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HYDROGEOLOGICAL MAPPING IN THE SEMI-ARID ENVIRONMENT OF EASTERN JORDAN USING AIRBORNE MULTIPOLARIZED RADAR IMAGES

R. Saint-Jean*
MIR Télédétection Inc.
588 Booth St., room 209
Ottawa (Ontario) K1A 0Y7

Tel. : (613) 947-1306
FAX : (613) 947-1385
stjean@ccrs.nrcan.gc.ca

V. Singhroy
Canada Centre for Remote Sensing
588 Booth St., room 207
Ottawa (Ontario) K1A 0Y7

Tel. : (613) 947-1215
FAX : (613) 947-1385
singhroy@ccrs.nrcan.gc.ca

Abstract

This study focuses on the information content of HH, VV, VH and HV polarized airborne SAR data to evaluate which of these polarizations is more appropriate to facilitate mapping of lineaments and detailed drainage of wadis. It is known that a good knowledge of surficial lineaments and drainage network can help to locate wells and surface water retention dams used for groundwater recharge.<p>

The study area is located near the village of Azraq in the semi-arid environment of Eastern Jordan. In Jordan, water availability is a very acute problem as the demand is increasing and reserves are decreasing. A large amount of the water has always been obtained from deep wells but now, the rate of pumping exceeds the rate of replenishment. Additionally, the salinity is getting to a level where it is unsuitable for consumption. The area receives an average of 50 mm of rain a year mostly between October and March. Natural vegetation is very scarce and survives only in the temporary river channels. Since vegetation is very scarce, the water is rapidly evacuated and recharge of the underground water table is minimal. The area has a flat topography with slight depression enabling drainage during the “rainy” season. <p>

We use a set of airborne Synthetic Aperture Radar (SAR) images of Eastern Jordan obtained from a survey flown in 1993, as part of the Canada Centre for Remote Sensing’s GlobeSAR-1 project. All images were analyzed in order to enhance a maximum of hydrogeological information. Results show that the crossed polarizations images (HV or VH) and to a lesser extent, the HH like polarization images show a good contrast and enough details to permit hydrographic network mapping in the wadi (dry river beds) where a minimum of vegetation is available. The VV polarization is not as sensitive to vegetation presence but permits a better positioning of the wadi banks and is useful to map roughness variations within playas.

KEYWORDS: multipolarized radar, lineaments, drainage, hydrogeology

Introduction

All expert in the world predict that in the next few years, the increase in population, in industrialization and the needs of agriculture will create a strong demand for water in several countries (FAO, 1999). On the other side, in most of these regions, the quality and the quantity of water is degrading.

The Middle East, is one of these areas where the problem is most acute. In Jordan for example, an arid to semi-arid country where over 96% of the territory receives less than 300 mm of rain per year, all water resources are known and exploited for a long time and worst, pumping of the underground water table exceeds the rate of replenishment (World Bank, 1994). Jordan is looking for new ways and new tools to optimize the available water reserves. Because of its sensitivity to surface features, Synthetic Aperture Radar (SAR) Remote Sensing provides a tool that can help significantly in doing this type of hydrogeological mapping.

The area of the Azraq oasis in Eastern Jordan is very interesting because of its natural environment and because it is a natural regional topographic depression. For many centuries now, Azraq has been known for its aquifers suitable for human consumption and agriculture. But now, well have to be dug deeper and salinity is increasing. All mean to remediate this situation has to be explored.

Previous work

Several authors have explored solutions avenues in environments similar to the one of Jordan. Smith, et al. (1997) has used a GIS and spaceborne images to pinpoint areas of high potential of underground water in the Sinai peninsula. They used a Landsat TM image in conjunction with parameters obtained from a DEM (slope, drainage, etc.) and created layers (drainage density, slope, lineament density, etc.) analyzed in a GIS.

Travaglia and Ammar (1999) present a study in Southern Syria, a few tens of kilometers North West of our test site where they have extracted lineaments and integrated several layers of data in a GIS. Minor *et al*. (1994) has also used a similar approach for groundwater exploration in Ghana.

All authors agree on the approach to be taken, which can be summarized as:

- Extract lineaments from a Remote Sensing image (SPOT, Landsat TM or SAR) to obtain the structural context of the region,
- Bring the extracted lineaments into a GIS and merge with the other layers of information such as geology, hydrographic network, slope, field observations, etc.

Results are obtained by the simultaneous interpretation of these information layers using mathematical formulas or by creating "favourability" layers.

Objectives

It is already known (Travaglia and Ammar, 1999; Saint-Jean *et al*., 1995) that optical (VIR) sensors are very efficient in arid and semi-arid environments. We will demonstrate that multipolarization SAR data can provide high spatial resolution data that is complementary to VIR data that can facilitate the interpretation work for hydrogeological mapping. In this study, we will do a visual qualitative interpretation based on three multipolarized images. The analysis will show that each of the polarizations shows specific characteristics features in this environment. In each polarization, the structural hydrogeological information will be analyzed to optimize the location of water retention dams and water exploration wells.

We do not intend to discuss the entire methodological process as was done by other authors but we will try to demonstrate the value of multipolarized radar images to underline high potential areas in this environment.

Hydrogeological model

In this environment, it is important to understand the process of water capture to recharge the water table. Each year, precipitation occur during short but intense rain events during which water flows rapidly at the surface (because of the very scarce vegetation and of the hard surface, water retention is low). Water is channeled through a temporary surficial network (wadis) towards temporary lakes (playas) located to the north of the study area. Part of the water infiltrates the soil and passes to the underground water. The water flow has two main components:

- A vertical component corresponding to the water recharging the underground reservoir. This component is small when porosity is low and high where macroporosity and fracturation is important.
- A horizontal component modulated by the regional gradient and controlled by the intensity of the fracturation (structural corridors).

The strategic positioning of retention dams could slow down the run-off process therefore increasing the rate of water percolation.

Description of the study site

The area is located 130 km SouthEast of Amman, the capital of Jordan (figure 1). Azraq, the nearest village is located 30 km to the NorthWest of the study site. The study area covers 38 square kilometers (4.5 km by 8.5 km).

The average terrain height is 550 m ASL and is basically flat with a light north regional slope. The dendritic drainage network (wadis) is well developed and leads to temporary playas (also known as sebkhas). Terrain morphology is monotone and is composed of quaternary alluvium up to approximately ten meter thick, locally dissected by wadis (figure 2a, b).

Geology is very simple and consist of unconsolidated sediments lying upon Pleistocene sediments of the Azraq formation (evaporites, sandstones and conglomerates) (Ibrahim, 1993). Gypsum and limestone duricrusts are frequent (Abdelhamid et Fadda, 1993). Wadis are slight silty and sandy depressions that fill up with muddy waters during the rain events. The surface of the soil is covered by desert pavement (fig. 2d) that protects the fine unconsolidated sediments from wind erosion.

Rain events occur from October to April and average up to 50 mm per year (average of the last 50 years) (Ministry of Water and Irrigation et UNDP, 1992).

Desert pavement

The chert pebbles of the unconsolidated sediment form the desert pavement. The fine matrix is removed are removed by wind erosion and by run off during rain events. Because the slopes are very low, pebbles are not removed and produce a protective cover with time. On the three SAR images (fig. 4a), the desert pavement has a fine and uniform granular texture in medium gray tone. When the surface is disturbed (road work, jeep trails), pebbles are displaced and fine sediments are exposed. It is why the trails appear in darker tones on the image. On the Landsat TM image (fig. 3), desert pavement has a dark green tone (low reflectance) while exposed sediments have a much lighter colors.

Wadis

An important wadi crosses the image from bottom left to top right. A second one can be found in the bottom right corner of the image (visible more distinctly on the VV image of fig. 4a). As for most drainage features, an underlying geological or structural feature (fault, fracture, and geological contact) controls the main wadis. The wadi shown here is a good example of these phenomena, the azimuth goes from N25° to N115° at the level of the curve at the center of the image and comes back at N25°. Many authors have demonstrated that the drainage network structural feature is related with the presence of an underground water table (Bailey and Halls, 1999; Minor *et al.*, 1994; Saint-Jean *et al*., 1995).

A characteristic of this environment is that some vegetation is found within the wadi. Some spherical bushes, about 50 cm tall are often found in the wadis. The architecture of these bushes produce an important volumetric diffusion of the radar signal that interacts slightly with the VV polarization but more strongly with the HH and HV polarization. This phenomenon is more important in cross-polarization (HV).

Data

The Canada Centre for Remote Sensing (CCRS) airborne SAR has acquired the data used for this study on Dec. 8, 1993 as part of the GlobeSAR-1 program. The data has been acquired in C band (5.30 GHz or 5.66 cm), in four polarizations (not calibrated), and in nadir mode (incidence angle between 0° and 72.4°). The data has been processed to 7 looks with pixels spacing of 4 m.

Images characteristics

This study uses a 1024 by 2048 sub image where incidence angle varies between 38° to 58°. Near side is always on the left side of the images (illumination from the left). The two parallel images (HH and VV) and one cross-polarization image (HV) has been retained due to the reciprocity of the coefficient in cross polarization (Raney, 1988).

On the 3 images presented in figure 4, no processing has been applied (except for a linear radiometric enhancement). Figure 3 show a Landsat TM image of the area for comparison.

Results and discussion

Several observations on the backscattering and on the texture can be made on the SAR images. The wadis are bright on the HH and HV images because of the strong backscattering of the vegetation (Saint-Jean *et al*., 1995). On the VV image, the radiometric contrast between the wadis and the desert pavement is low; this greatly limits the detection potential of the drainage network. However, this permits a better positioning of the areas where roughness is low (very low backscatter hence very dark tones). These zones are found where the wadis are more than approximately 50 m wide or within playas.

The desert pavement has a relatively homogeneous texture on most of the image indicating a low variability of the surface roughness and a relatively homogeneous pebble size. Lets now have a look a each image to examine the specific characteristics of each polarization.

HH Image

The main wadis produce a good backscatter on the SAR image (fig. 4a, left image). The affluents (second and third levels) are also enhanced facilitating the mapping of the drainage network. In several areas, the hydrographic network is parallel to the main wadi indicating again the importance of the underlying geological structures. Where the wadi is wider and where the sediments are finer (smooth flat surface) the tones are darker. The presence of vegetation in wadis is directly related with the intensity of the backscatter in HH polarization.

VV Image

The VV image (fig. 4a, centre image) show a very different response of the surface features. The contrast between the hydrographic network and desert pavement is low and it is hard to map the drainage network. The SAR signal has a minimal interaction with the architecture of the vegetation. However, this produces a stronger penetration of the vegetation and permits a better evaluation of the surface roughness. This is probably why the playa shown on the top right corner of the image shows more details in VV than with the other polarizations. For the same reason, the wadi seen in the bottom right corner is barely visible on the other images. Roads and trails and the roughness component features of the image (desert pavement) are also more easily visible on this image as their contrast is stronger. Since the drainage network is more difficult to extract on the VV image, it is also harder to identify lineaments of structural origin. Only the major lineaments or regional importance are visible.

HV Image

There is an important similarity between the HH and the HV image (fig 4a, right image). However, the contrast between the drainage network and the environment is better on the HV image. Also the amount of details is finer and more easily mapped producing a faster and more precise interpretation. This is especially noticeable on the cross polarization image where the depolarization caused by multiple diffusion of the trunks and branches of the woody vegetation adds up to the direct volumetric backscatter (Evans *et al*., 1986). The better contrast is better facilitating the interpretation of structural lineaments.

Drainage network and structural interpretation

The lower portion of fig. 4 shows three interpretations of the drainage network from the polarization images. The interpretation has been done visually from each image. The HV image shows more details than the other polarized images. The HH image is more or less useful, as its sensitivity is intermediate for drainage detection and to map the borders of the playas.

Figure 5 shows an intepretation of the lineaments made from the HV polarized image. We assume that the lineaments represent geological features (faults, fractures) that produce surface features that may be detected by the SAR system. The lineaments have been traced from an interpretation of the drainage network and also from the subtle tonal variations of the image that produces a significant more or less linear alignment. Several lineaments are very closely related to drainage features. For example, the N115° lineament (more or less parallel to the main road) seen near the center of the image. Along this direction, the major wadi makes a turn that constitutes a significant change in the area's drainage pattern and that brings the wadi parallel to the lineament. The same with the lineaments oriented N10° (right side of the image) that underline the straight section of the main wadi as well as several other minor affluents. Elsewhere on the image, the lineaments reflect the drainage network that is underlined by the presence of vegetation in the wadis.

Several lineaments, oriented N65-70° are seen in the bottom half of the image. Travaglia and Ammar (1999), in their study done in Syria to the north-West of our study site, noted this direction as being of regional importance and being the most promising taken into account the density, the opening and the macroporosity associated to these directions. It is important to remember that in this type of environment, the chances of having a successful well will depend on the density of fracturation of the rock and on the recharge capacity of the water table. It is therefore preferable to do a detailed structural interpretation and to validate the results with a drainage map to maximize the chances of success of the wells.

Recommendations

The green circles shown on figure 5 indicate the high productivity potential for underground water. These zones are defined by the following criteria:

- High lineament densities that imply an important macroporosity that allows free circulation of water in the underground water reservoir.
- Presence of long lineaments. The longer the lineaments, the higher the capacity of the reservoir.
- Lineaments intersection. As many lineaments intersect, reservoirs associated to these lineaments are connected therefore increasing the reserves available from a single well.
- Orientation of the lineaments. When lineaments are oriented along a favorable direction, the probability of success is higher.

- Coincidence of drainage network and lineaments. This factor is important as it provides a way to recharge the reservoir during rain events.

It is however difficult to indicate a favorable location for a dam as the topography is very low on our study site. Using natural depression (playas) would be ideal as they are natural reservoirs but it is not recommended due to their low volume, the high level of sanding and of the high salinity of this environment. We therefore recommend to locate some small dams downstream from the high fracturation areas (red rectangles on fig. 5) to promote recharge of the underground water table using the open fractures and downstream from a playa to promote direct percolation.

Conclusion

In conclusion, the polarized SAR images are useful for hydrogeological mapping in the arid to semi-arid environments found in Eastern Jordan. The HH and HV images show a good enhancement of the drainage network when some vegetation is present as it produces a strong radiometric contrast and allow a detailed mapping. However, the cross polarization (HV) image shows a better contrast and a finer and more detailed level of details on the drainage network than that of the HH image. The VV image shows an information content different from the other images. The VV image is useful to map playa borders and is somehow insensitive to vegetation.

This study was done in regards to the upcoming availability of multipolarized spaceborne SAR images of RADARSAT-2, ENVISAT and LightSAR that will be launched in the next few years. The proposed images characteristics of these systems (polarization, ground resolutions, etc.) will be very similar to the ones used in this study.

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FIGURES

Figure 1. Location of the study site

Figure 2a) Typical view of the study site, very flat surface covered by chert pebbles (desert pavement) and dissected by a wadi (temporary riverbed). Some vegetation can occur in the wadi beds. b) Example of vegetation in a wadi. The shrubs (height of 0.75 to 1 m) have very deep roots to fetch humidity. c) Dry silt in a wadi. From November to April, rain events are rare but violent. Since the area is flat, the fine sediments (silts and clay) accumulate in the wadi. d) Chert pebbles form a crust that protects the finer particles from excessive wind or rain erosion.

Figure 3. Landsat-5 TM (bands 4,5,7) of the Azraq area. The village and the agricultural settlements of the oasis are seen on the top half of the image. The red box indicates the study area. Wadis are in light tones while desert pavement is shown in green tones.

Figure 4. **A)** Top row: Airborne C-band SAR images in HH, VV and HV polarizations (VH is almost identical to HV and was therefore omitted). Images have not been processed except for a radiometric enhancement for display purpose. **B)** Bottom row: Interpretation of the hydrographic network from the polarized SAR images shown above. The HV polarized image shows the greatest details in wadis (red lines) were some vegetation is present while the VV polarization image underlines silty playas (blue lines) where no vegetation is present.

Figure 5. Structural interpretation from the HV polarized image. The green circles indicate the zones where the probable positive wells are to be expected. The red rectangles show the recommended locations of the dams.FIGURES

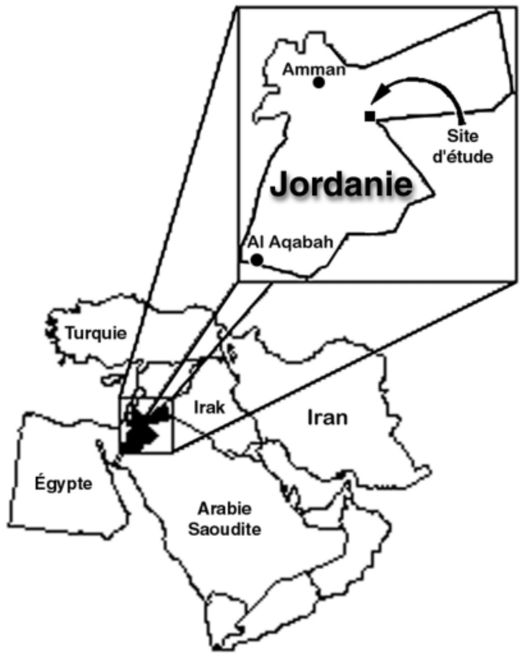

Figure 1

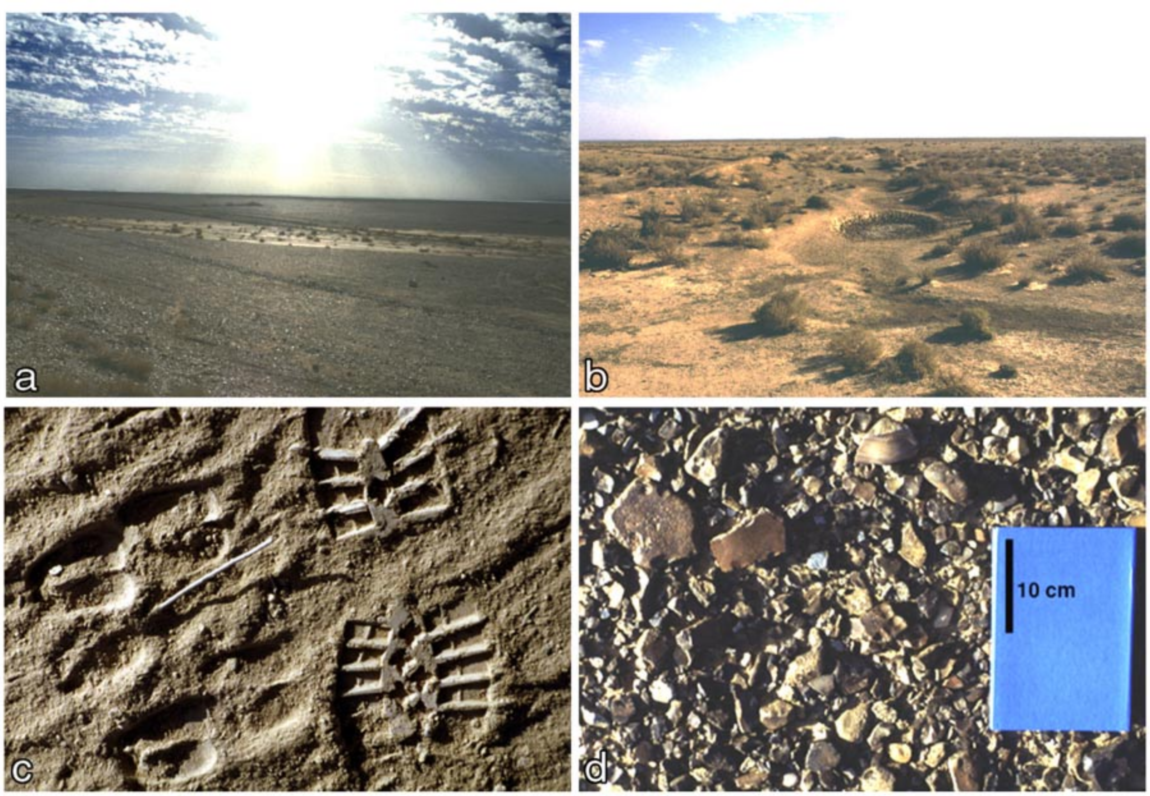

Figure 2

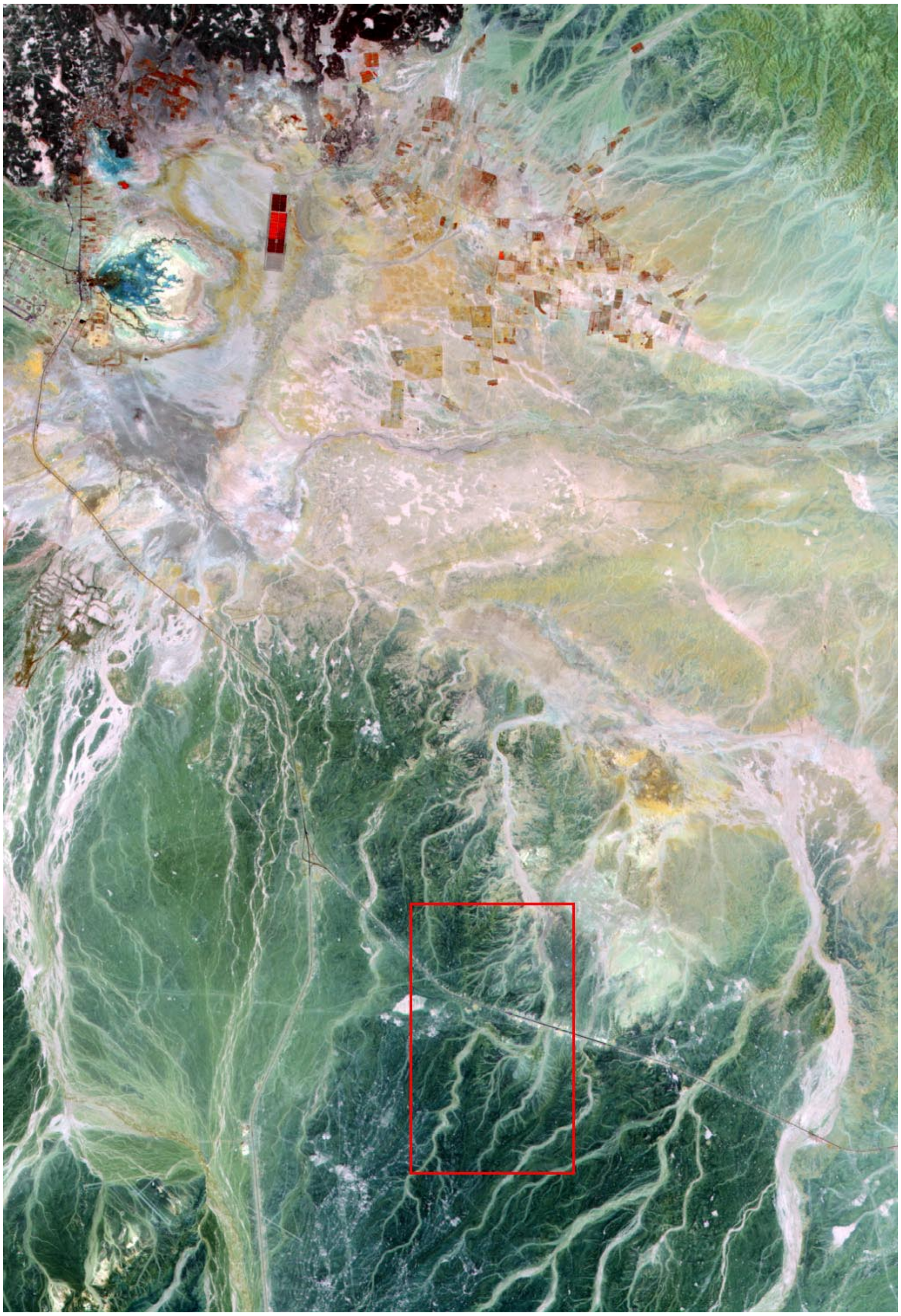

Figure 3

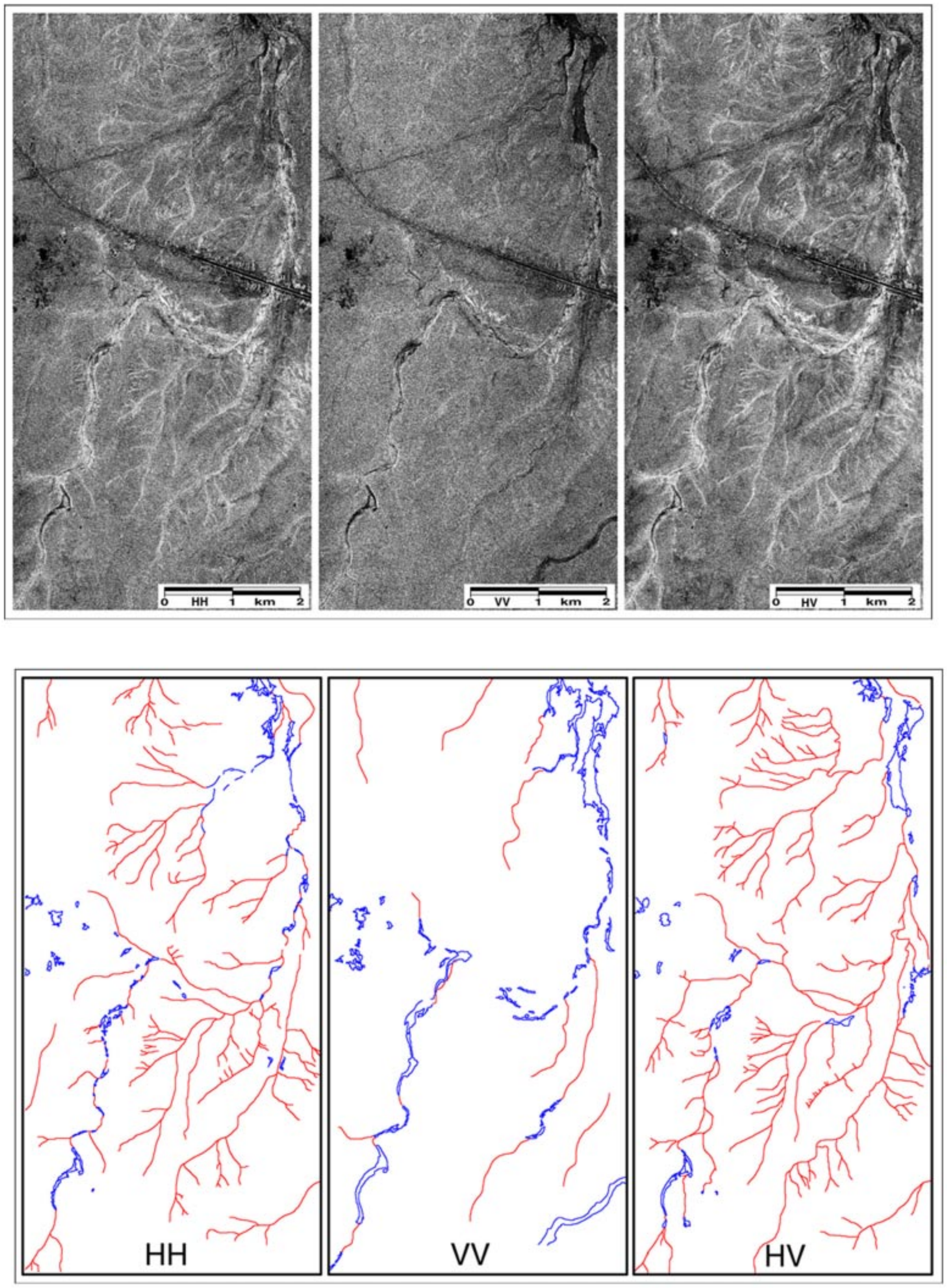

Figure 4

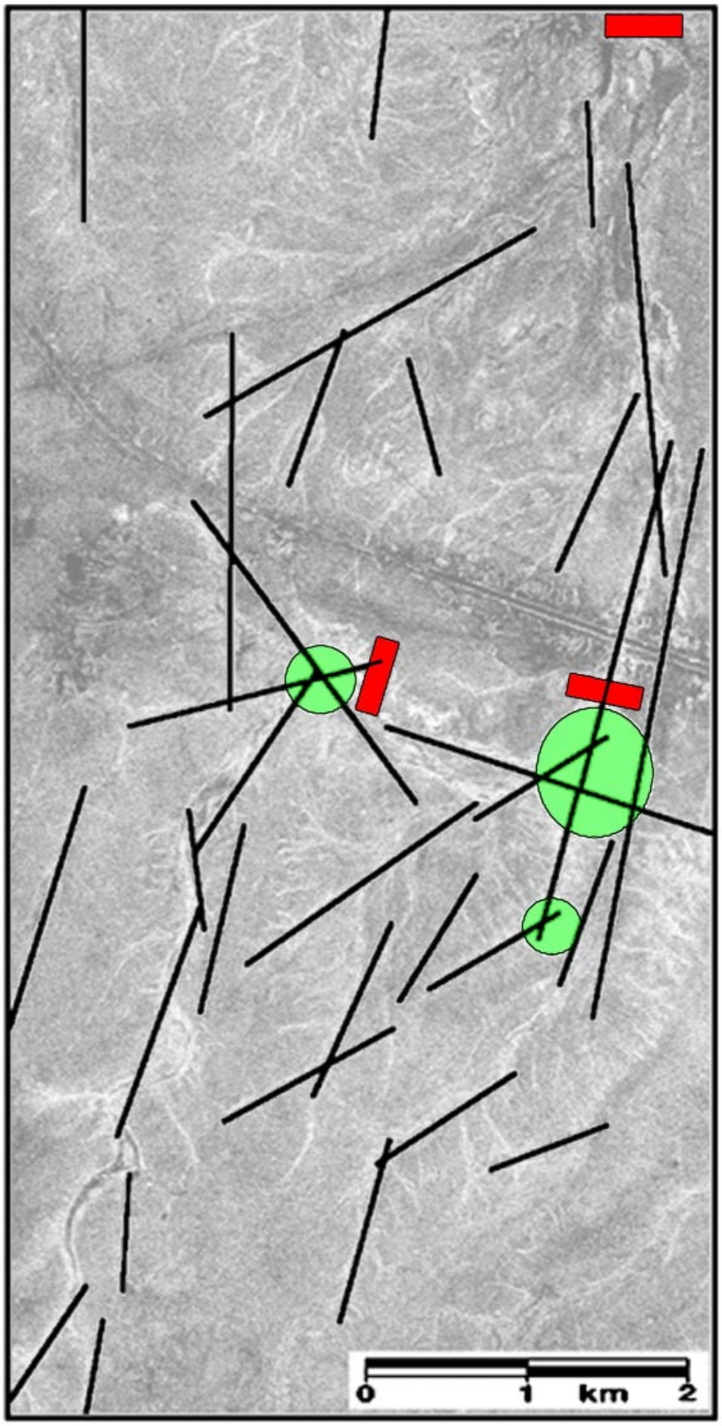

Figure 5.