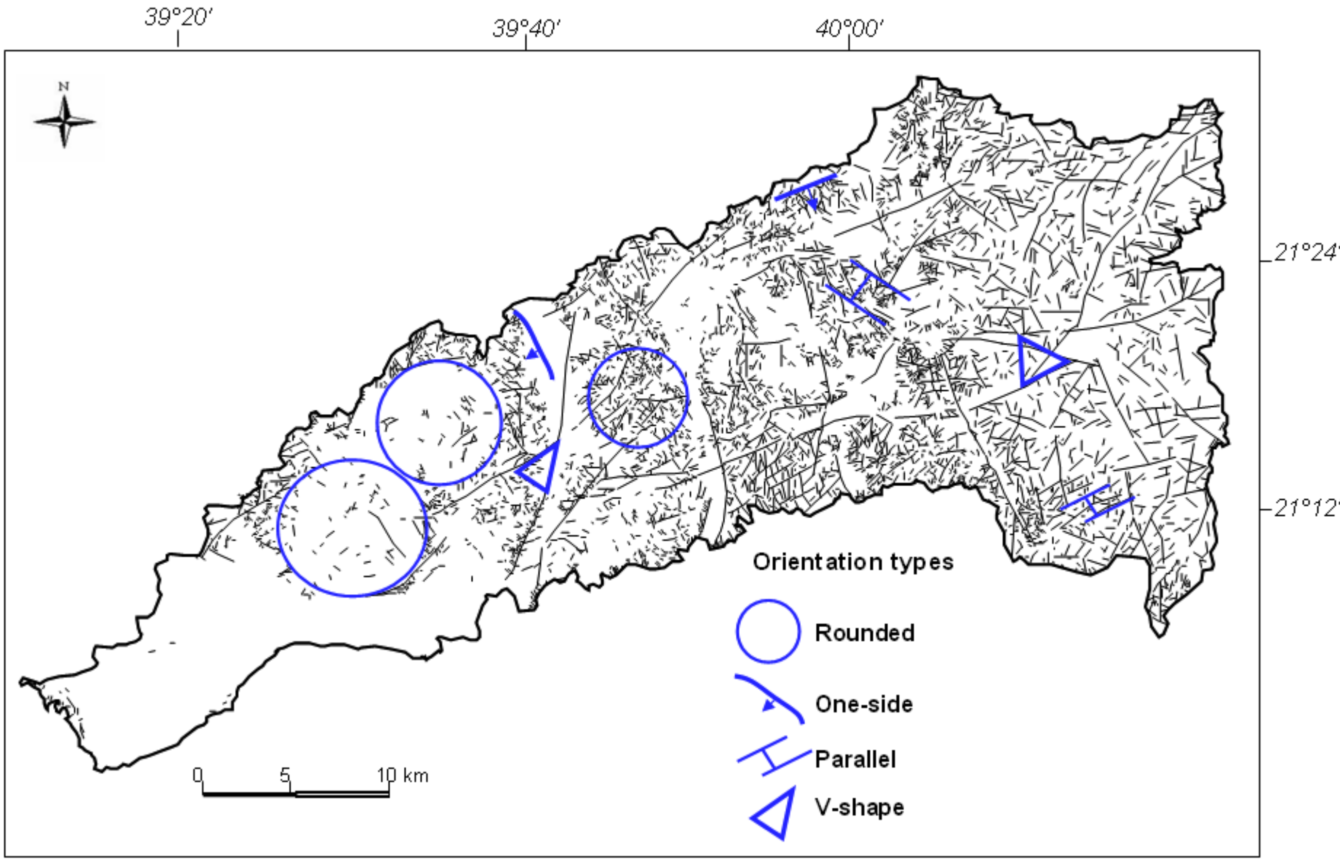

Fig. (8). Examples of major lineament orientations in Wadi Aurnah basin.

flects differences in the energy of tectonic forces between both types of lineaments.

5. CONCLUSIONS

The development of remotely sensed data introduced valuable and supplementary information on terrain characteristics. Linear features, the subject of this study, is one principal aspect of this information. Thus, several recent studies tackled these features, but the purpose and approaches of analysis differ from one study to another.

Wadi Aurnah basin, a major catchment in the western part of the Arabian Peninsula, was selected for this study. ASTER satellite images, with high spatial resolution (15m), were processed to achieve the lineaments map of the basin. Therefore, the obtained map was analyzed to diagnose major properties of linear features and their interrelation with each other.

Therefore, lineaments length, frequency, direction and orientation were analyzed and measured. Each of them treats certain geologic and geomorphologic criterion.

From the obtained analysis, several findings are resulted:

a. Some lineaments appear disconnected (as short linears) due to the existence of human activities along a lineament alignments of theses lineaments,

b. Many short lineaments are found as clusters of uncertain direction, thus representing intensive fracture systems of fissures and joints, which is almost due to domal or anticline structures.

c. Short lineaments are important in water infiltration, while long ones serve in groundwater flow regime for long distances,

d. The frequency of lineaments in Wadi Aurnah basin is concentrated in the middle part of the basin. This points out the high infiltration rate in this part, which needs further field verification,

e. There is a range of lineament directions in the study area. For each sort of direction, a diagnostic analysis was carried out,

f. A number of orientations were also reported, thus each of them is a function of specific geologic and geomorphic terrain behaviour, hence needs correlative analysis to infer the existing relationships.

Analyzing lineaments from satellite images enables obtaining a miscellany of terrain applications, such as the selection of landfill sites, determining terrain stability, dam sites, and many other applications, but the most effective are those related with water resources management.

In this view, several hydrogeologic studies show the creditability of using lineament maps as a major element in groundwater flow and storage regime. Thus, lineaments were utilized to identify:

a. Recharge potential zones: It implies the density of fracture systems, which allows surface water percolating downward through rocks and soil [13, 15, 21]. Hence, terrain surface with high recharge property is considered as a clue area for surface water to move downward and feed groundwater storage and flow.

b. Groundwater potential zones: Percolated water through the recognized recharge potential zones will continue to flow through fractures (identified lineaments) until stores in a geologic rock trap [13, 16, 18, 22, 23].

c. Groundwater flow to the sea: This is a common hydrologic criterion in many coastal aquifers where groundwater flows from land into the sea along faults/ or fracture systems (identified linear features) [24].

Even though, such applications in the Arabian Peninsula are still initiatives and sometimes lacking; however, this study extends an example of analyzing such observations from space (i.e., lineaments). Thus, further applications can be done to other parts of the Peninsula, especially in groundwater assessment.

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