Spot images remote sensing study of the fractured tabular Middle Atlas aquifer (Morocco)

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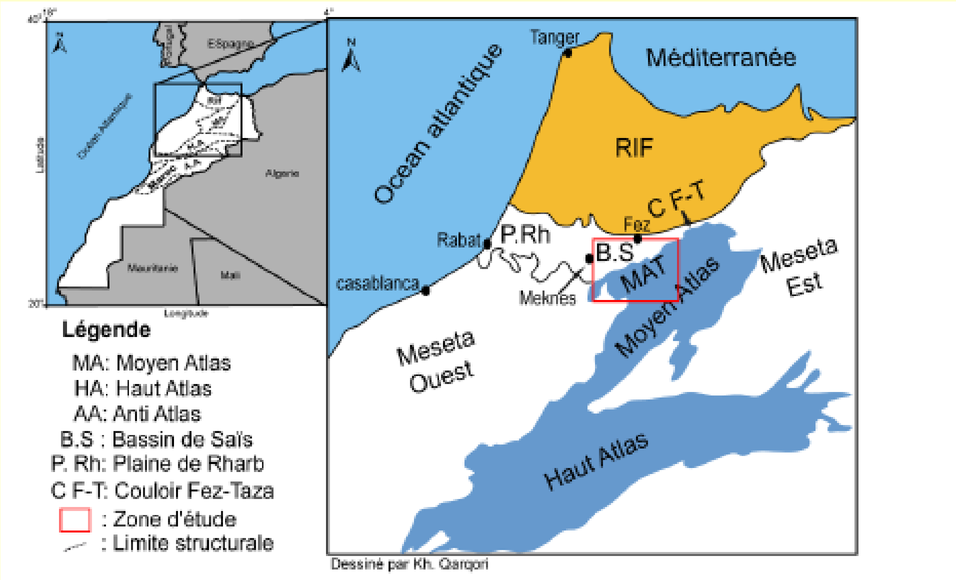
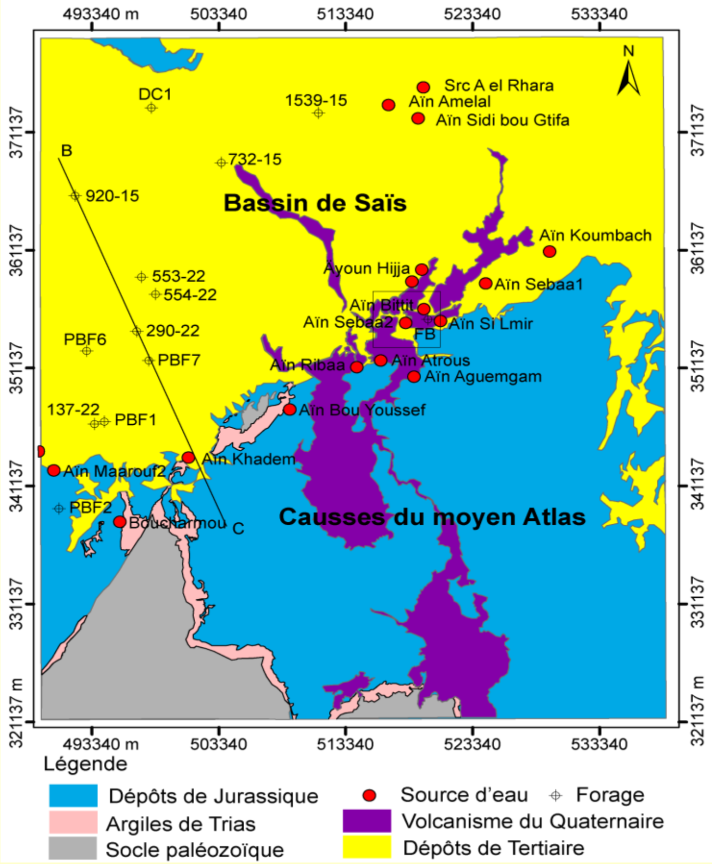
Objectives

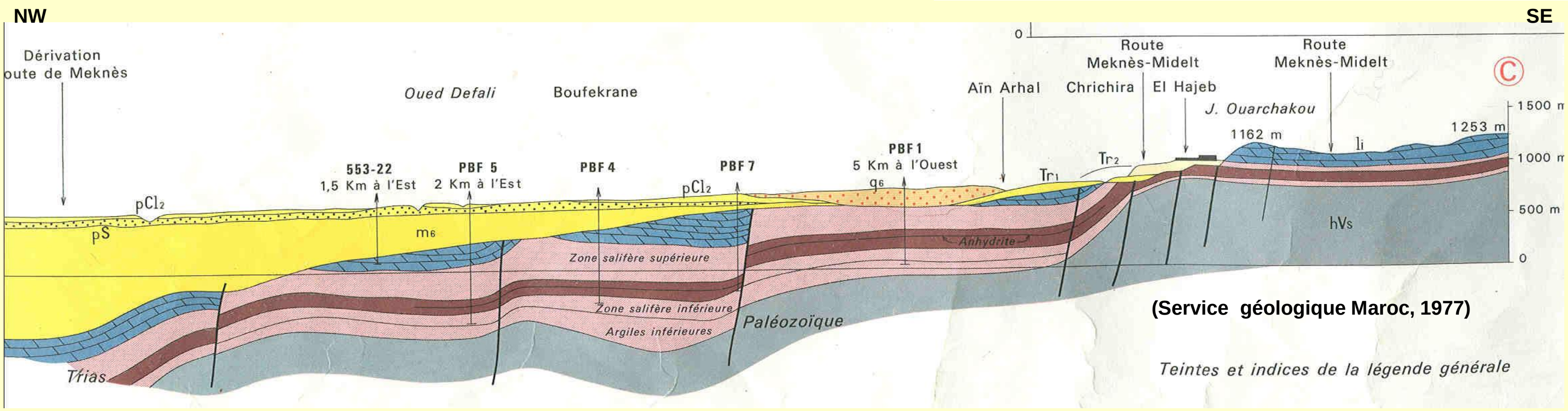
- Use of SPOT remote sensed images to study the fracture network of an important carbonate “hard-rock” aquifer in northern Morocco.
- Output: Reservoir fracture map, connectivity of fractures, targets identification, etc.
- Analyze of the scaling behavior and power-laws of fractures using the concepts of fractal geometry (Mandelbrot, 1982).
- Trying to extrapolate scaling laws and characteristic dimensions from surface analysis to the deep confined aquifer not directly accessible to observations.

Geological context



Location Map





(Service géologique Maroc, 1977)

Hydrogeological context

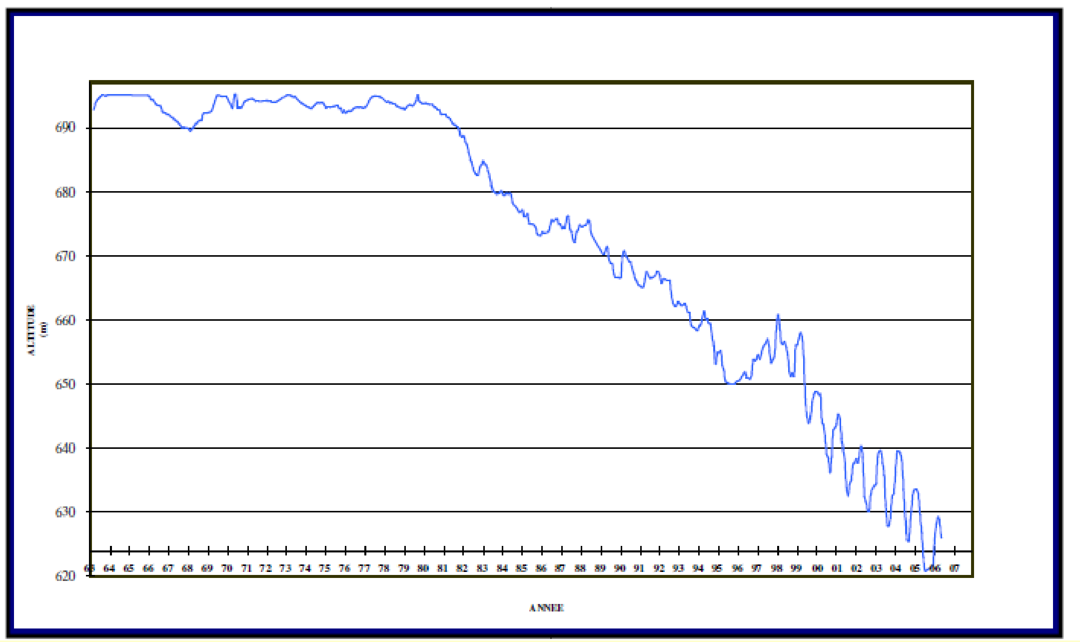
Tabular Middle Atlas (Causses) : 4600 km^2.

Average annual water balance: 277 Mm^3. Mobilized ressources: 50 Mm^3.

Average groundwater flow: 32-35 m^3/s.

About 10 m^3/s groundwater inflow towards Sais Basin.

(Bentayeb A. & Leclerc, 1977).

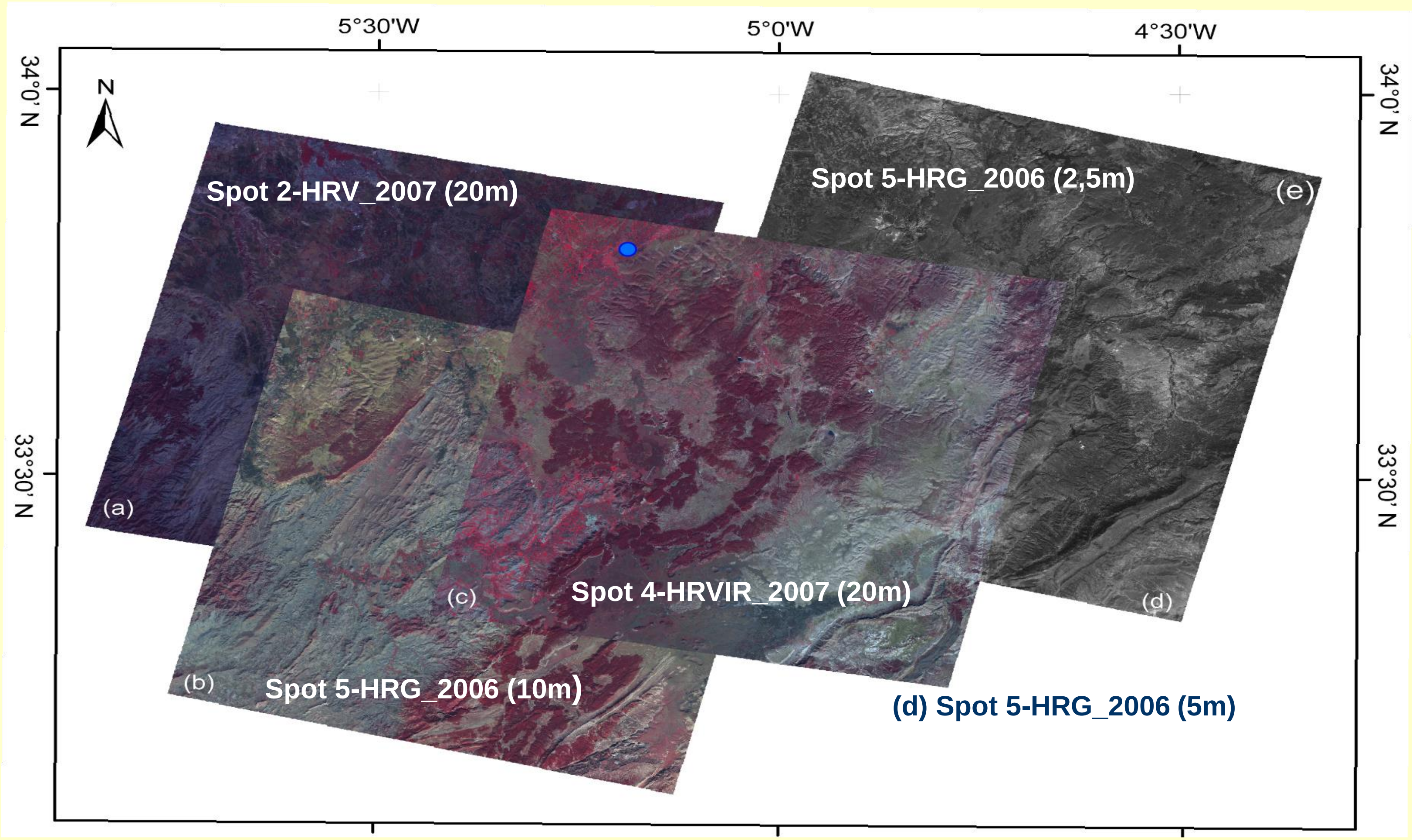


Well 290/22 (Haj kaddour, Sais Basin, 120 l/s)

64m drop of piezometric level in 24 years!!!

Over-Exploitation and Climatic Change!

Spot images



Georeferenced Spot images.
(a), (b), (c): Multispectral images ; (d) and (e): Panchromatic images.
Pixel size ranging from 2.5 to 20m.

Image processing

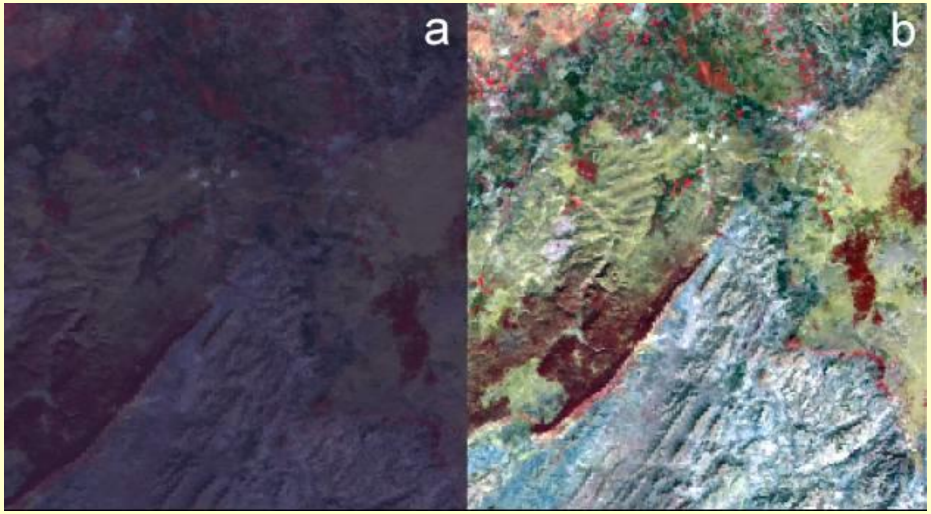
Classical way

- Dynamic stretching.
- Histogram equalization / Contrast enhancement.
- Edge detection / Directional filters:

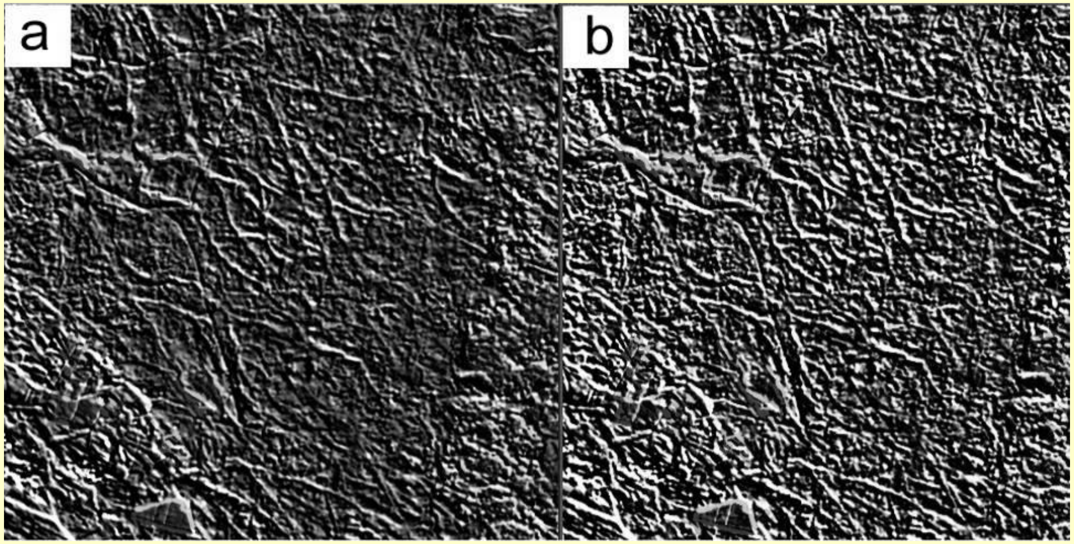
  Sobel (N-S, E-W, NE-SW, NW-SE).

  Laplacien of Gaussian.

  Gradient - Yésou et al. (1993).
- Image quality optimization.

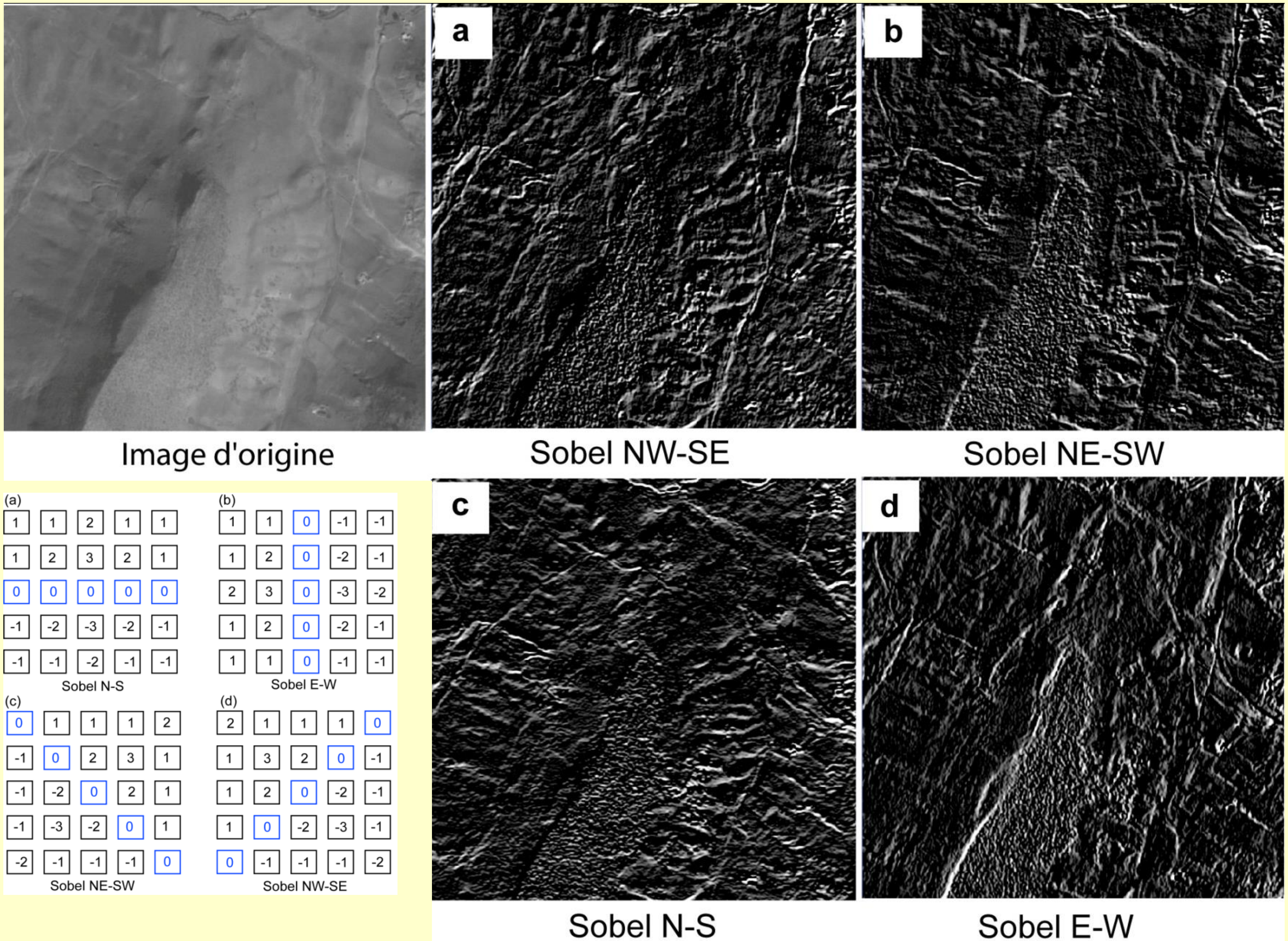


a) Raw image. **b**) Enhanced image.



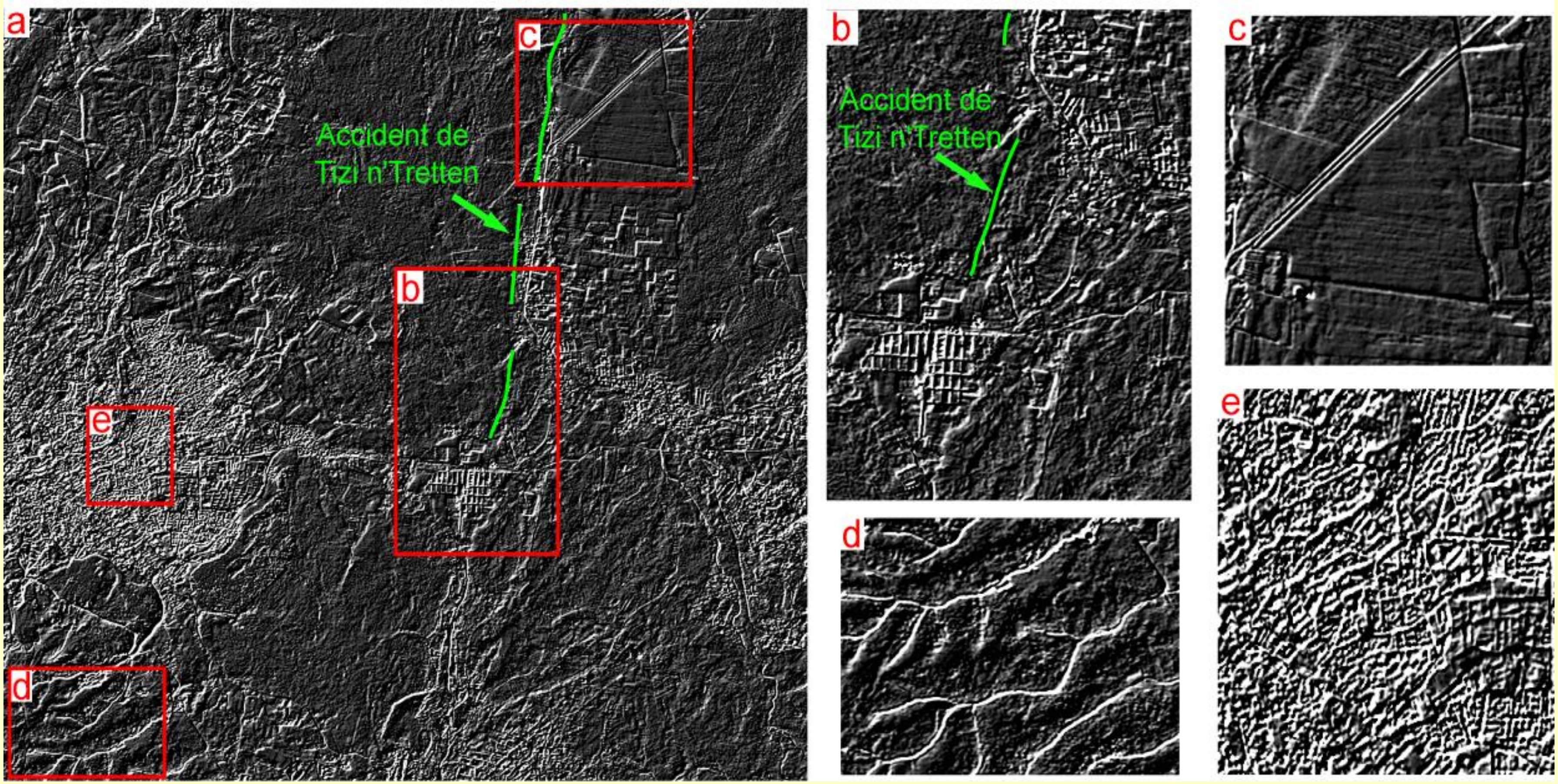
a) Sobel NE-SW. **a**) Enhanced Sharpness.

Directional filters / Edge extraction



Example of lineaments filtred by directional Sobel filters (5x5 pixels).

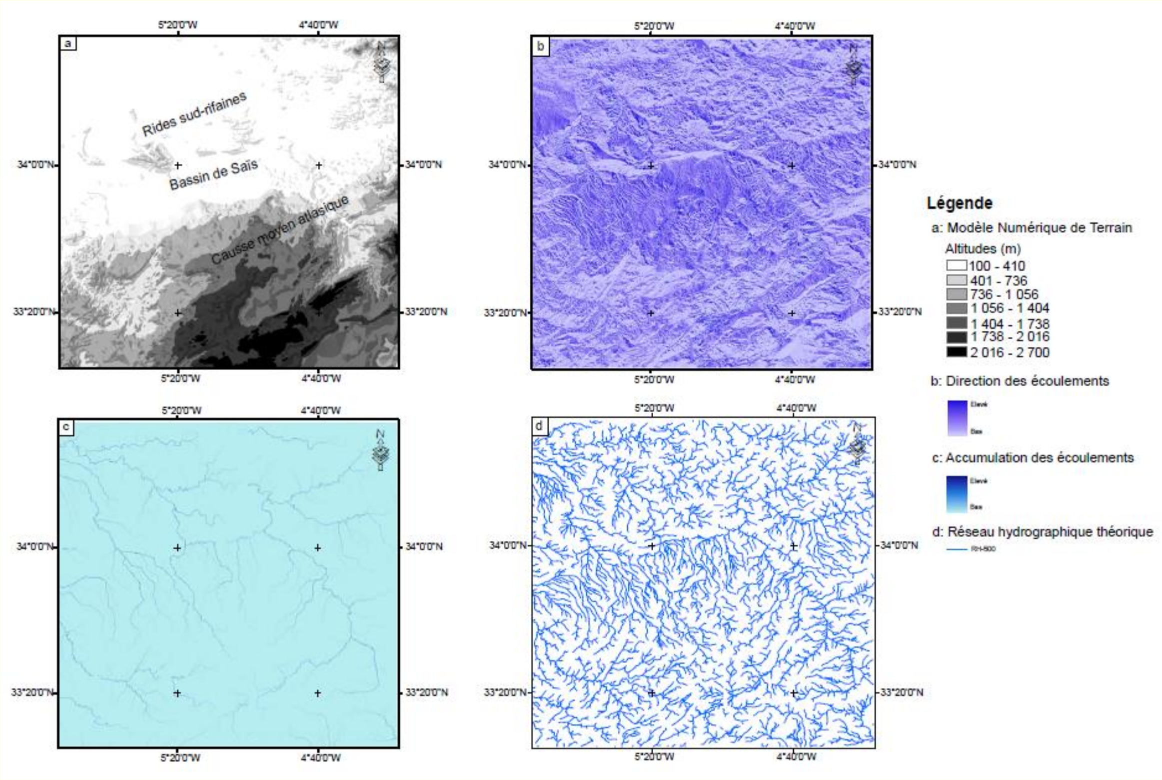
Example of processing



a) Panchromatic image filtered by Sobel NW-SE.
b) Geological fault « Tizi n'Tretten » visible north.
c) Cultivated area and road, **d**) Hydrography, and **e)** Urban area.

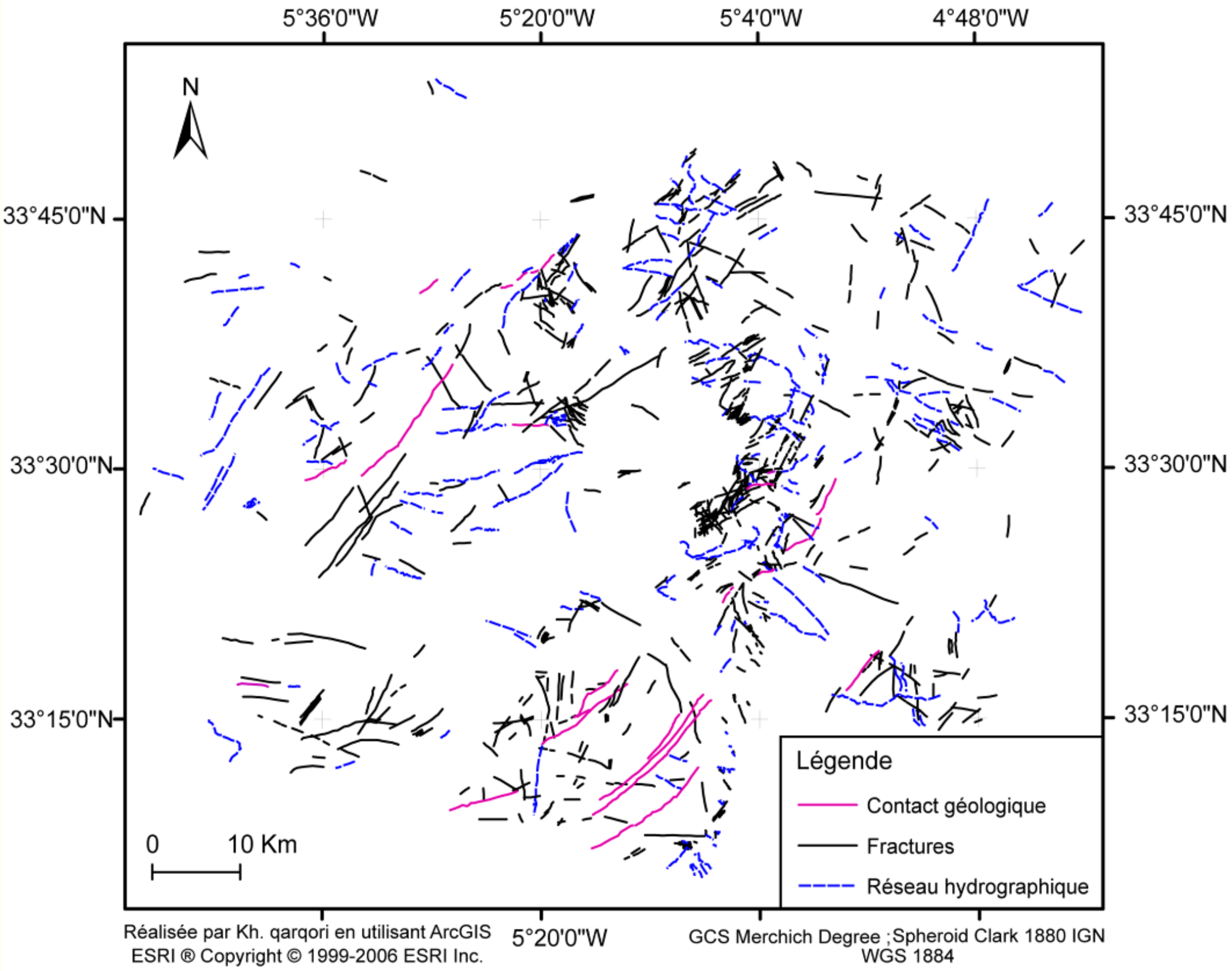
Cross-analysis of multi-source data

- Processed images have been georeferenced under GIS in order to map lineaments.
- Digitization of all extracted lineaments (faults and fractures, roads, streams, discontinuities, etc.).
- Cross-analysis of data in order to descriminates objects, using geological maps, DEM-SRTM (Shuttle Radar Topography Mission), etc.
- Analysis carried out with ArcGIS (Spatial Analyst Plus).

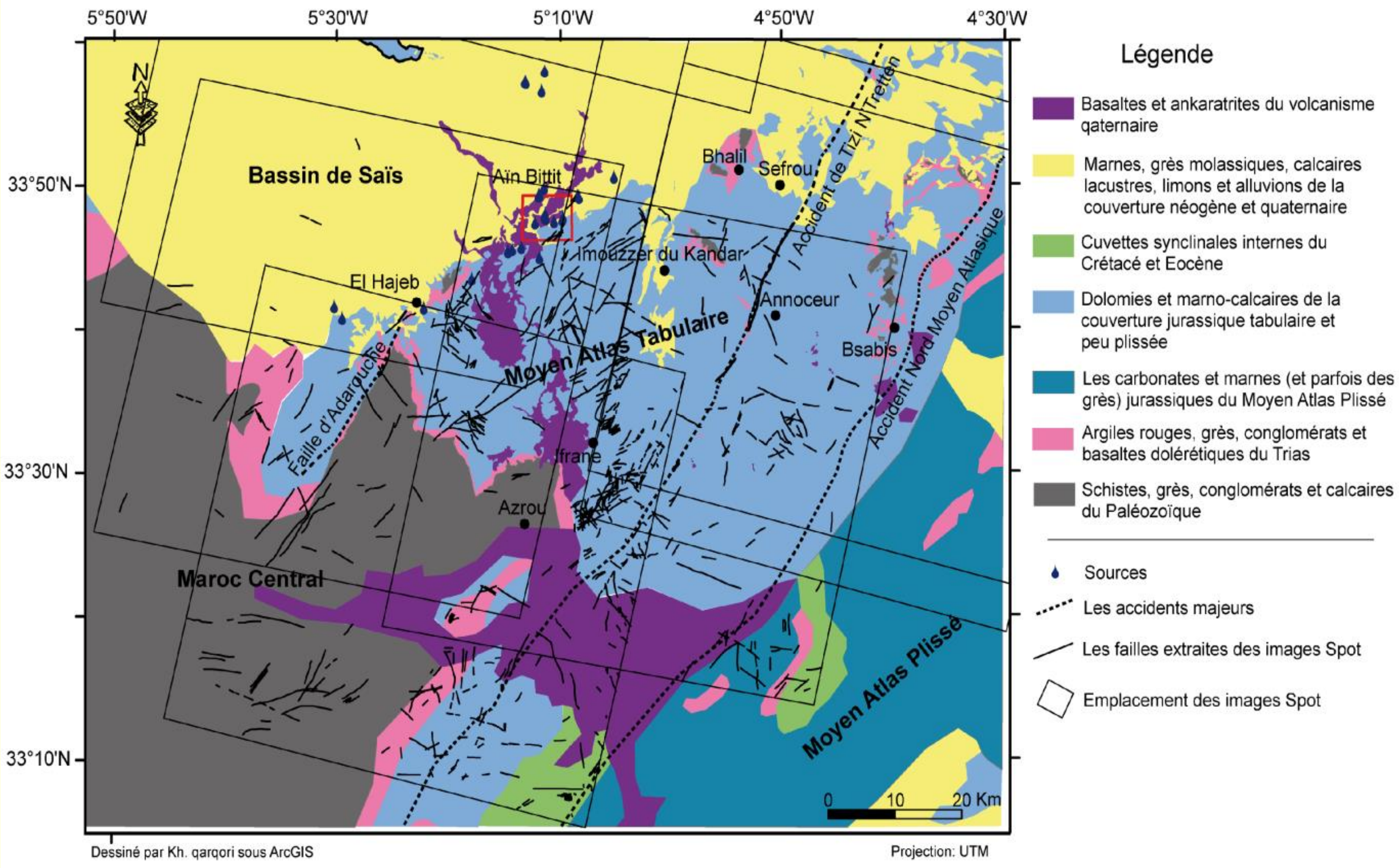


SRTM data.

Lineaments Map

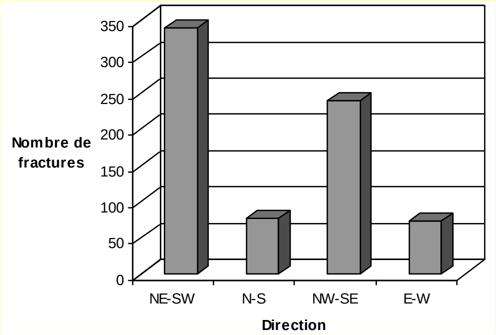


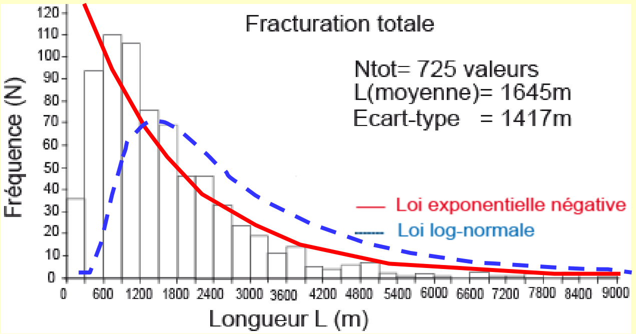
Fracture Network Map

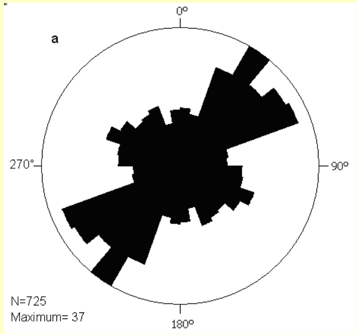


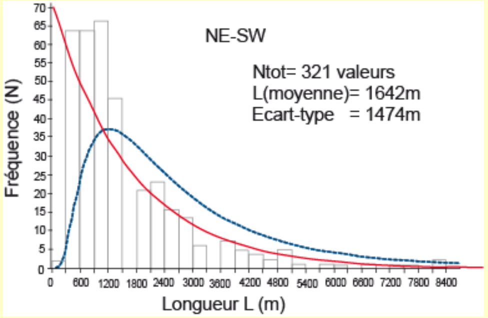
Map of the fractures extracted from the Spot satellite imagery.

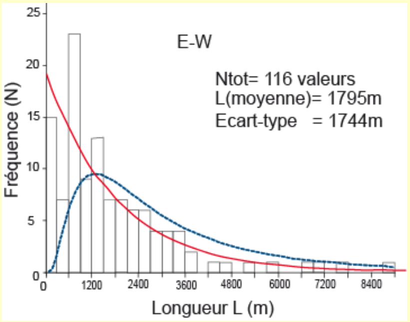
Fracture statistics

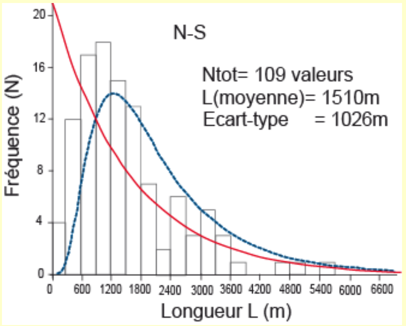


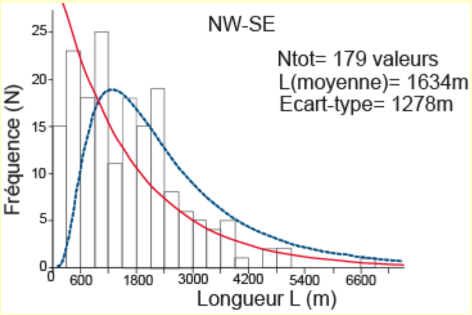






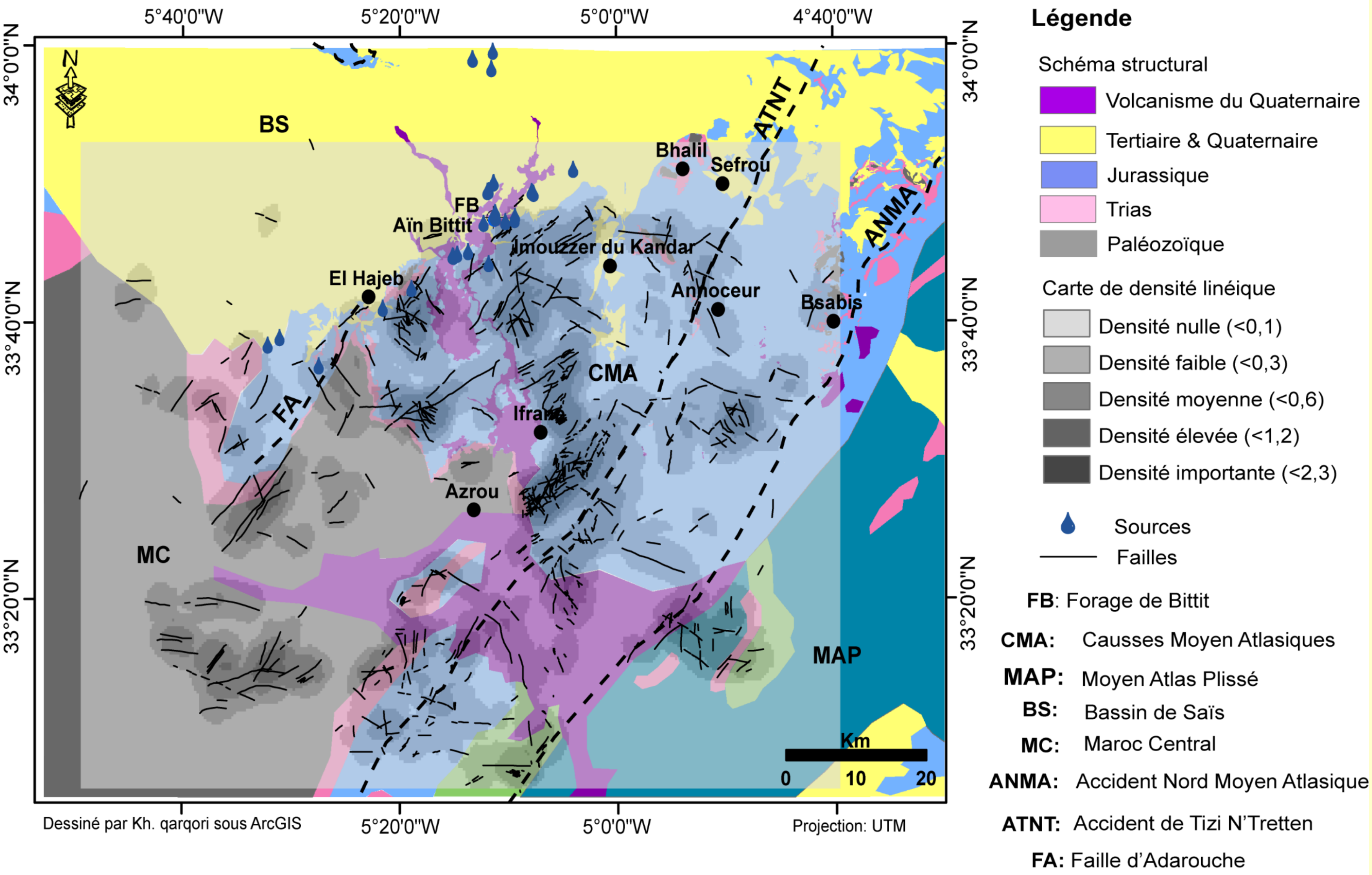






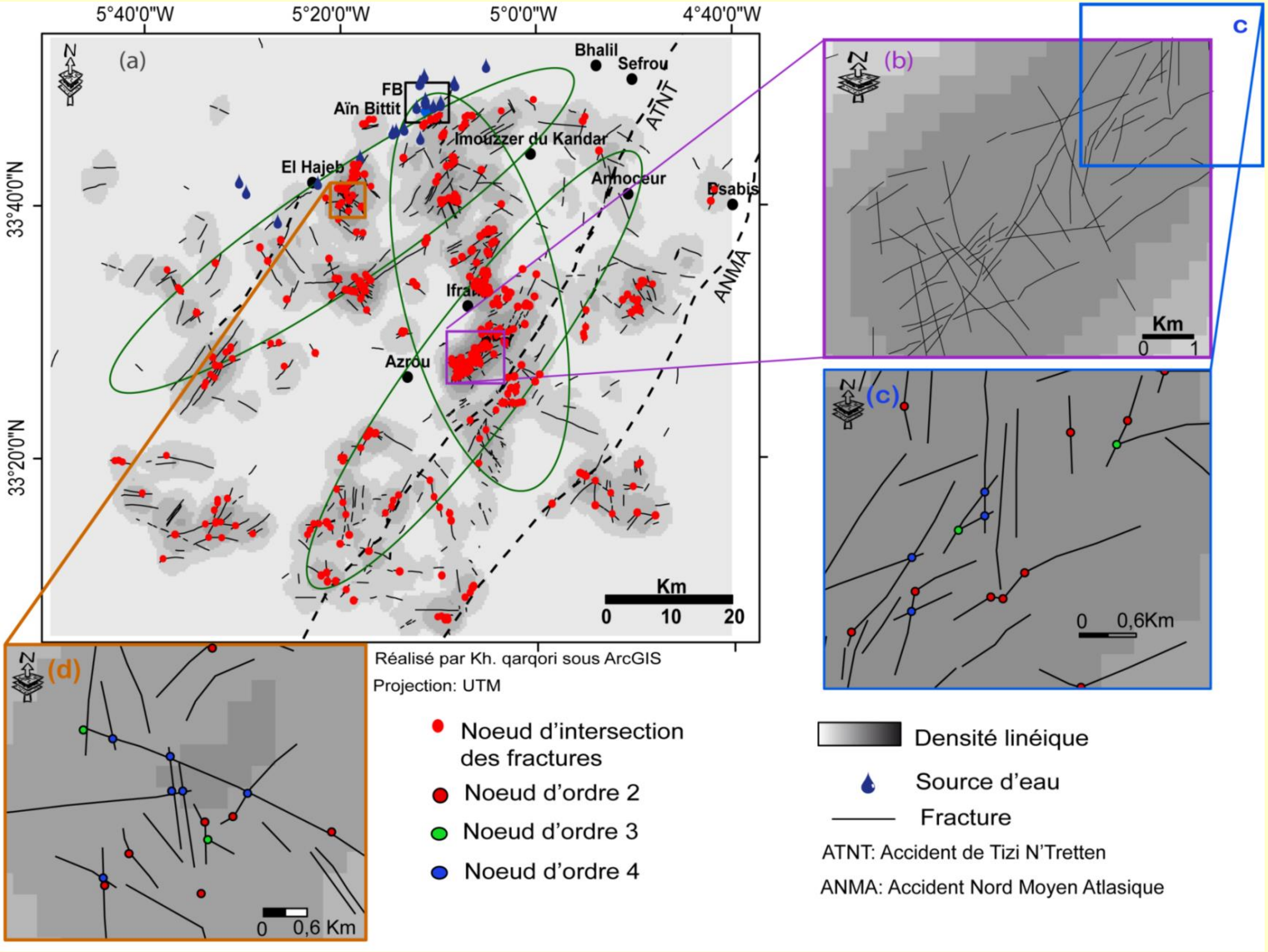
Fracture statistical distributions and rose diagram.

Fracture density map / Clusters



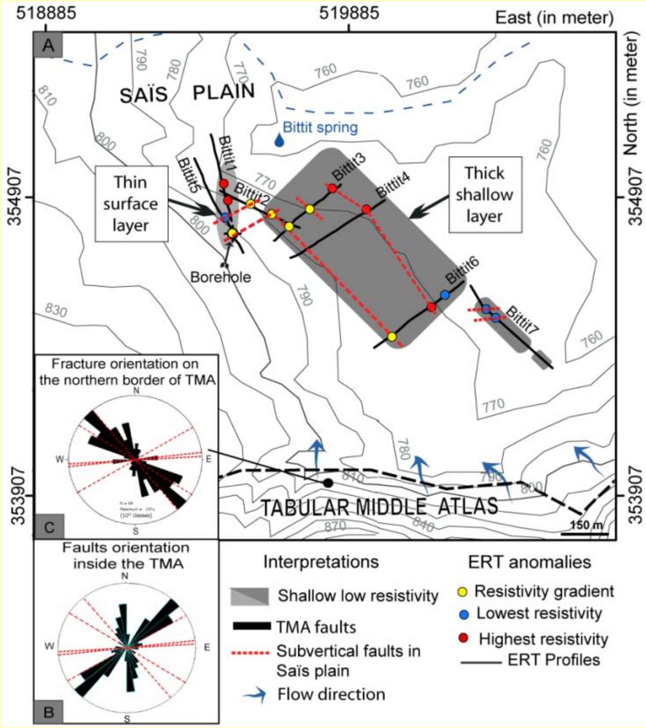
Map of linear density of fracture networks extracted from Spot images.

Fracture connectivity

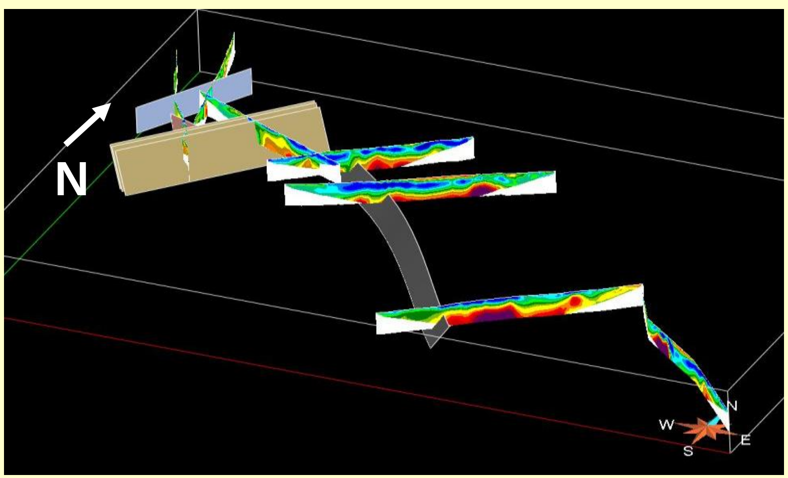


Fracture clusters & connectivity.

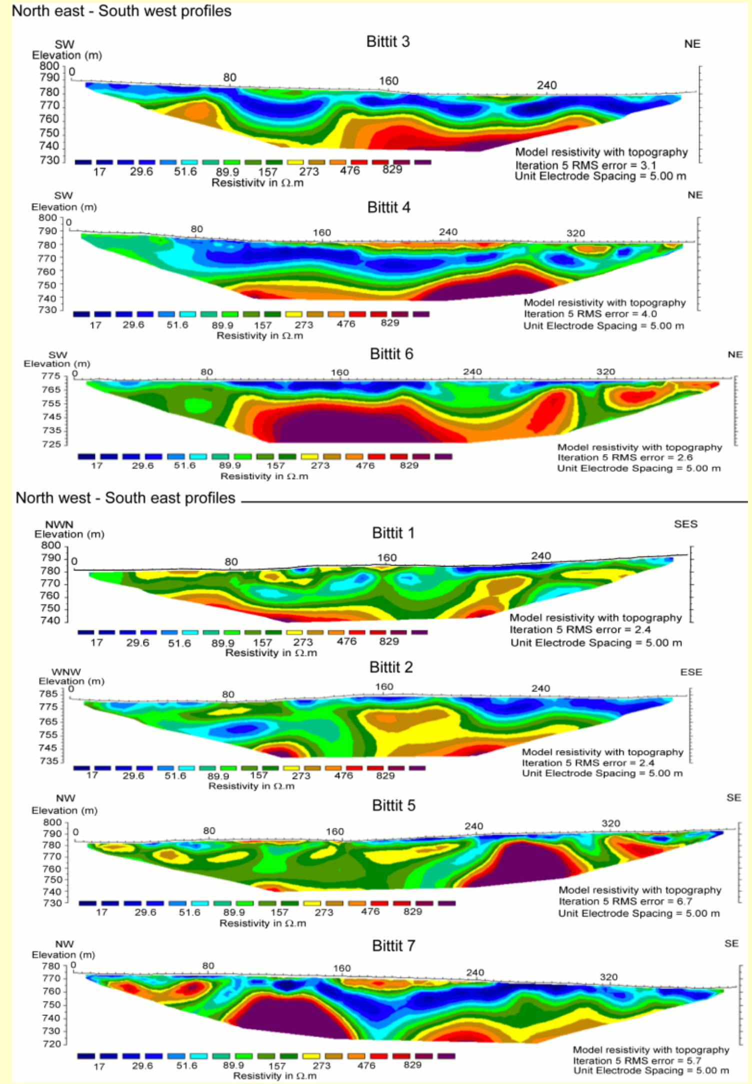
Geophysical prospecting on a target



Bittit Spring area.



3D Modeling.



2D ERT.

Other applied geophysical techniques: Electromagnetics (EM34, VLF), Microgravimetry, Seismic refraction, GPR.

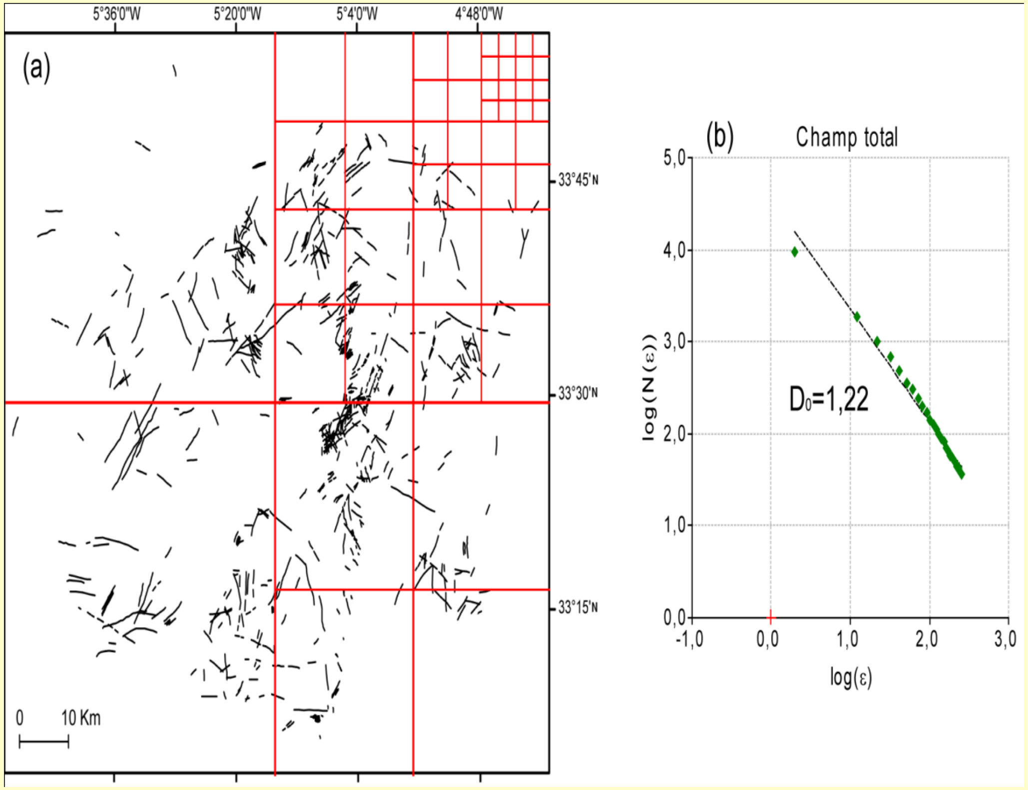
Fractal dimension

Box Counting Method

- A sequence of grids of different cell size ε is placed over the fracture map, the number of cells intersected or containing a fracture is counted.

- The fractal relation is: $N\varepsilon^{D_0} = 1$

- The box-counting fractal dimension is: $D_0 = \dfrac{\log N}{\log(1/\varepsilon)}$

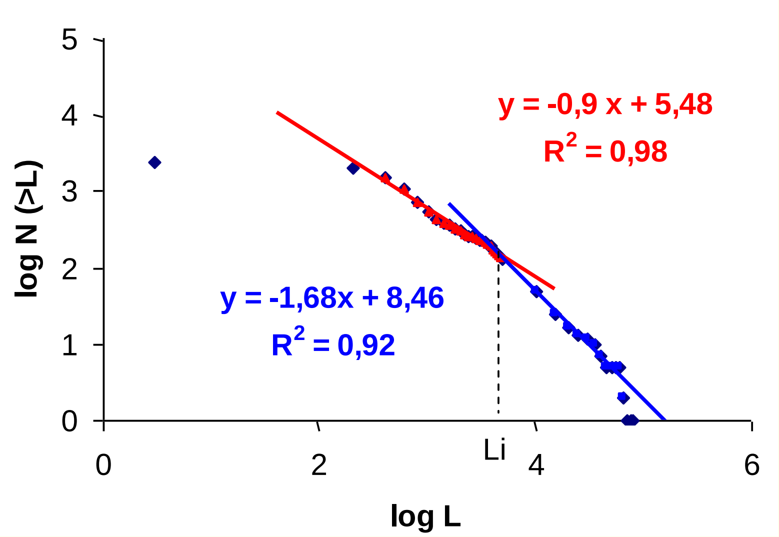


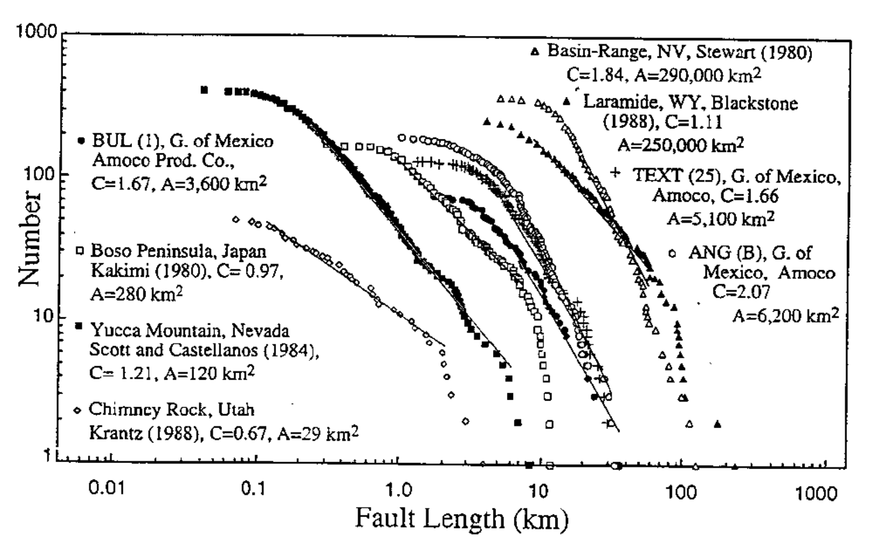
Power-Law Distribution of Fracture Lengths

Natural fracture length distributions show to obey to this fractal law:

$$N(L \geq l) \propto l^{-c}$$

N is the number of fractures having a length equal or greater than l, and c an exponent varying generally between 1 and 2 (Davy, 1993; Cladouhos & Marrett, 1996).





(Cladouhos & Marrett, 1996; 0.67<C<2.07)

- Best fit by 2 linear segments. 2 Power-laws. Bi-fractal regime.
- 2 exposants (C_1 = 0.9 et C_2= 1.68)
- Characteristic Cross-over length (Li~5km). 2 scale domains.
- The maximum extrapolated fracture length is about 30 Km.
- «*Sensoring effect*» at small scale.

Power-Law Distribution of Fracture Lengths

- The exponent *C* is linked to the amount of short and large fractures, and it has important consequence on connectivity properties (Bour & Davy, 1997).
- According to numerical modeling and on the basis of the percolation theory (Stauffer & Aharony, 1995), the connectivity of fractured media depends upon the power-law exponent and the fracture density. The small and large fractures will contribute to connectivity with an amount or ratio depending on exponent *C*.
- *C*~2 may be a critical value where 50% of fractures belong to the infinite cluster or correlation length. Berkowitz et al. (2000) analyzed the fracture connectivity on the light of relation of exponent *C* to the capacity fractal dimension D ; for *C* >D, connectivity does not depend on scale, inversely for *C*<D, the connectivity threshold is reached only at a critical value.
- In the tabular Middle Atlas Lias fractured reservoir, with D=1.22 ; C_1=0.9 and C_2=1.68, it is attempting to say that fracture connectivity is largely independent on scale for L > Li (infinite cluster). Conversely, connectivity will depend on scale for small fracture lengths.

Conclusion - Outlook

- Usefulness of remote sensed Spot images in such case, despite some limitations (vegetal cover in some limited areas, resolution).
- Interest and relevance of fracture quantification, connectivity and scaling laws in carbonate reservoir analysis.
- The fractal laws and exponents could be attributed to the entire reservoir, both at surface and in confined aquifer in Sais Basin. The fracture connectivity seems to be independent of investigation scale.
- The extrapolation to 3D analysis based on fractal mathematics and percolation theory will constitute an interesting field of research for a better understanding of fracture geometry and reservoir hydraulic properties.
- The management of data in a GIS could help to a better optimization of water prospecting of this region, focusing in fractured connected media to reduce dry wells.
- Prospecting Strategy: Identifying targets – Field geology - Geophysical prospecting - Testing.

Thanks for your attention