

# Contribution of gravity data and Sentinel-1 image for structural mapping. Case of Beni Mellal Atlas and Beni Moussa plain (Morocco).

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**Abstract.** The present work is a combined study of gravity and Sentinel-1 data for fracture mapping in the karstic massif of Beni Mellal Atlas and the adjacent plain of Beni Moussa. In order to locate the various faults that contribute to the study area structuring, the gravimetric contacts analysis method, based on the joint use of the horizontal gradient and the upward continuation at different altitudes, has been applied to the gravity data. To optimize the structural mapping in the study area, the gravimetric lineaments obtained were completed and correlated with the lineaments got from Sentinel-1 image. Four faults families of NE-SW; E-O; N-S and NW-SE directions have been highlighted. These fault families are perfectly combined with the studied area's surface water network, moreover, they corroborate with the previous geological and structural studies.

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## 1 Introduction

The northern border of Beni Mellal Atlas is a complex zone where two different geological domains cross via thrusts with various compositions [1]: Beni Mellal Atlas and Tadla plain. This junction zone has been an abject of numerous geological studies [2, 3, 4, 5, 6] which remain incomplete to this date, especially in structural mapping; because of the rugged landform that dominates this zone as well as a thick vegetal cover boosted by a semi arid climate. In such conditions of difficult field mapping, the new techniques of remote sensing and geophysical data allow to highlight geological structures and to realize the mapping of fractures, usually, hidden by vegetations.

The remote sensing with its possibilities of synoptic view, represent a key tool for lineaments detection [7-8]. The use of passive remote sensing has been described in morocco by many authors in different geographical contexts [9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. However, this technique remain strongly influenced by atmospheric conditions which affect the quality of acquired images and make hard the lineaments detection, in contrast with radar images -independent of atmospheric conditions[19]- which provide important informations in structural mapping. Geophysical prospecting methods are widely used in litho-structural mapping studies; they allow to decrypt different geological structures signatures and localize tectonic accidents in surface that define structural architecture of studied area.

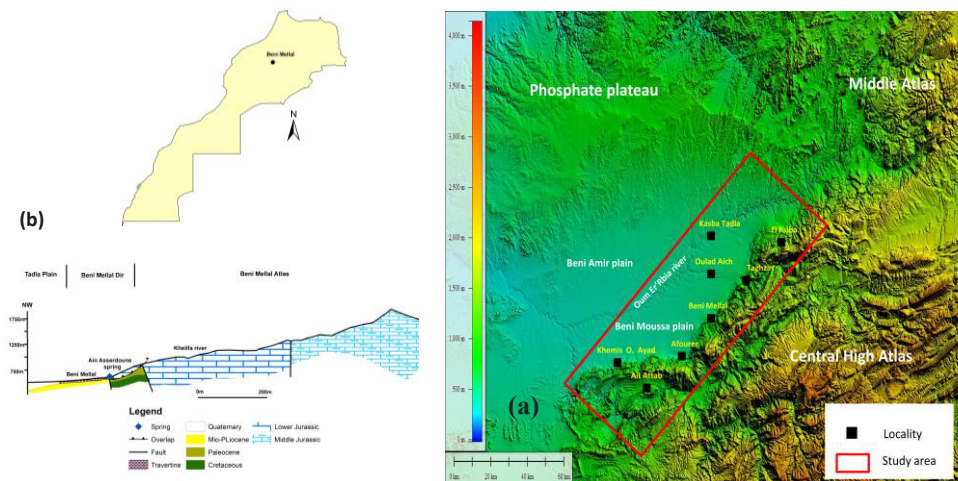
The present study represent a combined analysis of data provided by sentinel 1A radar image and gravity to optimize lineaments network mapping which cross the study area. Gravity data has been treated and analyzed in order to extract gravimetric lineaments which will be correlated and completed by the discontinuities deduced from sentinel 1A radar GRD type (Ground Range Detected) image analysis and filtering. This type of image is recognized as having a great potential, generally in geological applications and particularly in structural mapping [20, 21, 22]. Numerous examples in literature demonstrate the effectiveness of geophysical and satellite data coupling method in fractures detection and litho structural maps updating [23, 24, 25, 26, 27, 28].

The study area belongs to the superior basin of Oum Er'Rbia, it covers a surface of 2850 km<sup>2</sup>, its width includes the zone between El Ksiba et ait attab and crosses dozen of kilometers of Beni Mellal atlas mountains in south-east and Beni Moussa plain in north west (left edge of Tadla plain). It covers two different geological domains (Fig.1):

- In the south, Beni Mellal atlas is represented by the north occidental edge of central High Atlas [29, 2, 30]. It is located in the south of Tadla plain and the outskirts of the junction between high and middle atlas. The altitudes decrease from the south east to the North-West, They pass from 1000 m (in el Ksiba) in the atlas border to less than 500 m in Tadla plain. Its highest point is Jbel R'Nim that reaches 2411 m;
- The Tadla plain with altitudes limited between 400 and 700 m is shown like an asymmetric wide depression with ENE-WSW direction [31]. It extends to the phosphate plateau in the north and Beni Mellal atlas in the south. With its monotonous landscape, the Tadla plain is drained by Oum Er'Rbia river which divides it into two asymmetric sectors. Beni Amir in the right side and Beni Moussa in the left one.

Between the mountainous zone of Beni Mellal Atlas and the Tadla plain, there is a slim band of fertile lands named piemont zone or Beni Mellal Dir [32-33]. This rough contact between a glaxis in slight slope and steep terraces which dominate it occupies fifteen

kilometers of width in the south-west and become narrows in the north east. Along the northern karstic massif border, many springs row along the thrust fault of Tadla, they emerge from Lias contact at the level of tertiary thrusts and travertine of Dir (Fig.4a and b). Finally, they provide an abundant resource of good quality water which is exploited for drinking water supply and agricultural irrigation.



**Fig.1.** Location of study area. **a)** Digital Elevation Model of the study area , **b)** NW-SE geological cross-section showing the Atlas overlap on the Dir and Beni Moussa plain formations.

## 2 Geological and hydrogeological setting

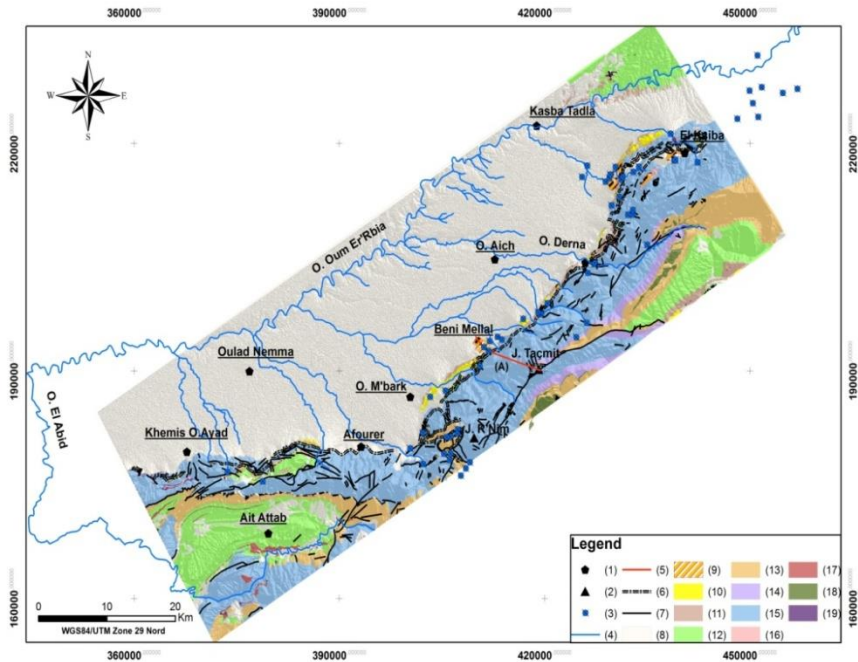
### 2.1 Geological setting

Beni Mellal Atlas is essentially constituted by a dolomitic massif facies from Middle and Lower Jurassic which is strongly fractured and karstified (Fig.4c and d). Facies lateral variations are observed when moving from the basin (marly limestones) to the platform (dolomitic limestones) [3-6]. Stratigraphic column starts with the Permo-Triassic and ends by the quaternary deposits. Its current structure is the result of tectonic movements occurring in hercynian and alpine phases [4, 34, 35, 36]. Therefore, the carbonate slab has been folded to the North-West, then it overlapped plio quaternary series of the plain [2, 37, 38, 39] (Fig.2).

To the north, Beni Mellal High Atlas dominates abruptly Beni Moussa plain because of faults system. The most important one is the north atlasic fault (Tadla overlap). Armed with a thick liassic limestone series, it leads up atlasic structures to Tadla plain (Fig.1c). Tadla plain is a wide dissymmetric depression that is oriented WNW-ESE [40, 41, 31]. Its axis is located in atlas border and support strong series of deposits moving from Triassic to Quaternary.

At the structural level, Beni Mellal karstic massif is fractured by a faults system oriented towards two main directions: NE-SW to ENE-WNW (N40-70°) and N-S (N150-180°). This system of faults facilitates atlas waters drainage to the subatlasic formations of the plain and allows their contact, at some points, with permeable facies. This contact makes easy

hydraulic connections either by underground circulation, or by re infiltration of Beni Mellal complex atlas-dir waters springs [39].



**Fig.2.** Geological map simplified of studied area [3, 5, 42].

(1) locality; (2) mountain ; (3) spring; (4) hydrographic network; (5) geological cross-section; (6) Tadla overlap; (7) fault; (8) Quaternary (alluviums + loams); (9) travertine; (10) Mio-Pliocene; (11) Paleocene-Eocene; (12) Cretaceous; (13) Middle Jurassic (Dogger); (14) Toarcian-Aalenian; (15) Lias (dolomitic and marly limestones); (16) Triassic (clay and pink marl); (17) Cretaceous basalts and dolerites ; (18) Middle Jurassic Igneous rocks; (19) Upper Triassic altered basalts.

## 2.2 Hydrogeological setting

In Beni Mellal atlas, the aquifer is represented by a karstic groundwater which is constituted by dolomitic limestones from Lower Lias [43]. It is drained by many springs which emerge from Tadla overlap. The most important one is ain Asserdoune spring (1,1 m<sup>3</sup>/s) (Fig.3a). This groundwater is supplied by rain waters, snow melting, waters originated from upstream Oued Derma basin and waters of Tasmit hinterland [38].

This karstic aquifer overlaps Dir thrusts that are fragmented into many little reservoirs, and thus, the transition can be possible with other Tadla plain aquifers which have been a subject of many hydrogeological studies [31, 38, 43, 44, 45, 46].

Those different aquifers observed in Tadla plain have a special organization. It consists in a multilayer system that is represented by four aquifers with an important hydrogeological potential:

- Turonian aquifer;
- Senonian aquifer;
- Eocene Aquifer;
- Tadla phreatic groundwater (Mio-Plio-Quaternary aquifer).

Turonian underground water is a reservoir with an important hydrological potential. It contains water resources strongly used in drinking water supply and industry [48-49]. The thickness of Turonian formations increase by moving from north to south. They measure 20 m in their outcrop and reach 80 m nearby the atlas.



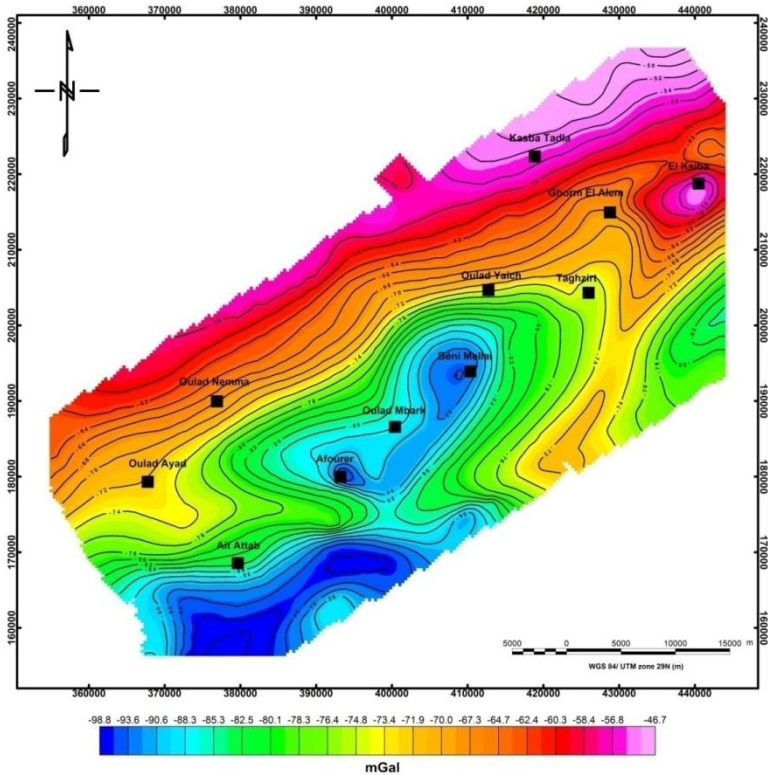
**Fig.3.** Pictures showing the fractured limestones and the emergence context of some springs. a) Ain Asserdoune spring; b) Tamegnounte spring; c) Liassic fractured limestones; d) El Ksiba thrusts.

### 3 Materials and methods

#### 3.1 Gravity data

The gravity data used in this study result from a measurement campaign carried out in 1961 by the African Company of Geophysics (CAG), for the Mines and Geology department (Ministry of Energy, Mines, and Water). The data are available in the form of a 1/200000 scale Bouguer anomaly map with a contour interval of 5 mGal and a reduction density of 2.2 g / cm<sup>3</sup>. This map was scanned and digitalized by using ArcGIS software (version 10.3) before proceeding with the various filtering techniques using Geosoft's Oasis Montaj software (version 8.2).

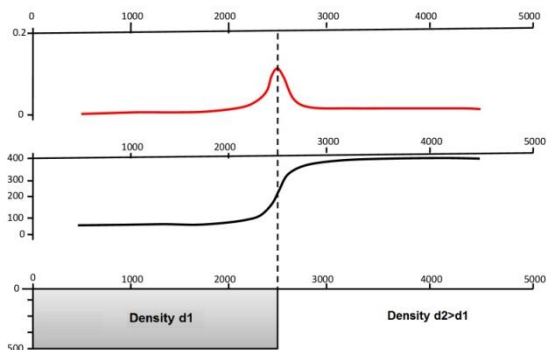
The Examination of Bouguer anomaly map shows local variations in the gravity field moving from -98 mGal to -47 mGal, which are clearly displayed as an increasing regional gradient from North-West to South-East (Fig.4). This regional anomaly, assimilated to a plane, was estimated by using the polynomial regression method and subtracted from the Bouguer anomaly in order to calculate the residual anomaly (Fig.7).



**Fig.4.** Bouguer anomaly map (reduction density  $d=2.2$ ; interval = 2 mGal).

The residual anomaly map shows several gravity gradient areas (high and low trend gravity) that may correspond to contacts or discontinuities (faults, flexures, etc.). In order to make better use of this gravity data and to bring out more informations compared to those can be drawn from the residual map, different filtering techniques have been applied to the gravity data to highlight the major structural axis that affect the study area [50].

We have applied the analysis contacts method based on the joint use of the horizontal gradient and the upward continuation (Fig.6). The interest of this method has been mentioned for a long time [51]. The success of this method's application has been demonstrated by numerous previous studies [51, 52, 53, 54, 55, 56, 57]. The principle of this technique is to compute the horizontal gradient of the residual anomaly and its upwards continuations at different altitudes. This treatment is very useful for localizing the geological contacts because the limit between two blocks of different densities corresponds to this gradient maxima [58, 59, 60, 61]. Indeed, above a vertical contact between two rocks of different density, the gravity field is manifested by a level's change marked by the passage of low values above low density rocks to higher values at the aplomb of high density rocks. The inflection point which marks the transition between the two zones is located at the vertical between the two types of rocks. Local maxima of the horizontal gradient are narrow lines above geological contacts marked by density contrasts [62-63] (Fig.5)



**Fig.5.** Representation of gravity anomaly caused by a vertical contact (black curve) and its horizontal gradient (red curve).

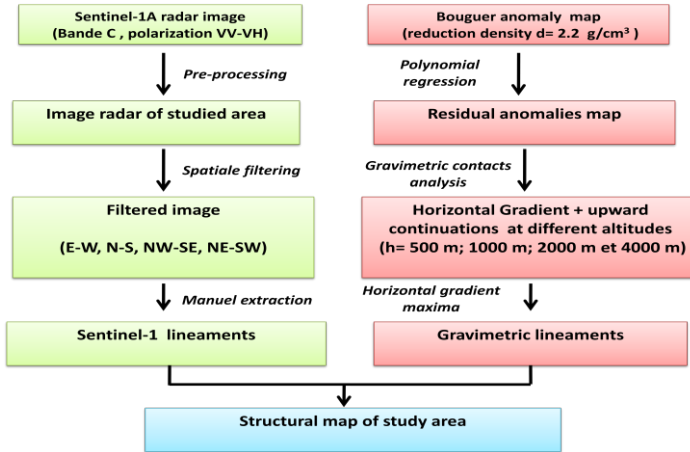
### 3.2 Sentinel-1A processing and analysis

In order to bring more precision to the structural mapping and to optimize the results obtained from the gravity data processing, we relied on the analysis of Level-1 Ground Range Detected (GRD) product of Sentinel. The radar image used in this study was acquired in 2 April 2016 in descending orbit and dual polarization VV and VH, with twenty meters (20 m) spatial resolution recorded in the band C (Table 1). It is available free on the website of the European Space Agency ESA (<https://scihub.esa.int/dhus/>). The different processing and filtering of the Sentinel-1A radar image were performed using SNAP ESA Sentinel-1 toolbox (S1TBX).

**Table 1.** Senyinel-1A data Characteristics

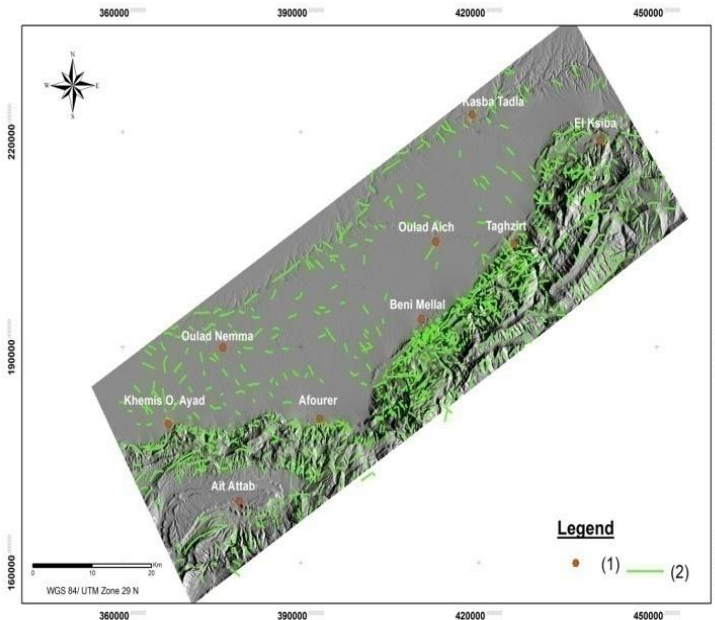
Specifications	Sentinel-1A data
Acquisition time	02 April 2017
Acquisition orbit	Descending
Imaging Mode	IW (Interferometric Wide)
Imaging frequency	C-band (5.4GHz)
Polarization	VV-VH
Data product	Level-1 GRD
Resolution mode	20 m (Full resolution)

A set of processing and filtering operations were applied to the Sentinel-1 radar image (Fig.6) to reduce uncertainty of the data, mainly due to atmospheric disturbances, as well as the topographic effects of the target [64] and improve the possibility of the lineaments extraction[65, 66, 67].



**Fig.6.** Flowchart of adopted methodology for lineaments extracted

In this study, the manual extraction by visual interpretation was adopted for the lineaments identification in the study area [18, 68, 69, 70, 71, 72, 73]. Those lineaments are materialized by the limits formed by the dark and clear zones lines [74-75] more or less regularized and the hydrographic network disturbances [76]. Their signature in the field is very diverse, they may correspond to contacts between formations of different lithology, outcrop limits or to fractures or faults lines [77-78]. The figure 7 shows a map of lineaments extracted from the Sentinel-1A image processing of the study area.



**Fig.7.** Map of lineaments extracted from Sentinel-1 image. (1) locality; (2) lineaments Sentinel-1.



## 4 Results and discussion

Residual anomalies map obtained from the regional trend removal, show values that vary between -20 mGal and more than 6 mGal (Fig.8a). Those variations are associated with underground density variations. Many positive anomalies (high trend gravity) and negative ones (low trend gravity) have been highlighted by this map. To understand their origin, we overlaid residual anomalies and study area geological maps [3, 5, 42], then we correlate those anomalies with existing borehole logs. By analyzing all this data, we can deduce the following principal structural traits:

### - Low trend gravity

- N1 negative anomaly: located in the map center with strong amplitude of 10 mGal and NE-SW direction, it corresponds actually to the lengthening direction of Tadla basin. It is a zone of subsidence that affects a steeply dipping socle, so, it allows a very important deposition of light tertiary and quaternary formations;
- N2 negative anomaly: located in the north of Afourer locality, it is less important than precedent anomaly. It shows a continuation to NE (where it extends to N1 anomaly). It corresponds probably to the effect of sedimentary fill of Tadla basin with a displaced depocenter to the south nearby the piedmont of atlasic chain;
- The two N3 and N4 anomalies, with low amplitude, correspond respectively to Middle Jurassic and cretaceous outcrops in the atlas.

The alignment of N1 and N2 negative anomalies represents Tadla basin axis, where the sedimentary cover is thick (Fig.8b). This result is consistent with the general asymmetric structure of Tadla basin. Correlations trials between existing boreholes (Fig.9) show clearly the syncline shape of Tadla plain [79-80] and the thickening of post-Palaeozoic cover towards the northern border of Beni Mellal Atlas [41, 46, 80]. The northern flank of N1 anomaly shows a strong gradient that can be explained by the presence of faults which lead the Liassic slab to overlap Dir northern and Tadla quaternary formations [30-81].

### - High trend gravity

- P1 and P2 positive anomalies

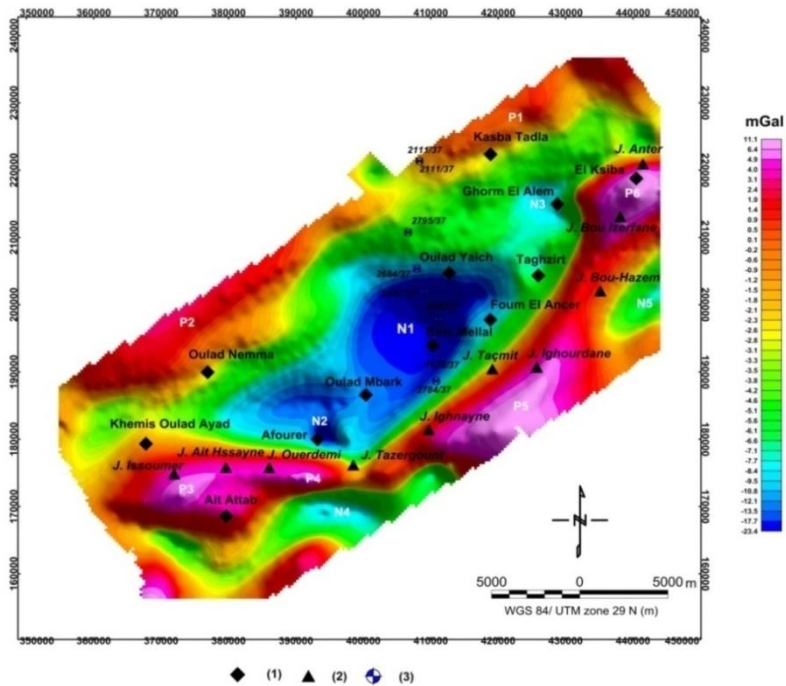
In the northern border of area study which corresponds to Beni Moussa plain, gravimetric axis linking P1 and P2 positive anomalies correspond to conglomerates formations represented in Tadla plain by lentils drowned in plio quaternary cover. This gravimetric axis would present a hydrogeological interest because it can play a role of underground waters accumulation and circulation seat.

- P3, P4, P5 and P6 anomalies:

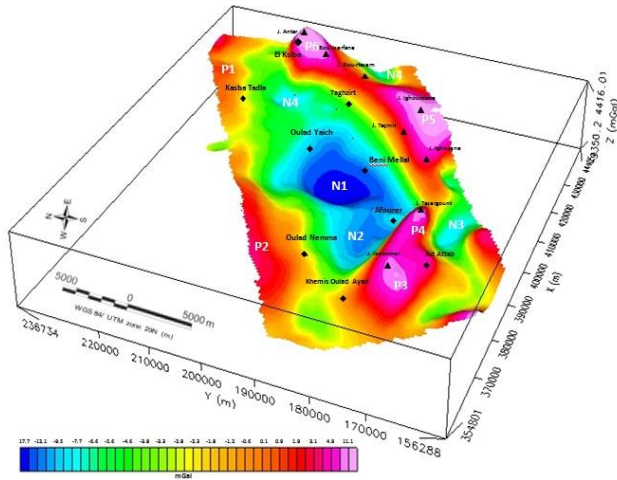
The southern part of area study is characterized by the existence of positive anomalies series (P3, P4,P5 and P6) which constitute pink to red coloured band. Those four anomalies are approximately oriented from NS-SW to ENE-WSW, they are probably caused by the

liassic slab elevated roof which overlaps tertiary and quaternary adjacent plain (Beni Moussa plain)

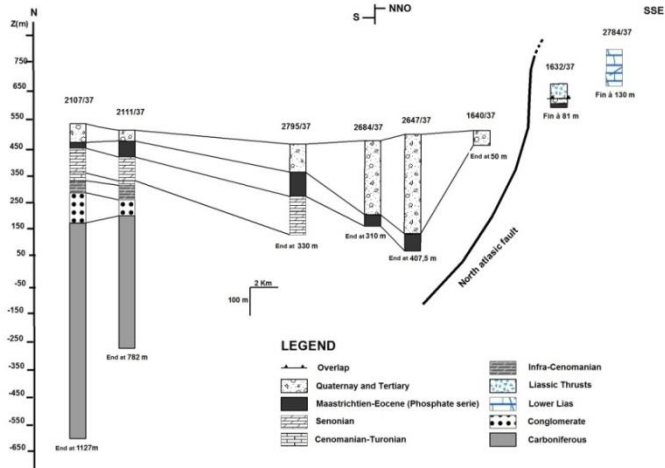
- P3 positive anomaly : caused by the anticline effect of jbel Imouzzer located in Afourer atlas;
- P4 positive anomaly: reflects gravimetric signature of jbel Tazergout's anticline overlapping [30];
- P5 positive anomaly: lengthened following a NE-SW direction with high amplitude. It is bordered by jbel Ighnayene and jbel Tasmit, it opens up towards the south where it should continue to Ouauizeght high atlas basin.
- P6 positive anomaly :located in the north-east of study area, it corresponds to the double effect of two anticlines respectively originated from jbel Izerfane and jbel Antar ( El Ksiba Atlas )



**Fig.8a.** Residual anomalies map of studied area. (1) locality; (2) mountain; (3) borehole.

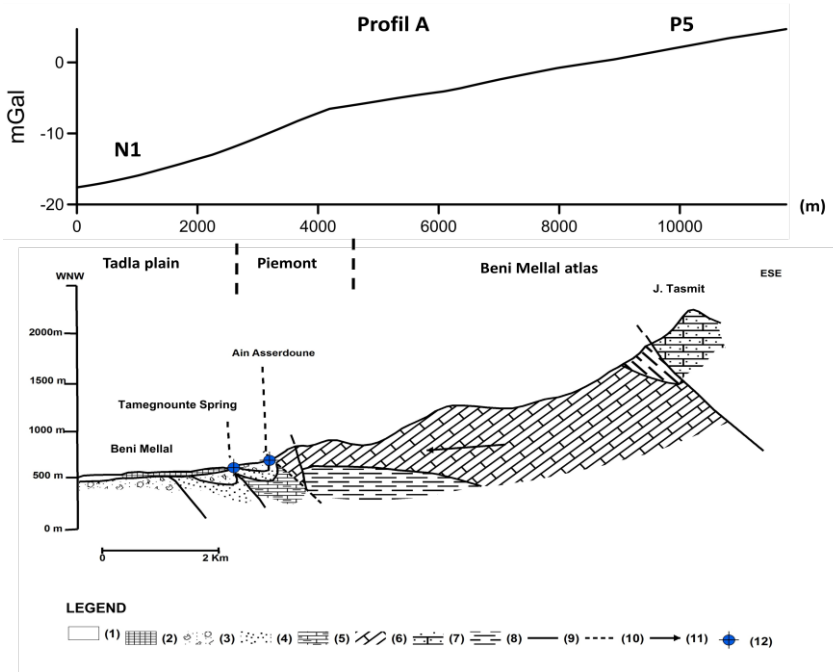


**Fig.8b.** 3D view of residual anomalies map of studied area.



**Fig.9.** Correlation between boreholes BJ101, 2795/37, 2684/37, 2647/36, 1640/37, 1632/37 and 2784/37.

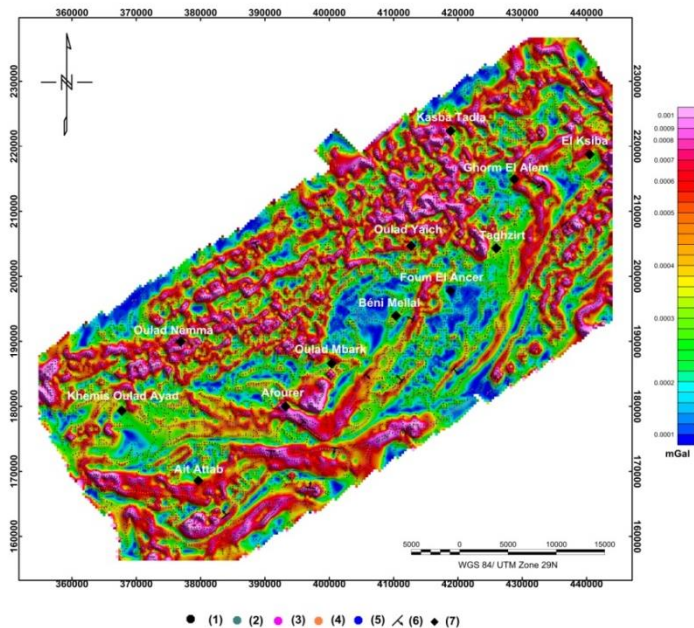
Indeed, this high trend gravity is consistent with Beni Mellal atlas general morphology. This mountainous chain is derived from a very open anticline [38-39] which overlaps in north-west direction. The progressive decrease of gravity anomalies values observed from South-East to North-West (towards Beni Moussa plain) is correlated with main study area structural traits (**Fig.10**). The Liassic slab that dominates Tadla plain underwent a displacement in north-west direction: a geological fact confirmed by the decrease altitude that we note in the same direction [29, 30, 38, 39, 40].



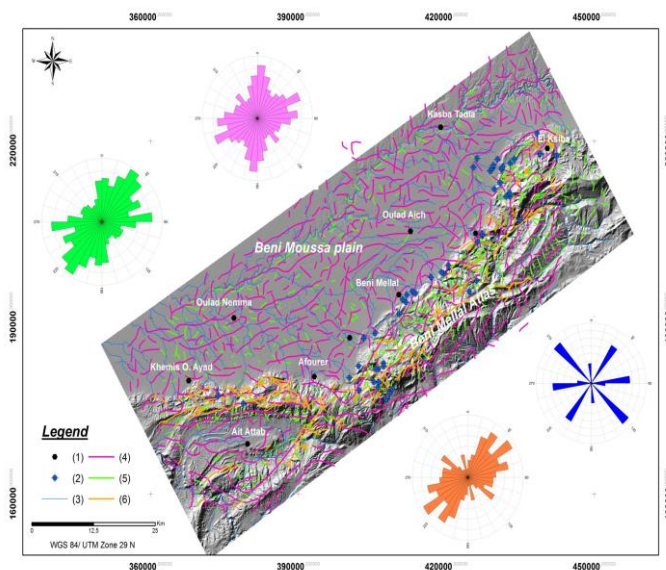
**Fig.10.** Correlation between the WNW-ESE geological cross-section [38] and the gravimetric profile crossing of central study area.

The results obtained from analyzing gravimetric contacts method, previously described, allow to highlight different faults which participate to structure the study area. The figure 11 summarizes all horizontal gradient maxima of the residual anomaly as such as its upward continuations at different altitudes represented by different colours. Linear contacts can correspond to faults while circular ones can represent diapirs limits or intrusive bodies [60, 82, 83, 84].

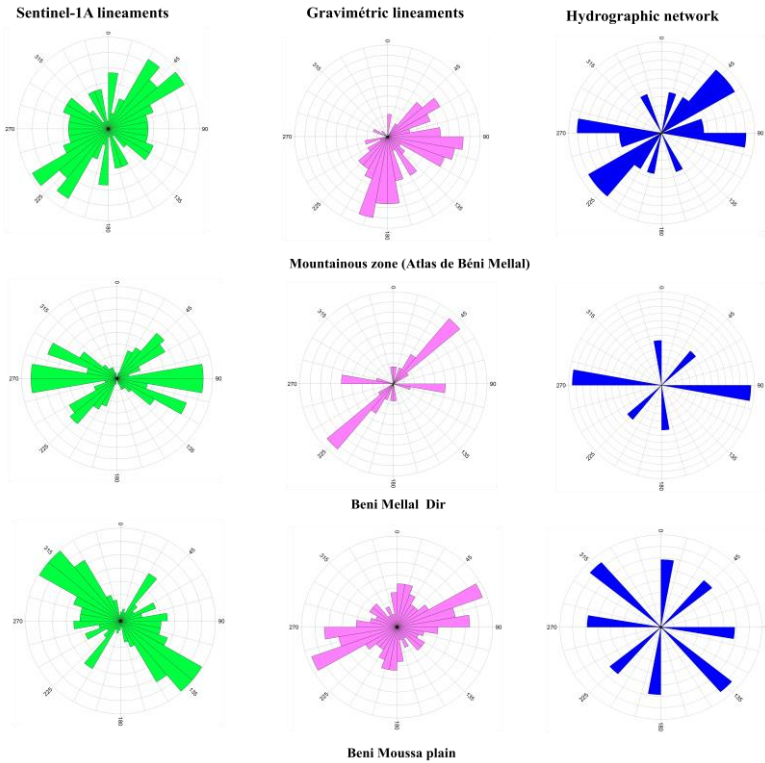
Gravimetric lineaments show a polymodal directionnel distribution that is similar to the one revealed by lineaments deduced from Sentinel-1 data (Fig.12). The main lineaments directions are, preferably, oriented in NE-SW à ENE-WSW (N20-40° to N40-70°); N-S (N150-180° and N20°) ; E-O (N90°) and NW-SE (N120-140°) directions. The first two directionnel ranges are dominant in the study area, they are mainly identified in the mountainous zone that correspond to Beni Mellal karstic massif [2, 38, 39], while the latter two directions are revealed by previous geophysical studies that have been realized in Tadla plain [55]. The two directions NW-SE and NE-SW guide in surface the majority of hydrographic network as well as the main springs distribution which emerge from the northern atlasic border of Tadla plain. Indeed, [16-85] had demonstrated the influence of the brittle tectonic on the drainage network organization and the spring resurgence because it accelerates the erosion and alteration processes and therefore the rivers development



**Fig.11.** Superposition of horizontal gradient anomaly and its local maxima obtained from residual anomalies map (1) and its upward continuations at different altitudes: 500 m (2); 1000 m (3); 2000 m (4) et 4000 m (5); (6) Dipping direction ; (7) locality.



**Fig.12.** Synthetic lineaments map of study area and rose diagrams for highlighted directions. (1) locality; (2) spring; (3) hydrographic network; (4) gravimetric lineaments; (5) Sentinel-1 lineaments; (6) mapped faults from geological map of study area [3, 5, 42].



**Fig.13.** Rose diagrams of hydrographic network (in the right); gravimetric lineaments (in the center) and lineaments deduced from Sentinel-1 image (in the left) in the different sectors of study area.

For a better results analyzing and in order to rule on structural origin [70-86] of deduced lineaments from gravity data and radar images combination, we proceeded with a breakdown of the study area into tectonic sectors. Gravimetric lineaments and the ones deduced from the Sentinel-1 image were correlated and compared for different parts of the study area (Fig.13). Indeed, the structural map obtained (Fig.12) shows a clear difference in the distribution and fractures density in the study area. The southern part of the study area (mountainous area of the Beni Mellal Atlas); dominated by NE-SW to ENE-WSW and N-S directions; shows a high fracturing density which decreases towards the Beni Moussa plain (northern sector). At this level, quaternary alluvial deposits make difficult the lineaments identification. The latter has a NW-SE trend in its orientation. Those two sectors are separated by an intermediate zone that corresponds to the Beni Mellal piemont. In turn, this zone presents a NW-SE and E-O trend in its orientation. The analysis of rose diagrams for each sector (Fig.13) revealed the following important points:

- The major directions NE-SW to ENE-WSW and NS distributed in the Beni Mellal Atlas (southern sector) bear witness to the importance of the structural heritage [87, 88, 89, 90] noticed by several authors [4, 40, 91, 92]. These directional peaks characterize the Atlas chain evolution during Mesozoic and Cenozoic periods [81-93]. The direction NE-SW to ENE-WSW is parallel to the Atlas chain structural direction [39] and also to the Tadla basin lengthening. While the direction N-S;

orthogonal and posterior to the previous one; corresponds to the alpine orogenesis phase [6-88]. These fractures are responsible for the Beni Mellal carbonate reservoir karstification, they favor karsts evolution and underground caves and cavities formation by increasing the carbonates dissolution [94, 95, 96]. [97] carried out a speleological exploration of Beni Mellal Atlas where he deduced that the majority of the underground cavities (mainly avens, caves and absorbent holes) are developed on the N60 ° and N150- 180 ° directions faults resulting from the atlasic tectonics;

- The gravimetric lineaments in E-O direction (N80-90 ° to N100 °) are timidly represented in the Dir of Beni Mellal compared with those identified from the Sentinel-1 image. The faults associated with this direction have guided the Mesozoic sedimentation in order to be reactivated during the Plio-Quaternary period into dextral strike-slip faults. Dominate the Dir sector, they are the seat of an intense compression linked to the overlap movement (The northern atlasic border) [2, 88, 91, 98]. These faults are carried by the overlaps that mark the north-east of the Beni Mellal Dir (Taghzirt-El Ksiba alignment), they rarely allow the sources emergence unlike those of NE-SW direction. The spatial arrangement of these faults is responsible for the Beni Mellal piemont thrust pronounced particularly in the El Ksiba Atlas hence the name of “El Ksiba thrusts” [2] (Fig.3c);
- The family N120-140 ° direction is very widely represented in the Beni Moussa plain. It is mainly detected by the radar image, in contrast to the one identified by the gravity data analysis whose frequency is relatively low. The associated faults facilitate the water drainage from the Atlas to the Beni Moussa plain (southern part of the plain), which confirms the decrease of local waters salinity in the plain [31, 45, 55, 99]. This direction is related to the compressive constraint results due to the two African and European continents rapprochement [36, 40, 87]. As we approach the Beni Mellal Atlas, the NW-SE direction becomes a minority or even absent to give place to another faults family oriented NE-SW. This latter controls the drainage network orientation in the mountainous area of the Atlas.

The comparison between the different rose diagrams of the lineaments obtained and the hydrographic network made it possible to establish a correlation between the principal fractures directions and those runoff waters circulations. Indeed, in the mountainous area of the Beni Mellal Atlas the hydrographic network borrows the major fractures of NE-SW to ENE-WSW and E-O directions, characterizing the said zone. In Beni Mellal Dir, the rivers – of atlasic origin- coincide perfectly with the major thrust faults oriented E-W. They also borrow the minority directions NE-SW and N-S that imposes a circulation in these two directions.

In the Tadla plain, the surface water drainage network is oriented mainly, in order of importance, in the NW-SE, E-O, NE-SW and N-S directions. All of the atlasic origin rivers converge towards the Beni Moussa plain which corresponds to a subsidence zone where a streams accumulation occurs. Those latter end up joining the Oum Er'Rbia river in the Tadla plain. The revealed directions perfectly conjugate with the major faults directions affecting the Beni Moussa plain. They represent weakness areas used by rivers to minimize the energy required for their flow [100].

## Conclusion

The results obtained in this study provide informations on the study area structuring and highlight a major accidents mapping that affect it. The results obtained by the integration of the gravity data and the Sentinel-1A radar image, show that four fractures directions were highlighted in the studied area: NE-SW to ENE-WSW; E-O; N-S and NW-SE. In the three identified tectonic sectors, the lineaments are predominantly oriented NE-SW to ENE-WSW and E-W. The directions N-S and NW-SE, in turn, characterize respectively the mountains zone of the Beni Mellal Atlas and the northern sector of the Beni Moussa plain. The directional correlation between the resulting lineaments and the surface hydrographic network shows a general parallelism between the preferential directions of the runoff circulation and the fracturing. The NE-SW and E-O directions are the most frequent in the study area in general and particularly in the mountain zone of the Beni Mellal Atlas, they control the drainage network and allow the springs emergence. This general coincidence between the hydrographic network directional distribution and that of fractures makes it possible on the one hand to confirm that these identified lineaments correspond to real fractures continuing in depth and on the other hand to validate the methodology adopted for lineaments mapping based on the combination of gravity data and radar imagery.

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