Iraqi Geological Journal

Journal homepage: https://www.igj-iraq.org

Gravity Interpretations to Investigate the Deep Geological and Structural Status of Middle Atlas Chain Region, Morocco

Youssef Ouahzizi[1,*], Driss El Azzab[1], Mohamed Charroud[1], Mohammed J. Tazi[1] and Abdelkhiar Ait Ali[1]

[1] Intelligent Systems, Georessources and Renewable Energy Laboratory, Faculty of Sciences and Technics, Sidi Mohamed Ben

* **Correspondence**: Youssef.ouahzizi@usmba.ac.ma

Received:
31 January 2023

Accepted:
6 June 2023

Published:
31 October 2023

Abstract

The Moroccan Middle Atlas is an intracontinental chain characterized by a combination of tectonic, sedimentary, and magmatic events. These events influenced the Middle Atlas basement structure and its morphology. In order to improve our understanding of the subsurface and deep geological structures, a gravimetric investigation was carried out. A residual gravity map and its horizontal derivative were computed and interpreted. We present in this work the main findings: The residual gravity anomaly map shows fourteen positive anomalies which are well correlated with the undulated Paleozoic basement in the Middle Atlas or with the High Moulouya and the Merhraoua Anticlinorium in the Northeastern part of the Middle Atlas chain.It also exhibits sub-circular negative anomalies related to the thick subsurface Meso-Cenozoic cover of the Middle Atlas chain depocenters located in the center and southeastern parts of this chain. These anomalies are correlated with the Bou Anguer, Bekrit, Tazouta, Enjil, and Almis Mermoucha basins; the Bounacer mount; and the extension of Boumia granite in the High Moulouya. The horizontal gravity gradient map discloses that the study area is mainly affected by the NE-SW trends as major faults, while the N-S, NW-SE, and E-W are minor faults. They're superposed with the Southern Middle Atlas Accident, the North Middle Atlas Accident the Tizi N'tretten Accident, and their branches. They are due to the alpine neotectonic reactivation phases of the Paleozoic and Jurassic heritaged faults. A synthetic structural map displaying the lateral extension of most Middle Atlas faults was postulated. Consideration is also being given to explore the buried faults or unmapped ones. Our final map represents an efficient and effective tool to help decision-makers during mining exploration.

Keywords: Middle Atlas, Residual anomaly; Paleozoic basement; Depocenter; Granite

1. Introduction

The Middle Atlas chain is one of the fold-belt Moroccan chains (Frizon de Lamotte et al., 2008). It bounded in the North by the Sais basin and the Riffian domain; in the East by the Oriental Meseta, Guercif, and Missour basin, in the South by the Central High Atlas and the High Moulouya plain; and in the West by the Occidental Meseta (Fig. 1). The Middle Atlas was subdivided into two domains (Piqué, 1996; Fig. 2). The first one is located in the septentrional part of the chain, corresponding to the tabular Middle Atlas. It is composed of Liassic formations separated by the NE-SW Middle Atlas Tabular Fault as the Tizi N'tretten Accident (TTA). These rock blocks are progressing toward the northwest. The tabular domain is separated from the second domain by the accident of the North Middle

DOI: 10.46717/igj.56.2D.1ms-2023-10-7

Atlas. It's a folded domain made up of a series of broad and deep synclines and narrow anticlinoriums that are linked to the major faults of the Middle Atlas, which were affected by the alpine orogeny (Fedan, 1989).

Morocco is one of the countries that developed its mining sectors and proceeded with the exploration and exploitation of industrial resources. Therefore, geophysical, geological, and hydrogeological studies are beneficial to the discovery, enhancement, and guidance of the mining prospect. Through its history during the Paleozoic and Meso-Cenozoic, it experienced several magmatic, metamorphic, and sedimentary events during these periods. The magmatic and metamorphic events were responsible of forming the mineral deposits. While the sedimentary processes produced the deposition of industrial materials like phosphate, clay, marls, schists, gypsum, etc.,

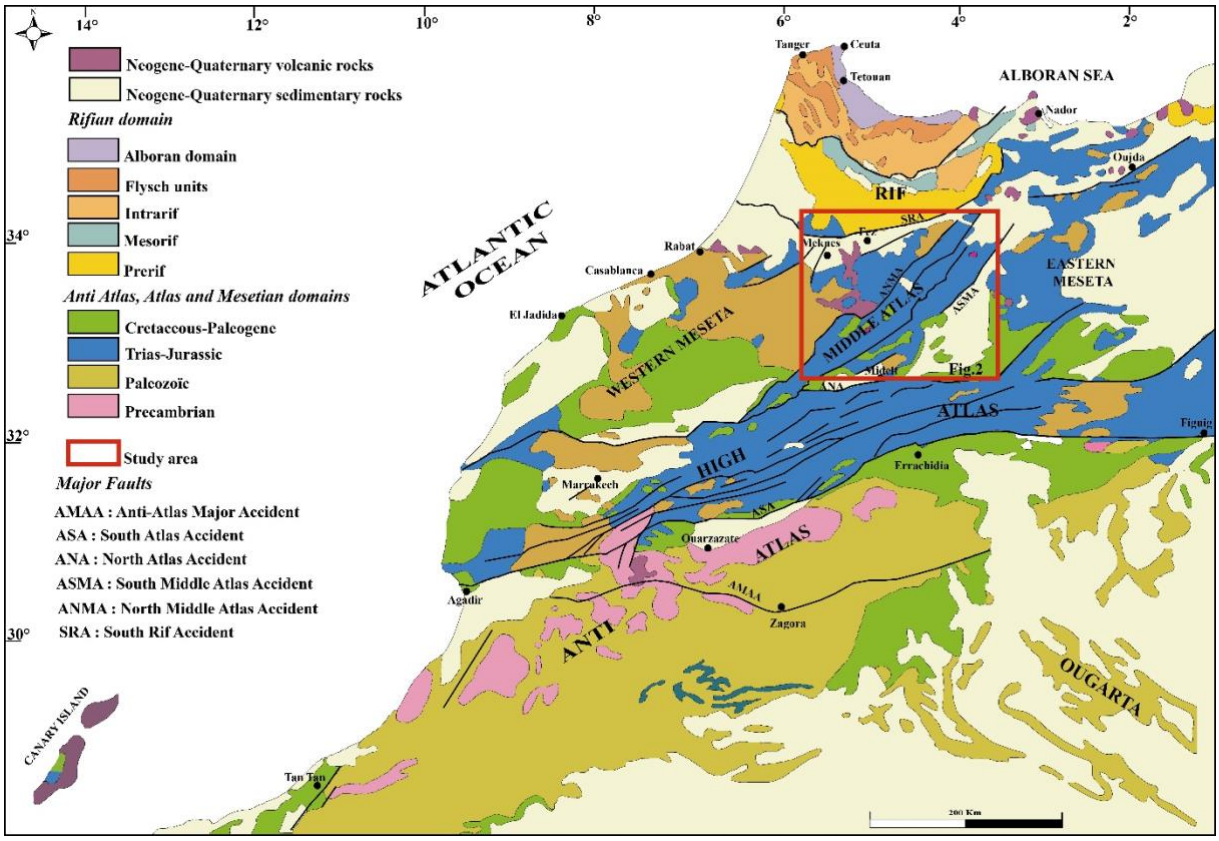


Fig. 1. Simplified geological and geographical setting of the study area (Hollard et al., 1985)

The current study aims to determine of the structural context of the chain, namely the distribution of the fracturing intensity, the localization, the directions, their association with salt diapir along the chain, and their extension behind it. Secondly, the determination of the vertical-lateral variation of the density of the subsurface along the chain is necesseray in order to identify their distribution and compare it with the results of the structural-sedimentary results identified by Fedan, (1989); Charrière, (1990); Piqué, (1996); Aboussalam et al. (2020), etc. However, these studies are based on surface data, while the subsurface structures remain unidentified. We used the gravimetric data and their processing by adopting different techniques different techniques to realize a synthetic structural map, also to provide an interpretative displays related to the ambiguous zones of the chain, and follow the major faults of the Middle Atlas.

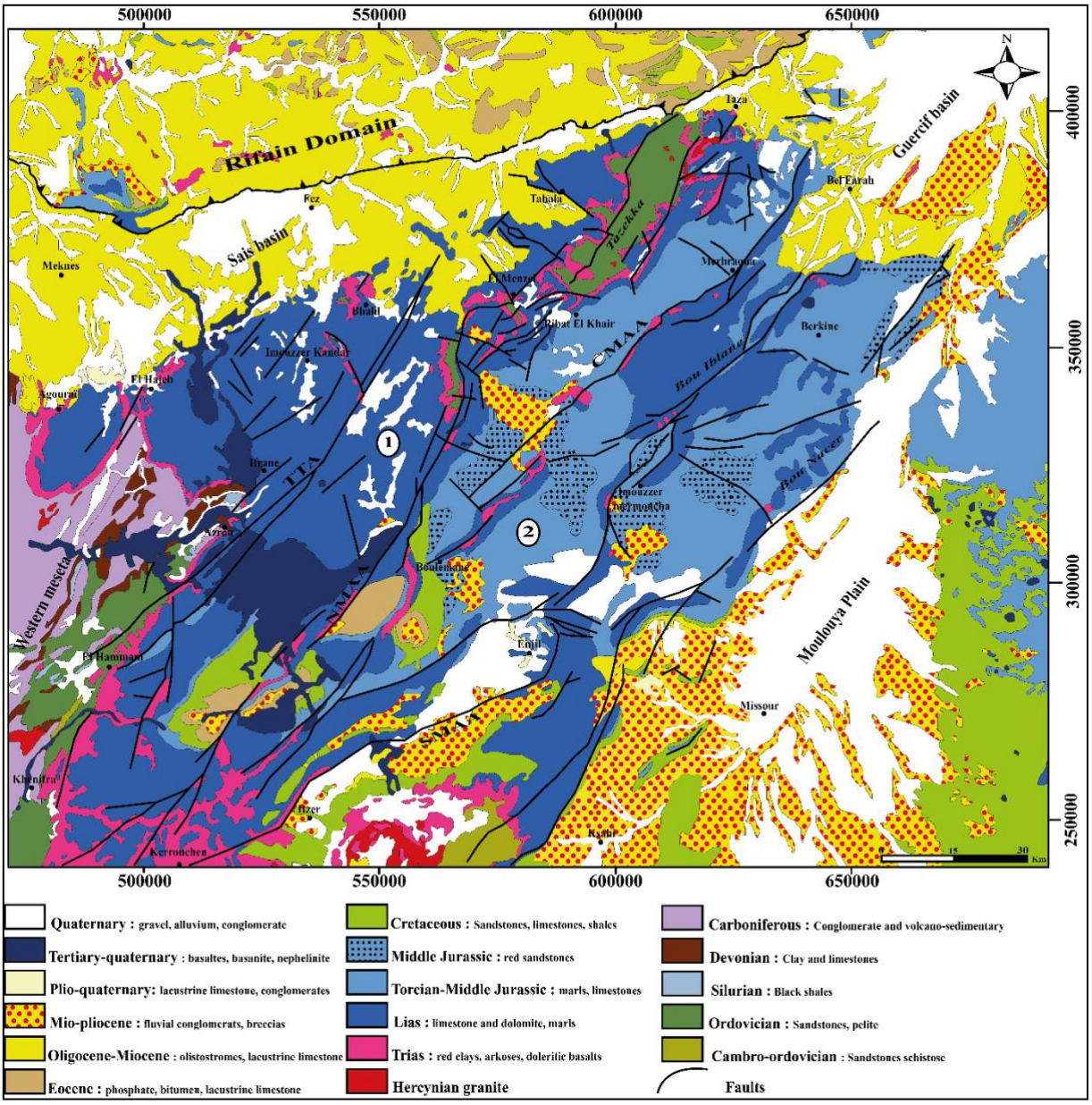


Fig. 2. Geological map of the Middle Atlas Chain (from a geological map of Morocco, 1/1 000 000 after Hollard et al., 1985; modified); 1: Middle Atlas tabular domain; 2: Folded Middle Atlas domain; SMAA: South Middle Atlas Accident; CMAA: Central Middle Atlas Accident; NMAA: North Middle Atlas Accident; TTA: Tizi N'tretten Accident

2. Geological Setting

The Middle Atlas chain corresponds to an intracontinental chain that was progressively formed and structured during the succession of extensive and compressive events that marked its geological history during the Mesozoic and Cenozoic (Mattauer et al., 1977; Fedan, 1989; Laville et al., 2004). It begins with extensive events due to the Atlasic Rifting and the creation of intraplate basins along the periods of Mesozoic and Cretaceous (Benzaquen et al., 1965; Fedan, 1989). These basins marked a tectonic inversion due to the Alpine orogeny from the Maastrichtian to the present (Mattauer et al., 1977; Laville et al., 2004;).

The formations of the Hercynian basement of the Middle Atlas chain are outcropped in several inliers, the most numerous of which is that of Tazekka (Hoepffner, 1987), and others such as Bsabis,

Menzel, and Kerrouchen, and that of Immouzzer Kandar (Piqué, 1996; Aboussalam et al., 2020), etc. Their lithological content is almost similar to that of the Meseta in the metamorphic context and the biostratigraphic content of the Paleozoic facies. These formations are commenced by Cambrian-Ordovician detrital sandstone sedimentation, generally schistose (Piqué, 1996; Oudy et al., 2020), followed by Silurian black shales rich in graptolites, pursued by Devonian clays, and surmounted by a volcano-sedimentary series. They are affected by tight folding and an NNE-SSW-oriented crystallophyllous schistosity (Piqué, 1996).

In the Middle Atlas, except for the Paleozoic inliers, the Middle Atlasic domain is covered by Meso-Cenozoic formations (Fig. 3), which mark the geological history of the domain that can be subdivided into two major stages.

2.1. Atlasic Rifting Stage: the Individualization of the Triassic-Liasic Basins and the Compression of the Dogger

During the Triassic and Lias, the Atlasic Rifting allowed the installation and individualization of pull-apart basins in the Atlasic domain, especially in the Middle Atlas. This installation was guided by the reactivation of faults inherited from previous orogenies. These faults have NE-SW to E-W trending (Fedan, 1989), which guided the rifting under an extension regime. They allowed the basins to collapse and be filled with detrital rocks of continental origin. These detrital rocks are composed of conglomerates, sandstones (Fig. 3), and arkoses passing through siltstones and mudstones intercalated with "argilo-saliferes" evaporites, becoming from Meseta paleoreliefs and surmounted by doleritic basalts (Fedan, 1989; Charroud et al., 1996). These basalts have an age of between 210 ± 2.1 Ma and 196.3 ± 1.2 Ma (Fiechtner et al., 1992), while Knight et al. (2004) and Verati et al. (2007) give an age of 200 Ma.

During the Lower Lias, the MA domain experienced an episode of carbonate platform emplacement (Fedan, 1989; Ellouz et al., 2003), which was uniform, deep, and delimited by the same faults with tectonic stability. Therefore, the main control responsible for the installation of the carbonate platform is the western Tethyan transgression (Fedan, 1989; Ellouz et al., 2003) with the deposition of pure carbonate sedimentation (limestone and dolomite) in the entire Atlas domain (Benzaquen et al., 1965; Ellouz et al., 2003). At the Lower Lias–Middle Lias transition, the carbonate platform is dislocated (Laville and Fedan, 1989; El Kochri and Chorowicz, 1996; Choukrad et al., 2022) due to the reactivation of the same faults that allowed large subsidence in the western part of the Central High Atlas and the southern part of the Middle Atlas (Ellouz et al., 2003), with a normal component at the ENE-WSW faults and a sinistral set at the NE-SW faults (Mattauer et al., 1977), demonstrating a general distensive context (Fedan, 1989). This context allows differentiation between a platform domain where carbonate sedimentation continues and a basin domain where sedimentation thickens and marl intercalations occur (Fedan, 1989). The individualization of these basins continued throughout the Middle and Upper Liassic, with paroxysmal subsidence peaking during the Lower Domerian–Toarcian. It corresponds to the Toarcian tectonic crisis due to the combination of the distensive regime and marine transgression.

At the Upper Toarcian–Lower Aalenian transition, the Middle Atlas Basin evolved as a basin system with depocenters and ripples running NE-SW, NW-SE, N-S, and E-W, indicating marine regression due to the transpressive context. Furthermore, this intraplate basin is characterized by deep subsidence and marly sedimentation (Benzaquen et al., 1965; Fedan, 1989) with a syntectonic aspect. It is marked by a transition from carbonate deposits to marl with a ferrous surface, indicating the Toarcien–Aalenian limit. During the Lower Aalenian–Bajocian, the environment became shallower with the deposition of limestones (Benzaquen et al., 1965), followed by a marine transgression responsible for the deposition of the large series of Boulemane marl formation (Fedan, 1989) and its equivalent Bouchyene formation, which testifies to the tectonic activity of the middle Atlassian wrinkles during

this episode. In continuity, at the Upper Bajocian, the Middle Atlas domain marked a reinstallation of the carbonate platform (Fedan, 1989) with calcareous sedimentation called "Limestone corniches," which marked a decrease in subsidence.

After the Bajocian transgression, the Middle Atlasic domain experienced a regression due to the closure of the marine trench of the Western Tethyan (Brede et al., 1992). This closure is recorded by the succession of detrital geological units of continental origin, with the deposit environment evolving from a marginal-littoral swamp to a shallow intracontinental sedimentation instead of the former Tethyan trench. Moreover, the asymmetric basin filling and the besetting of these formations retain an unconformity at the approach to the ridge. (Charrière and Haddoumi, 2016; Haddoumi et al., 2019) argue that the transpressive regime is the primary control of closure and deposition variation.

The geodynamic context of the Atlassian domain during the Bathonian–Callovian is a blockage of the rift system due to the acceleration of the Atlantic Rifting. While Missenard et al. (2006) and Frizon de Lamotte et al. (2008 and 2009) describe the presence of a major thermal seat due to crustal thinning, the rifting stage is left behind, with Jurassic–Cretaceous magmatic activity at the core of major rifts (Fedan, 1989). However, the Middle Atlas experienced an Atlantic-Tethysian marine transgression with an evolution from a fluvial-lacustrine sedimentation to a marine one during the Aptian to the Senonian (Fedan et al., 1989). Thus, these are marine transgression series during the Cretaceous under an NNE-SSW distensive regime.

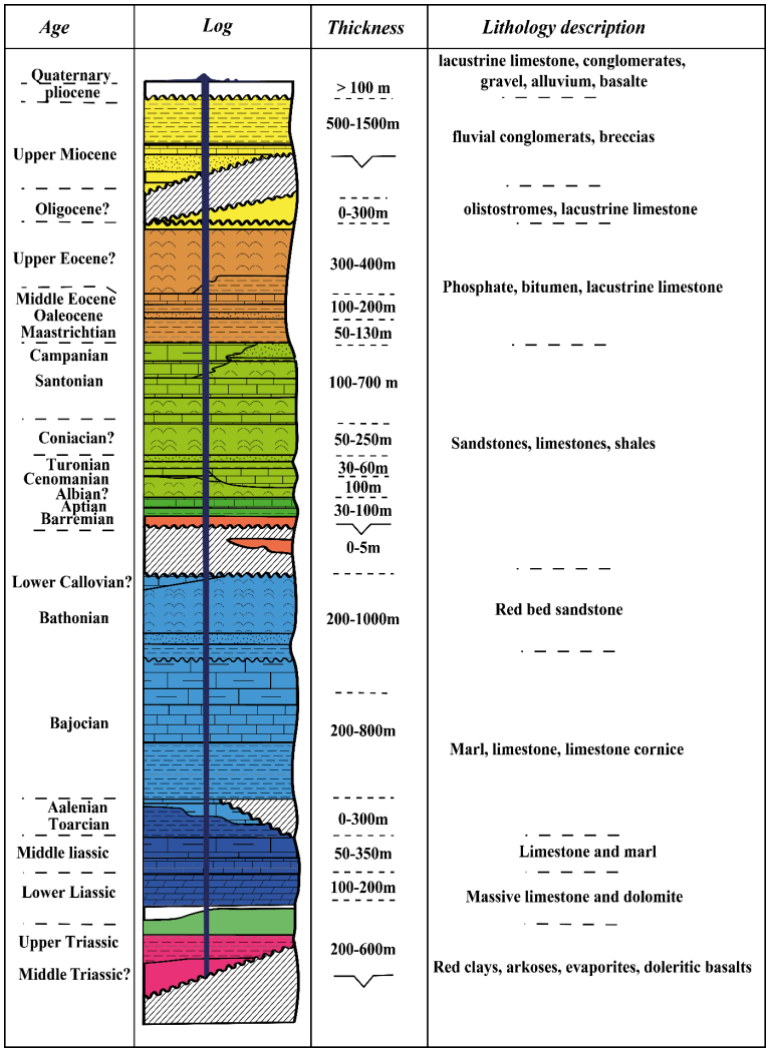


Fig. 3. Synthetic lithostratigraphic log of Middle Atlas Chain (Charrière, 2011, modified)

2.2. Stage of the Alpine Orogeny: The Surrection of the Chain during the Late Cretaceous to the Present

During the Cenozoic, plate reorientation caused the atlas chains to lift, resulting in a progressive convergence of the African and Eurasian plates (Ellouz et al., 2003). In general, the Atlasic tectonic inversion characterized by polyphase compression starts in the Senonian period and continues to the present day, with an evolution from marine to molasses sedimentation, marking the opening and closing of several basins, and more intense magmatic activity in the Middle Atlas. Therefore, it can be summarized as a compressive history of the Middle Atlas, which begins with the formation of certain basins in the form of gulfs and lagoons with marly and bituminous sedimentation in the Senonian (Charrière, 1990). It is due to the Atlantic transgression, guided by the extensive regime of NW-SE accidents (Fedan, 1989). In the Maastrichtian, the sedimentation becomes more phosphate and bituminous (Timhdite bituminous shales), outcropping in the Guigou-Timhdit and Oudiksou depocenters. The bituminous sedimentation is a marker of the confinement and maximum subsidence of the environment (anoxic condition). In the Paleogene, the Middle Atlas marks the progressive disappearance of the phosphate-bituminous formations (Fedan, 1989) and the migration of the subsidence zones from the NE to the SW by the tectonic style of the major Middle Atlas accidents (Fedan, 1989). In the Palaeocene, the phosphate and bituminous sedimentation became detrital with the deposition of calcarenite, sandstone, conglomerates, and marls (Fig. 3), indicating the installation of a lagoon system. These detrital deposits are surmounted by lower Eocene limestones (Fedan, 1989) or middle Eocene lacustrine limestones. In the Upper Eocene, the deposits of the Middle Atlas are gypsum-marl (Charrière, 1990), then flinty limestone. This evolution from marine sedimentation to a lagoon-lacustrine one shows a brutal surrection of the Middle Atlas chain and thus a complete sea withdrawal at that time. During the Oligocene, the Middle Atlas sedimentation was composed of conglomerate, sandstone, limestone, and marl from Jbel Hayane and Ain Nokra, with synsedimentary activity responsible for the Oligocene–Eocene unconformity. During the Miocene, the marine transgression arrives from the northwest, penetrates the Middle Atlas at Ribat Al Khair, and reaches the Skoura syncline. The sedimentation accompanied by this transgressive phase is composed of conglomerates, gypsum marl, and sandstone limestone (Fedan, 1989) in a NE-SW distensive context (Charrière, 1984). The latter induces the individualization of continental basins associated with magmatic activity dated 10-9.7±0.5 Ma, presented by dykes intersecting ESE-WNW to NW-SE faults, which is part of the Middle Atlas Volcanic Province (Frizon de Lamotte et al., 2009). During the Upper Miocene to Quaternary, the tectonic context was a submeridian compressional regime that affected the Riffian domain, and the Atlasic domain (Charriere, 1984). This context influenced sedimentation so that it is purely continental molasses. The molassic products come from the erosion of the ridges, and they are deposited in the basins in a local extensive regime. In the same period, the MA experienced magmatic activities grouped in the Middle Atlas Volcanic Province (MAVP). The latter is a field of intraplate volcanism (El Azzab and El Wartiti, 1998a; Lakroud et al., 2019), represented by volcanic cones and fissural volcanoes dated from 16.5 to 0.5 Ma by the K/Ar method (El Azzouzi et al., 2010). It is composed of alkaline to sub-alkaline basalts, basanites, and nephelinites (El Azzab and El Wartiti, 1998b; El Azzouzi et al., 2010). The emplacement of magmatic activity and its concentration in the tabular Middle Atlas rather than the folded Middle Atlas confirm the existence of an extensive regime in the first domain with a sinister regime of NW-SE and other compressive faults in the folded Middle Atlas during the same period (Gomez et al., 1996). The magma emplacement is linked to the hot spot recognized globally (Frizon de Lamotte et al., 2008 and 2009) due to lithospheric thinning. Therefore, we can summarize that the sedimentary evolution of the Middle Atlas during the Tertiary and Quaternary was guided by NE-SW, NW-SE, and E-W faults under an alternating regime of transpression and distention with reorientation stress.

3. Gravity data and Methodology

The gravity data used in this study is in the numeric format of the Bouguer Anomaly Map, published by Van den Bosch (1971). It was based on numerous surveys carried out for the Moroccan Direction of Mines and Geology. These surveys cover the entire Middle Atlas domain. The Bouguer anomalies represents the summation of gravimetric effects which related for both near surface sedimentary cover and deep basement rocks causative . The Bouguer Anomaly map shows the deep regional and local sub-surface structures. The Bouguer anomaly data will be transformed by filters and mathematical techniques to exploit the subsurface heterogeneity, and to detect the possible geological sources of anomalies which related to subsurface density variation. The residual field represents mainly the anomalies due to density variations within the sedimentary cover, including the variation in basement density, the thickness, and the density of the sedimentary layers underlain by the metamorphosed basement. It was obtained by subtracting the regional field anomaly from the complete Bouguer anomaly.The horizontal gradient is a method of detecting the exact sources of anomalies, used for structural mapping and lateral density variation (Cordell, 1979; Cordell and Grauch, 1985; Blakely, 1996); the point of inflection of the curve is at the plumb line of this contact, thus materializing the maximum of the horizontal gradient (Cordell and Grauch, 1982, 1985; Blakely and Simpson, 1986). Therefore, the horizontal gradient can be used to map the lateral variation of near-surface lithology and discontinuities due to density variation (Cordell, 1979; El Azzab et al., 2019; Benyas et al., 2022).

4. Results

4.1. Bouguer Anomaly Map

The Bouguer anomaly map of the Middle Atlas (Fig. 4a) shows negative values ranging from a minimum of -130 mGal to a maximum of -4 mGal, indicating a significant density variation in the subsurface and the deep structure, such as the presence of faults, thick sedimentary basins, metamorphosed basements, and intrusive body boundaries. High negative value is referring to (negative anomalies) , while low negative values considered as (positive anomalies). The Highly negative are located in the Middle Atlas's center, southern, and eastern parts. The low negative anomalies are in the northeastern, northern, and western parts of the chain.

The regional field (RF) was estimated by first-order polynomial regression of the Bouguer anomaly, increasing (0.67 mGal/km) from the SE towards the NW. The RF behaviour is compatible with the seismic data results (Ayarza et al., 2014) that indicate the depth of the Moho at 35 km in the south and around 31 km to the north of the Middle Atlas chain (Fig. 4b).

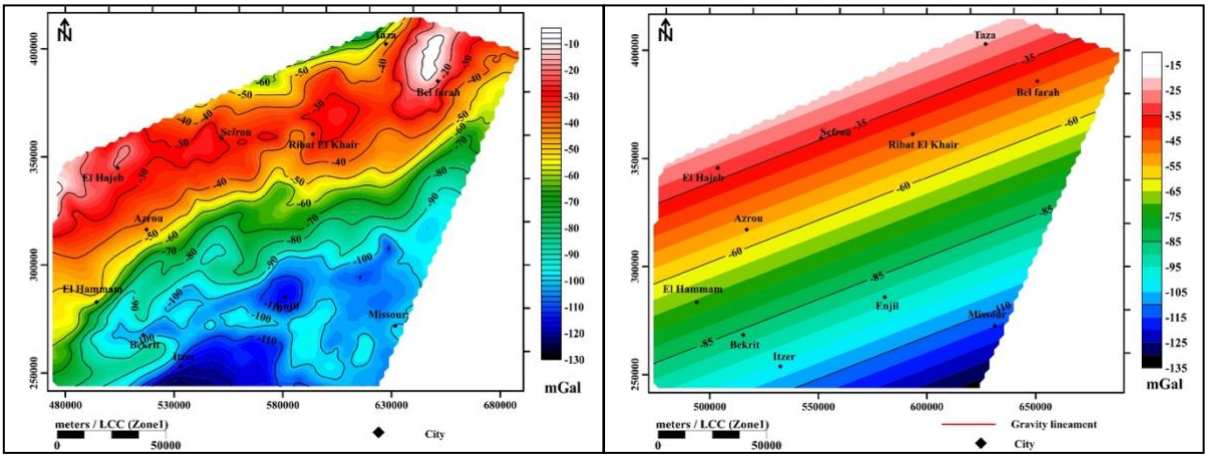


Fig. 4. a) Bouguer anomaly map of the Middle Atlas chain (reduction density: d=2.67 g/cm^3); b) Gravity regional anomaly map of the Middle Atlas chain (reduction density: d=2.67 g/cm^3)

4.2. Residual Anomaly Map of the Middle Atlas Chain

The residual anomaly map (Figs. 5 and 6) shows fourteen positive anomalies (P1 to P14) and eleven negative anomalies (N1 to N11), ranging from a minimum of -60 to a maximum of +32 mGal of amplitude, that can be effectively correlated with several known geological structures of the Middle Atlas chain.

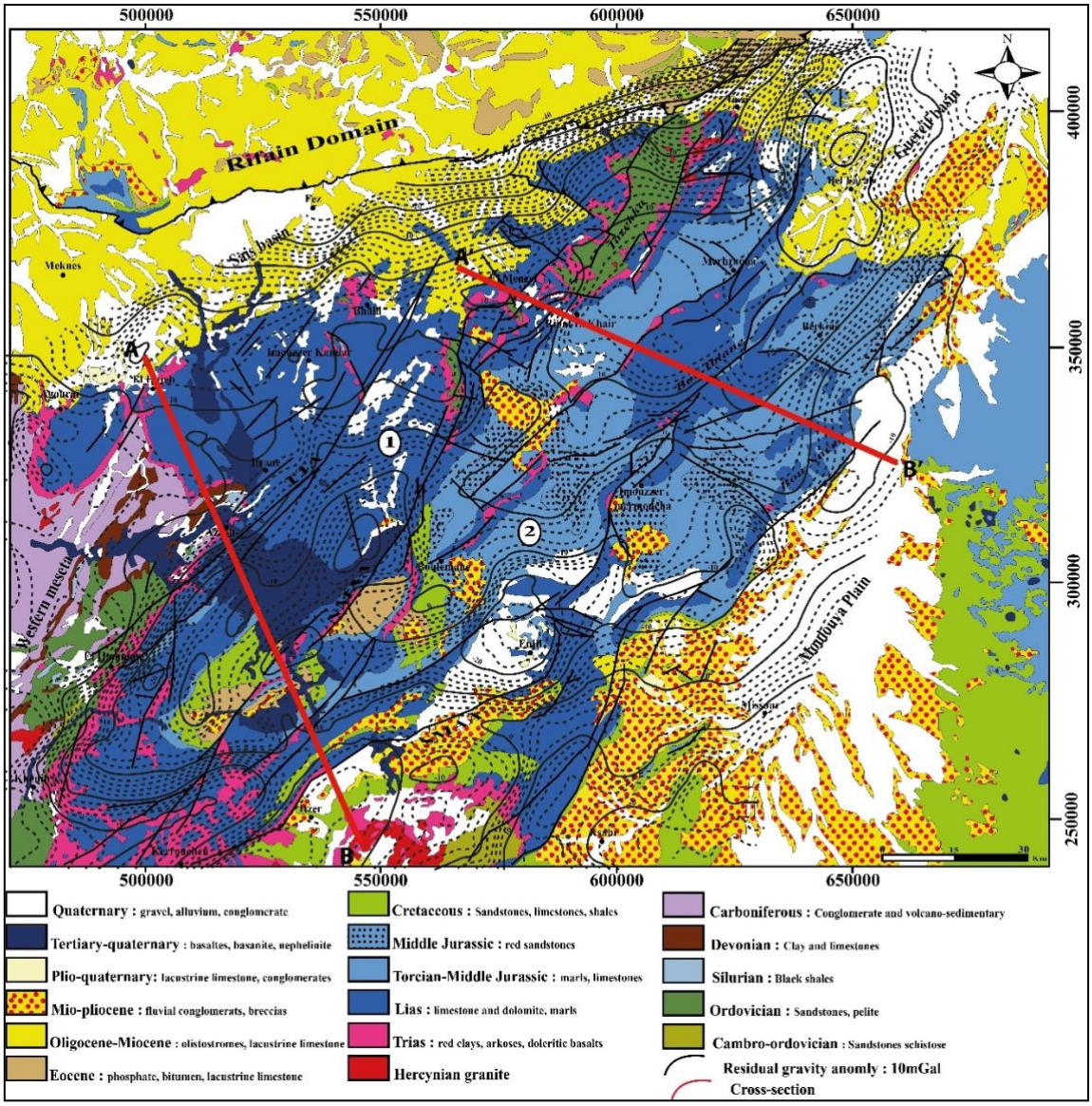


Fig.5. Residual anomaly map superposed on the geological map

The residual anomaly map (Fig. 6) shows that there are 14 positive anomalies (P1–P14) and 11 negative anomalies (N1–N11), with amplitudes ranging from –60 to +32 mGal, which can be linked to several known geological structures in the Middle Atlas chain.

The superposition of the residual anomaly map and the geological map (Fig. 6) concluded that the significant anomalies could be correlated with:

The positive anomalies of the residual anomaly map (Fig. 6) reflect dense bodies outcropping or near the surface that correspond mainly to the Paleozoic basement.

The positive anomaly P1 has a NE-SW direction with an intensity of +32 mGal. This anomaly can be related to the extension of the Merhraoua anticlinorium, where the Paleozoic basement is near the surface.

P2 and P3 have the same direction as P1 with an intensity of +10 mGal. P2 is superposed with the SW part of the Ribat El Khair plateau, and P3 coincides with the Bou Iblane anticline.

The positive anomalies P4, P5, P6, P7, and P8 have an intensity of between 10 and 14 mGal. They are superposed with El Manzel, El Bsabis, Imouzzer Kandar, El Hajeb, and Ifrane Inlier, in that order.

P10 and P12 coincide with the El Hammam and Azrou Paleozoic inliers. Whereas the positive anomaly P11 is correlated with the uplift of the Paleozoic basement beneath the Kerrouchen Basin.

P9 and P13 have an intensity of +10 mGal and are superposed with the High Moulouya Inliers (Ahouli-Mibladen inlier).

The negative anomalies on the residual anomaly map (Fig. 6) show the relatively light bodies that match the thick Triassic, Cretaceous, Tertiary, and Quaternary cover:

The anomalies N1, N3, N4, and N5 of the elongated shape of the major NNE-SSW direction correspond to the North Middle Atlasic Accident and basins (depocenters) filled by thick layers of Cretaceous and Tertiary formations. They are, respectively, the northwestern part of the Bekrit tertiary basin, the Bou Angour, the Skoura, and the Tazouta basins.

The negative anomaly N2 with an E-W direction corresponds to the NE part of the Bekrit basin with outcrops of thick tertiary series and fissural basalts coinciding with the Central Middle Atlasic Accident (CMAA).

The anomalies N6 and N7 indicate the width and length of a depocenter superimposed on the Enjil Basin in the SE of the Middle Atlas chain. Tertiary and Quaternary formations occupy this basin with deep thicknesses indicated by the anomaly intensity value of -20mGal.

A sub-elongated anomaly of large amplitude (-10 mGal, N9), is due to the extension of the Boumia granite basement, which reaches areas north of the Itzer village. This anomaly is intersected by another one (N10) of ENE-WSW orientation, which correlates with Triassic diapers related to the one branch of the North Middle Atlasic Accident (NMAA).

The N11 anomaly has a direction ranging from E-W to NNE-SSW, following the direction of the atlasic middle south fault with the thickness of Triassic saliferous clays and thick Jurassic sedimentary beds whose intensity is lower than -10 mGal in Bou Nacer Mountain.

4.3. Horizontal Gradient Map of the Middle Atlas Chain

Horizontal gradient (HG) is considered the most common method for detecting target edges or gravimetric effects of a fault separating two mediums of different densities (El Azzab et al., 2019; Benyas et al., 2022). This is why our proposal is to apply HG to residual anomaly gravity data, especially to identify the deep faults, their limits, and their branches (Everaerts and Mansy, 2001). It should be noted that in our study area, the elongated anomaly is generally created by faults, whereas the sub-circular one corresponds to diaper or intrusive body limits

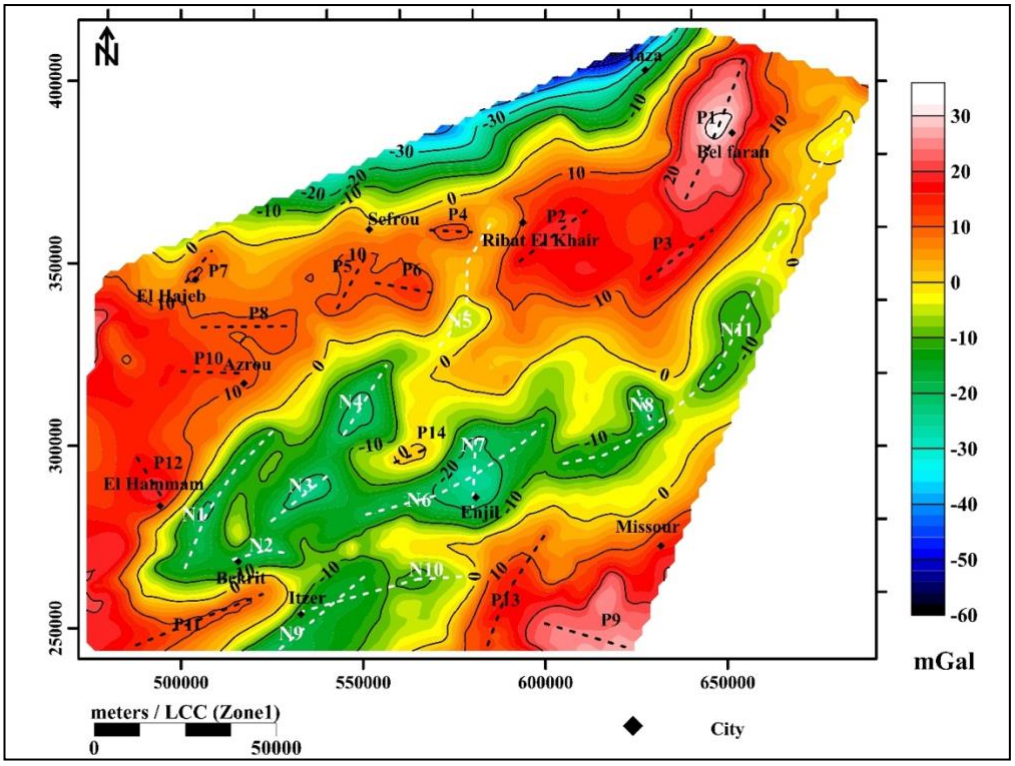


Fig. 6. Residual gravity anomaly map of the Middle Atlas Chain (reduction density: 2.67 g/cm3); P: Positive anomaly; N: Negative anomaly

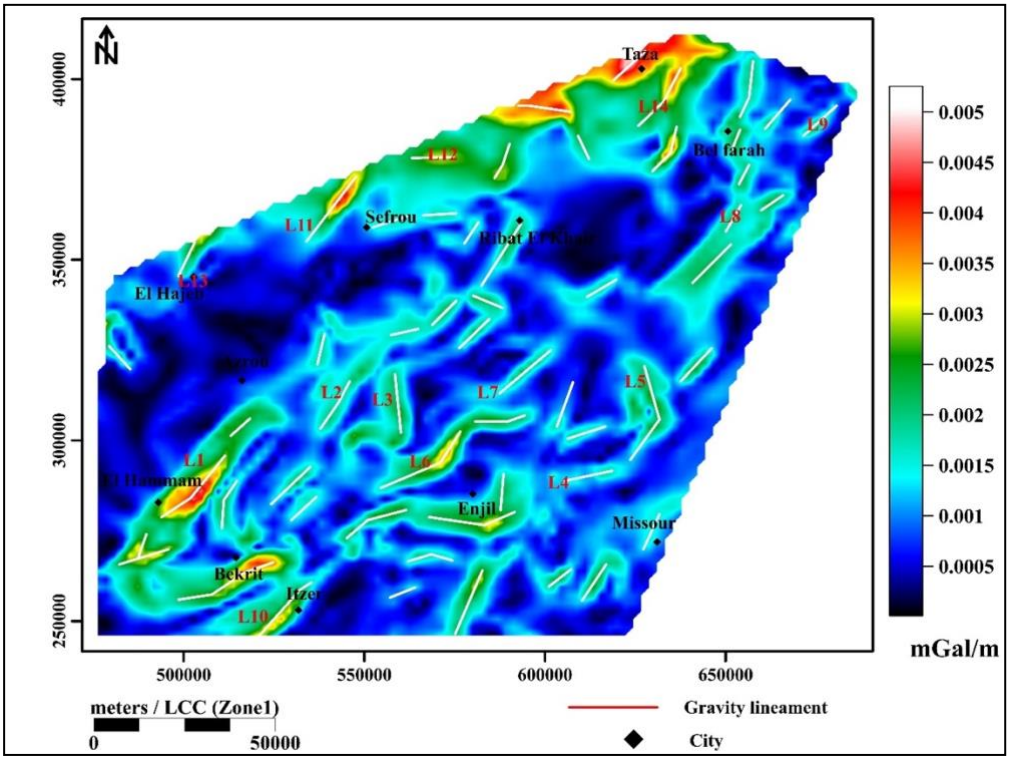


Fig. 7. Gravity horizontal gradient map of the Middle Atlas Chain

The Middle Atlas horizontal gradient map (Fig. 7) shows a network of lineaments that reflect the gravity heterogeneity of the causative bodies. The local maximum was digitized, which is interpreted as faults or diapiric domes. Their statistical treatment revealed the existence of four systems of directions : NE-SW, N-S, NW-SE, and E-W. These contacts can be connected to each other with the dominance of the NE-SW direction, following the major trend of the Middle Atlas chain accidents. Some of the founded lineaments overlap with the mapped regional faults, while others are hidden by the Mio-Plio-Quaternary formations or have not been discovered yet. The obtained results are summarized in the table 1 as follows:

Table 1. Principal Horizontal Gradient Lineament of the Middle Atlas Chain

Lineament	Direction	Location	Source
L1	NE-SW	From SW of El Hammam to Ifrane	Ouiouane Diaper associated with TTA
L2	NE-SW	From Bekrit to Ribat El Khair	North Middle Atlas Accident
L3	NE-SW	From Bekrit to Aderj	Central Middle Atlas Accident Branche
L4	NE-SW to E-W	From Itzer Village to Oulad Ali	South Middle Atlas Accident Branche
L5	ENE-WSW to NE-SW	From South of Oulad Ali to East of Immouzzer Mermoucha	Oulad Ali Fault
L6	ENE-WSW	from the north of Enjil to north of Imouzzer Mermoucha	Central Middle Atlas Branche
L7	NE-SW	from the East to north of Imouzzer Mermoucha	Central Middle Atlas Branche
L8	NNE-SSW	South of Berkine	Bourached River (Fault under quaternary cover)
L9	NE-SW	Bel Ferah Basin	Continuity of Bou Iblane Anticline
L10	NE-SW	North of Itzer village	Southern branch of South Middle Atlas Accident
L11	NE-SW	El Bhalil area	El Bhalil accident associate with a diapiric dome
L12	NE-SW to E-W	From east of Sefrou to Bir Tamtam	Extension of Tizi N'tretten Fault
L13	NE-SE	El Hajeb area	Adarouch Fault
L14	NE-SW	Southern part of Taza village	North Middle Atlas Accident

5. Discussions

The interpretation of the gravimetric anomalies of the Middle Atlas based on recent treatment methods, notably the residual anomaly and the horizontal gradient, allowed us to identify the sources of gravity anomalies. These sources are related to the extension of granite bodies and Paleozoic basement as anomalies of lithology and to the origin related to the fracturing of subsurfaces and salt diapers to exhibit the lithology-structural relationship of the Middle Atlas Chain.

5.1. Lithological Heterogeneous of Middle Atlas Domain

In the first part of this present study, we correlate the residual gravity anomaly map (Fig. 5) with the geological data (Hoepffner, 1987; Fedan, 1989; Charrière, 1990; Piqué, 1996), which allows us to

discuss the subsurface-lithologic features that contrast between the folded Middle Atlas part and the tabular part. The positive anomalies in most parts of the Tabular Middle Atlas indicate the subsurface or outcropping of the Paleozoic basement. This conclusion is confirmed by the geological study of many Paleozoic inliers of the Middle Atlas Chain. In this part of the chain, the low thicknesses of the Triassic-Liassic formations that have tens to hundreds of meters or are completely absent by erosion phenomena along with the major accidents; the El Hajeb Paleozoic basement outcropping by the Adarouch Fault; whereas the Imouzzer and El Bhalil ones were outcroppings by the El Bhalil Faults. El Bsabis and El Manzel are outcroppings caused by the North Middle Atlas Accident. Generally, the tabular Middle Atlas domain is characterized by an uprising of the basement, in contrast to the major part of the folded Middle Atlas. whereas in the north of the Tazekka massif, even if the Paleozoic basement outcrop is present, the residual anomaly lacks corresponding evidence at the surface, which can be explained by a buried granite massif beneath the Paleozoic formation. This agrees with the outcropping of Hercynian granite in the northern part of the Tazekka massif (Hollard et al., 1985; Ajamay et al., 2009). The Ribat El Khair and Merhraoua regions, a part of the folded Middle Atlas where Jurassic formations outcrop in the southern part of the Tazekka massif and Paleozoic basement are deep by a hundred meters or less, are where the anomaly positive contrasts occur (Fig. 8.1). Consequently, their approach is due to the convergence of the overlaps of the Middle Atlas accidents and the diaper phenomenon. We continue in the westernmost part of the Guercif Basin, precisely in the Bel Ferah region, where the residual anomaly has a high amplitude that can be related to the continuation of the overlapping of the middle atlas under the Cenozoic formations. Then, the outcropping of Triassic formations in the SE of Bel Ferah Village in the center of the anticline is considered the Bou Iblane anticlines' continuation. Therefore, Bel Farah's basin corresponds to anticlines under the Cenozoic formation characterized by the upwelling of the Paleozoic basement to the surface. Finally, the Merhraoua, Bou Iblane, and Bel Ferah areas can be considered uplift maximum zones.

The center and meridional parts, the reflectance of gravity data, give the presence of the depocenters (basins), characterized by the minima of residual anomalies that correspond geologically to the deep basins where, according to Charrière (1984) and Fedan (1989), their center is occupied by thousands of meters of Jurassic and Cenozoic formations. These basins are Bou Angeur, Bekrit, Tazouta, Ait Kermous, Enjil, Skoura, and El Mers, which are composed of thick detrital and limestone series dated from Trias to Quaternary, with evolution following the basin's geodynamic setting before inversion at Maastrichtian and heterogeneous and deeply of the sedimentation of these basins and other regions of the chain; whereas, the Bou Nacer and Tighardine Mount are considered as anticlines, characterized by a high topography and occupied by the Jurassic formation (Fig. 8.2). They passed by the South Middle Atlas Accident. This accident has an important rejection of overlapping and gives a thickening of the Jurassic cover. The local minima (Fig. 8.3) located in the Itzer region show that the reflectance corresponds to the extension of Boumia granite under the Meso–Cenozoic sedimentary cover (Fig. 8.4). It is an outcropping in the Zaida-Boumia province and is dated to 329 Ma (Hoepffner et al., 1994). It can be thought of as stopping the Middle Atlas domain from overlapping with the Paleozoic basement of High Moulouya.

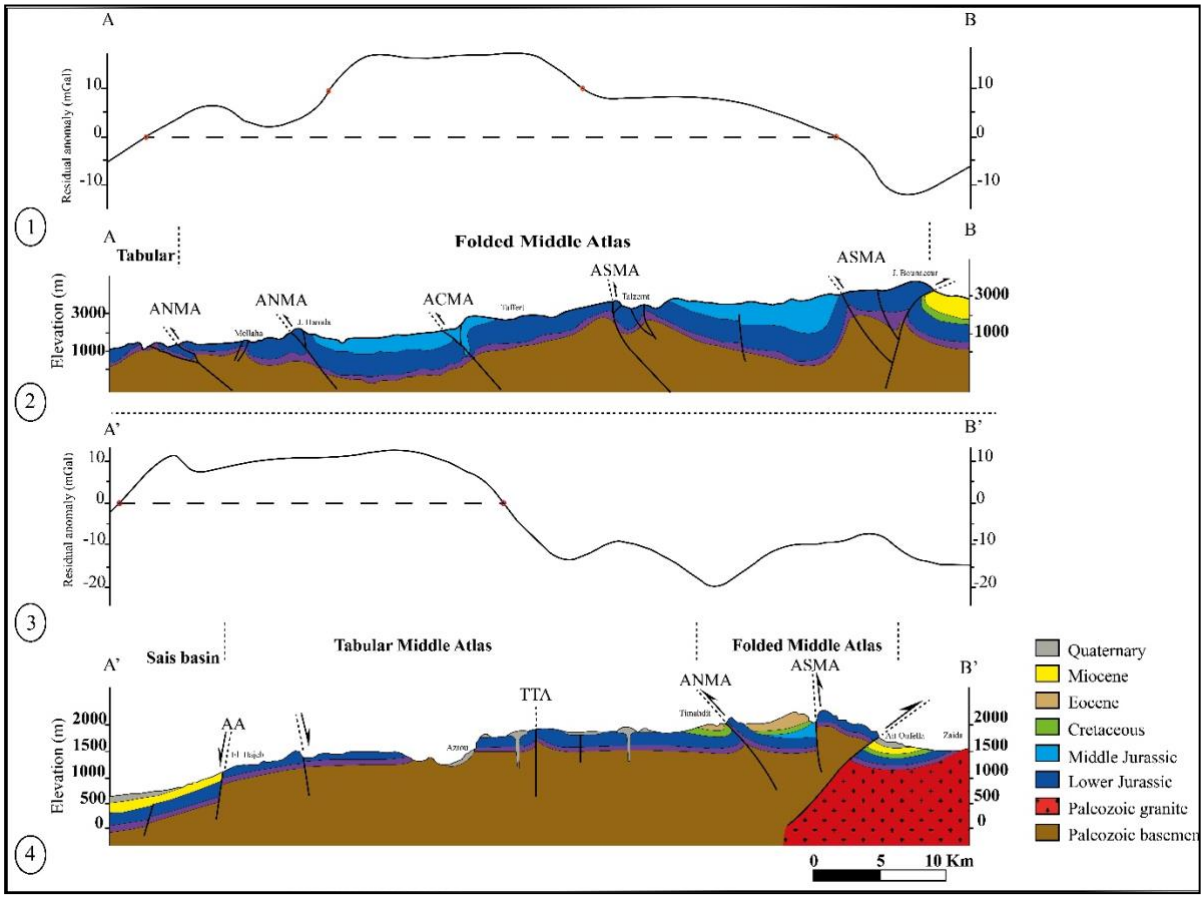


Fig. 8 : The residual gravity profil and the corresponding geological cross-section; 1) The residual gravity anomaly profile from the Sefrou-Bounaceur cross-section (AB, WNW-ESE); 2) The geological cross-section of the Central Middle Atlas (After Sabaoui, 1998); 3) The residual gravity anomaly profile from the Boufekrane-Zaida cross-section (A'B', NW-SE); 4) The geological cross-section from the Middle Atlas (After Mounir et al., 2019, modified)

5.2. Structural Mapping and Features of Middle Atlas Domain

The new structural map of the Middle Atlas (Fig. 10) is elaborated based on the analysis of the horizontal gradient gravity and the previous geological studies (Charriere, 1984; Fedan, 1989; Gomez et al., 1996; Charroud, 2002; Frizon de Lamotte et al., 2008). It helped us find faults that hadn't been mapped and figure out the main direction and location of gravity lineaments.

The rose diagram of lineaments derived from HG (Fig. 9b) shows four directions, with the major NE-SW trend and E-W, NW-SE, and N-S minor trends that are very similar to the geological fault system rose diagram (Fig. 9a). Those rose diagram results give the guided evaluative system that the Middle Atlas chain followed from the basin stage (rifting) to the uplifting stage (belt).

The results of lineaments show the dominance of the NE-SW trend that is very correlated firstly to the accidents of the Middle Atlas Chain, where the longest coincided with the great accidents like the TTA, the Adarouch Accident, and the El Bhalil Accident in the tabular part, the NMAA and the SMAA in the folder part. Secondly, these faults are known as the evolution of Hercynian, Jurassic, and Alpine deformations.

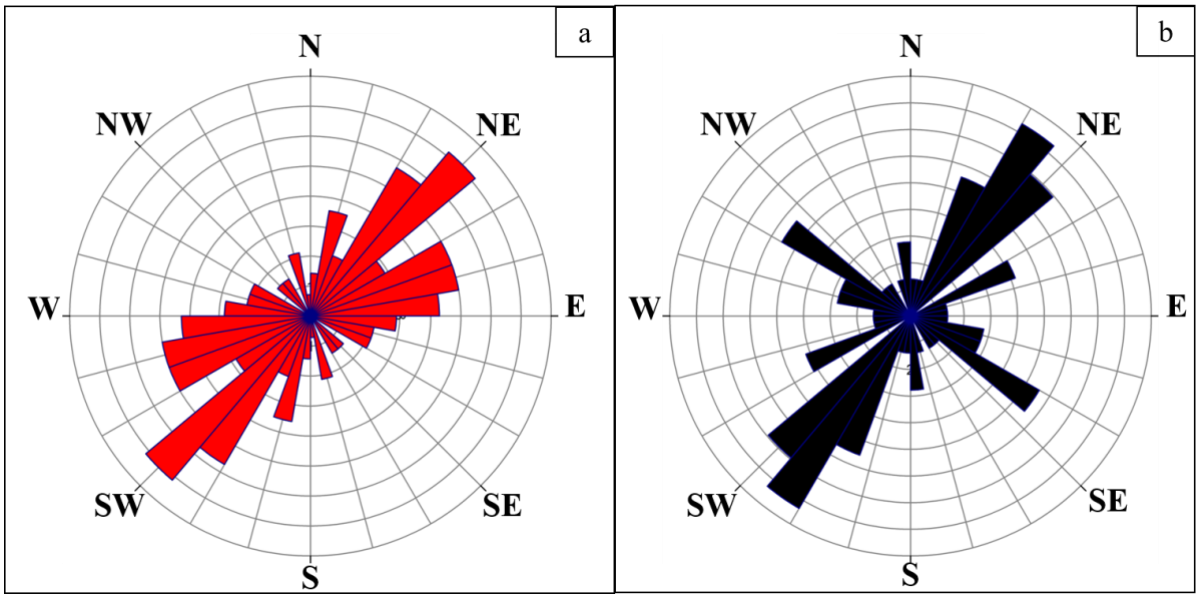


Fig. 9. Rose diagram of fault systems derived from geological data (a) and HG gravity data (b)

The first Tizi N'tretten that coincided with L1 is located in the chain's tabular part. Moreover, it is described by Charrière (1990) as a sinistral strike-slip with a normal component that allows the collapse of the Guigou and Ifrane-Imouzzer Blocks and its extension to the center of the Sais Basin in Bir Tamtam and can be branched to the Southern Riffian Fault. This fault is associated in the south of El Hammam with the salt diaper of Ouiouane. While most of the lineaments of the horizontal gradient in the folded Middle Atlas have the longest NE-SW, some are very correlated with the South, Central, and North Middle Atlas faults (SMAA, CMAA, NMAA), while some other unmapped faults are considered hidden faults where they coincide with the principal rivers of the chain. They are covered by thick sedimentation or by quaternary basalts. Also, we note that the folded Middle Atlas is characterized by a strong fracturing intensity that gives an interpretation of the distribution of the many basins in this part. Those faults are a thrust to the sinistral strike-slip component (Fedan, 1989). Most of these are extended under the Cenozoic formations of the Guercif Basin when they follow the anticlines or the rivers (Bourached, Mansour, and Melloulou).

The system of NW-SE trending faults is also observed in the Middle Atlas, the longest of which cuts across the domain from Oulad Ali at the borders of the chain with the Missour Basin to the Bir Tamtam area of the Sais Basin in the east of Fez. This fault (L5), mapped in some areas and sometimes hidden under dogger formations, allows us to say that it is a blind fault even for the whole system, reflecting the formation mode and structure of the lozenge morphological Cenozoic basins of the Middle Atlas. It allowed the outcropping of some Paleozoic inliers; therefore, it is considered a Hercynian heritage fault.

The E-W direction fault system is considered a major accident a major accident direction in the chain to which branches are attached. Therefore, most of them have a thrust with a sinistral strike-slip component, and they are outcropping or hidden under the Cenozoic formation. Likewise, the part of lineament L10 that coincided with the South Middle Atlas and deviated to E-W followed the limit of Boumia granite, which is considered a blockage of overlapping of the Middle Atlas domain. The L4, the second branch of SMAA, has the same direction as the L10, where most of it is hidden under the Quaternary sedimentation of the Enjil basin.

These three fault systems are very likely related to ancien faults that guided the Paleozoic sedimentation and the emplacement of the granite in the Tazekka, Boumia, and El Hammam Zones (Fig. 10). The faults NE-SW were reactivated as normal faults during the Triassic, Lower, and Middle

Jurassic. That gave rifting and subsidence of the intraplate basins and their evolution of sedimentation, while the NW-SE has a strike-slip component.

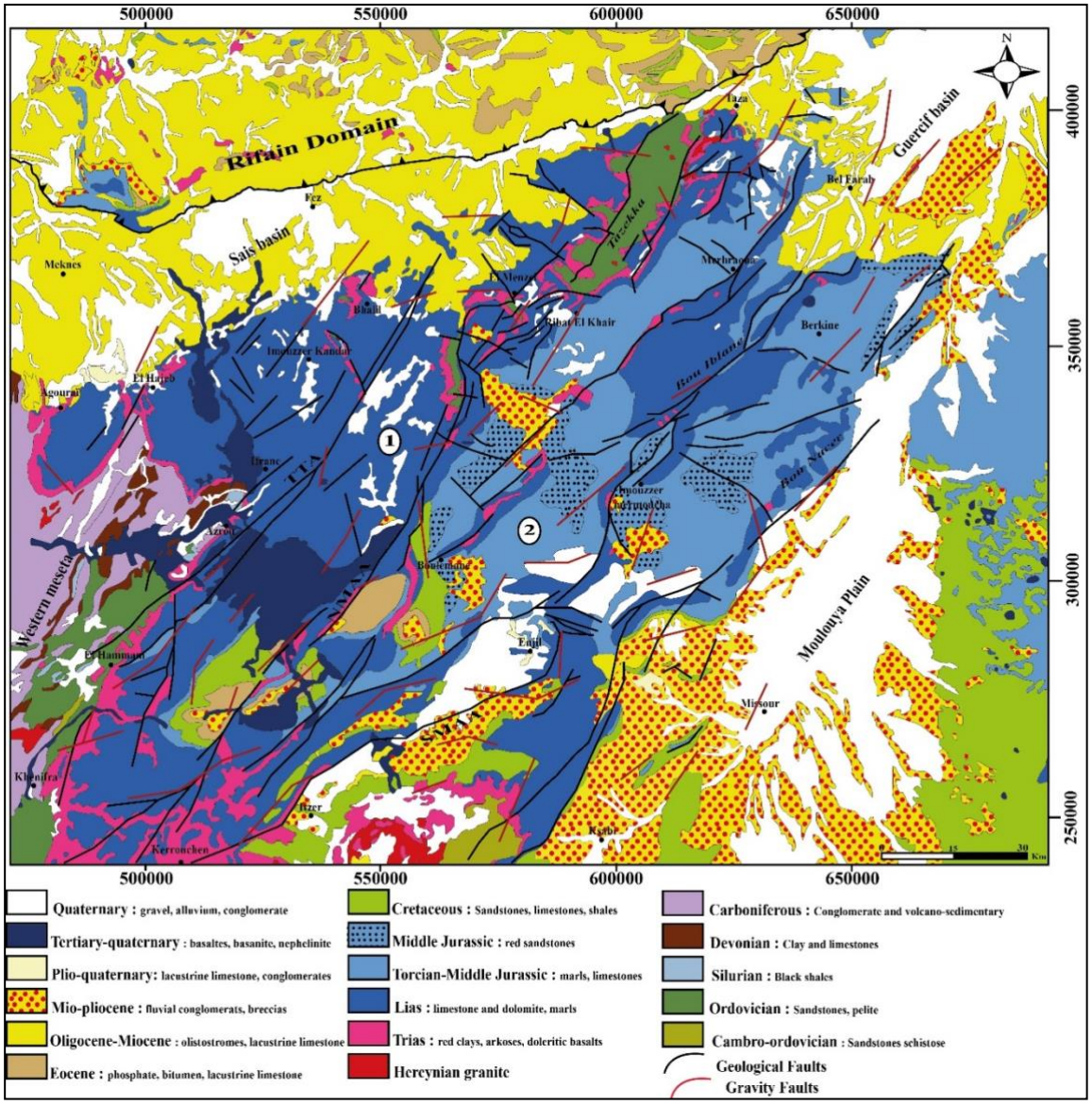


Fig. 10. Subsurface structural map of the Middle Atlas Chain derived from gravity and geological faults

6. Conclusions

The interpretation of the gravity data of the Middle Atlas chain allowed us to identify the major gravity causative structures and establish a synthetic structural map (Fig. 10).

The qualitative analysis of the residual anomaly data made it possible to highlight a relationship between the positive anomaly with the uplift or outcrop of the Paleozoic basement caused by the major accidents of Middle Atlas and the negative anomaly with the presence of granite bodies, diapers associated with Middle Atlas accidents, and deep sedimentary basins.

The fracturing analysis linked to the local maximum of the residual anomalies horizontal gradient shows three main systems of lineaments, which are NE-SW, E-W, and NW-SE, affecting the two parts of the middle atlas domain. The tabular domain does not present strong fracture intensity and is crossed by NE-SW accidents (Fig. 10), corresponding to the Adarouch Fault, El Bhalil Fault, and Tizi N'tretten. While the local maximum of HG in the folded Middle Atlas shows that a strong fracture intensity

characterizes it, most of the faults are NE-SW coincident with the North Middle Atlas, Central Middle Atlas, and South Middle Atlas accidents, which are connected with the E-W lineament, and are crossed by NW-SE given the structure of the anticlines and synclines of this part of the Middle Atlas chain. The most important faults are associated with salt diapers such as Ouiouane, Selouane, and El Bhalil diapers. These faults are considered like a guide controller for the sedimentation and morphology of the chain during the Jurassic and Cenozoic ages.

The results of this study area can be considered a qualitative analysis stage of gravity data, they are rich in information about geological subsurface structures and will be very useful in the phosphates, mining, and geo-material resources explorations in the Middle Atlas Chain.

References

Aboussalam, Z.S., Becker, R.T., Richter, J., Hartenfels, S., EL Hassani, A., Eichholt, S., 2020. The unique Devonian of Immouzer-du-Kandar (Middle Atlas basement)–biostratigraphy, faunas, and facies development. Frontiers in Science and Engineering 10.

Ajamay, H., Boushaba, A., Fadli, D., El Wartiti, M., Hoepffner, C., Moutaqi, A., Kharbouch, F., 2009. Evolution tectonique et magmatique du NW du massif de Tazekka (Maroc oriental). Tectonic and magmatic evolution of the NW Tazekka massif (Eastern Morocco). Pangea infos 45, 5–17.

Ayarza, P., Carbonell, R., Teixell, A., Palomeras, I., Martí, D., Kchikach, A., Harnafi, M., Levander, A., Gallart, J., Arboleya, M.L., 2014. Crustal thickness and velocity structure across the Moroccan Atlas from long offset wide-angle reflection seismic data: The SIMA experiment. Geochemistry, Geophysics, Geosystems 15, 1698–1717.

Benyas, K., Aarab, A., Lakhloufi, A., Qarbous, A., Manar, A., Amar, M., Idrissi, A., El-Mimouni, M., 2022. Contribution of the Airborne Magnetic Field to the Structural Study of the Variscan Granitoid of Rehamna, Morocco. Iraqi Geological Journal 55, 21–39. https://doi.org/10.46717/igj.55.1A.2Ms-2022-01-21

Benzaquen, M., Hamel, C., Medioni, R., 1965. Etude stratigraphique préliminaire des formations du bassin de Guercif. Rapport inédit Bur. Bass. Sédim., 74.

Blakely, R.J., 1996. Potential theory in gravity and magnetic applications. Cambridge university press.

Blakely, R.J., Simpson, R.W., 1986. Approximating edges of source bodies from magnetic or gravity anomalies. Geophysics 51, 1494–1498.

Brede, R., Hauptmann, M., Herbig, H.-G., 1992. Plate tectonics and intracratonic mountain ranges in Morocco-The Mesozoic-Cenozoic development of the Central High Atlas and the Middle Atlas. Geologische Rundschau 81, 127–141.

Charrière, A., 1990. Heritage Hercynien et evolution geodynamique Alpine d'une chaine intracontinentale: le Moyen-Atlas au SE de Fes (Maroc).

Charriere, A., 1984. Évolution néogène de bassins continentaux et marins dans le Moyen Atlas central (Maroc). Bulletin de la Société Géologique de France 7, 1127–1136.

Charrière, A., Haddoumi, H., 2016. Les «Couches rouges» continentales jurassico-crétacées des Atlas marocains (Moyen Atlas, Haut Atlas central et oriental): bilan stratigraphique, paléogéographies successives et cadre géodynamique. Boletín geológico y minero 127, 407–430.

Charroud, A., Charroud, M., Fedan, B., Laville, E., Rioult, M., Piqué, A., Du Dresnay, R., Medina, F., 1996. Dynamique sédimentaire des formations triasiques du Moyen Atlas méridional. Le Permien et le Trias du Maroc: état des connaissances, PUMAG, Marrakech 269–289.

Charroud, M., 2002. Evolutions géodynamiques comparées du Moyen Atlas, du bassin de Guercif et des Hauts plateaux (Maroc), Etat PhD thesis, Es-Sciences. ed.

Choubert, G., Faure-Muret, A., 1967. Le Jurassique de la region d'el Mers-Skoura (Moyen Atlas). Editions du Service géologique du Maroc.

Choukrad, J., Ouahzizi, Y., Ait Ali, A., Charroud, M., 2022. Geology, mineralogy, geochemistry and deposit model of iron and manganese in Bouarfa mine, Eastern High Atlas, Morocco. Scientific African 18, e01401.

Cordell, L., 1979. Gravimetric expression of graben faulting in Santa Fe Country and the Espanola Basin. Presented at the New Mexico Geological Society Guidebook, 30^< th> Field Conference, New Mexico, 1979, 59–64.

Cordell, L., Grauch, V., 1985. Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico, in: The Utility of Regional Gravity and Magnetic Anomaly Maps. Society of Exploration Geophysicists, 181–197.

Cordell, L., Grauch, V., 1982. Reconciliation of the discrete and integral Fourier transforms. Geophysics 47, 237–243.

Du Dresnay, R., 1975. Influence de l'héritage structural tardi-hercynien et de la tectonique contemporaine sur la sédimentation jurassique, dans le sillon marin du Haut-Atlas, Maroc. IX Congr. Intern. Sédimentologie, Nice, thème 4 «tectonique et sédimentation 1, 103–108.

El Azzab, D., El Wartiti, M., 1998a. Paléomagnétisme des laves du Moyen Atlas (Maroc): rotations récentes. Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science 327, 509–512.

El Azzab, D., El Wartiti, M., 1998b. Mise en place de la chaîne volcanique du moyen Atlas (Maroc): Traitement des données aéromagnétiques. The middle Atlas volcanic orogen setting (Morocco): aeromagnetic data analysis. Pangea infos 29, 45–51.

El Azzab, D., Ghfir, Y., Miftah, A., 2019. Geological interpretation of the rifian foreland gravity anomalies and 3D modeling of their Hercynian granites (Northeastern Morocco). Journal of African Earth Sciences 150, 584–594.

El Azzouzi, M., Maury, R.C., Bellon, H., Youbi, N., Cotten, J., Kharbouch, F., 2010. Petrology and K-Ar chronology of the Neogene-quaternary Middle Atlas basaltic province, Morocco. Bulletin de la société géologique de France 181, 243–257.

El Kochri, A., Chorowicz, J., 1996. Oblique extension in the Jurassic trough of the central and eastern High Atlas (Morocco). Canadian Journal of Earth Sciences 33, 84–92.

Ellouz, N., Patriat, M., Gaulier, J.-M., Bouatmani, R., Sabounji, S., 2003. From rifting to Alpine inversion: Mesozoic and Cenozoic subsidence history of some Moroccan basins. Sedimentary Geology 156, 185–212.

Everaerts, M., Mansy, J.-L., 2001. Le filtrage des anomalies gravimétriques; une clé pour la compréhension des structures tectoniques du Boulonnais et de l'Artois (France). Bulletin de la Société géologique de France 172, 267–274.

Fedan, B., 1989. Evolution géodynamique d'un bassin intraplaque sur décrochements: le Moyen Atlas (Maroc) durant le Méso-Cénozoïque (Thèse). Université Mohammed V, Rabat, Maroc.

Fedan, B., Laville, E., El Mezgueldi, A., 1989. Le bassin jurassique du Moyen Atlas (Maroc); exemple de bassin sur relais de decrochements. Bulletin de la Societé géologique de France 1123–1136.

Fiechtner, L., Friedrichsen, H., Hammerschmidt, K., 1992. Geochemistry and geochronology of Early Mesozoic tholeiites from Central Morocco. Geologische Rundschau 81, 45–62. https://doi.org/10.1007/BF01764538

Frizon de Lamotte, D., Zizi, M., Missenard, Y., Hafid, M., Azzouzi, M.E., Maury, R.C., Charrière, A., Taki, Z., Benammi, M., Michard, A., 2008. The Atlas System, in: Michard, André, Saddiqi, O., Chalouan, A., Lamotte, D.F. de (Eds.), Continental Evolution: The Geology of Morocco: Structure, Stratigraphy, and Tectonics of the Africa-Atlantic-Mediterranean Triple Junction. Springer Berlin Heidelberg, Berlin, Heidelberg, 133–202. https://doi.org/10.1007/978-3-540-77076-3_4

Frizon de Lamotte, D.F., Leturmy, P., Missenard, Y., Khomsi, S., Ruiz, G., Saddiqi, O., Guillocheau, F., Michard, A., 2009. Mesozoic and Cenozoic vertical movements in the Atlas system (Algeria, Morocco, Tunisia): An overview. Tectonophysics, The geology of vertical movements of the lithosphere 475, 9–28. https://doi.org/10.1016/j.tecto.2008.10.024

Gomez, F., Barazangi, M., Bensaid, M., 1996. Active tectonism in the intracontinental Middle Atlas Mountains of Morocco: synchronous crustal shortening and extension. Journal of the Geological Society 153, 389–402.

Haddoumi, H., Charrière, A., Feist, M., Baidder, L., Ferrière, J., Karim, M., Ettachfini, E.M., Mamoun, S.M., Chennouf, R., Rachdi, A., 2019. A Barremian-? Aptian Tethyan precursor of the Cretaceous marine flooding of Morocco: Evidence from the red-bed series within the "Marginal Folds" of the eastern High Atlas. Cretaceous Research 95, 37–60.

Hoepffner, C., 1987. La tectonique hercynienne dans l'Est du Maroc (thesis). Université Louis Pasteur.

Hoepffner, C., El Hassani, A., Piqué, A., Tahiri, A., 1994. La zone Midelt-Tazekka-Bsabis, le domaine interne de la chaîne varisque et ses relations avec le Massif hercynien central. Bull. Inst. Sci 169–191.

Hollard, H., Choubert, G., Brenner, G., Marchand, J., Sougy, J., 1985. Geologic map of Morocco, scale 1: 1000000. Notes et mémoires du Service géologique du Maroc.

Knight, K., Nomade, S., Renne, P., Marzoli, A., Bertrand, H., Youbi, N., 2004. The Central Atlantic Magmatic Province at the Triassic–Jurassic boundary: paleomagnetic and 40Ar/39Ar evidence from Morocco for brief, episodic volcanism. Earth and Planetary Science Letters 228, 143–160.

Lakroud, K., Remmal, T., El Hassani, I.-E., Mountaj, S., El Kamel, F., van Wyk de Vries, B., Boivin, P., Balcone-Boissard, H., Makhoukhi, S., Soufi, M., 2019. Monogenetic Strombolian Activity at Aguelmane Sidi Ali Volcano (Middle Atlas Volcanic Province, Morocco), 60, 109–125.

Laville, E., Charroud, A., Fedan, B., Charroud, M., Pique, A., 1995. Inversion negative et rifting atlasique; l'exemple du bassin triasique de Kerrouchene (Maroc). Bulletin de la Societé géologique de France 166, 365–374.

Laville, E., Fedan, B., 1989. Le système atlasique marocain au Jurassique: évolution structurale et cadre géodynamique. Sciences Géologiques, bulletins et mémoires 84, 3–28.

Laville, E., Pique, A., Amrhar, M., Charroud, M., 2004. A restatement of the Mesozoic Atlasic rifting (Morocco). Journal of African Earth Sciences 38, 145–153.

Mattauer, M., Tapponnier, P., Proust, F., 1977. Sur les mecanismes de formation des chaines intracontinentales; l'exemple des chaines atlasiques du Maroc. Bulletin de la Société géologique de France 7, 521–526.

Michard, A., 1976. Elément de la géologie du Maroc. Notes et Mémoires du Service géologique du Maroc., Maroc.

Missenard, Y., Zeyen, H., Frizon de Lamotte, D., Leturmy, P., Petit, C., Sébrier, M., Saddiqi, O., 2006. Crustal versus asthenospheric origin of relief of the Atlas Mountains of Morocco. Journal of Geophysical Research: Solid Earth 111.

Morin, P., 1962. Geologie-Premiere Preuve Paleontologique De Lexistence Du Cambrien Dans Le Maroc Central. Comptes Rendus Hebdomadaires Des Seances De L Academie Des ScienceS 254, 2198.

Mounir, S., Saoud, N., Charroud, M., Mounir, K., Choukrad, J., 2019. The Middle Atlas Geological karsts forms: Towards Geosites characterization. Oil & Gas Science and Technology - Revue d'IFP Energies nouvelles 74, 17. https://doi.org/10.2516/ogst/2018089

Oudy, A., Ouahzizi, Y., Lamrani, O., 2020. Etude pétrographique et microstructurale des schistes du massif hercynien de Moulay Bouazza (meseta occidentale, Maroc). International Journal Of Engineering And Computer Science 9, 07–16.

Piqué, A., 1996. Géologie du Maroc, les domaines régionaux et leur évolution structurale. Pumag,.

Saadi, M., 1972. Relations des alignements structuraux du Maroc avec différents phénomènes géologiques et leur contribution à la compréhension de l'évolution structurale du pays. Notes Mém. Serv. Géol. Maroc, Rabat 236, 113–118.

Sabaoui, A., 1998. Rôles des inversions dans l'évolution méso-cénozoïque du M. Atlas Septentrional (Maroc). L'exemple de la transversale El Menzel-Ribat Al Khayr-Bou Iblane.. Etat, Rabat, 410.

Van den Bosch, J., 1971. Carte gravimétrique du Maroc (provinces du Nord) au 1/500 000. Notes et Mém. Serv. géol. Maroc 234.

Verati, C., Rapaille, C., Féraud, G., Marzoli, A., Bertrand, H., Youbi, N., 2007. 40Ar/39Ar ages and duration of the Central Atlantic Magmatic Province volcanism in Morocco and Portugal and its relation to the Triassic–Jurassic boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 244, 308–325.