19 Rue Pierre Waguet
60000 BEAUVAIS

Specialty Energy Ressources
Promotion 080

Université de Bretagne Occidentale

Technopole Brest Iroise
Rue Dumont-d'Urville
29280 PLOUZANE

Institut Européen de la Mer

Digital Elevation Model analysis of land/sea active faulting in North Africa (Algeria, Tunisia)

Jules JAUFFRET

Internship report **Technical part**

Internship supervisor: Jacques DEVERCHERE, University professor in *Université de Bretagne Occidentale*

Internship tutor: Julien BAILLEUL, teacher-researcher in sedimentary geology and basins analysis in *UniLaSalle*

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Résumé

La zone étudiée est une région présentant un taux de sismicité élevée puisqu'elle se situe à la frontière de convergence des plaques africaine et ibérienne/européenne. Afin de définir au mieux le risque sismique, et au vue des différences observées chez certains auteurs ayant cartographié la zone, une carte structurale présentant les failles actives dans la région du Tell-Atlas a été réalisée. Les segments de failles ont été tracés selon la morphologie présente sur des modèles numériques de terrain onshore et offshore. Cette analyse cartographique permet de mettre en évidence plusieurs grands alignements de failles de directions variables au centre et à l'est de l'Algérie, dont un système septentrional à cheval entre terre et mer. De manière générale, l'approche spatiale amène à identifier des systèmes de faille plus discontinues que ceux parfois répertoriés dans la littérature, ce qui peut être expliqué, selon les cas, par (1) des taux de déformation trop faibles comparés à la sédimentation ou l'érosion pour permettre une cartographie complète, (2) une segmentation importante (et donc un niveau de maturité structurale encore faible de certains systèmes de failles), et/ou (3) une tendance à des extrapolations abusives par certains auteurs, pouvant amener à surestimer la magnitude maximum de grands séismes. La direction de convergence oblique des deux plaques et la direction des failles cartographiées suggèrent qu'il existe entre ces systèmes un partitionnement de la déformation active entre la composante compressive et la composante décrochante.

Abstract

The study zone is an area presenting a high seismicity rate because it lies on the boundary between African and Iberian/European plates. In order to define at best the seismic risk, and given discrepancies observed with previous authors who mapped this area, a structural map presenting active faults in Tell-Atlas region has been realized. Faults segments have been traced according to the morphology existing on onshore and offshore digital elevation models. This cartographic analysis enable to highlight several large fault systems with different directions in central and eastern Algeria, with one northern fault system which lies between land and sea. Spatial approach leads to characterize fault systems less continuous than in the bibliography, which may be explain by (1) low strain rate compared to sedimentation or erosion, (2) an important segmentation, and/or (3) a trend for some authors to extrapolate that can lead to over-estimate the magnitude of earthquakes. The oblique direction of convergence of plates and the fault systems directions suggest there is between those system a strain partitioning of active deformation between the compressive component and the strike-slip component.

Mots-clés
Modèle numérique de terrain, identification de failles actives, Tell-Atlas

Keywords
Digital elevation model, active faults recognition, Tell-Atlas

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List of abbreviations

IUEM	Institut Universitaire Européen de la Mer
UBO	Université de Bretagne Occidentale
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
CNRS	Centre National de la Recherche Scientifique
IRD	Institut de Recherche pour le Developpement
DEM	Digital Elevation Model (=MNT: Modèle Numérique de Terrain)
FMS	Focal Mechanism Solution
ASTER	Advanced Spaceborne Thermal Emission and Reflection
SRTM	Shuttle Radar Topography Mission

Glossary

Strain partitioning: When considering a plate boundary, motion between the two plates is rarely parallel. Just like between African and European /Iberian plates, the plates slide past each other in an oblique manner. The movement of the opposing plates can be expressed as "Homogenous" and "Partitioned" styles. In partitioning system, strain is heterogeneously distributed, and oblique subduction induce the development of shear zones which strike parallel to the mountain belt.

"Transpressional strain acting upon structurally anisotropic rocks can be partitioned into separate deformational domains of pure shear and simple shear. This contrasts with homogeneous transpression in which both the pure shear and the simple shear strain components are uniformly distributed across the zone of deformation. Structural weaknesses capable of partially or fully accommodating one component of deformation include lithological contacts, rheological heterogeneities, and faults or shear zones situated within the deformation zone or lying along its boundaries. Partitioning of transpressional strain can occur when stress is applied oblique to pre-existing structural weaknesses, or can occur during later stages of progressive strain, when the early deformation of isotropic rocks imparts sufficient anisotropy to allow subsequent strain to be partitioned. Partitioning of transpressional strain into domains lying parallel to the deformation zone boundaries can be distinguished from 'fault-stepped' transpression, in which strain is partitioned along the length of a segmented fault zone." (Jones and Geoff Tanner, 1995)

Introduction

This internship took place from 16th July to 27th August 2018 at Laboratoire Géosciences Océan in IUEM in Plouzané.

The general purpose of this internship is to analyze digital elevation models onshore and offshore to realize a structural scheme of active tectonics in the north-east of Maghreb along Algeria and Tunisia. Considering the location of this region between two tectonic plates, North Algeria and Tunisia are high seismicity regions, they have underwent some destructive earthquakes. That's why it's interesting to identify active structures which are sources of those earthquakes. A similar work has been done in 2014 by Rabaute and Chamot-Rooke (2014) for the eastern part of the Maghreb using literature and seismic data. However, the structural schemes in recent papers depict several important discrepancies at a regional scale, especially on land at the border between Tunisia and Algeria, and also offshore. Furthermore, many published maps report incomplete patterns at local scale or ambiguous schemes that mix inherited faults and active structures. There are also a few discrepancies in authors' interpretations. Some faults are mapped at the same location but are interpreted differently. Some faults also are mapped as large structure instead of some segments which can impact the purpose of active fault recognition which is earthquake risk prevention. It is known that fault or rupture length is linked with magnitude of an earthquake. Rupture can be contained within the dimensions of the original fault trace, or break through in several faults, connecting segments into one large fault line (BLACK et *al.,* 2004). It is essential to have a good estimation of fault's length, to estimates the fault's magnitude. Stepovers also play a role in controlling rupture length. Large stepovers (>4 km wide) stop earthquake ruptures, and smaller stepovers, which are much more common, sometimes stop ruptures and sometimes do not (ELLIOTT et al, 2009), hence the difficulty to estimate an earthquake magnitude.

The digital elevation model (DEM) can be used in some studies but not all of those, we'll see hereinafter how it has been used, why it is an interesting datum in order to achieve this work, and what are its limitations.

This work is divided into several steps to achieve a new structural map of North Africa:

- Bibliographic search on active tectonics in the area and on existing data to produce a useful digital elevation model
- Data search and processing on ArcGis software
- Fault extraction on the final digital elevation model

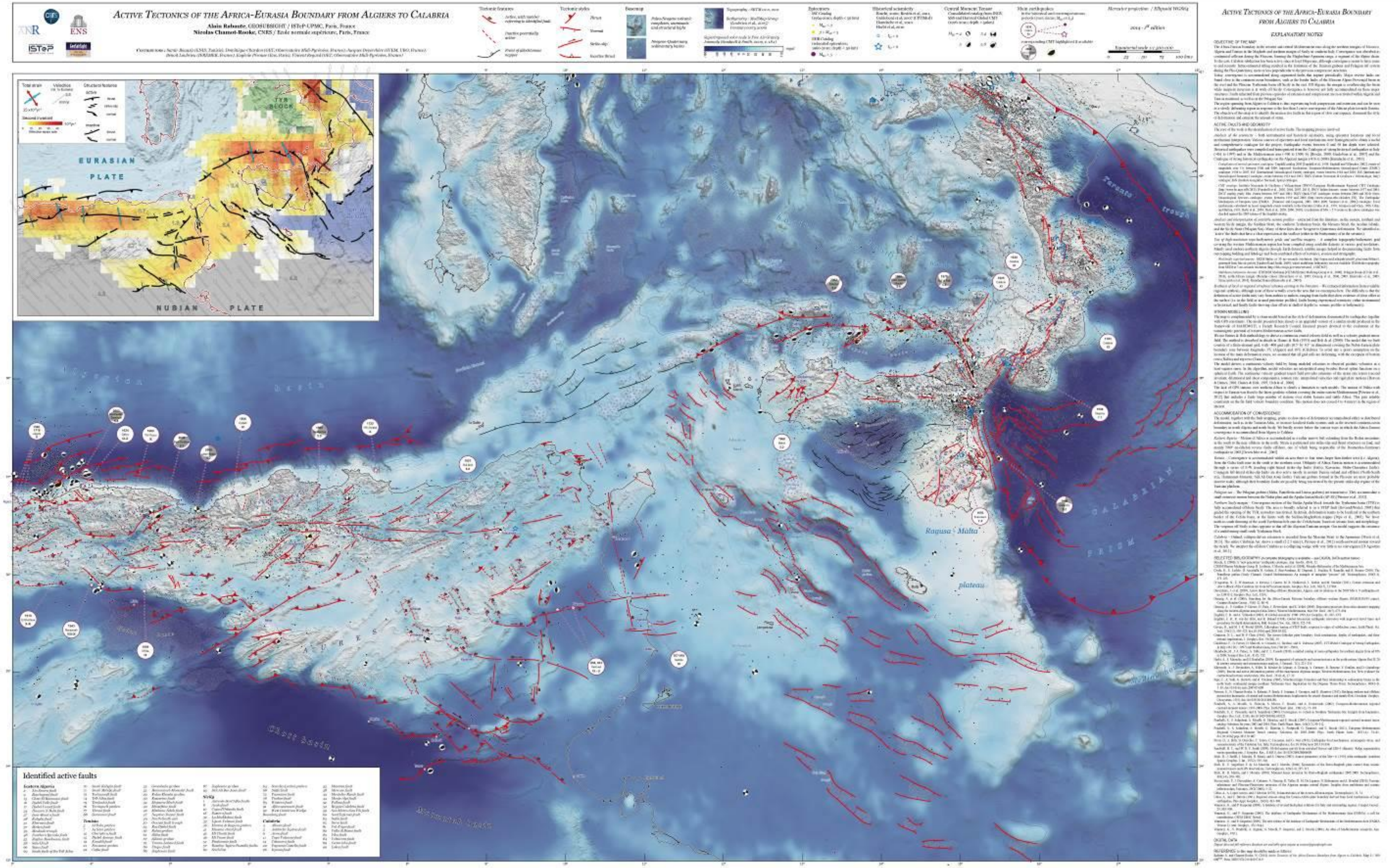


Figure 1 Map of active tectonics along Africa Eurasia boundary from Algiers to Calabria (from RABAUTE and CHAMOT-ROOKE, 2014)

1. Overview of activities proposed by IUEM

First of all, IUEM is a university school which relies on UBO (Université de Bretage Occidentale). Its purpose is to prepare future marine geoscientists. The institute proposes courses as marine biology, oceanography among others, and field camps.

Besides bachelor and master's students, IUEM hosts PhD students which do their thesis work. They are directly in contact with teacher-researchers to achieve their work. Moreover students present their thesis defense which attract many geologists, from business world or universities and research organizations, and it contribute to improve the institute's reputation and exposure.

IUEM also have a research mission, with 6 research laboratories, one of which is Laboratoire Géosciences Océan. Each laboratory have research teams (see organization chart in *Rapport Entreprise*). These research teams also work on different projects. My internship work is a continuation of a previous one: Algerian project. This team is involved in studying tectonic, petrochemistry, and sedimentary evolution and formation of Algerian margin. Several oceanographic cruises have been realized to have a better understanding of how this oceanic domain formed until present day. IUEM also work with IFREMER, CNRS and IRD on some missions.

2. Overview of intern tasks inside the institute

During this internship, I had a lot of autonomy to run this project. We updated the progress of the project about one time a week to keep my supervisor abreast of my work. In parallel, two internship reports were realized. This work divided into several steps:

(1) A **Bibliographic study** of the geological and structural framework of northern Maghreb, to bring to light the purpose of this project.
(2) **Data research**, **data analysis** and comparison, to select and use the suitable dataset.
(3) **Data processing on ArcGis**, using tools and methods to highlight the geomorphology of the area, and produce an adequate DEM.
(4) **Fault extraction**, manually on the produced DEM, and **results interpretation** and redaction to put forward something new in this project.

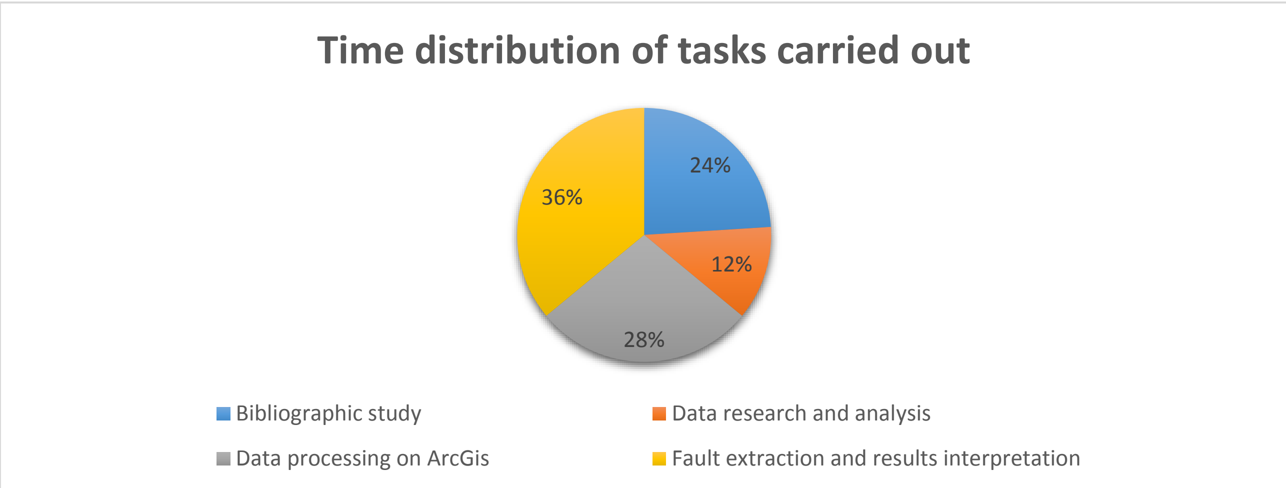


Figure 2 Pie chart of time distribution of tasks carried out during the 3 months internship

Many skills were acquired or improved, like handling of ArcGis tools (in a professional way), work in autonomy (find the data, organize its work), scientific communication to highlight and discuss about my work.

3. Geological and geographical setting

The study areal is located north of Africa, in north-east Algeria and in north Tunisia. The Maghreb region is a key area to understand and identify active tectonics in the Western Mediterranean because it is a convergent plate boundary between African and Eurasian/Iberian plates. Nowadays, convergence is oriented NW-SW and oblique to the coastline. The convergence began 70 million years ago and is still active (MEGHRAOUI and PONDRELLI, 2012). Studies have shown that the direction of the compression in North Africa is N-S to NW-SE.

The convergence follows the sense of the length of Atlas mountain range that spreads along 2500 km. This mountain belt separates the Mediterranean Sea to the north from the Saharan desert to the south. It splits into several sub-ranges (figure 3):

- Anti-Atlas, High Atlas and Middle Atlas (Morocco)
- Tell-Atlas (Morocco, Algeria, Tunisia)
- Aurès Mountains (Algeria, Tunisia)
- Saharan Atlas (Algeria)

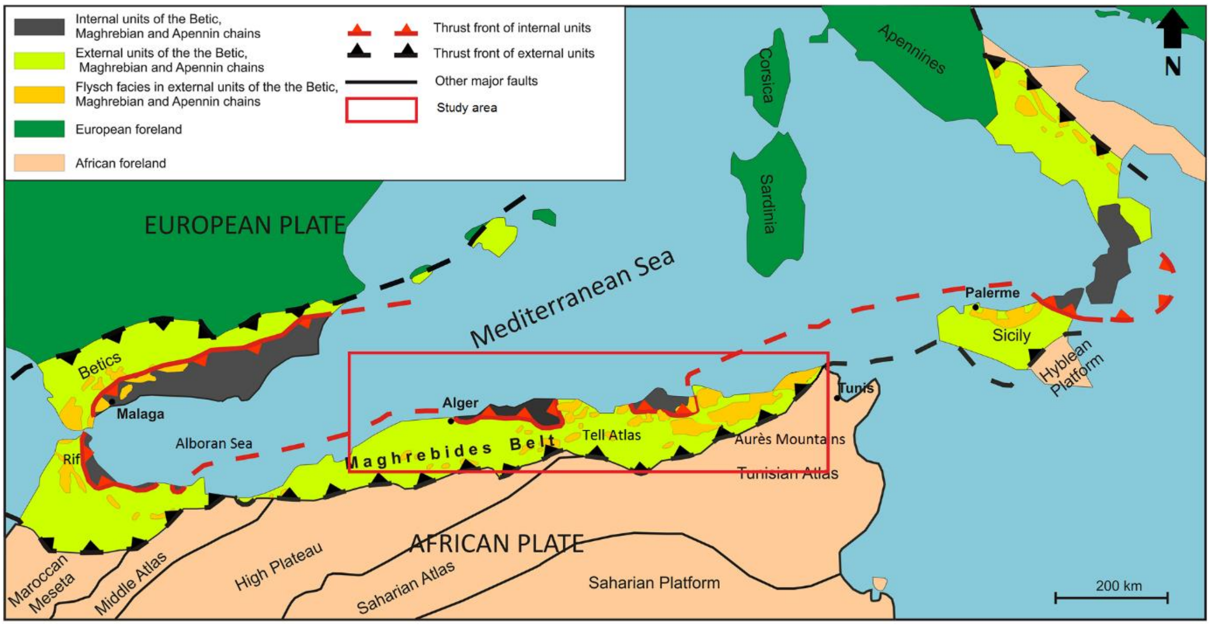


Figure 3 Structural scheme of Western Mediterranean Sea (from ESSID et al., 2018)

The crustal and lithospheric geometry of western Mediterranean is mainly the result of a Late Cretaceous-Neogene convergence between Europe, Iberia and Africa, which generates the subduction of the Maghrebian Tethys Ocean below the southern continental margin of the Iberian and European plates and the tectonic inversion of pre-existent continental Mesozoic rift systems (BENAOUALI et al, 2006). During Oligocene, the southward and westward rollback of the subducting Tethys oceanic slab resulted into extensional basins as Alboran or Algerian Basins by back-arc spreading in the upper Iberian plate. This subduction zone also led to the building of complex system of orogens as Maghrebides.

The Tell system results from the closure of Tethys Ocean, it is an “Alpine belt”. It comprises: (1) the Internal Zones (the Kabylides) made of European crust, (2) the Flyschs domain, which is the former sedimentary cover of the Maghrebian Tethys, and (3) the External Zones which are the inverted African paleo-margin of the Maghrebian Tethys. (BENAOUALI et al, 2006)

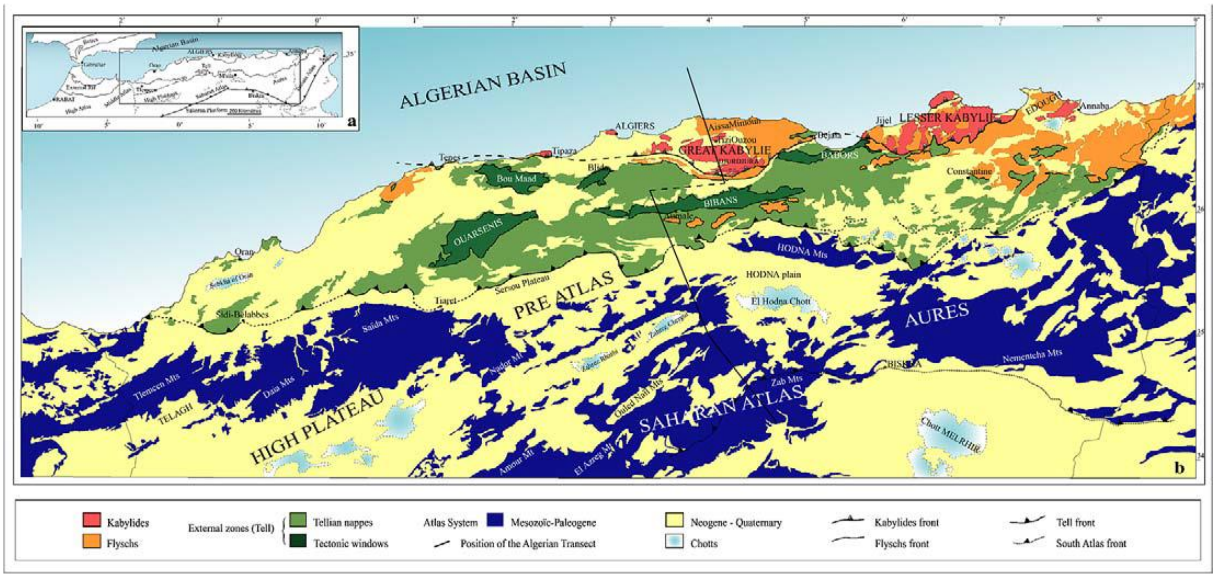


Figure 4 Structural map of North Algeria, scale 1:500 000 (from BENAOUALI et al., 2006)

Atlas Mountains are among the most active zones in the Mediterranean region, due to African-Eurasian plates convergence. Large and moderate sized shallow seismic events have been recorded over the last few decades along this plate boundary (MEGHRAOUI and PONDRELLI, 2012). The map below (figure 5) shows focal mechanisms of earthquakes. A Focal Mechanism Solution (FMS) is the result of an analysis of seismic waves generated by an earthquake and recorded by a number of seismographs. It describes the deformation in the source region that generates seismic waves and provides important information, including the origin time, epicenter location, focal depth, seismic moment, and the magnitude and spatial orientation of the 9 components of the moment tensor. From the moment tensor, we can resolve the orientation and sense of slip of the fault.

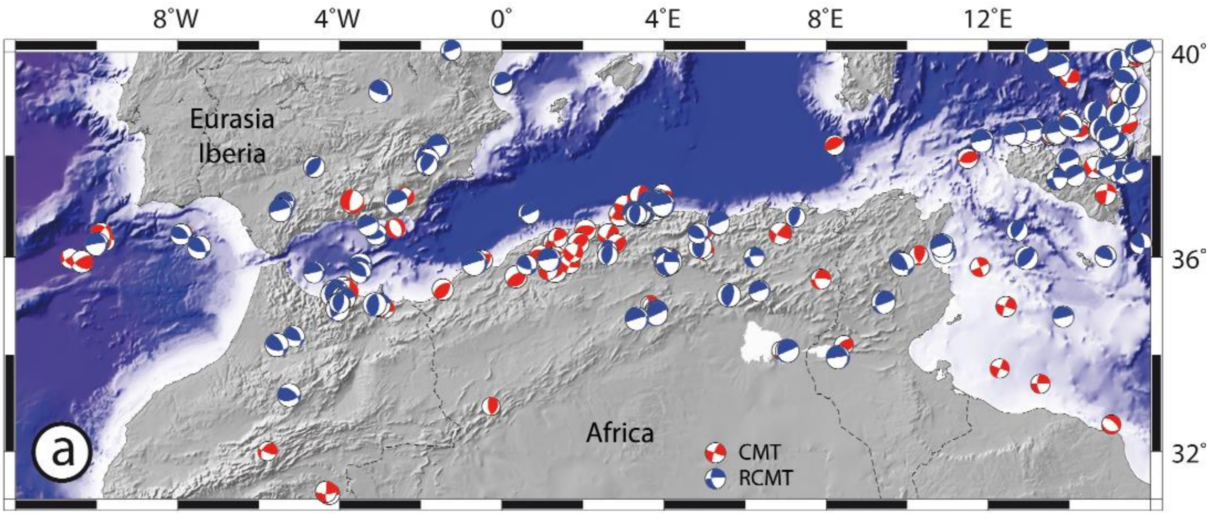


Figure 5 Focal mechanism dataset. Global Centroid Moment Tensors in red and European Mediterranean Regional Centroid Moment Tensors in blue (from Meghraoui-Pondrelli, 2012)

There are some catalogues which compile regional earthquakes in northern Algeria (HAMDACHE et *al.,* 2010). The resulting catalogue includes 923 main events above magnitude M_w 4.0 from 856 to June 2008. It is the most seismogenic regions in the westernmost Mediterranean area (HAMDACHE et *al.,* 2010). One of the last most destructive earthquake was in Boumerdes, on 21st May 2003 with magnitude M_w = 6.9. Detailed catalogue of earthquakes with magnitude reaching M_w>6.0 is included in the annexes (annex B).

4. Data research

1. Bibliography

Some researchers have used DEM to realize structural maps. SRTM is the most used DEM because it's a radar interferometry, which means that's vegetation and anthropogenic elements do not enter the equation for topographic data. For example, topography of Gibraltar arc is extracted from SRTM (USGS – NASA for the onshore area) global database, combined with GEBCO97 (Project launched in 1997 under the auspices of IOC-Intergovernmental Oceanographic Commission and IHO-International Hydrographic Organization) for the offshore region (MARTÍNEZ-GARCIA et *al.,* 2010). This type of DEM is also used in several other articles (GHARBI et *al.,* 2015) (ESSID et *al.,* 2018). Some satellites images Landsat (remote sensing program launched by Americans agencies, NASA and USGS-United States Geological Survey) combined with Aster DEM are used to observe lineaments and compare their shape and length with faults studied in the literature (YELLES-CHAOUCHE et *al.,* 2006). Some base maps are also produced with elevation data from NASA 30m ASTER (GHARBI et *al.,* 2015).

SRTM DEM can also be combined with SPOT aerial photographs to produce precise geological and structural maps at a scale of 1:50.000 with pre-existing 1:100.000 ONM (Office National des Mines) geological map (GHARBI et *al.,* 2015). These images are provided for free by the ISIS program (CNES, distribution SPOT images, S.A.).

2. DEMs comparison

It's necessary to retrieve the suitable data to use the GIS software. First of all are needed two different types of data to realize a structural scheme of active tectonics in North Africa, digital topographic and bathymetric data to recognize faults or geomorphologic structures on the ground and under the sea. The institute can access to some of the bathymetric data, especially in Algeria where geophysics campaigns have been realized with IFREMER. There spatial resolutions can be variable, 30m for the most accurate.

For the topographic data, digital elevation model (DEM) is needed. SRTM and ASTER DEMs are the most popular high resolution and accessible data we can find for free on Internet. The table below presents a comparison of the two last releases of ASTER and SRTM.

Data	**ASTER GDEM V2**	**SRTM3 DEM**
Meaning	Advanced Spacebone Thermal Emission and Reflection Radiometer	Shuttle Radar Topography Mission
Acquisition technique	Stereoscopy	Radar interferometry
Provider	METI (Ministry of Economie, Trade and Industry) and NASA (USA)	NASA and NGA (National Geospatial-intelligence Agency) (USA)
Projection system	Geographic	Geographic
Spatial resolution	1 arc-second (30m)	1 arc-second(30m)
RMSE – Root mean square error	17m	7,59m
Cover	North 83° - South 83°	North 60° - South 60°
Format	Geo TIFF	Geo TIFF
Geodetic system	WGS 84	WGS 84

Table 1 Comparative table of ASTER and SRTM DEMs

For each of these DEMs (or GDEM-*Global Digital Elevation Model)*, which can also be called DTM (Digital Terrain Model), there are benefits and drawbacks. For example, SRTM doesn't cover Polar Regions. The main difference is that SRTM uses radar interferometry, which means the measure, can go through vegetation and humans' constructions. In other words, ASTER measures the elevation of the canopy, and SRTM measures the elevation of the ground.

Very high resolution photography can also be generated from satellites images as *SPOT* or *Pleïades*.

Both ASTER and SRTM DEMs have been downloaded to preview and compare those from <https://earthexplorer.usgs.gov/>, website from USGS, United States sole science agency. Data can be downloaded in TIFF format, by photo tiles. I have downloaded data for all northern Africa (figure 6). These data products can be processed. First, SRTM elevation data are processed from raw C-band radar signals spaced at intervals of 1 arc-second (approximately 30 meters) at NASA's Jet Propulsion Laboratory (JPL). Then it occurs that voids are present in some areas, because the initial processing did not meet quality specification. NGA filled the voids using interpolation algorithms in conjunction with other sources of elevation data.

The methodology used by Japan's Sensor Information Laboratory Corporation (SILC) to produce the ASTER GDEM involves automated processing of ASTER archive. Stereo-correlation is used to produce individual ASTER DEMs, to which cloud masking is applied to remove cloudy pixels. All cloud-screened DEMs are stacked and residual bad values and outliers are removed. Selected data are averaged to create final pixel values, and residual anomalies are corrected before partitioning the data.

a) Function Minus

In order to compare DEMs, function Minus (Spatial analyst tool) can be used. It makes the difference between every value of elevation for every pixel (figure 6). This figure shows in red, pixels where ASTER DEM is at least 10m bigger than SRTM DEM, in green where ASTER DEM is at least 10m smaller than SRTM DEM, and in yellow and black, where both DEM are respectively approximately equal and equal.

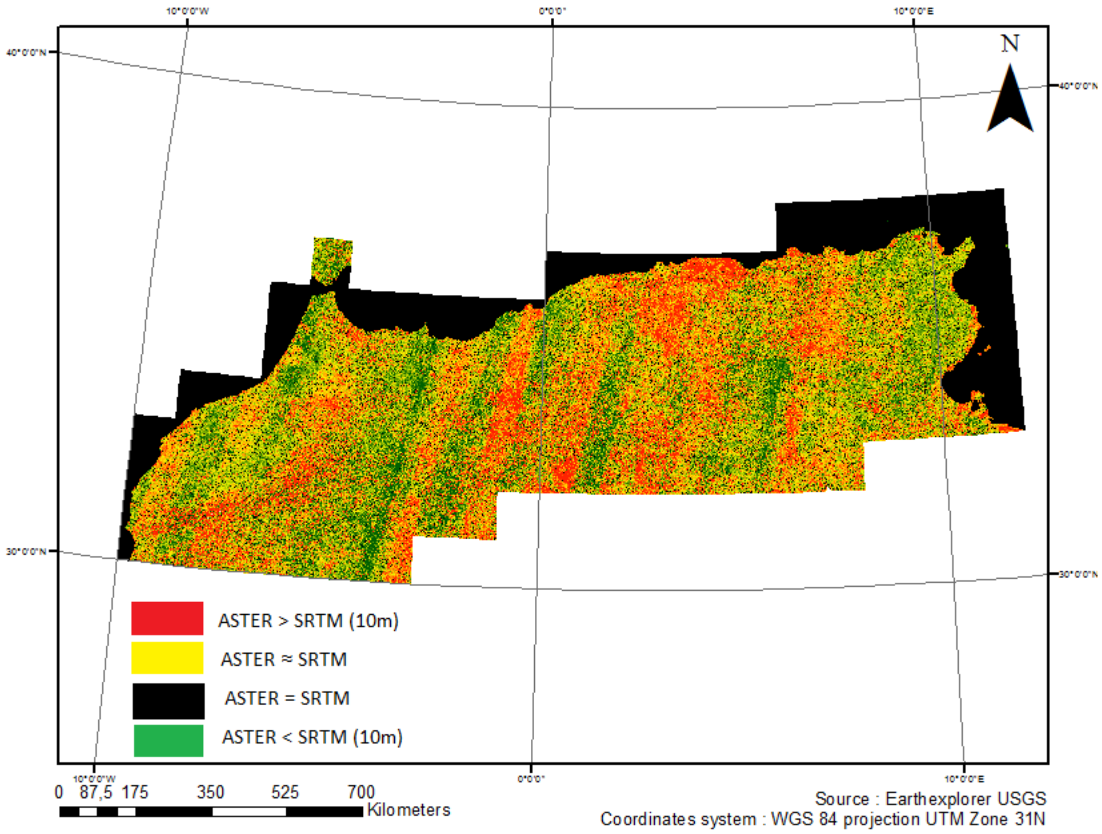


Figure 6 Map of Minus function for Maghreb on ArcGis (ASTER - SRTM)

This function has created artefacts oriented NNE-SSW, it may be because of the data acquisition techniques or the creation of mosaic of Raster tiles. It appears that it isn't a geomorphological shape of the area. Some preferential direction of lineaments can be observed but at this scale it isn't very useful. In order to make real observation of differences between ASTER DEM and SRTM DEM, a larger scale is needed.

b) Stack profile

To compare the two DEMs, the "stack profile" tool in ArcGis allows to calculate elevation along a straight section drawn on the map.

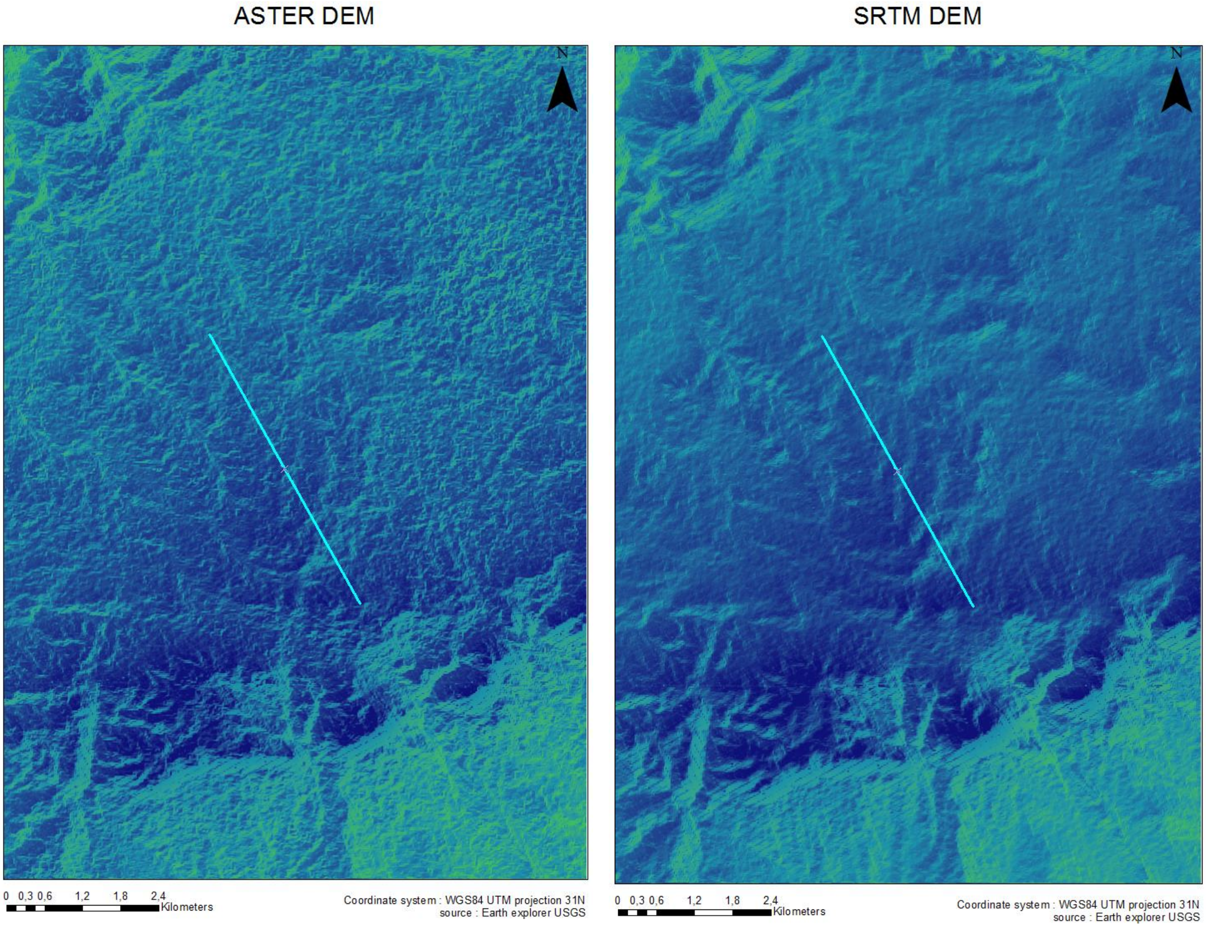


Figure 8 Comparison of ASTER and SRTM DEMs with stack profile feature

Figure 8 shows the two DEMs, just colored with blue to yellow symbology. It seems that there is more details on ASTER DEM, because SRTM DEM seems smoother. We can verify this using stack profile tool along the blue line (see figure 9 below).

ASTER DEM contains more high frequencies than SRTM signal, and the signal is more affected with artefacts and has a "bumpiness" aspect. Both data has been corrected by the supplier before being accessible, but ASTER DEM data looks a little bit noisy, it can be verify on the map (figure 8) and with the stack profile tool (figure 9).

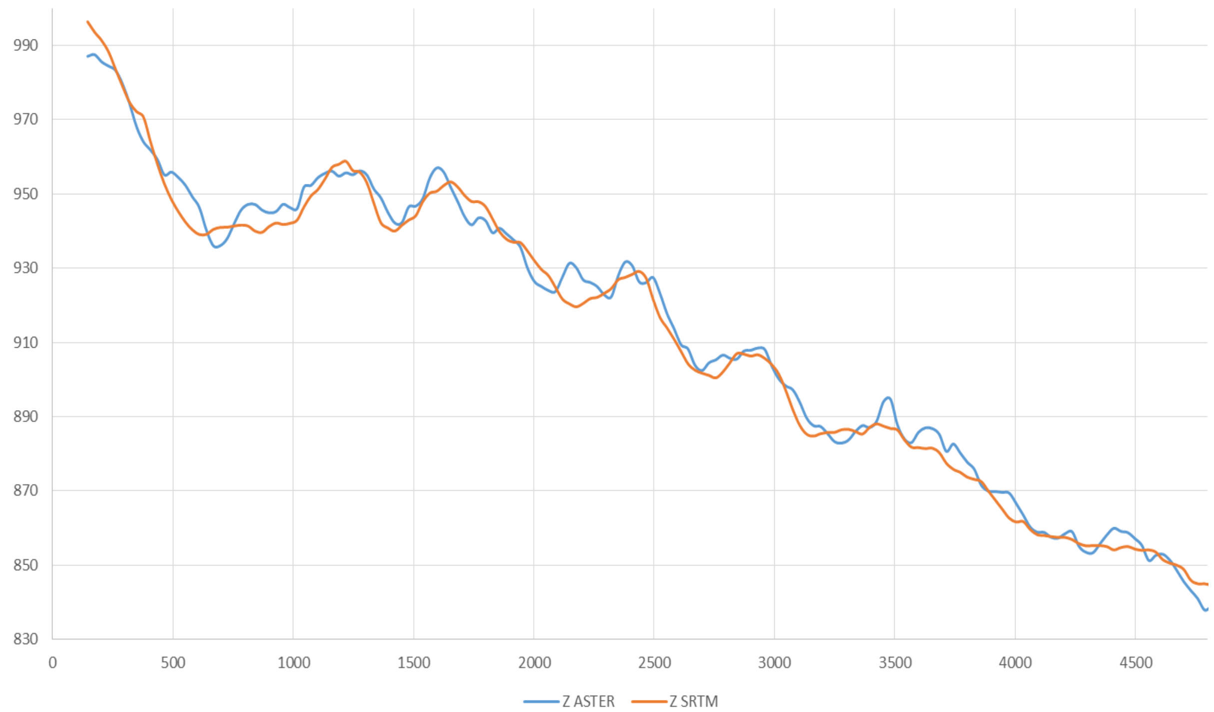


Figure 9 Stack profile result along figure 8 line

c) Hillshade effect

Hillshade effect is another Arcgis tool which is a 3D representation with shades of grey. It takes the relative position of the sunlight into account. According to previous structural scheme, Azimuth 315 is a good value to appreciate structures in this area.

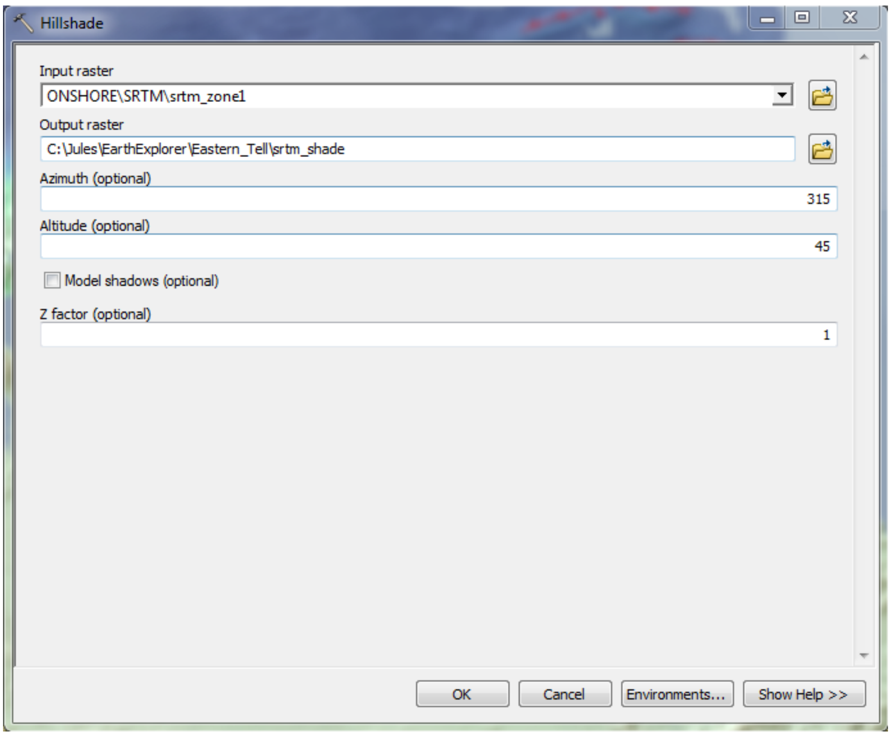


Figure 10 Hillshade tool window in ArcMap software

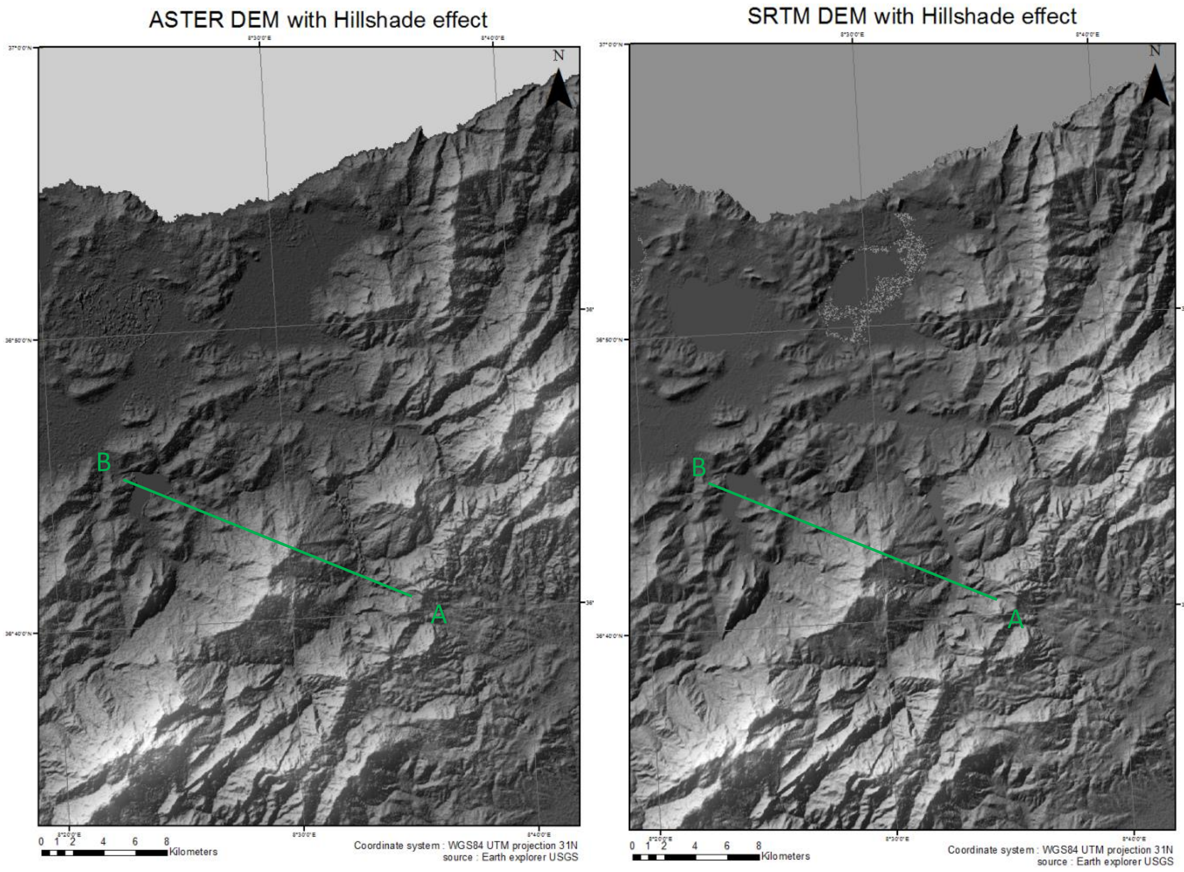


Figure 11 Comparison of ASTER and SRTM DEMs with Hillshade effect

On figure 11, representing the two DEMs with Hillshade effect, SRTM still has void in their values (North of the map, grey pixels), after verifying theses voids occurs in bodies of water. And at the center it looks like a structure has not the same interpretation for ASTER and SRTM DEMs, let's verify with a stack profile along the green line.

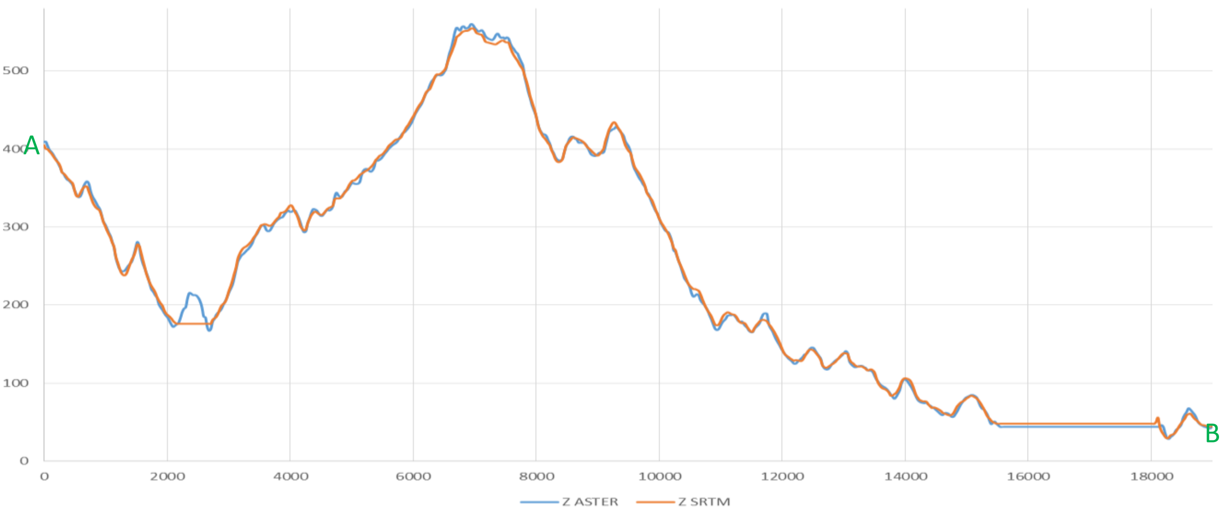


Figure 12 Stack profile result between point A and B along line of figure 11

So at 2000 meters from (A), ASTER DEM is interpreted as a marked relief while SRTM is interpreted as a flat geomorphology, in fact it is a lake so ASTER data is over interpreted here. Furthermore at 7000 meters from (A) it seems that ASTER DEM contains more high frequencies data, while SRTM signal is smoother.

d) ASTER or SRTM?

To conclude, after comparing the two DEMs, both free on internet, and both with 30m resolution, it has been decided to choose SRTM to continue the study, for all arguments above-mentioned, since the signal is smoother and less noisy than ASTER signal. Given the results of this comparison, it seems SRTM has a better representation of the field reality and is more convenient to observe active structures.

3. Offshore data

Offshore bathymetric data are more complicated to find with a high resolution. In fact, available data on internet can be provided with low resolution and it's not suitable with the scale wanted to work on ArcGis. For example GEBCO (General Bathymetric Chart of the Ocean) is a publicly available chart of the world's ocean. An international group of experts in seafloor mapping has developed these bathymetric data sets and data products under the joint auspices of the IHO (International Hydrographic Organization) and the IOC (Intergovernmental Oceanographic Commission). These data have a 30 arc-second (900m) resolution, therefore this data set is significantly less accurate compared to the 1 arc-second resolution (30m) onshore data.

That's why, with help of M. Jacques DEVERCHERE and IFREMER institute researcher, data from oceanographic cruises (MARADJA 2003, MARADJA 2005, SAMRA 2005 and PRISME 2007 and SPIRAL 2009) have been used during this work. Detailed information of those campaigns can be find in the annexes (annex A) (MAUDIRE, 2014). Those data have a resolution from 50m to 100m, and cover all the Algerian coast line. Unfortunately, those data don't cover an offshore zone from 5 to 20km of the coast. It is due to the shallow water in those area which make the cover longer and more expensive.

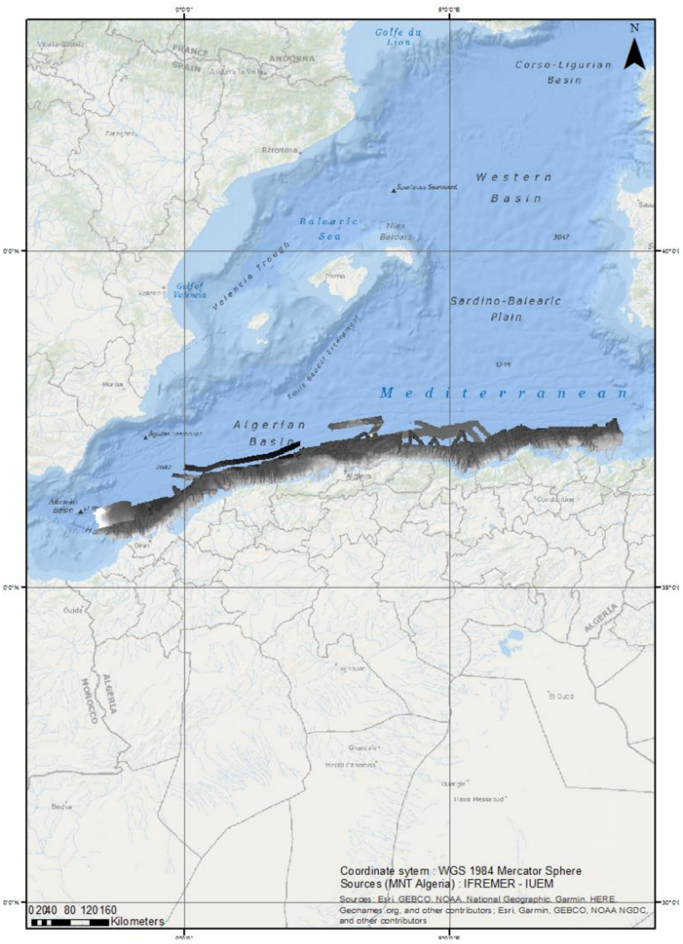


Figure 13 Bathymetric DEM dataset preview of North Algeria

5. Fault extraction

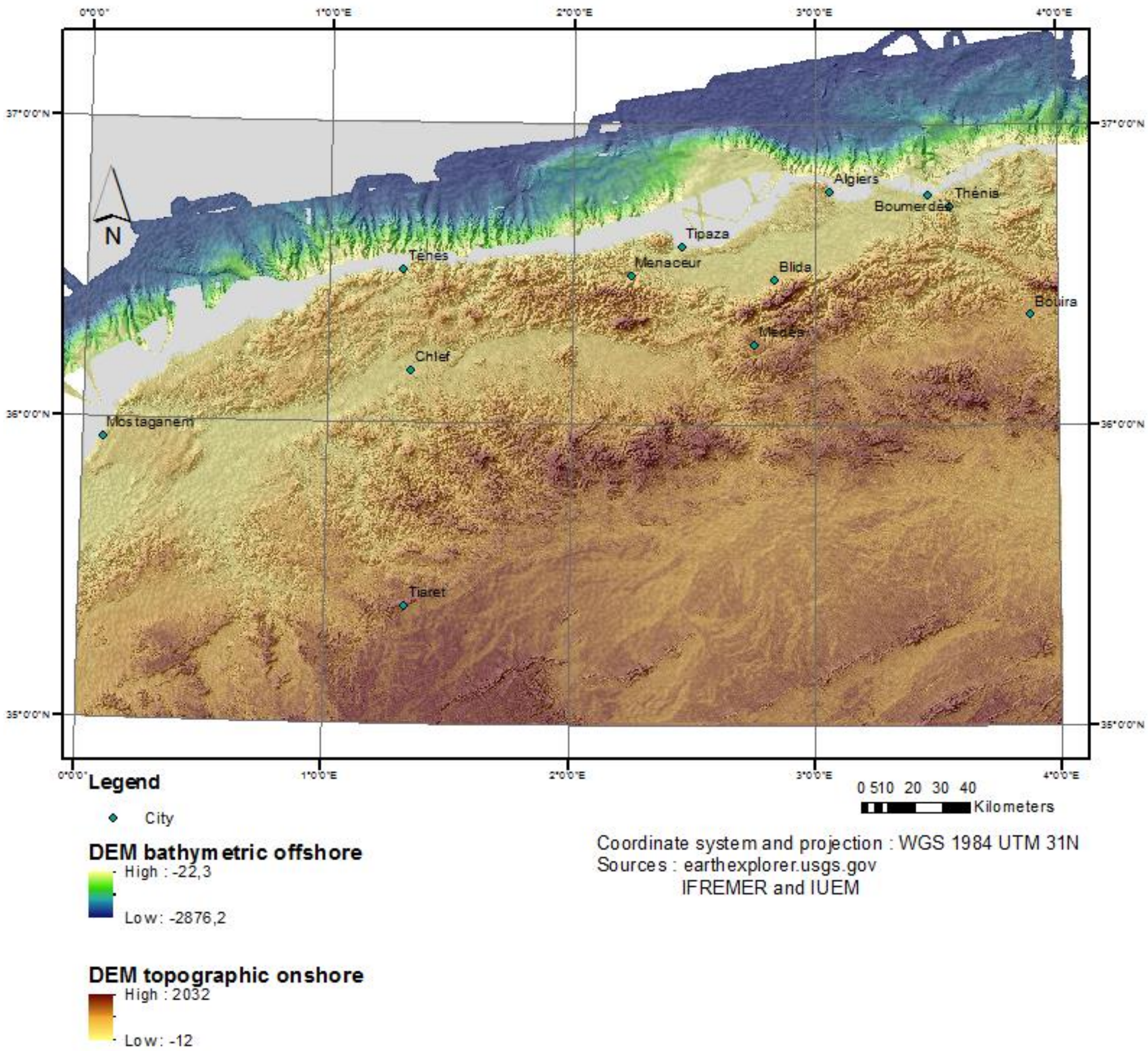


Figure 14 Global DEM with Hillshade effect of Western Tell area

Figure 14 shows the final DEM with topographic and bathymetric data for one of the three analyzed zone. This is Western Tell area, others are Middle Tell area and Eastern Tell area. Grey parts are no data zone on figure 14.

1. Methodology

To provide active faulting maps of North of Algeria, many previous works and structural maps have been studied, to figure if faults noticed were apparent on this 30m horizontal resolution DEM. If needed maps have been georeferenced on ArcGis using known particular points as position of cities (see Annexe C for one example of this method). Geological maps also have been georeferenced to distinguish active faults and geological contacts.

Offshore fault recognition is more complex than onshore fault recognition because of erosion, and sedimentation transport which can easily cover faults on the surface. Moreover because of the no data zone along the coast, the interpolation between on and offshore faults is limited.

a) Slope

For each cell, the slope tool calculates the maximum rate of change in value from that cell to its neighbors. Basically, the maximum change in elevation over the distance between the cell and its eight neighbors identify the steepest downhill descent from the cell; the lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain. Here is an example on adjacent figure 15 with arbitrary chosen degree values.

Slope image can highlight and identify lineaments which can lead to fault extraction.

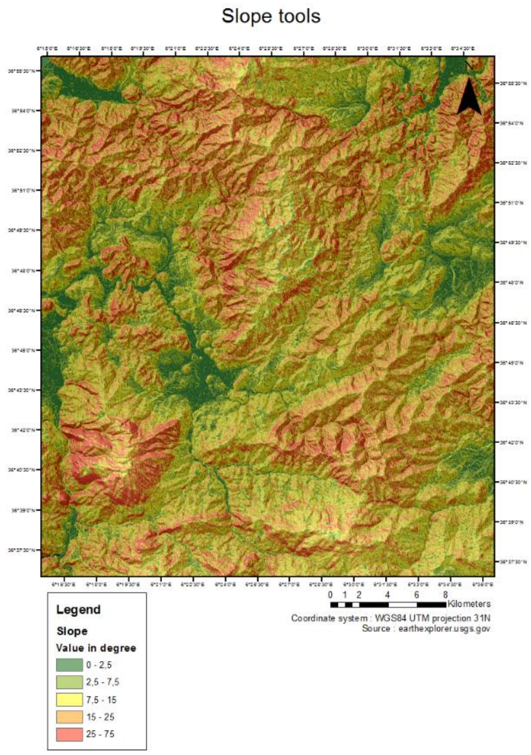


Figure 15 Result of Slope tool

b) Water System

Water System is a contribution in fault extraction. In fact, faults, in particular strike-slip, can be detected by horizontal displacement. This displacement can coincide with discontinuities in the water system. Water system can be calculated with three tools. Flow Direction, which calculate the direction of flux for each pixel. Flow Accumulation enable to calculate the number of cells which flow in each cell. And with SetNull tool, it is achievable to identify the water system. Considering FlowAcc as the result of Flow Accumulation tool, we have:

If FlowAcc <= 100
WaterSystem = 0
If not
WaterSystem = 1

It gives the water system as on adjacent figure 16, delineated with black lines. An example of using Water system to recognize a fault is presented in the annexes (Annexe D).

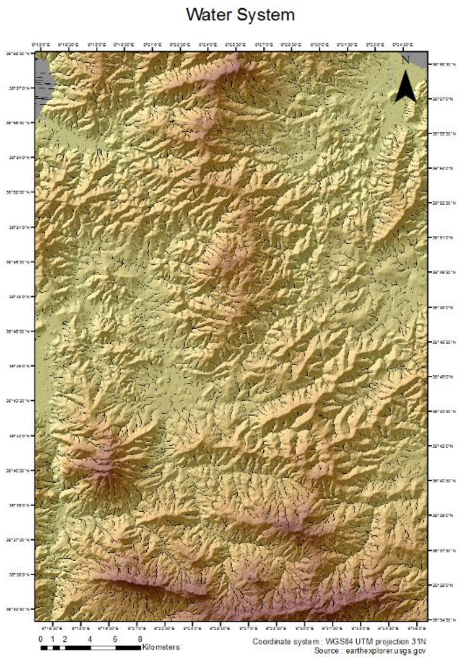


Figure 16 Result of Water system process

2. Active faulting diagnostic per zone

a) Western Tell

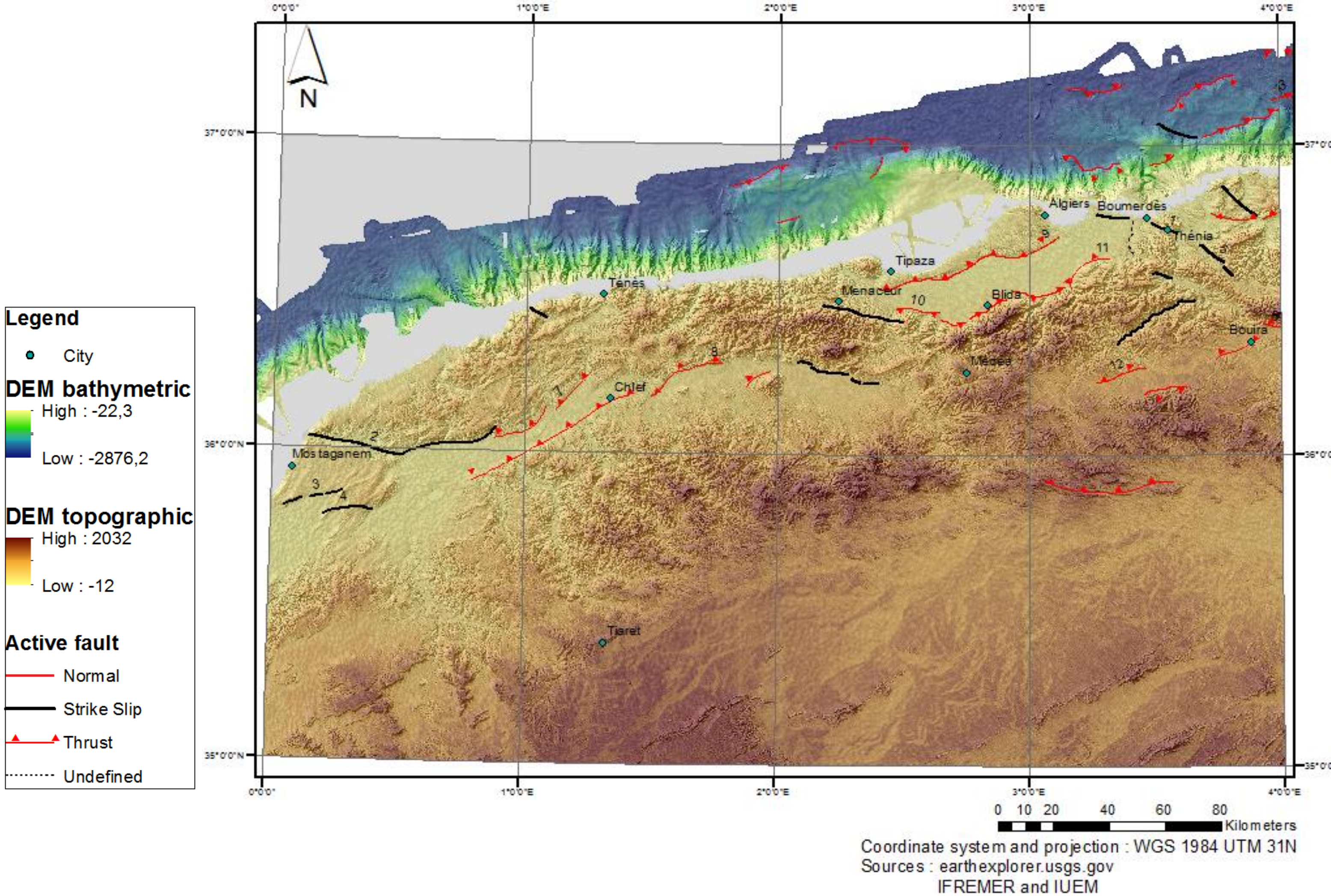


Figure 17 Structural scheme of Western Tell area (from RABAUTE and CHAMOT-ROOKE, 2014; ANSBERQUE, 2011; YELLES-CHAOUCHE et al, 2006; YELLES-CHAOUCHE et al, 2017; SOUMAYA et al, 2018; DOMZIG, 2006

Identified active faults in Western Tell:

1. **Thenia fault.** The NW-SE striking Thenia fault appears in mostly all previous work in Algiers region (YELLES-CHAOUCHE et *al.,* 2006 ; RABAUTE and CHAMOT-ROOKE, 2014).The fault is known and monitored by GPS data, to record horizontal displacement , with 9 stations installed by CRAAG (Centre de Recherche en Astronomie Astrophysique et Géophysique) (Semmane et *al.,* 2005).
2. **Chélif fault.** The presence of dextral strike-slip Chélif fault is justified by thesis work with horizontal and vertical offset observed with drilling data and 90m resolution DEM (ANSBERQUE, 2011).
3. **Aïn Nouïssy fault.**
4. **Relizane fault.** Aïn Nouïssy fault and Relizane fault are both dextral strike-slip. They affect fold axis, which express their striking nature (ANSBERQUE, 2011).
5. **Kabylia fault.** According to (RABAUTE and CHAMOT-ROOKE, 2014) and (SOUMAYA et *al.,* 2018) Kabylia fault is an active right lateral strike-slip fault.
6. **Isser-Bouira fault.** Isser-Bouira fault is recorded in several previous work as a thrust fault (RABAUTE and CHAMOT-ROOKE, 2014 ; YELLES-CHAOUCHE et *al.,* 2017)
7. **Ténès Oued Allalah fault.** This NE-SW fault is identified as a thrust fault with North dip. It has been discovered with field observations and seismic data (YELLES-CHAOUCHE et *al.,* 2006).
8. **Oued Fodda fault.** This fault, also known as Chleff fault is a NE-SW thrust fault with NW dip. It can be justify by geomorphologic observations and paleoseismologic studies realized on this fault
9. **Sahel fault.** Sahel fault is a thrust with South dip according to field studies, and paleoseismology (YELLES-CHAOUCHE et *al.,* 2006).
10. **South Mitidja fault.** South Mitidja fault is also in many studies and appears clearly on geomorphology (RABAUTE and CHAMOT-ROOKE, 2014; YELLES-CHAOUCHE et *al.,* 2017).
11. **Reghia-Boudouaou fault.** (RABAUTE and CHAMOT-ROOKE, 2014)
12. **Medea fault.** (RABAUTE and CHAMOT-ROOKE, 2014)
13. **Zemmouri fault.** Zemmouri is an offshore fault present in a few studies, it was mapped during MARADJA oceanographic campaign, and was discovered with recent Boumerdes seism dated 21st May 2003 (Magnitude: 6, 8). (RABAUTE and CHAMOT-ROOKE, 2014; YELLES-CHAOUCHE et *al.,* 2006).

This map (figure 17) was realized by using previous work on active faulting on this area (RABAUTE and CHAMOT-ROOKE, 2014; ANSBERQUE, 2011; YELLES-CHAOUCHE et al, 2006; YELLES-CHAOUCHE et al, 2017; SOUMAYA et al, 2018; DOMZIG, 2006).Structural maps realized on this area were georeferenced to track active faults, if there is an apparent geomorphological structure on the digital elevation model.

Offshore faults are more complex to find than onshore faults. For example in thesis work from (DOMZIG, 2006), many active faults are referenced in Algerian margin, but not all of them are visible on DEM. Author used more data as high resolution seismic profile, reflectivity data. A lot of those faults can be hidden by erosion, or sediment transport which shape the geomorphology of the margin.

Medea area

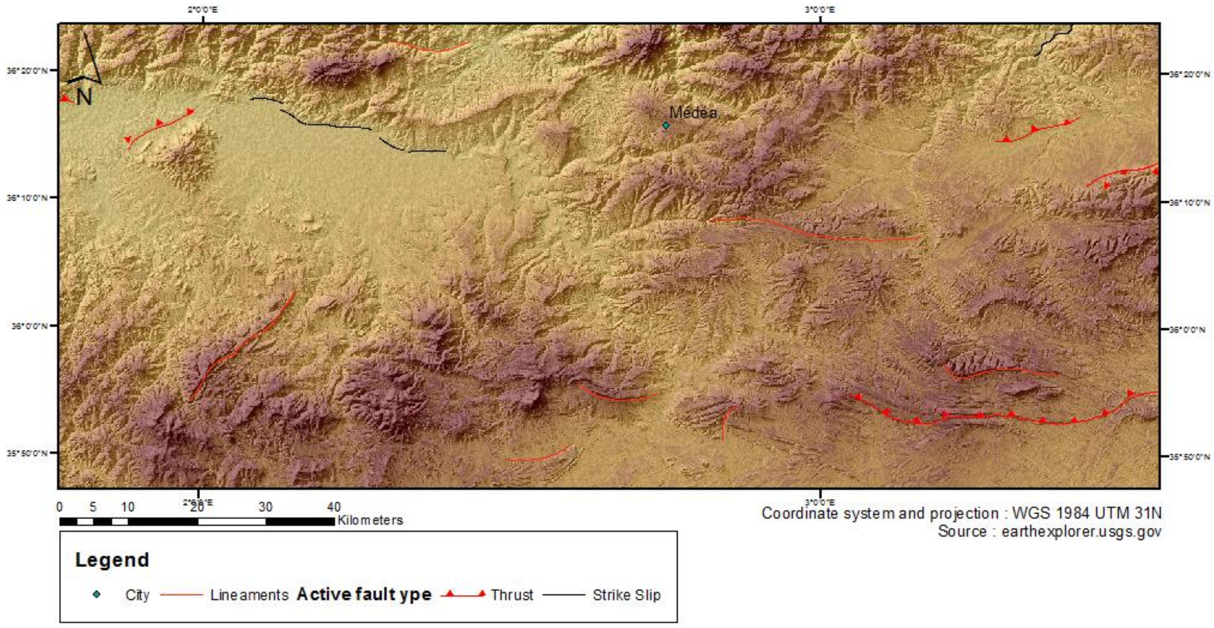


Figure 18 Structural scheme and lineaments in Medea area (made with RABAUTE and CHAMOT-ROOKE, 2014; YELLES-CHAOUCHE et al., 2017)

Many lineaments exist in the area of Medea, in particular south of the city but were not referenced in other previous work. It could be active faults, previously not detected. It could be interesting to collect some data during a field work to confirm or deny this hypothesis.

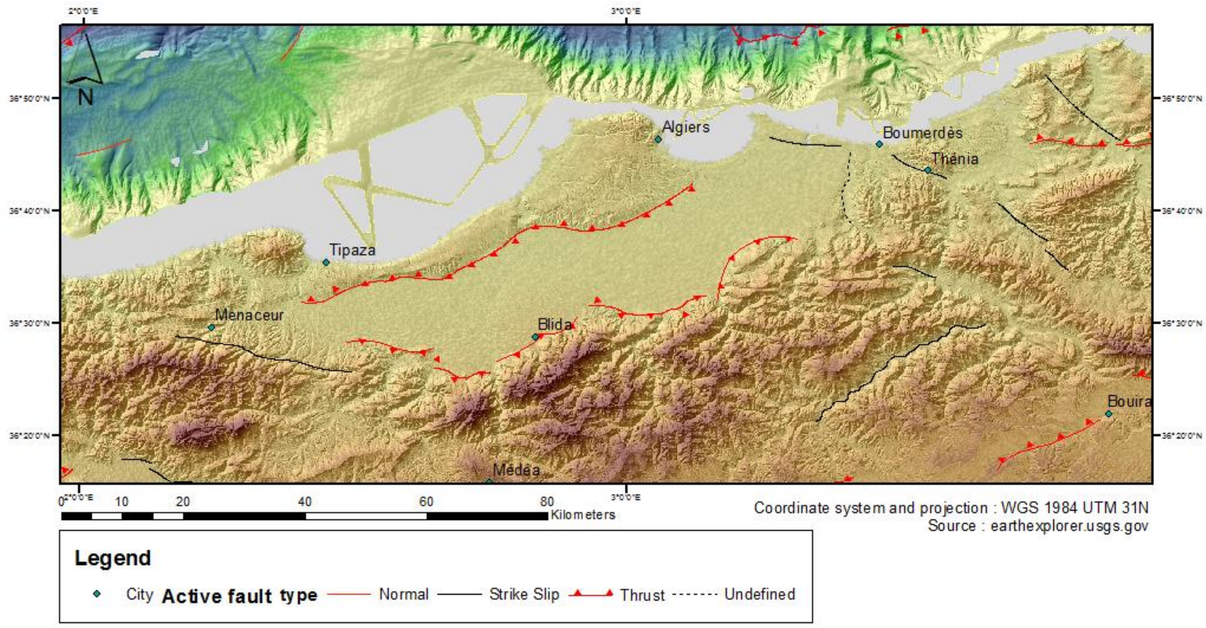


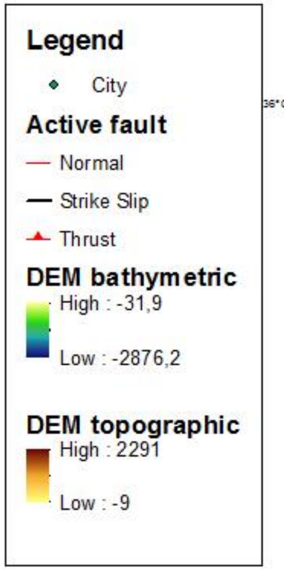
Figure 19 Structural scheme of the area of Algiers (made with Domzig, 2006; Rabaute and Chamot-Rooke, 2014; Yelles-Chaouche et al., 2017)

On figure 19, we can see two major reverse fault systems NE-SW in the Mitidja Basin. To the south of the basin, there are relay fault, delimited by offset area where conjugate strike-slip fault which relies thrust faults and can produce earthquakes.

b) Middle Tell

<u>Identified active faults in Middle Tell:</u>

1. Chott El Hammam fault
2. Djebel Youcef fault
3. Isser-Bouiral fault
4. Kherrata fault
5. South Kabylia fault
   (RABAUTE and CHAMOT-ROOKE, 2014)



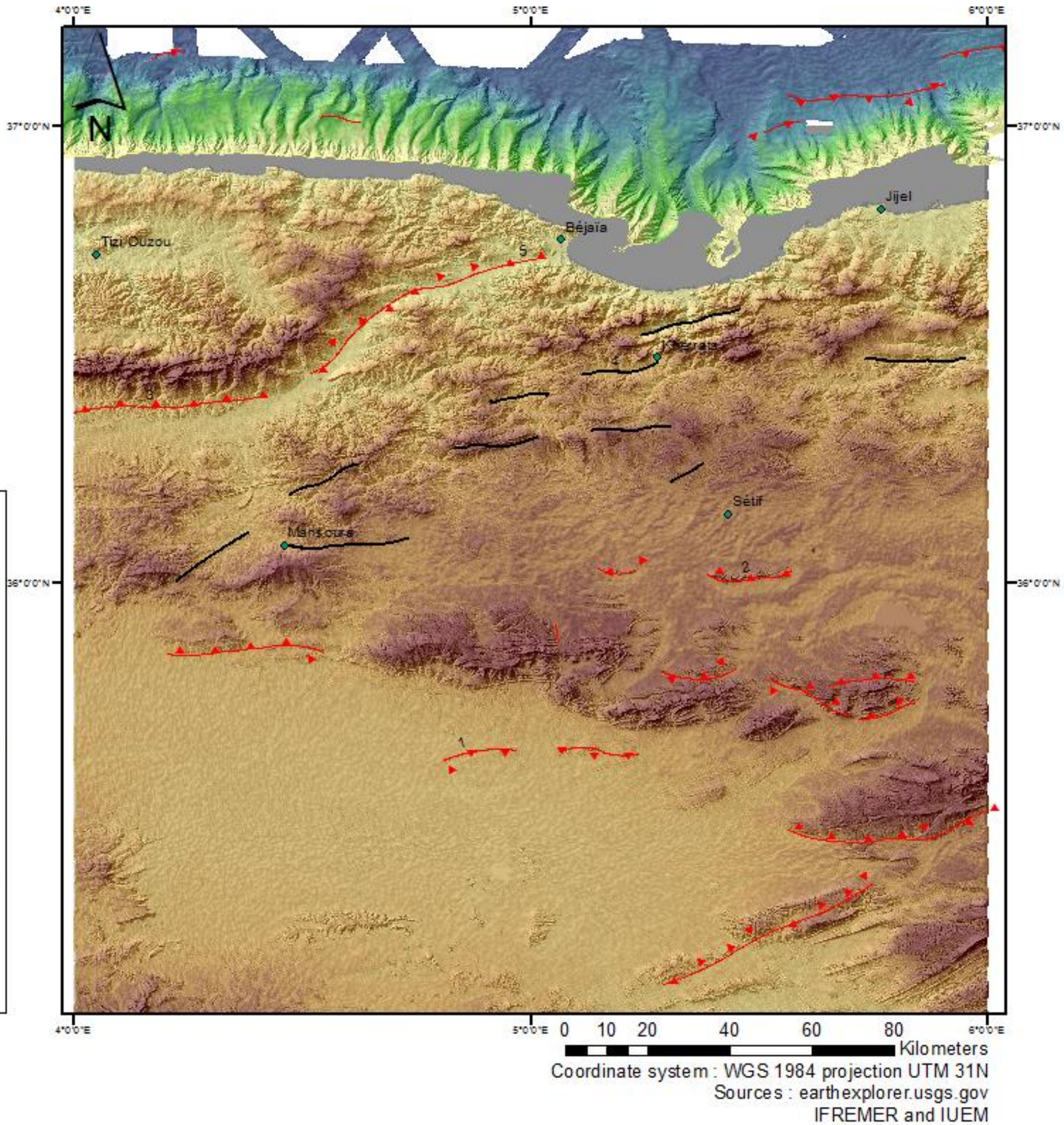


Figure 20 Structural scheme of Middle Tell area (from RABAUTE and CHAMOT-ROOKE, 2014; DOMZIG, 2006)

In Middle Tell area, we can observed many strike-slip fault segments E-W to the East and NE-SW to the West of the map. It is the ending of the large E-W strike-slip structure which affect North East of Algeria and North of Tunisia.

On figure 20, in Middle Tell area, without mentioning South Kabylkia fault, two groups of faults are distinct. To the north NE-SW dextral strike-slip faults and to the south E-W thrust faults. Considering the strain in the region NW-SE, it could be a sign of partitioning in East Algeria or a changing trajectory of main constraint SHmax.

Sétif area

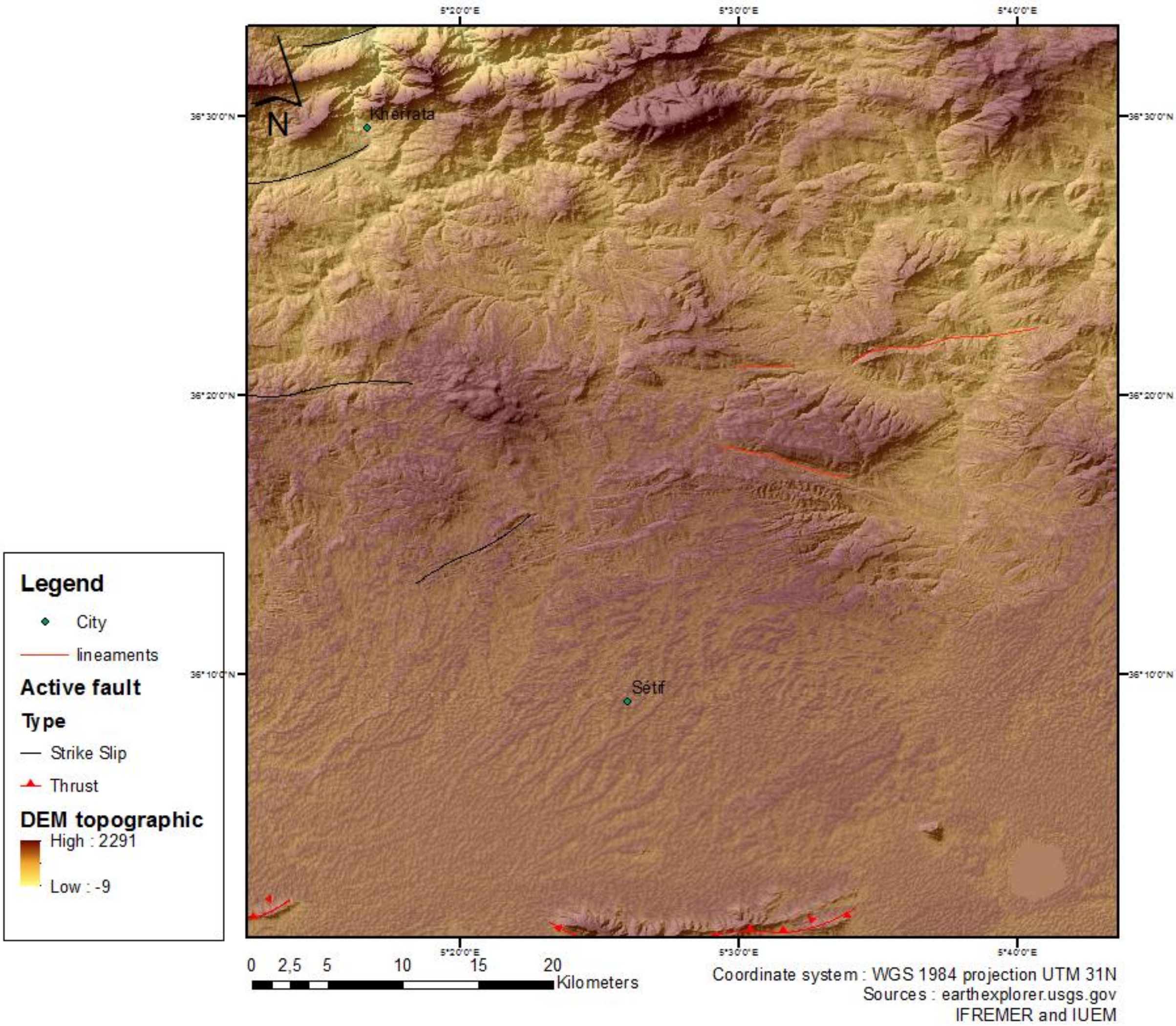


Figure 21 Structural scheme and lineaments of Sétif area

To the north of Sétif city, three lineaments suggest the existence of faults in this area. It could be the extension of right lateral strike-slip toward west. Moreover, tens of earthquake's epicenters have been recorded in this area according to figure 1(RABAUTE and CHAMOT-ROOKE, 2014).

c) Eastern Tell

<u>Identified active faults in Eastern Tell:</u>

1. North-South Axis
2. Sigus fault
3. South fault of the Tell Atlas
4. Tell-Atlas fault
5. Siliana graben
6. Hamam El Balis fault
7. Bouchefouf fault
8. Rohia graben

(RABAUTE and CHAMOT-ROOKE, 2014)

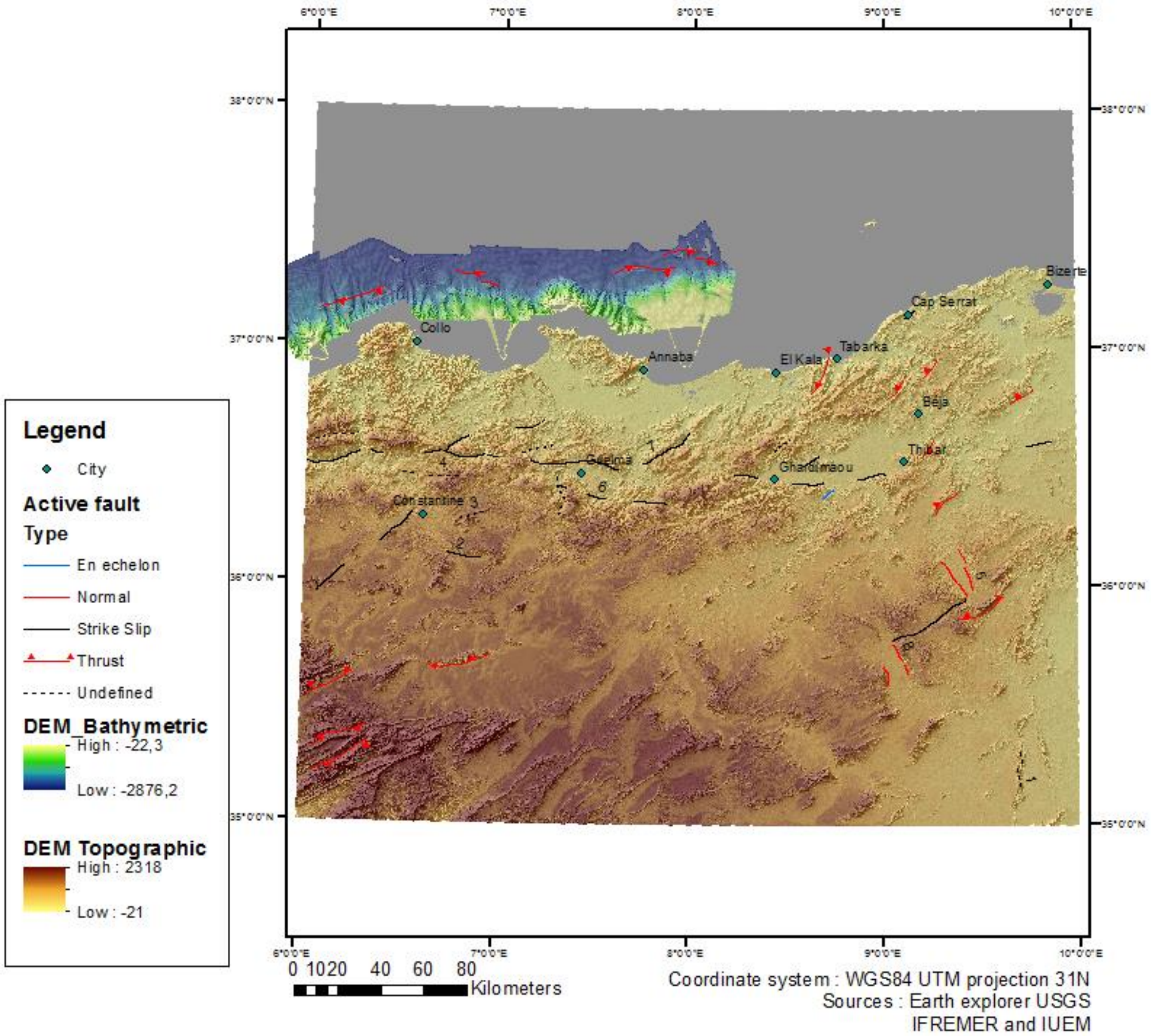


Figure 22 Structural scheme of Eastern Tell area (from RABAUTE and CHAMOT-ROOKE, 2014; DOMZIG, 2006; SOUMAYA et al., 2018)

On this map (figure 21), a large W-E strike-slip clearly appears on the geomorphology of the area. This structure exists as a large, continuous fault system in several works previously published (RABAUTE and CHAMOT-ROOKE, 2014; SOUMAYA et al, 2018 *etc*). Nevertheless, discrepancies observed in this area concern length of those faults. For example, (SOUMAYA et *al.,* 2018) present four faults from Bejaïa (Middle Tell, Algeria) to Thibar (Eastern Tell, Tunisia), faults of 100 Km (figure 22). (RABAUTE and CHAMOT-ROOKE) present about 10 faults, from 10 to 60 Km (figure 21 and 23). On the DEM, strike-slip faults observed are shorter, maximum 50 Km. It has its importance because fault's length is one of the parameters useful to deduce the magnitude of an earthquake. Knowing the possible magnitude of an earthquake also help to anticipate intensity and damages. There is also multiple fault ruptures which can create a single event. It is possible that fault is truncate at young Quaternary alluvium for example (BLACK et *al.,* 2005). Question here is to estimate at best the length of multiple segments forming one fault and creating one single event. Some data would be useful to constrain fault geometries as geophysical data. If we estimate this large strike-slip is composed with 6 faults from 40 to 60 Km. According to empirical relationship among Moment Magnitude M_w and rupture length (WELLS and COPPERSMITH, 1994) : $M_w = 5,16 + 1.12 \times log(Length)$, those strike-slip could produce earthquakes reaching M_w = 6.9 to M_w = 7.1.

Fault extraction with the digital elevation model lead to many segments, and therefore faults are less continuous than in the bibliography. This segmented pattern could be partly related to the degree of structural maturity of the faults in the present-day compressional stress regime (MANIGUETTI et *al*., 2007). This area is also characterized by diffuse deformation, displacement is in the order of a few millimeters per year and so sometimes it does not appear in the geomorphology owing to the competition between tectionics and erosion and to relatively high sedimentation rates that may conceal the morphology, both on land and at sea.

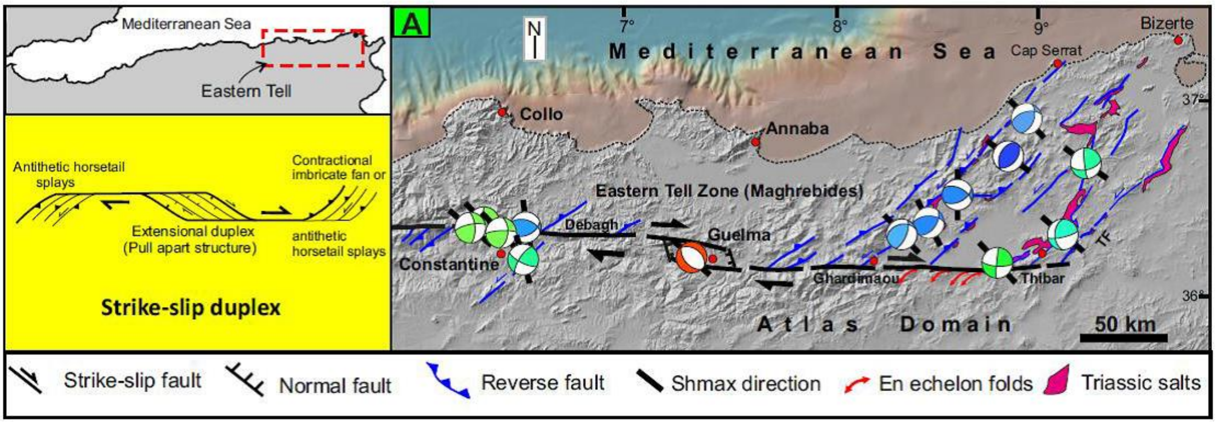


Figure 23 Active strike-slip fault system of Eastern Tell region with focal mechanisms (from SOUMAYA et *al*., 2018)

Furthermore, some authors (SOUMAYA et *al.,* 2018; GHARBI et *al.,* 2014) mapped large NE-SW thrust fault north of Tunisia, some lineaments, less continuous, were observed but below 20 Km on the digital elevation model. Common point is that NE-SW structures seems to end to the South on strike-slip E-W structure. Also only one *en echelon* fault is remarkable to the East of the city of Ghardimaou (figure 21 and 22).

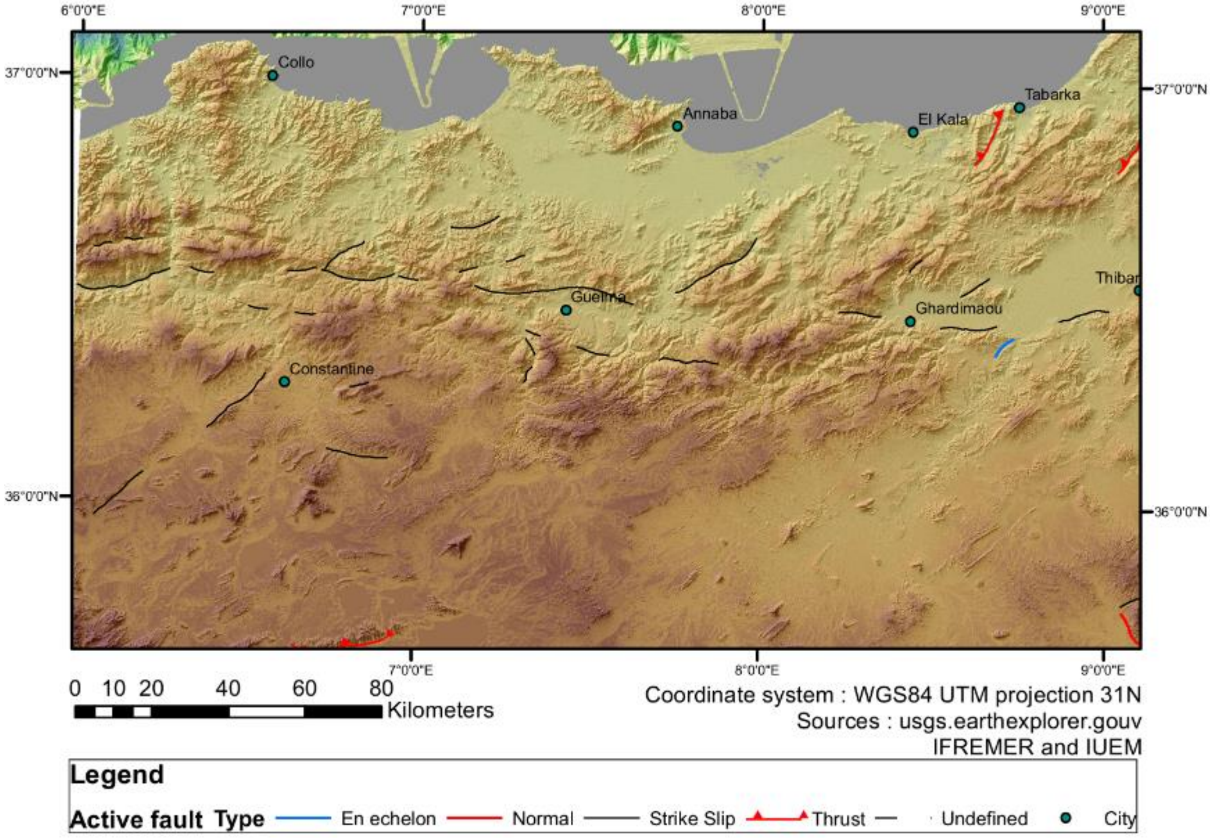


Figure 24 Active strike-slip faulting around the Guelma city

There are many relay faults in the Eastern Tell area maybe because of the former constraints. Guelma basin appears between two right lateral strike-slip ruptures to the North and to the South (figure 22 and 23). It could be an overlap zone between two former normal fault inherited from former extensive constraints now reactivated in this relay zone in which displacement is transferred between the strike-slip faults. The explanation on figure 22 of a pull apart basin may be realistic despite the fact subsidiary faults that branch from the main faults cannot be found on the DEM.

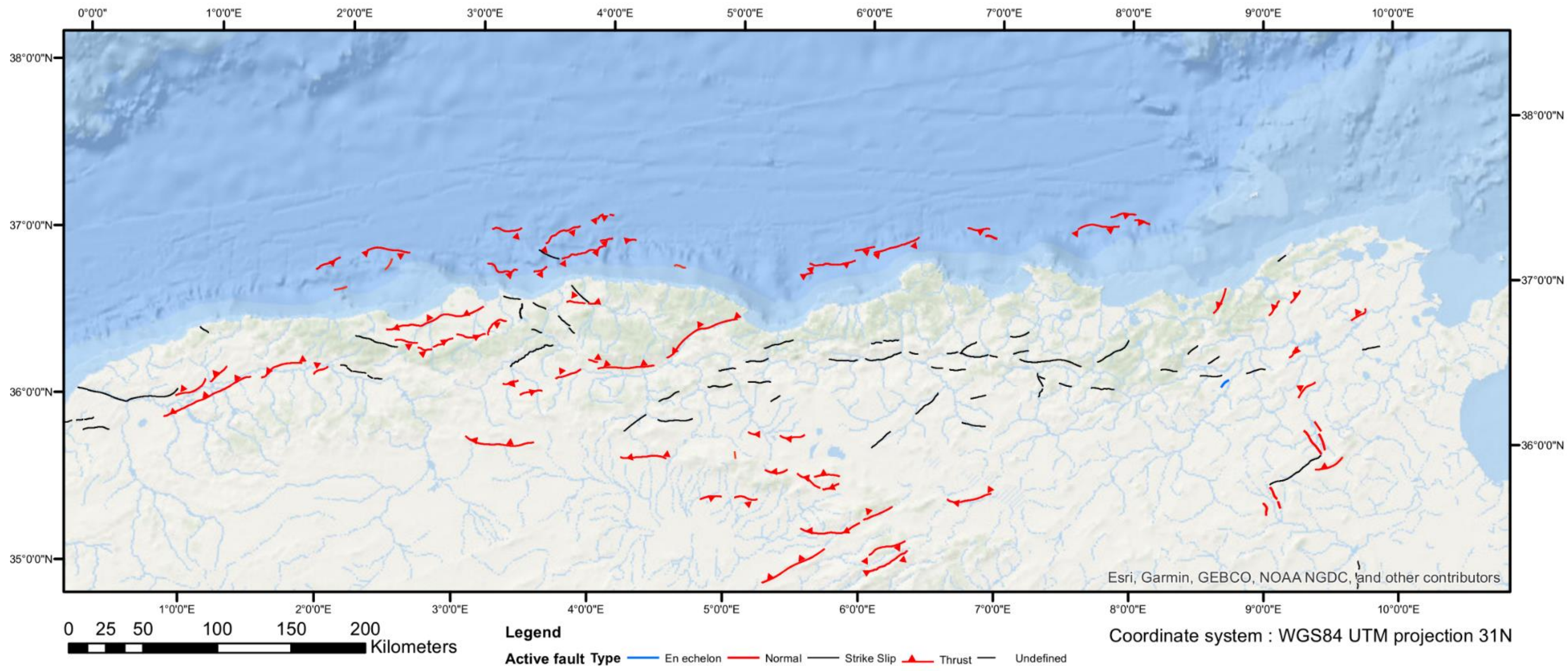


Figure 25 Structural scheme of active faulting in North Maghreb from Mostaganem (Algeria) to Bizerte (Tunisia)

Conclusion

The work completed during this internship is an objective report of faults segments onshore and offshore started from DEM data. The synthetic map (figure 25) summarize this work. Faults have been classified with small interpretation as strike-slip, thrust, or normal faults.

It appears on figure 25 large structures, not over-interpreted. From West two large NE-SW thrust faults which can be related linked from onshore to offshore. Then starting from Bejaïa, a long E-W strike-slip fault system where a there is many segments and relay faults which can generate pull-apart basin as Guelma Basin. The direction of faults in Middle Tell area suggests that strain partitioning occurs To the East of Middle Tell. And to the East, in North Tunisia some NE-SW thrust segments seems to end on E-W strike-slip faults. This structural map presents many segments which shape continuous structure. General constraint in the region is NW-SE convergence which create perpendicular NE-SW thrust faults and E-W oblique strike-slip faults which define a homogeneous oblique convergence. However the direction of faults and the direction of the convergence in Middle area suggest the partitioning of the oblique convergence.

This work has used a method purely spatial which make it limited in interpretation and maybe under-interpreted. That's why it distinguishes with previous work where faults were large and continuous over hundreds of kilometers. It is a careful approach, in this low strain rate area where displacements are only a few millimeters per year. Faults can be hidden in geomorphology by sedimentation or erosion.

This work is full of future research opportunity. It would be interesting to correlate and compare these results with terrain observations because fault type interpretation was mostly made with bibliography. These results could also be improved by geophysics, as radar or seismic profiles.

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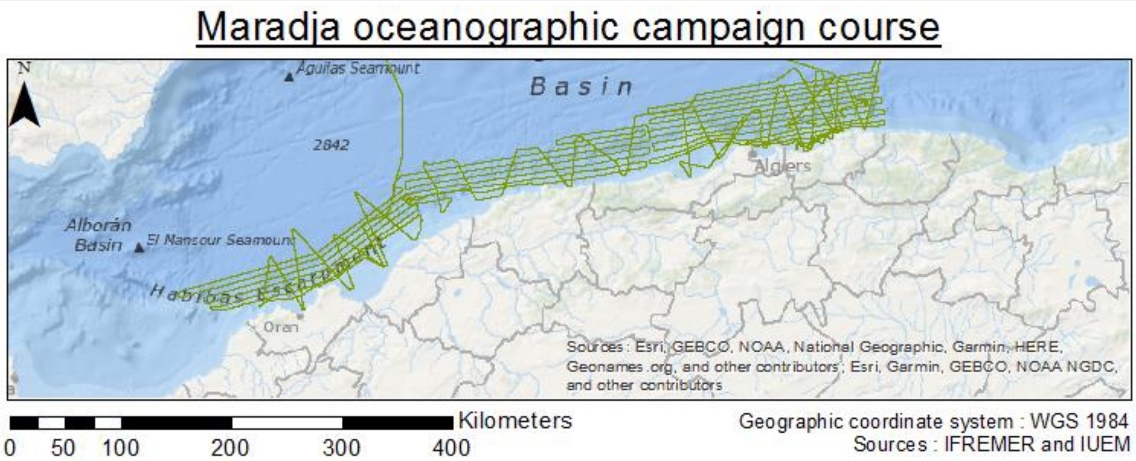
Annexes

A) Oceanographic cruise descriptions

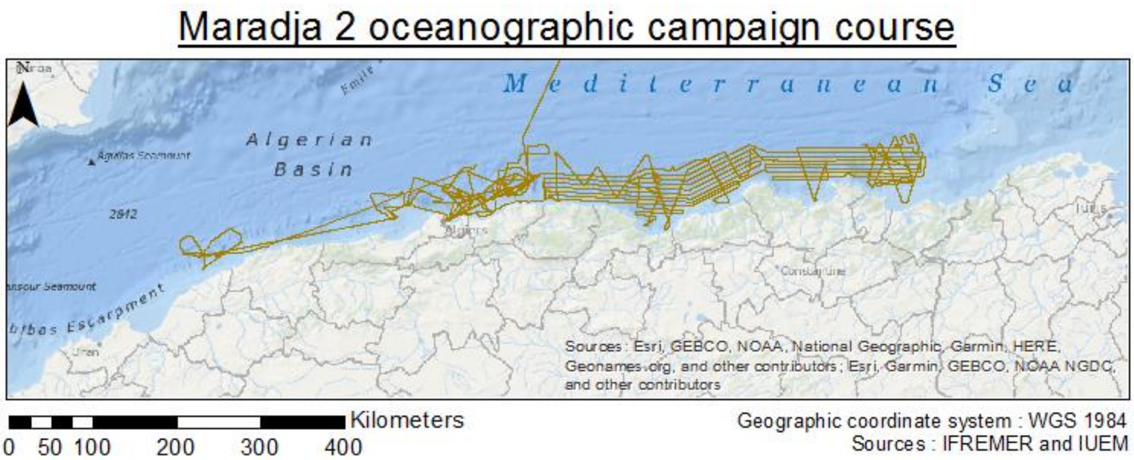
MARADJA

Type	Oceanographic cruise
Ship	Le Surcroît
Ship owner	IFREMER
Dates	21/08/2003 - 18/09/2003
Chief scientist(s)	Jacques DEVERCHERE
DOI	10.17600/3020100
Objectives	(1) Detailed mapping of bathymetry and reflectivity and looking for the roots of active faults along the Algerian coast between West of Oran and East of Alger, giving priority to the 21/05/03 rupture zone and infering its seismogram potential (2) Style, relative size and distribution of the deformation and role played by tectonic heritage (3) Identifying gravity-induced instability on the slope near the large canyons and of the rupture zone of the Boumerdes quake on 21/05/03, and the effects of Messinian salt at the foot of the slope (4) Testing margin deformation models using geomorphological and structural surveying and quantification of the vertical and horizontal movements detected (5) Contributions to geodynamic reconstitutions to the north of Algeria and the Alboran area. The related project is GDR MARGES INSTABILITES, ACI RISQUES NATURELS, ESF EUROCORE EUROMARGINS, "WESTMED" project.



MARADJA 2

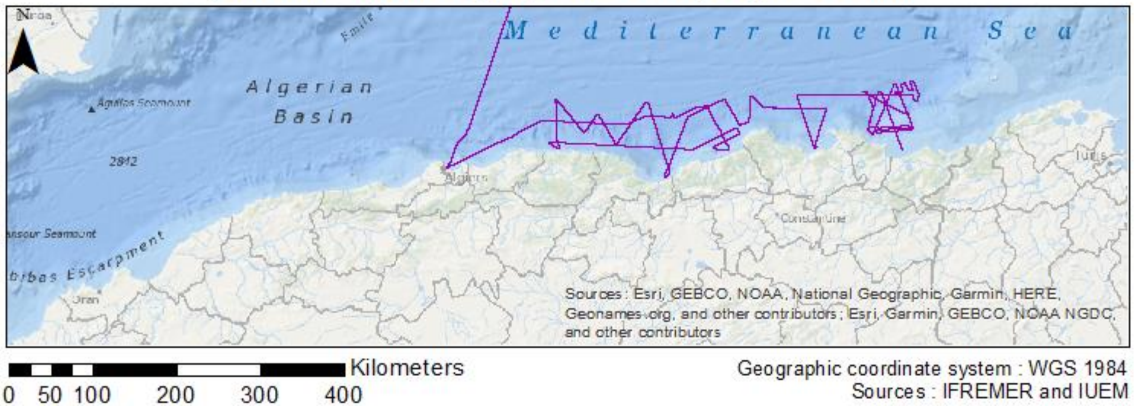
Type	Oceanographic cruise
Ship	Le Surcroît
Ship owner	IFREMER
Dates	25/10/2005 - 03/12/2005
Chief scientist(s)	Jacques DEVERCHERE Bruno SAVOYE
DOI	10.17600/5020080
Objectives	The general objective is to reduce seismic and gravity hazards in Northern Algeria though a detailed examination of the submarine geomorphology and subsurface structures. There are seisms reaching a magnitude of 7.5 and sedimentary movement phenomena which interact on this continental board on different time scales. This Franco-Algerian operation aimed to use several methods (SMF, chirp, corers, SAR, OBS, piezometers) at various resolutions of time and space to increase knowledge and understanding of these phenomena on the central and eastern part of the Algerian margin, including the Boumerdès zone where the quake of 21 May 2003 (magnitude 6.9) took place. These areas are still poorly known. The related programmes are: 'ESF-EUROCORE-EUROMARGINS WESTMED', 'ACI Risques Naturels' and 'GDR MARGES'.



SAMRA

Type	Oceanographic cruise
Ship	Le Surcroît
Ship owner	IFREMER
Dates	03/12/2005 - 12/12/2005
Chief scientist(s)	Jacques DEVERCHERE Abdelkrim YELLES
DOI	10.17600/5020090
Objectives	The general objective is to reduce seismic and gravity hazards in Northern Algeria though a detailed examination of the submarine geomorphology and subsurface structures. There are seisms reaching a magnitude of 7.5 and sedimentary movement phenomena which interact on this continental board on different time scales. This Franco-Algerian operation involved 10 SAMRA cruise days, financed by the Algerial ministry of Research (Algerian Scientific research and Development directorate). It aimed to use several methods (SMF, chirp, corers, etc.) at various resolutions of time and space to increase knowledge and understanding of these phenomena on the still poorly known central and eastern part of the Algerian margin. This part concerned transversal profiles of easern Algeria. The related programmes are: 'ESF-EUROCORE-EUROMARGINS WESTMED', 'ACI Risques Naturels' and 'GDR MARGES'.

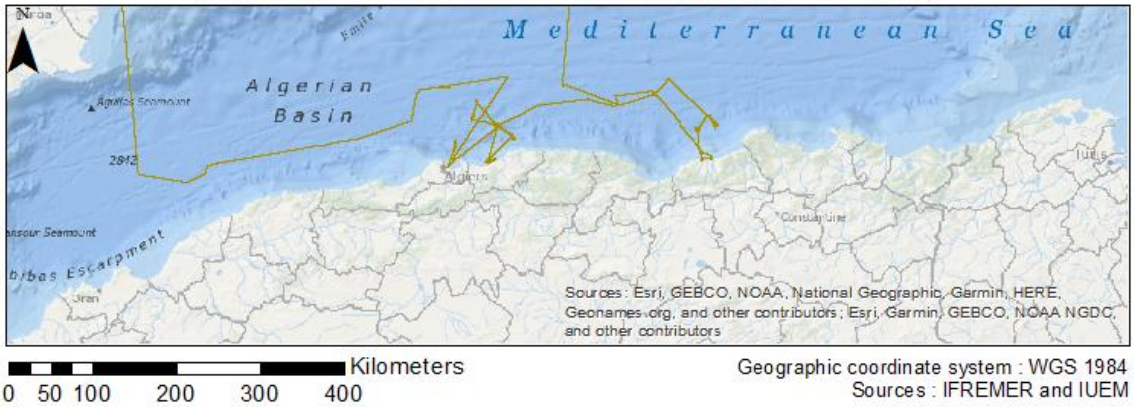
Samra oceanographic campaign course



PRISME

Type	Oceanographic cruise
Ship	L'Atalante
Ship owner	IFREMER
Dates	07/10/2007 - 07/11/2007
Chief scientist(s)	Nabil SULTAN
DOI	10.17600/7010090
Objectives	The PRISME cruise objectives were to: - quantify the risk of earthquake-induced sedimentary liquefaction (for areas studied on the Algerian margin and slope off Nice, France); - quantify the risk of instability and failure due to loss of resistance in sensitive clay (slope off Nice); - quantify the risk of slope breaks and erosion caused by bottom currents (canyon heads - gulf of Lion); - identify the triggering factors for slides seen off Ibiza; - and begin to identify the turbidity related to seismic activity along the Algerian margin. This falls under the ANR-Isis a dGDR Marges projects.

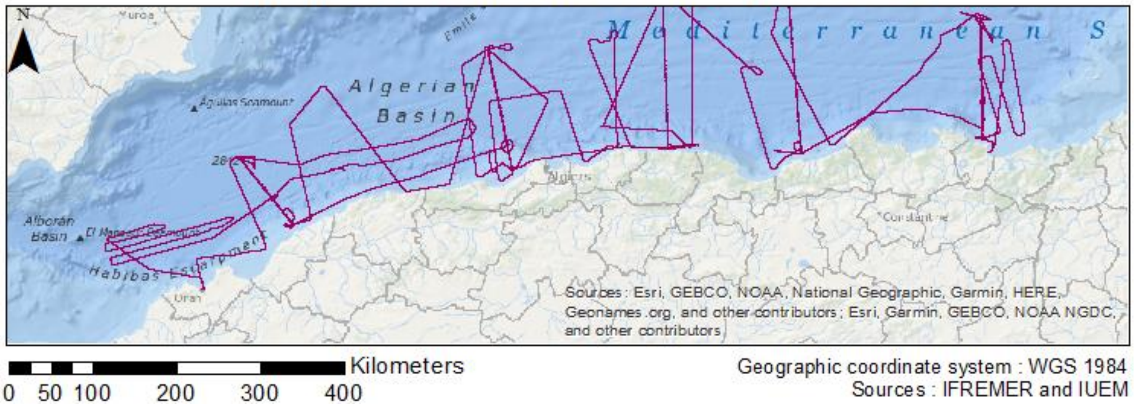
Prisme oceanographic campaign course



SPIRAL

Type	Oceanographic cruise
Ship	L'Atalante
Ship owner	IFREMER
Dates	26/09/2009 - 10/11/2009
Chief scientist(s)	David GRAINDORGE Françoise SAGE Frauke KLINGELHOEFER
DOI	10.17600/9010050
Objectives	The multi-annual partnership-based research programme SPIRAL (deep seismic and regional investigation in northern Algeria) aims to study the deep structure of the North Algerian margin using "high penetration" seismic methods: low frequency vertical reflection shooting, as well as wide angle reflection and refraction with deployment of listening stations on the seabed and onshore. The first strand of the SPIRAL programme SPIRAL involves the sea cruise to acquire geophysical data. This cruise took place aboard RV L'Atalante in two legs, respectively from 26/09 (Oran) to 10/10 2009 (Annaba) and from 13/10 (Annaba) to 10/11 2009 (Oran). These two legs provided acquisition of wide-angle seismic and penetrating multichannel seismic reflection data, which was the main objective of the project, as well as additional data like very high resolution (Chirp or sediment sounder type), magnetic and gravimetric, and multibeam bathymetric echosounder data. The profiles acquired during SPIRAL should supply elements to characterize the structural levels in and under the sediment cover (crust) down to the mantle in the targeted zones given in the cruise report; obtain accurate images of faulted and folded area and the major boundaries like the Moho; constrain the physical and rheological properties (particularly velocity models) which should help determine things like the nature of the crust at the continent-ocean transition. These constraints will make it possible to perform thermo-mechanical modelling on the scale of the Maghrebides belts to the base of the crust (temperature, density) and thus specify the main boundaries of the large crustal domains.

Spiral oceanographic campaign course



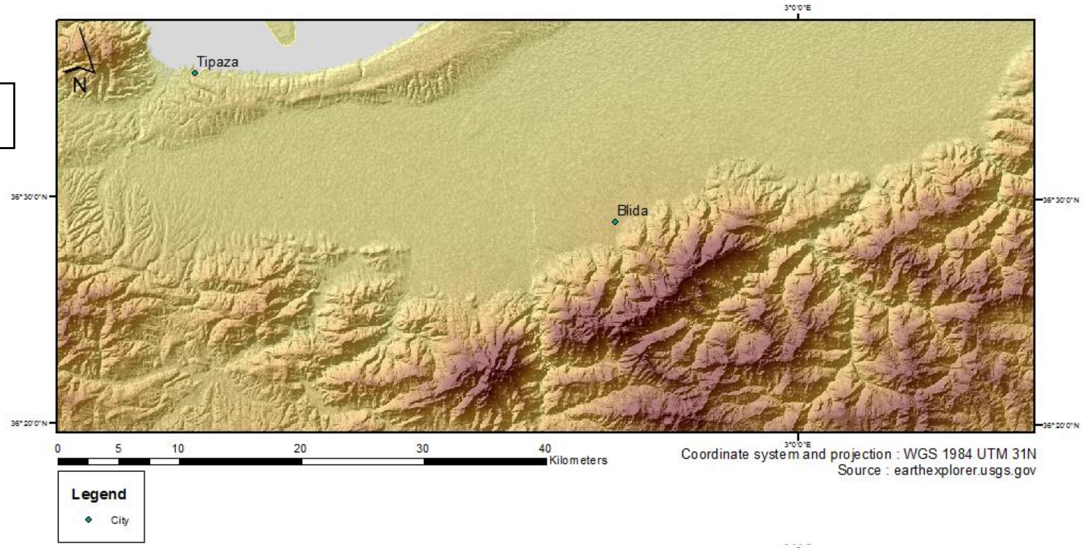
B) Table of cataloged earthquakes with a magnitude equal or above M_w 6,0 (from Hamdache et *al.,* 2010)

TABLE 1 Cataloged Earthquakes with a Magnitude Equal to or Above M_W 6.0.								
Date mm/dd/year	Hour GMT	Longitude	Latitude	Depth (km)	Reported Magnitude	Maximum Intensity	Location	Unified M_W
12/03/ 856	—	9.900	35.650	—	—	X	Tunis. Tunisia	7.0[b]
01/03/1365	18:00:00	3.050	36.770	—	—	X	Algiers. Algeria	7.0[b]
04/05/1504	—	5.600	37.400	—	—	IX	N Jijel. Algeria	6.4[b]
11/09/1518	23:30:00	–1.866	37.233	—	—	VIII–IX	W Almería. Spain	6.1[b]
09/22/1522	10:00:00	–2.667	36.967	—	M_W 6.5[a]	VIII–IX	Almería. Spain	6.5
09/22/1522	—	2.500	36.910	—	—	IX	N Tipaza. Algeria	6.4[b]
09/30/1531	04:00:00	–2.733	37.533	—	—	VIII–IX	Baza. Spain	6.1[b]
05/11/1624	—	3.891	36.920	—	—	IX–X	Dellys. Algeria	6.7[b]
10/09/1680	—	4.400	36.500	—	—	IX	Tizi Ouzou. Algeria	6.4[b]
02/03/1716	02:00:00	3.100	36.700	—	—	X	Algiers. Algeria	7.0[b]
11/27/1722	—	7.600	37.080	—	—	X	NW Annaba. Algeria	7.0[b]
10/09/1790	01:15:00	–0.600	35.700	—	—	X	Oran. Algeria	7.0[b]
03/01/1819	—	0.100	35.400	—	—	IX	Mascara. Algeria	6.4[b]
03/02/1825	07:00:00	2.900	36.500	—	—	X	Blida. Algeria	7.0[b]
03/09/1856	—	1.800	36.300	—	—	IX	Kherba. Algeria	6.4[b]
03/09/1858	04:30:00	1.800	36.300	—	—	IX	Kherba. Algeria	6.4[b]
01/02/1867	07:13:56	2.833	36.467	—	—	X–XI	Blida. Algeria	7.3[b]
12/03/1885	20:00:00	4.600	36.100	—	—	IX	M'sila. Algeria	6.4[b]
01/15/1891	04:00:00	1.800	36.500	—	—	X	Gouraya. Algeria	7.0[b]
01/13/1901	—	4.690	36.610	—	—	IX	Sidi Aich. Algeria	6.4[b]
06/24/1910	—	3.690	36.140	—	—	X	S El Ghozlane. Algeria	7.0[b]
12/24/1920	13:06:06	3.100	36.967	—	—	V	N Algiers. Algeria	6.2[c]
08/22/1922	11:47:00	1.300	36.300	4	—	X	Cavaignac. Algeria	7.0[b]
02/06/1946	05:17:58	–2.400	36.700	—	M_S 6.0	—	Gulf of Almería	6.0[d]
02/12/1946	02:43:24	4.950	35.750	—	M_S 6.0	VIII–IX	M'Sila. Algeria.	6.0[d]
10/25/1949	08:32:00	3.200	37.000	—	—	VI	N Ain Taya. Algeria	6.3
07/08/1954	03:51:50	4.033	36.700	—	M_S 6.8	III	Tizi Ouzou. Algeria	6.8[d]
09/09/1954	01:04:37	1.467	36.283	—	M_S 6.7	X–XI	NW Beni R. Algeria	6.7[d]
09/04/1963	05:06:42	5.200	36.000	—	m_{bLg} 6.3	—	SW Setif. Algeria	6.8[e]
01/01/1965	17:32:21	4.500	35.700	—	M_S 6.5	VIII	M'Sila. Algeria	6.5[d]
05/29/1965	20:40:56	1.600	36.400	—	M_W 6.2	VI	Djebel Frina. Algeria	6.2
10/10/1980	12:25:23	1.447	36.153	5	M_S 7.3	IX	Chlef. Algeria	7.3[d]
10/29/1989	19:21:52	2.444	36.740	10	M_W 6.0	—	N Tipaza. Algeria	6.0
05/21/2003	18:44:19	3.720	36.819	15	M_W 6.9	IX–X	Boumerdes. Algeria	6.9

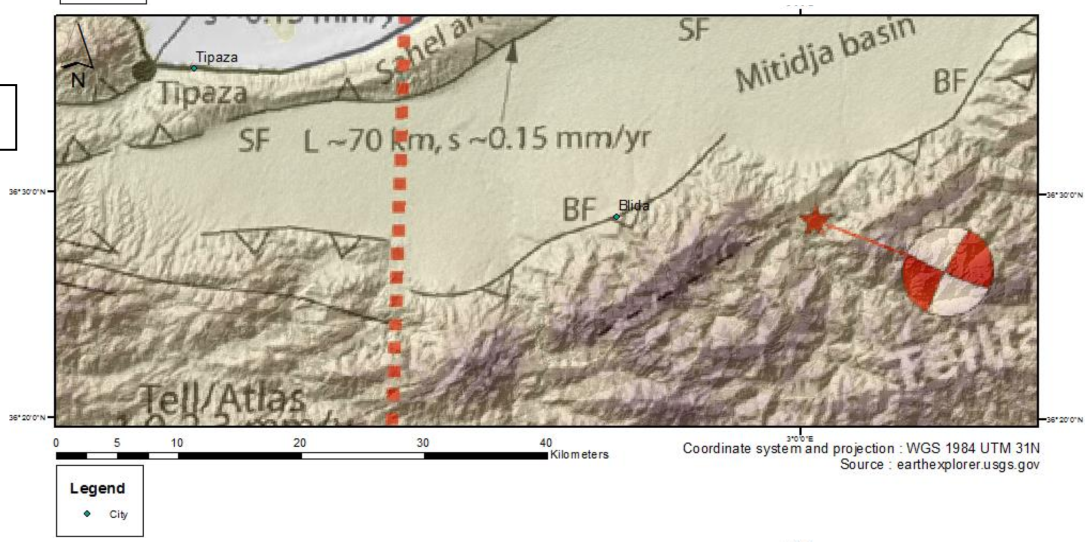
a. Martínez Solares and Mezcua (2002), from intensity data, using the Bakun and Wentworth (1997, 1999) approach
b. From *Imax*, using the Mezcua (2002) relationship between *Imax* and *MW*
c. From reappraised epicentral intensity for offshore epicenters using the López Casado *et al.* (2000) attenuation relationships and the Mezcua (2002) relationship among *Imax* and *MW*
d. From *MS*, using the Johnston (1996) relationship between *MS* and *MW*
e. From *mbLg*, using the Rueda and Mezcua (2002) relationship between *mbLg* and *MW*

C) Example of fault recognition method (with bibliography)

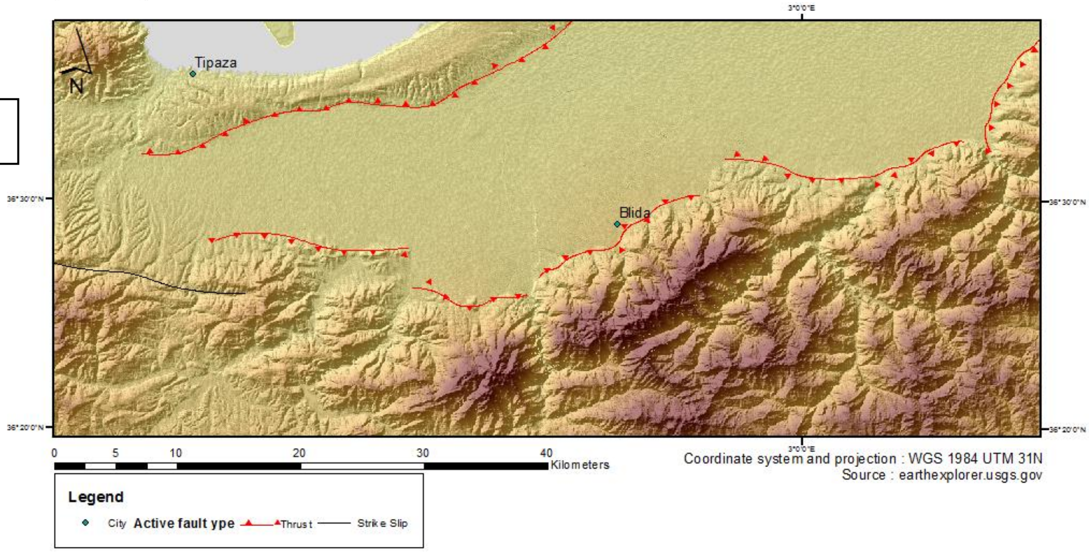
a)



b)



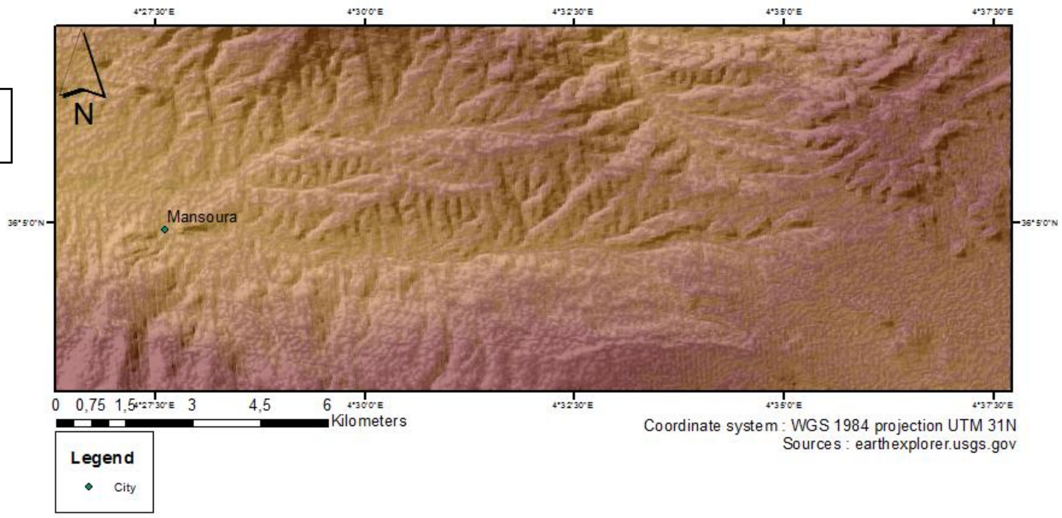
c)



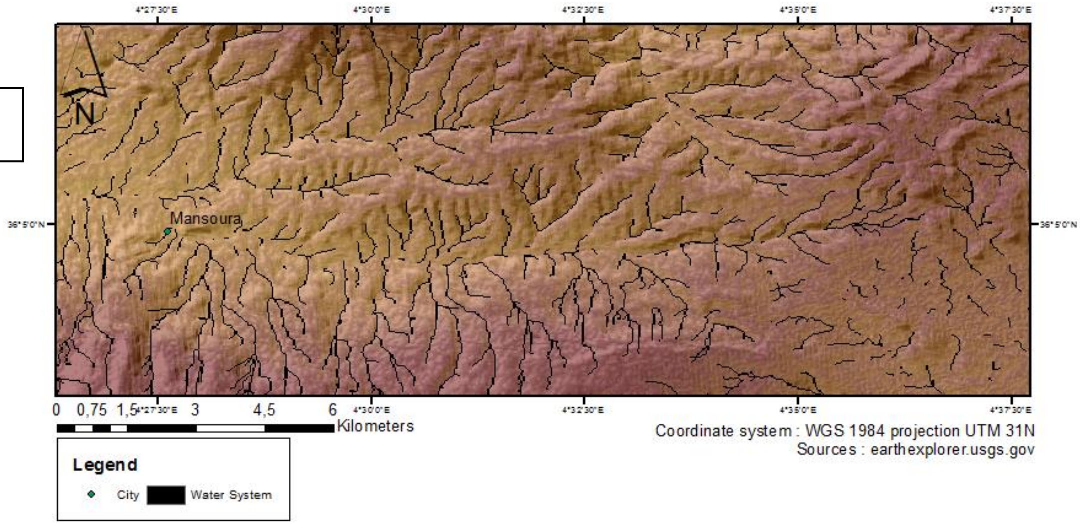
To recognize faults in the geomorphology, here is one of the methods used. On **a)**, the DEM where we can observe structures around Mitidja Basin. On **b)**, a structural map previously made has been georeferenced and made transparent (YELLES CHAOUCHE et *al.,* 2017). On **c)** the active faults have been drawn on the DEM.

D) Example of fault recognition method (with water system)

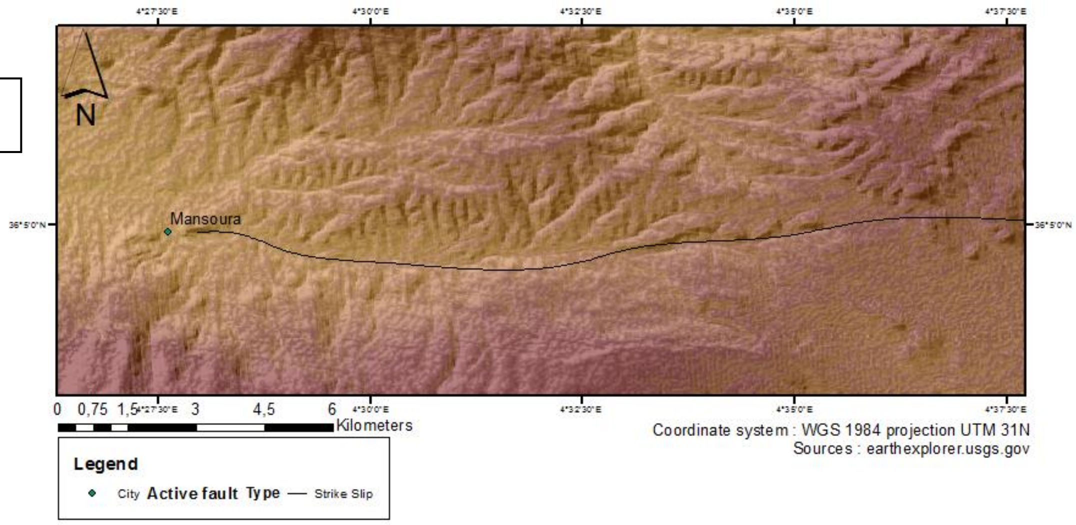
a)



b)



c)



On this example, figure **a)** is the DEM where we can observe a deformation in the DEM. Figure **b)** presents the water system in black lines. Water system shows small displacements to affirm there is a strike-slip fault. Figure **c)** presents the final active fault on the DEM.

E) Self-assessment grid of report's presentation

Le document est agrafé ou relié (pas de pochettes transparentes). Les normes sont respectées (exemple en annexe du document EVE124) : - Page de titre comportant : ○ Titre ○ Auteur (Prénom NOM) ○ Nom, adresse et logo UniLaSalle ○ Nom et adresse de l'organisme hébergeant le stage ○ Type de document (« rapport de stage ») ○ Spécialité ○ Année de scolarité ○ Promotion ○ Nom, prénom et qualité du maître de stage et du tuteur de stage - En-tête et/ou pied de page avec *a minima* le titre du rapport, le nom de l'élève et son n° de promotion - Marges suffisantes	Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non Xoui □non
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L'expression est précise.	Xoui □non
La pagination commence dès la page de titre (cette dernière est comptée mais non numérotée).	□oui Xnon
La pagination est continue, annexes et illustrations comprises.	Xoui □non
Le sommaire des tableaux est distinct de celui des autres illustrations.	Xoui □non
Les abréviations, symboles et unités sont définis dès qu'ils apparaissent pour la première fois dans le texte. (*Ils peuvent être définis dans le texte, mais, s'ils sont nombreux, il est préférable de les définir à part, dans une liste*).	Xoui □non
Les abréviations ou symboles sont ceux que recommande la norme ISO 1000 (disponible au centre de documentation) ou par des normes nationales ou des spécifications d'organismes compétents.	Xoui □non
Les termes qui demandent explication sont définis dans un glossaire.	Xoui □non
Le texte commence par une introduction, il est suivi du développement divisé en plusieurs parties, éventuellement sous-parties, et se termine par une conclusion.	Xoui □non
Chaque illustration comporte une légende précise, horizontale et non encadrée, avec mention de la source.	Xoui □non
Chaque illustration comporte, le cas échéant, en plus de la légende : échelle, orientation, grille, datum et système de projection.	Xoui □non
Les références des figures issues de la littérature sont annoncées dans la légende en mettant entre parenthèses le nom de l'auteur en majuscules suivi d'une virgule et de l'année de publication [Exemple : (PHILIPPE, 1994)].	Xoui □non
Les références sont annoncées dans le texte en mettant entre parenthèses le nom de l'auteur en majuscules suivi d'une virgule et de l'année de publication [Exemple : (PHILIPPE, 1994)].	Xoui □non
Les citations courtes (comportant moins de quatre lignes) sont incorporées au texte et placées entre guillemets.	Xoui □non
La liste de références bibliographiques contient les éléments nécessaires et respecte les normes figurant dans le document EVE124.	Xoui □non
Les documents éventuellement mis en annexe contiennent des informations qui ne sont pas essentielles à la compréhension du texte principal.	Xoui □non
Toute annexe est annoncée dans le texte principal.	Xoui □non
Les pages des annexes sont numérotées ; leur pagination doit continuer celle du texte principal.	Xoui □non
Chaque annexe est séparée des autres par une page de garde, sur laquelle est donnée en grande police sa lettre majuscule d'identification et son titre.	Xσoui □non