[PS]Multi-Scale Lineament and Geological Mapping Elucidates Subsurface and Regional Tectonic Influences in Kuwait*

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Abstract

This paper presents efforts to generate a completely new surface dataset in the form of lineament maps at different scales using remote sensing techniques, to elucidate major subsurface and regional tectonic influences in Kuwait. USGS Landsat-7 imagery TM bands 1 and 4 were enhanced using image processing software for the regional lineament mapping of over 12,000 km^2 in central Kuwait. In ground truth, these were found to be linear relief features in the form of subtle escarpments, ridges, and valleys, occasionally forming characteristic drainage patterns. One hundred and nineteen regional lineaments, with an average length of 6,500m were mapped, which showed NW-SE and NE-SW trends. ESRI's high-resolution world images of 70 km^2 adjoining Mutla Ridge on the Jal Az-Zor trend, parallel to the northern coastline, were interpreted for detailed geological and lineament mapping, using ArcGIS Explorer. The area showed excellent rock exposures of Late Oligocene to Pleistocene ages. The lineaments observed were mainly of two types. The coastal lineaments were several hundred meters long and up to 12 meters wide linear depressions of subtle relief that appeared darker due to higher moisture content. On the other hand, the Mutla Ridge lineaments were longer, linear ridges, escarpments and prominent linear valleys often having lighter tone due to recent alluvial and aeolian sands fills. Two hundred and four lineaments, with an average length of 300m, were mapped. The coastal lineaments showed primarily NW-SE trends while the Mutla Ridge lineaments showed both NW-SE and NE-SW dominant trends. The lineament analysis was carried out using GEOrient, and all maps were integrated on ArcMap 10.1 using topographic and image web base maps. The subsurface seismic and well data from nearby oil fields, were integrated with the findings of Jal Az-Zor area to conclude that a Tertiary fault shaped the straight NE-SW trending coastline, while the adjoining Jal Az-Zor escarpment is a geomorphic feature formed by the erosional retreat. The present study successfully relates surface based multi-scale lineaments using direct remote sensing observations with key subsurface structural elements for the first time in Kuwait. The analysis concludes that the Cenozoic compressional forces and the present day maximum horizontal stresses related to the Zagros orogeny, within the context of geodynamic stresses of the plate tectonic setting, shaped the surface and near subsurface structural elements of Kuwait.

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1. Introduction

Kuwait is located in the Northern Arabian Peninsula and shares borders with Iraq on the north and Saudi Arabia on the south. On the east it has the Arabian Gulf which forms Kuwait's coastline. In addition, two major islands in the Arabian Gulf constitute as part of Kuwait and are known as Bubyan and Failaka. It has a land area of approximately 26,000 sq. km, the topography of which is generally flat. Overall, Kuwait's topography consists of flat to gently sloping planes, low hills (e.g. sand dunes), low depressions, sabkhas (saline flats) with occasional river valleys and erosional escarpments (ridges).

Kuwait contains some major mega-scale features such as structural arches and gentle domal anticlines many of which are major oil-fields of Kuwait. These structural elements are identified using seismic lines, seismic structure maps, stratigraphic data logs from oil wells, remote sensing/ imaging data (including gravity, Landsat and borehole imagery data) as well as rocks from cores and outcrops (Carmen 1996). The fault related tectonic elements are seen shaping straight coastlines and headlands aligned with lineaments while the arches and anticlines coincide with the oil fields formed by structural entrapment (Fig. 1). Particularly noteworthy are north-south trending oilfields namely Burgan, Minagish and Sabriya on Kuwait Arch, and the northwest-southeast trending oil fields namely Wafra and Umm Gudair. Another prominent trend is the northeast-southwest subsurface structural lineations coinciding with Jal Az-Zor, Jal Al-Liyah, and the 3 headlands (Dasman, Al Salmiya and Mina Sa'id) further down on the east coast.

2. Project Aims and Objectives

This project aimed to prepare the lineament and fracture trend map of selected Kuwait surface outcrops using remote sensing techniques and relate them to structural and tectonic influences. It mapped the intensity and orientations of faults/ fractures/joints in the selected area of Jal Az-Zor and in Mutla ridge area. Needed field traverses and ground checks were undertaken on selected outcrops/ coastal exposures of Kuwait.

3. Methodology

The research methodology involved critical review and integration of previous works done on geomorphology, structure and geology to identify detailed field mapping areas and traverses. The tools for this project were remote sensing data, utilising GIS computer software ArcGIS and regional lineament mapping of selected area using satellite images of requisite bands. The satellite data was processed using a software called ImageJ to locate the lineaments by enhancing their contrast and trends by digital image processing techniques. Furthermore large scale Google Earth images and high resolution aerial photographs were also used for interpreting geology and structure of the areas identified for detailed mapping.

A four week field work was undertaken for collecting geological, structural and geomorphological data for mapping of the selected area. The fieldwork consisted of taking strike measurements of lineaments and strike and dimensions of fracture sets. The dip and strike data was interpreted using a freeware called GEOrient which helped in plotting stereonets and rose diagrams for the research. These field observations were integrated with remote sensing based observations and interpreted along with published magnetic, and gravity anomaly maps within the context of present day geo-mechanical stresses in the Arabian plate tectonics setting. Some oil well and seismic data from published literature was also used to infer subsurface tectonic influences.

Figure 1: Location of study area in Kuwait (Basemap: Esri Webmaps, 2012)

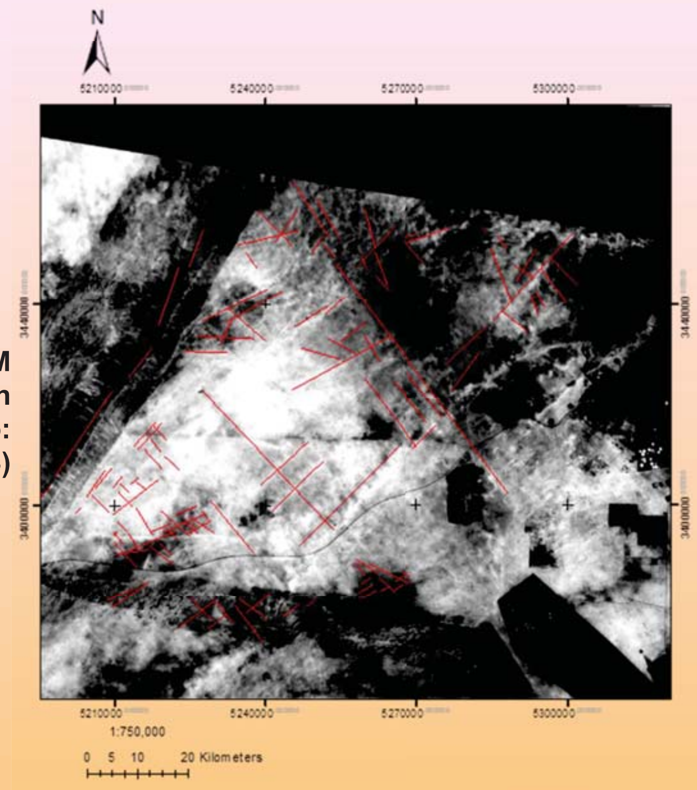

Figure 2: LandSat-7 Image (TM Band 4) based Lineaments in Regional Study Area (Basemap: USGS Satellite Imagery, 2003)

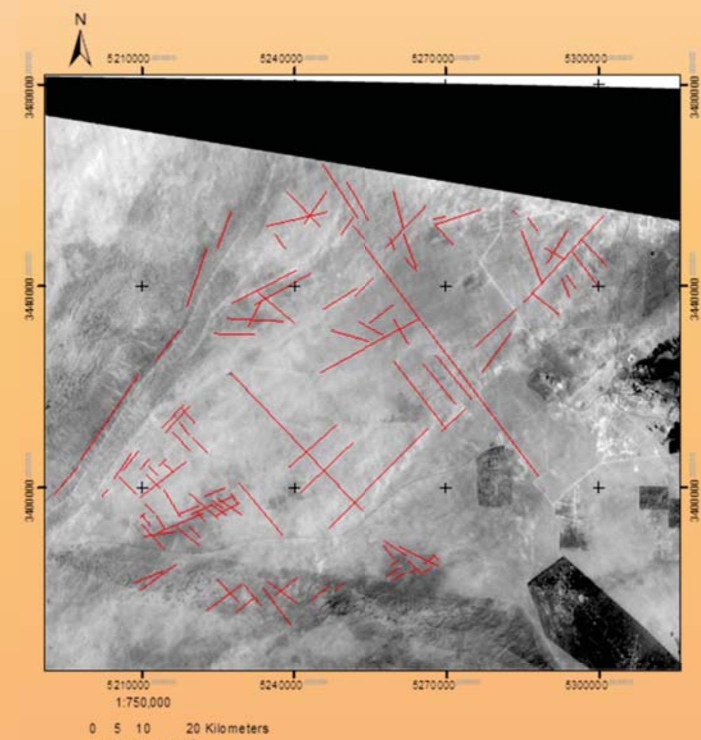

Figure 3: Landsat-7 Image (TM Band 1) based Lineaments in Regional Study Area (Basemap: USGS Satellite Imagery, 2003)

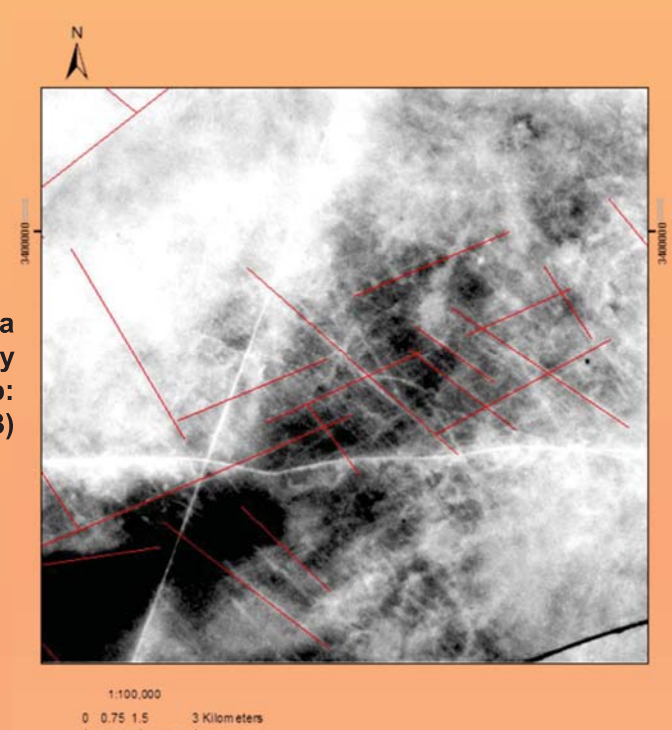

Figure 4: Example of a Lineament (cluster) in Salmy Area, South Kuwait (Basemap: USGS Satellite Imagery, 2003)

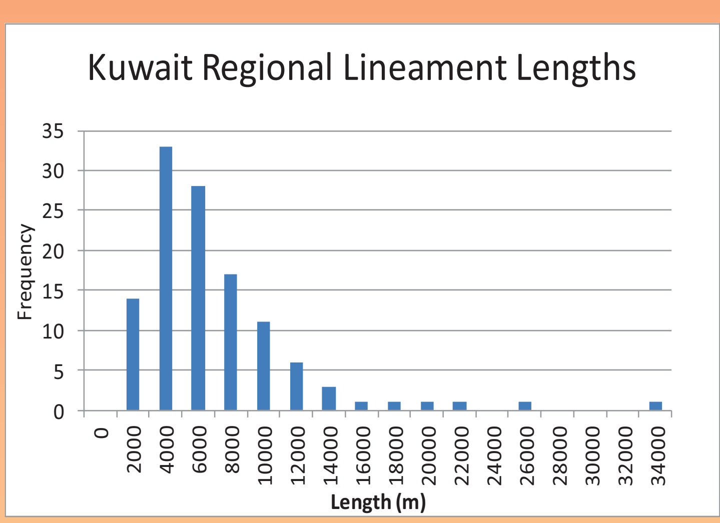

Figure 5: Length Distribution of Regional Lineaments

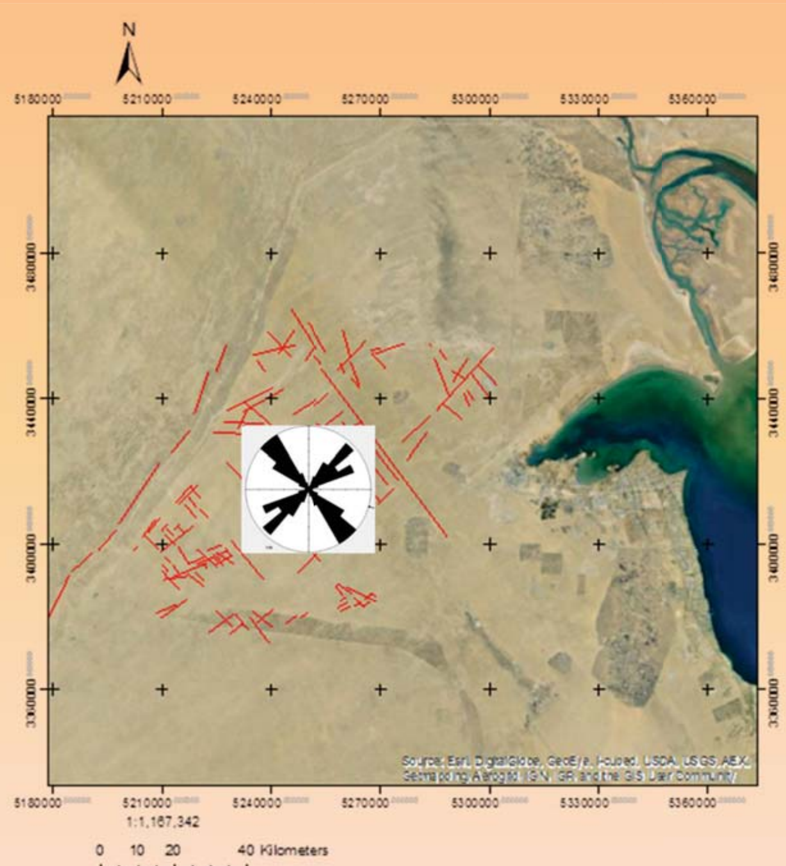

Figure 7: Central Kuwait Regional Lineament Trends (Basemap: Esri Webmaps, 2012)

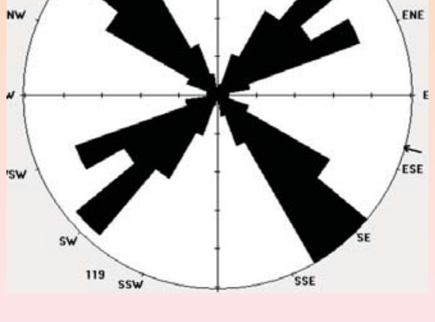

Figure 6: Central Kuwait Regional Lineam`ent Orientations

5. Regional Lineament Mapping

Regional lineament mapping was carried out using Kuwait's Landsat-7 satellite imagery downloaded from a USGS website using global visualization dataset interface. Several image analysis processes such as sharpening, contrast and filtering were applied in different thematic bands to map geological features and lineaments. Many false colour, lighting, and shaded relief schemes were experimented with, to enhance the visualization and understanding of the observed features and phenomena. The band 1 and band 4 images were found to be most useful on which the regional lineaments were mapped (Fig 2 and 3). The large scale lineaments were validated on web-based ESRI topographic elevation base map showing shaded relief with elevation contours. Utmost care was taken to avoid man-made linear features such as roads, pipelines, trenches, bunds (man-made levees) and property fence boundaries.

Most lineaments were found to be linear relief features in the form of subtle escarpments, ridges, and valleys. On large scale zoomed ESRI images, the Salmy cluster in southern Kuwait (Fig. 4) showed patterns similar to those observed in the coastal lineaments in Jal Az-Zor area. The NE-SW regional lineaments near the Western Kuwait border were found to be valleys parallel to the Wadi Al-Batin forming a trellis drainage pattern. The southernmost criss-cross cluster near Saudi Arabia border showed NW-SE & NE-SW trending valleys forming a rectangular drainage pattern.

6. Regional Lineament Results:

A total of 119 regional lineaments were mapped using satellite images in the central Kuwait regional study area. The regional lineament lengths varied from 250m to 50,150m with a mode of 4000m and an average length of 6,500m (Fig.5). The orientation of lineaments show three prominent trends, NW-SE, NE-SW and – ENE-WSW corresponding to general NW-SE and NE-SW structural elements observed in Kuwait (Fig. 6). The NW-SE trending set is oriented between N30ºW and N50ºW while the NE-SW trending lineaments have two trends oriented N45ºE and N65ºE (Fig. 7).

7. Detailed Jal Az Zor Lineament Mapping

Further to the regional lineament study, the Jal Az-Zor lineament trend was selected for further study in view of its tectonic significance. In this area, both detailed geological as well as lineament mapping were undertaken along with the field work in 70 km² area adjoining Mutla Ridge.

The detailed lineament mapping for the Jal Az-Zor area was a 2 pronged approach starting with the use of ArcGIS Explorer to find possible lineations in the mapping area. The database has a capacity of accurately zooming up to a scale of 1:4800. This method of mapping tested both the ability to do effective fieldwork and distinguishing geological features using satellite imagery and large scale ESRI web-maps. The second part was to map the exact location of any lineations found on the map. It involved driving to the coordinates of the possible lineaments, locating them on the ground and confirming whether they are actual lineaments or other man-made artefacts such as trenches, bunds and vehicle tracks in the desert. The ground truthing was made incredibly efficient by the use of a GPS device. The coordinates from ArcGIS Explorer were used to convert the lineaments into routes, for further analysis. If the lineament was confirmed then it was marked on the map with the correct orientation and subjected to further lineament analysis using GEOrient & Microsoft-Excel.

The lineaments were mainly observed in the coastal and the Mutla ridge areas while the intervening area, covered with drift fluvial deposits, had few lineament traces. The lineaments are seen as long linear tracks which are mostly larger than surrounding tracks made by vehicles on the surface of the desert area (Fig. 8). The features seen were confirmed as lineaments only after the field-check. In the field, the coastal lineaments were found to be depressions of between 0.5 to 1m relief, ranging in width from 2 to 12 meter and lengths between 10's to 100's of meters. Most coastal lineaments were subtle, moisture-rich, darker, linear depressions as compared to the surrounding areas (Fig. 9).
In comparison, the Mutla Ridge lineaments are prominent linear valley cuts, linear ridges and escarpments formed as erosional features. Often, the valleys are filled with alluvial and aeolian sands giving a lighter tone and texture as compared to surrounding rock exposures generating a sharp contrast (Fig. 10).

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8. Lineament Analysis:

The actual length and strike of each lineament was recorded and plotted as histograms. A total of 204 lineaments were mapped in the Jal Az-Zor study area. The lineament lengths varied from 25m to 1,0171m with an average length of 297m. The result of the orientation and length analysis of the Jal Az-Zor lineaments are shown in Figure 11.

Mutla Ridge lineaments showed three preferred orientations in the area. The primary trend of NW-SE is displayed by nearly 25% of the lineaments while two secondary trends of WNW-ESE and ENE-WSW are displayed by nearly 14% and 12% of the lineaments respectively. The primary orientation is similar to the coastal lineaments, which is proof that the lineaments are genetically related and correspond to a local preferred structural grain.

9. Result:

The analysis result of the detailed lineament study revealed that the lineaments originate from tectonic or structural forces and not from human or environmental processes such as the linear sand dunes caused due to prevailing wind direction. There is noteworthy parallelism between Kuwait's Regional and Jal Az-Zor area lineament orientations as they both have NW-SE as a major trend. The ENE-WSW trend is also observed in both, although it is less pronounced in the Jal Az-Zor area. Subtle differences such as absence of the NE-SW trend, seen in regional lineaments, and presence of a more pronounced WNW-ESE trend, particularly in Mutla area, seems to be related to local forces that shaped the northern coastline and the Jal-Az Zor escarpment. Furthermore, the relationship of the lineaments with smaller scale joint-sets is evident from the rose diagram showing joint trends in Western Mutla (Carmen 1996) shown in Figure 12. This proves parallelism between structural features observed in different scales from large scale regional lineaments, to local Jal Az-Zor lineaments as well as the small scale joint set trends affirming the genetic relationship.

10. Subsurface Geology Interpretation

The subsurface data from nearby drilled wells, available from published literature, has been integrated with findings in the Jal Az-Zor area to understand the subsurface structural influences on surface geology. The location of the cross sections NNE of the Jal Az-Zor area is shown in Figure 13.
The cross section along Mutla-1, Bahra-3 and Bahra-2 wells (MT-1, BH-3 and BH-2) running NE-SW perpendicular to Jal Az-Zor shows gradual thinning of the Kuwait Group towards north-east but without a discontinuity (Fig. 14).

In comparison, the Bahra -8, 3, 7 and Medina-1 wells (BH-8, BH-3, BH-7 and ME-1) cross section, perpendicular to the Jal Az-Zor escarpment, shows clear evidence of a fault in the Kuwait Bay running parallel to the escarpment and the coastline (Fig. 15). The well log correlation confirms the fault interpretation due to an elevation difference between the Rus and Radhuma Formation tops. Furthermore, the increase in thickness of Dammam and Rus Formations in the downthrown side suggests it to be a growth fault with a throw of between 50 to 70m (Al-Sarawi, 1982). This fault seems to have shaped the straight NE-SW trending coastline, while the present day Jal Az-Zor ridge escarpment seems to be a geomorphic feature formed by escarpment retreat through river erosion. Lack of any fault or discontinuity underneath today's escarpment also confirms this interpretation.

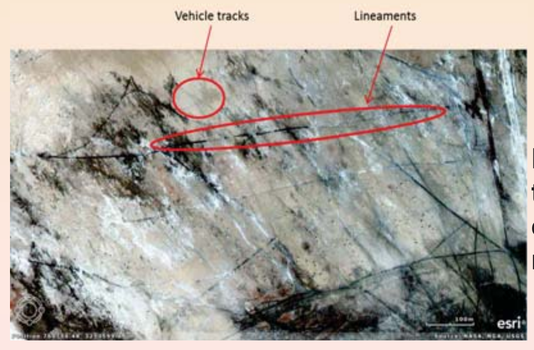

Figure 8: Aerial map view showing typical coastal lineament expressions (Basemap: ESRI Web map, 2012)

Figure 9: Field photograph showing coastal lineament (perpendicular to photograph plane)

Figure 10: Typical Mutla Ridge lineament examples (Basemap: Esri Webmap, 2012)

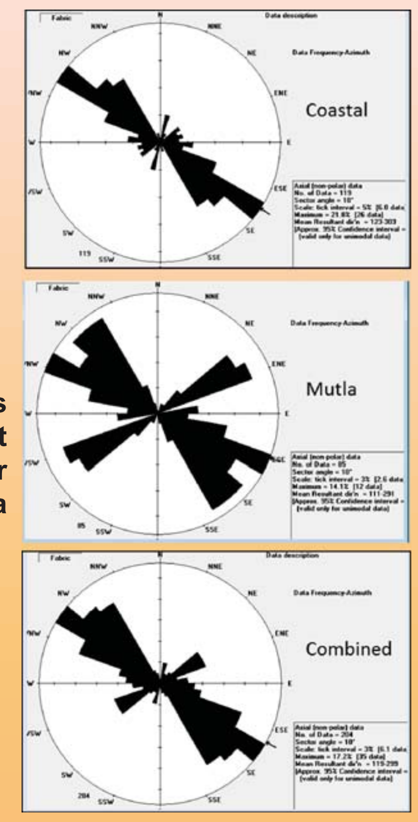

Figure 11: Rose Diagrams Showing Lineament Orientations in the Jal Az-Zor Area

Figure 12: Comparison of Lineament Trends (squares) with Joint Trends (circle) in the Jal Az Zor Area (Basemap: Esri Webmap, 2012)

Figure 13: Location of subsurface Cross sections along nearby Drilled Wells (Basemap: Esri Webmaps, 2012)

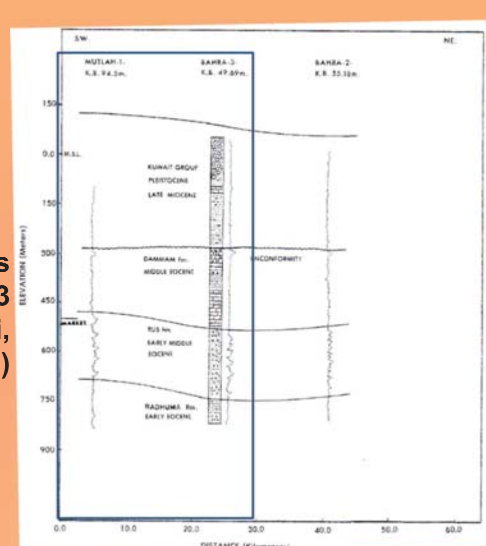

Figure 14: Geological Cross Section along Mutla-1, Bahra-3 and Bahra-2 Wells (Al-Sarawi, 1982)

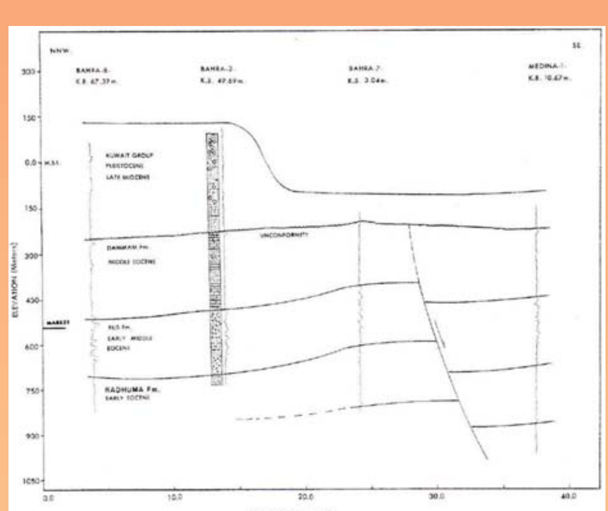

Figure 15: Geological Cross Section along Bahra - 8, 3, 7 and Medina - 1 (Al-Sarawi, 1982)

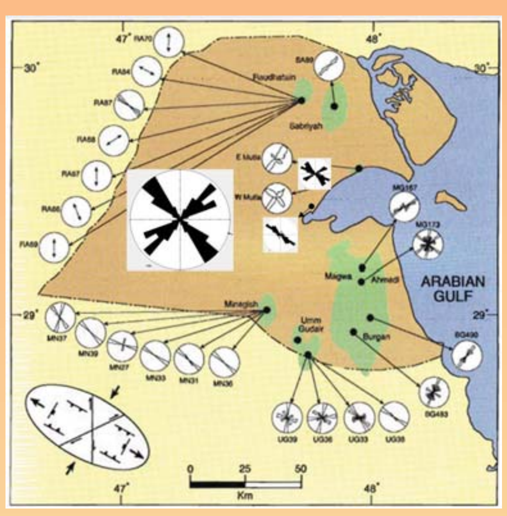

Figure 16: Regional Stress Field Indicators in Kuwait (Carmen 1996) Supplemented with present study results (square boxes)

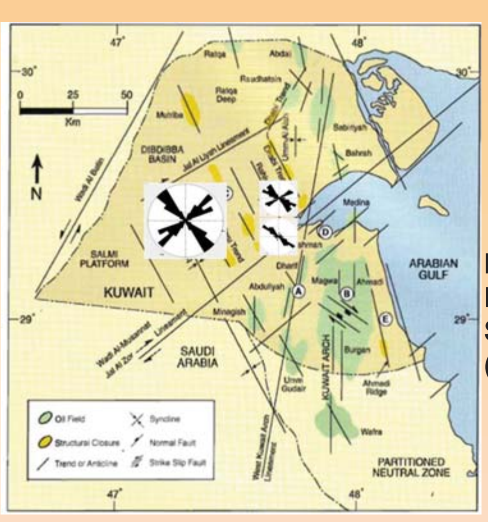

Figure 17: Comparison of Mapped Lineament Trends with Major Structural Elements of Kuwait (Carmen, 1996)

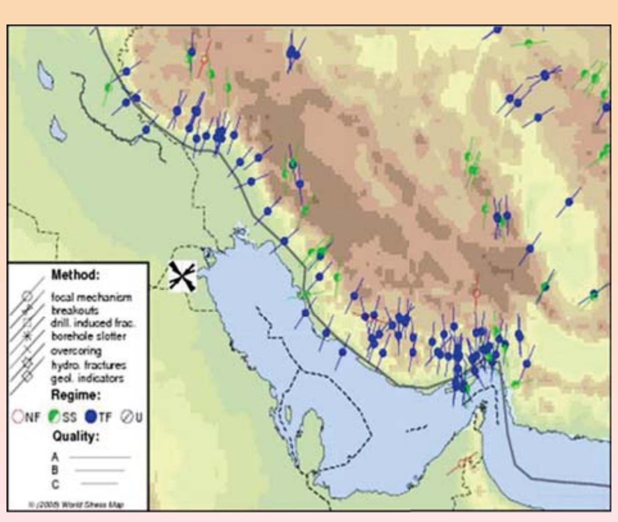

Figure 18: Comparison of Kuwait's Regional Lineament Trends with Regional Stress Trends (Basemap: Heidbach, World Stress Maps, 2013)

11. Integrated Lineament Interpretation

The smaller Jal Az-Zor lineaments and longer Central Kuwait regional lineaments were combined to plot their length frequency histograms (Fig. 6). The histogram clearly shows that many more smaller lineaments were mapped on large scale ESRI images as compared to longer lineaments using satellite imagery. The combined orientation diagram shows that nearly 55% of the lineaments have the main N45ºW trend. This is caused by the NW-SE folding as a result of the compressional forces related to the Zagros Orogeny. The secondary ENE-WSW to NE-SW trend displayed by nearly 20% lineaments is parallel to the regional maximum horizontal stress direction prevalent in Kuwait (Fig.16 and Fig.18).

The mapped lineaments have provided a new type of observed data set for the first time in Kuwait; as most earlier observed data were either joint sets mapped on outcrops or borehole breakout data over oil fields (Carmen, 1996). What is more important is that the Central Kuwait lineaments have provided data in an area where no published data was available earlier (Fig. 16).

It is noteworthy that the present study not only validates earlier work (Carmen, 1996), but enhances the understanding of known structural elements of Kuwait, as the mapped NW-SE & NE-SW trends are found in both Jal Az-Zor and Central Kuwait areas (Fig. 17). Furthermore, it is noticeable that the second predominant NE-SW trend, parallel to the Jal Az-Zor and Liyah trends, matches well with the regional stress field; having a maximum horizontal stress perpendicular to the Zagros trend (Fig. 18).

12. Conclusions:

This was *the first morpho-tectonic study of Kuwait* and was successful in proving that the surface imprints mapped on the regional and local scales are related to the geology and structure of Kuwait. The observed lineaments have originated due to the late Cenozoic tectonic forces, and are accentuated by the present day regional stress field of the Zagros Orogeny. At the regional level, the result validates the known large scale structural elements of Kuwait and *successfully provides a new, previously unavailable, dataset for Central Kuwait.* The regional Kuwait lineament orientations accurately correlate with the NW-SE folding and NE-SW maximum horizontal stress trends related to the Zagros Orogeny. At the local level, this is affirmed by the positive correlation between the Jal Az-Zor lineament trend, and the trends seen from the borehole breakout/ joint set data in the Mutla ridge area. Sufficient proof has also been presented using the cross section data, from the local oil wells in the area, to prove that the *Jal Az-Zor escarpment is indeed a retreating erosional escarpment and is not caused by immediate subsurface faulting.*

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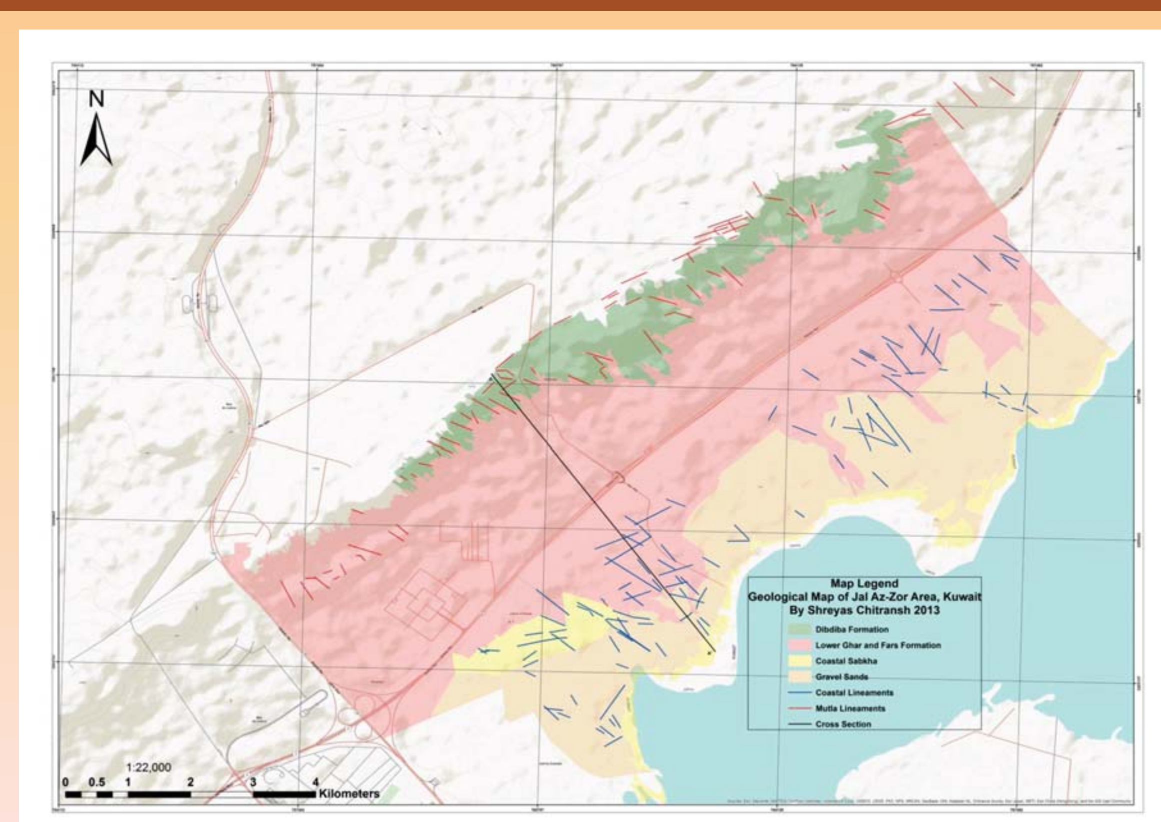

Figure 19: Geological and Lineament Map of the Jal Az-Zor area showing the lineaments (Basemap: Esri Webmaps 2012)