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Analysing the late Neoproterozoic - lower Cambrian period structural impacts in the eastern Anti-Atlas, Morocco: comparison between the Saghro and Ougnat massifs using sedimentological and aeromagnetic approaches

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ABSTRACT The Saghro-Ougnat area belongs to the eastern Anti-Atlas belt. This area has always captivated the attention of researchers due to its geological history and mineral richness. The present study was conducted to supplement the outcomes of previous researches and to contribute to the Saghro-Ougnat geological record with new insights. The intent of the paper is to compare the sedimentological and structural events which occurred from the Late Neoproterozoic to the Cambrian period in the Saghro-Ougnat region. Therefore, a sedimentological study was carried out both in Saghro and Ougnat to establish the sedimentological sections. The field study was combined with aeromagnetic analysis to gain a clearer understanding of the geological factors behind the Cambrian sedimentological architecture in the area. These sedimentological sections reveal a significant variation in thickness. In Saghro, the thickness increases towards the eastern zones, while in Ougnat the thickness increases towards the western regions. To explain this, several processing techniques were applied to the aeromagnetic data, including the Euler Deconvolution and the Source Parameter Imaging techniques. These methods helped identify a set of magnetic lineaments and their corresponding depths, as well as the basement topography. The geophysical processing outcomes enabled the identification of tectonic features responsible for the sedimentological architecture of the Cambrian deposits in the area.

Key words: Saghro, Ougnat, eastern Anti-Atlas, Cambrian rifting, grabens, sedimentation.

1. Introduction

The eastern Anti-Atlas is primarily composed of the Jbel (massif) Saghro and the Jbel Ougnat. The geological formations of these edifices extend from a Neoproterozoic basement surrounded by Palaeozoic strata, to Mesozoic-Cenozoic sedimentary basins. The geological record testified that the eastern Anti-Atlas underwent diverse structural events over time. In this study, we are interested in the late Neoproterozoic to Cambrian geological epoch. It has been established that, during the Cambrian period, the Anti-Atlas was submitted to rifting which led to the development of horst and graben structures (Saquaque *et al*., 1992; Idrissi *et al*., 2021). However, the geometry of the tectonic structures responsible for this configuration remains poorly understood. Several studies approached the geological evolution of the eastern Anti-Atlas (Ouguir *et al*., 1996; Tuduri, 2005; Burkhard *et al*., 2006; Raddi *et al*., 2007; Levresse *et al*., 2016; Gouiza *et al*., 2017; Miftah *et al*., 2017, 2021; Pouclet *et al*., 2018; Hejja *et al*., 2020; Idrissi *et al*., 2021, 2022. To date, there is little data to quantify the geometry of the tectonic features and their role in Cambrian sedimentation trapping in both the Saghro and Ougnat massifs.

Given that the structural features of the Cambrian rifting are hidden by subsequent sedimentation, we hypothesised that geophysical techniques could provide valuable insights into buried geological structures. Aeromagnetic surveys especially have proven to be effective in delineating subsurface geological features and have been employed for various purposes by several authors (Amiri *et al*., 2011; Azaiez *et al*., 2011; Skalbeck *et al*., 2014; Miftah *et al*., 2017, 2021; Adebiyi *et al*., 2020; Benyas *et al*., 2021, 2022; Boufkri *et al*., 2021, 2023). In this work, aeromagnetic data are used to complement and expand a previous study by Idrissi *et al*. (2021). The study (Idrissi *et al*., 2021) covers the northern flank of Saghro, which is a small area of the Saghro-Ougnat region. The rest of the mentioned region is a large-scale area that has never been a subject of similar studies. Therefore, the present research aims to address this gap by applying aeromagnetic surveys and field data to develop a comprehensive structural and sedimentological framework for the broader study area.

2. Geographical and geological setting

The Ougnat Massif constitutes the eastern extension of the Saghro Massif. Both massifs belong to the eastern Anti-Atlas belt of Morocco, and they are interpreted as a mobile zone of the Pan-African segment (Saquaque *et al*., 1992).

The study area (Fig. 1), located on the northern rim of the West African Craton (Destombes *et al*., 1985), has recorded numerous geological events ranging from the Pan-African to the Alpine orogeny (Ighid *et al*., 1989; Mokhtari, 1993; Burkhard *et al*., 2006; Charrue, 2006; Baidder *et al*., 2016; Gouiza *et al*., 2017).

2.1. Sedimentological setting

The study area encompasses the eastern inliers of the Anti-Atlas Pan-African belt, outcropping under a Palaeozoic cover. It comprises a Neoproterozoic basement (Choubert, 1963; Leblanc, 1981; Paille, 1983), unconformably covered by the Palaeozoic sedimentary deposits.

The Neoproterozoic basement of the study area is a combination of crystalline, metamorphic, and sedimentary rocks (Saquaque, 1992). It is composed of the PII metamorphosed siliciclastic beds and granitoids, together with PIII ignimbrite sheets, vitroclastic tuffs, shallow lacustrine sedimentary rocks (cherts, pelites, dolostones), and minor volcanic rocks (Paille, 1983).

The post-Pan-African sedimentary elements of the Anti-Atlas begin with terminal Neoproterozoic deposits and include the entire Lower Cambrian to the Late Carboniferous sediments. The entire sedimentary unit is about 8 to 9 km thick in the western Anti-Atlas and about 4 to 5 km thick south of the Saghro and Ougnat massifs. This Palaeozoic series was formed in shallow marine environments and it is extremely fossiliferous and almost continuous (Michard *et al*., 2008).

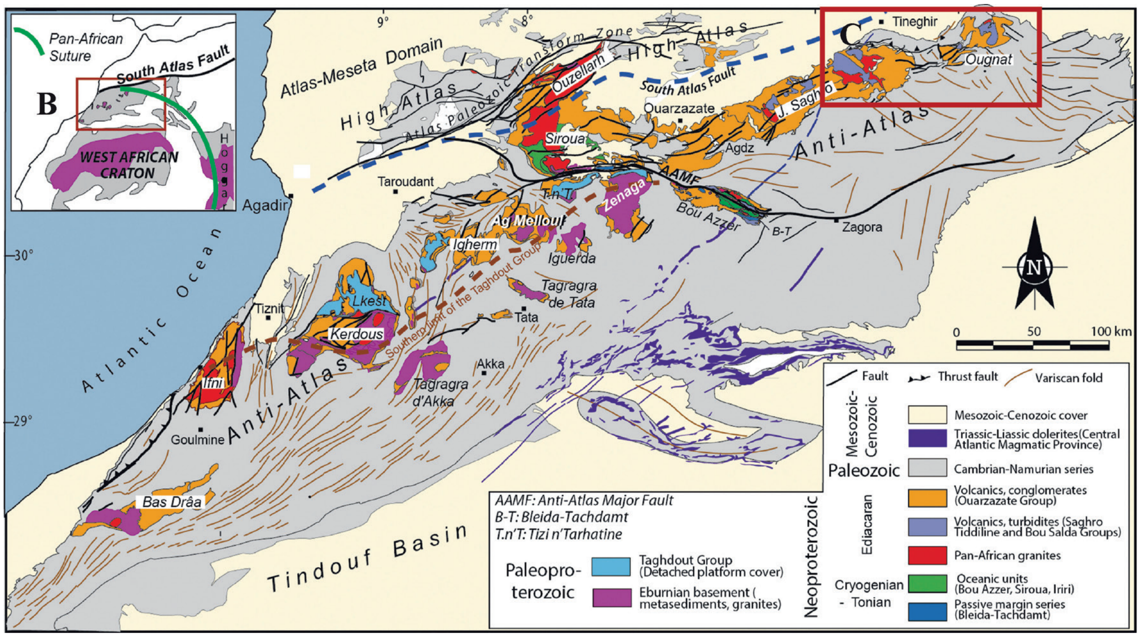

Fig. 1 - A) The Anti-Atlas mountain range [after Gasquet *et al*. (2008) modified by Soulaimani *et al*. (2018)]; B) position of the Anti-Atlas on the northern rim of the West African Craton; C) the location of the study area.

2.2. Structural setting

From the late Neoproterozoic to the Lower Cambrian period, the Saghro and Ougnat massifs underwent various stresses.

The main deformation of the late Neoproterozoic in the Anti-Atlas is characterised by a highly heterogeneous geometry and kinematics (Leblanc, 1973, 1976, 1977; Leblanc and Lancelot, 1980; Ennih and Liegeois, 2001). The orientation of the deformation changes from 30° N in Ougnat and 50-80° N in eastern Saghro to 100-130° N in western Saghro (Saquaque *et al*., 1992; Abia *et al*., 2003). Saquaque *et al*. (1992) demonstrated that the primary deformation phase in the Saghro Massif is distinguished by a profusion of schistosities flowing through the rock and regional conjugate shear zones that developed in response to a NW-SE compression. During the late stage, compression turns to the NE-SW directions. Abia *et al*. (2003) further confirmed that the late Neoproterozoic 30° N trending faults exposed in the Ougnat Massif display a polyphase history, beginning with a normal-sinistral event, followed by re-activation as normal faults, and culminating in NW-SE extensional tectonics.

The Upper Neoproterozoic epoch was an extensive phase that probably led to an ocean basin opening in the eastern Anti-Atlas (Mokhtari, 1993). Based on the synthesis of sedimentological analyses and synsedimentary tectonics, Fekkak *et al*. (2001, 2003) suggested a NW-SE to WNW-ESE trending extension.

During the Lower Cambrian, a rifting phase was initiated in Moroccan lands, due to which the Anti-Atlas was structured into horsts and grabens. In the eastern Anti-Atlas, the extension was NW-SE oriented and generated by normal NE-SW trending faults (Hejja *et al*., 2020; Idrissi *et al*., 2021).

3. Data and methods

3.1. Aeromagnetic data

The Moroccan Ministry of Energetic Transition and Sustainable Development provided the aeromagnetic maps collected in 1977 and utilised in this study. At a height of 2600 m above mean sea level, the aircraft was directed along 135° N oriented lines and 45° N directed tie lines. At the time of data gathering, the International Geomagnetic Reference Field was no longer present. The paper-format residual magnetic field maps that were filtered in this study have been previously calibrated [parameters: unit = gamma, (1 = 1 nT); tilt = 43.49°; declination = -6.4°]. Within a grid of 750 m^2, the aeromagnetic data is interpolated using the minimum curvature approach.

3.2. Methods

3.2.1. Geological field survey

The major target of the field survey was, first, to explain the thickness variation of the sedimentary series within the study area, so as to deduce the influence of the tectonics on the sedimentary filling during the late Neoproterozoic and Cambrian. The second target was to verify and confirm the outcomes of the aeromagnetic data analysis. Given the spaciousness of the study area, it was imperative to conduct several field trips to rigorously verify the thickness of the Cambrian sediments around the Saghro and Ougnat massifs. As the aim was to verify the thickness of the Cambrian deposits rather than the material or facies, in this paper, it was preferred to provide sections logged in terms of age, main formations, and thickness.

3.2.2. Aeromagnetic data processing

Using various mathematical filters, such as Reduction To the Pole (RTP), Euler Deconvolution (ED) and Source Parameter Imaging (SPI), aeromagnetic data interpretation resulted to be a trustworthy method for examining the magnetised geological features of the subsurface. In geophysical exploration, these filters have been extensively employed, particularly for mapping geologic contacts, faults, and dykes. ED and SPI are also dedicated to identifying the profundity of the causative sources.

Nevertheless, aeromagnetic data needs to be corrected due to the inclination of the Earth's magnetic field before the filtration procedure is started. The RTP approach transforms magnetic anomalies into anomalies that would be observed if the field were vertical, assuming that there is just an inducing magnetic field (Baranov, 1957; Baranov and Naudy, 1964). The RTP approach makes the spatial position of the anomalous source geometry match more closely to the shape of the magnetic anomalies.

SPI. To determine the depth of magnetic sources, SPI employs an extension of the complex analytical signal (Nabighan, 1972). The SPI method is a fast function developed by Thurston *et al*. (1997) and it has been extensively used by several authors since then (Thurston and Smith, 1997; Salako, 2014). The approach employs the relationship between the source depth, which can be calculated for any point within a data grid via horizontal and vertical gradients, and the observed field local wavenumber (k) defined as the rate of change of the analytic signal phase (Bracewell, 1965).

The outcome of SPI is an image that can be easily interpreted (Thurston and Smith, 1997; Smith *et al*., 1998). It reveals the estimated depth and shape of anomalous features using an automatic application on SPI software included in the Oasis Montaj Package (version 8.4).

ED. After reducing the residual map to the pole, ED transformation was applied to the RTP map. This method was initially established by Thomson (1982) and later developed by Reid (1990). Since then, it has been largely employed by several authors. It is an effective technique to locate and delineate geological structures of variable forms (Table 1) and estimate their depth based on the structural index (SI) involved (Table 2) (Reid *et al*., 1990). ED is a derivative-based technique that is conceived to be fast processing to analyse magnetic grids and provide precise data on structural settings and tectonic trends. Its equation is formulated after Thompson (1982) as following:

$$N\,(B-T) = \frac{(x-x0)\partial T}{\partial x} + \frac{(y-y0)\partial T}{\partial y} + \frac{(z-z0)\partial T}{\partial z} \quad (1)$$

where *T* is the residual magnetic field reduced to the pole, $\frac{\partial T}{\partial x}$, $\frac{\partial T}{\partial y}$, and $\frac{\partial T}{\partial z}$ are the first horizontal derivatives following X, Y, and Z, respectively.

In this work, a SI equal to 0 was used in order to delineate the magnetic faults and highlight their depth.

Table 1 - *N* values by source geometry (Reid *et al.*, 1990).

Geometric source	No. (magnetism)
Sphere	3
Vertical cylinder	2
Horizontal cylinder	2
Dyke / Sill	1
Contact	0

Table 2 - ED equation terms.

Equation terms	Meaning
x_0, y_0, z_0	Position of the magnetic sources
x, *y*, *z*	Observation point position
T	Total field detected at (*x*, *y*, *z*)
B	Regional value of the total field
N	Degree of homogeneity often referred to as the structural index (SI) which characterises the type of source

4. Results

4.1. Field survey

According to our field work, the eastern Anti-Atlas recorded deltaic sedimentation during the Cambrian period. The main sedimentary formations mapped are described below.

The Lower Cambrian formations are: the Igoudine conglomerates, Issafen clays, and terminal pink sandstones. These are followed by the deposition of paradoxides-rich pelites, and the Tabanite Sandstone Formation, of the Middle Cambrian (Destombes *et al*., 1985). Such formations present several facies that have been differentiated by taking into account classical sedimentary criteria such as grain size, sedimentary patterns and structures, and thickness and lateral extension of the beds. The most important outcome of this study is that the thickness of the Cambrian formations varies from one area to another in the eastern Anti-Atlas. In the coming paragraph, this variation will be explained in relation to tectonic and structural factors.

The Late Cambrian sedimentation was not deposited and, in fact, Ennih and Liégeois (2001) and Destombes and Feist (1987) confirmed that during the late Cambrian, the Anti-Atlas domain was emerged. However, the Late Cambrian was locally identified at the top of the Tabanite sandstones in central Anti-Atlas, by the presence of Périgondowanien Ollentela Africana trilobites, revealing, then, for the first time the existence of Late Cambrian in Africa (Destombes and Feist, 1987).

4.2. Source Parameter Imaging

The SPI interpretation method was applied to the RTP map to compute the depth of the study area basement. The identification of the basement profundity helped determine the sediment thickness of the Palaeozoic cover, especially in the Cambrian series. The depth estimation results of the SPI method were substantially consistent with the findings of the study area field survey.

The SPI map of the study area (Fig. 2) reveals a range of depths between 685 m and 7964 m. Compared to the field research and the geological map, the profound depths coincide with the deep sources hidden by the Palaeozoic and Mesozoic-Cenozoic sedimentation sites, and the shallower depths coincide with the basement outcrops.

The eastern Anti-Atlas basement is characterised by the heterogeneity of its rocks, including Middle Neoproterozoic granitoids and dense metamorphic rocks, overlaid by Upper Neoproterozoic andesites and conglomerate deposits (Leblanc, 1976; Aït Malek *et al*., 1998; Piqué, 2003). The distribution of Upper Neoproterozoic deposits locally conceals earlier terrains, which explains the increase in depth of anomalous sources even at the basement level, especially in the Ougnat Massif. This explains the great depth of the causative sources in the basement areas.

4.3. The Euler Deconvolution solution

Using the Euler3D Geosoft software tool, we were able to generate the ED solutions, involving a SI equal to 0, usually adopted to indicate large scale faults (Harrouchi *et al*., 2016).

The ED solutions shown in Fig. 3 present the location of linear magnetic features and their corresponding depth. The statistical analysis of ED solutions plotted on the geological map reveals a predominant NE-SW trend, indicating the presence of elongated faulting structures, particularly notable between the Saghro and Ougnat massifs.

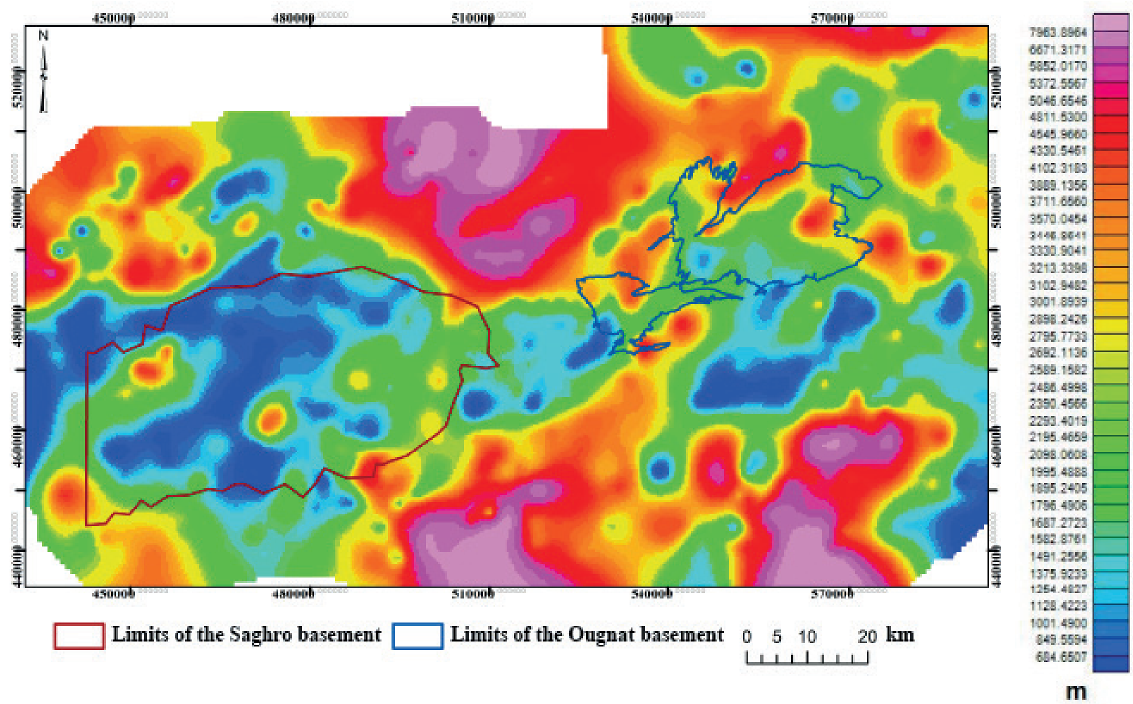

Fig. 2 - SPI map showing the depth of the study area substratum (the projection system used is Merchich Zone 1, the limits of the area are approximately: X_1: 435000, X_2: 590000, Y_1: 440000, Y_2: 510000).

These fault patterns, ranging in depths from 0.3 m to 1022 m, provide valuable insights into the geological history of the region. The consistent NE-SW orientation of the detected faults suggests regional stress regimes or significant tectonic events that have influenced the area over time. The ED analysis highlights the significance of these fault systems in shaping the regional geology, emphasising their role as structural features, potentially contributing to the elevation of the adjacent massifs of Saghro and Ougnat.

5. Discussions

5.1. Sedimentation context

The field work permitted to log several cross-sections, correlated to each other, around Saghro and Ougnat. The correlation of the Cambrian sedimentary sequences of the study area enabled us to recognise the geometry of the sediments. The correlation of the sequences from one section to another was performed on several transects linking all the sections. The Middle Cambrian roof was used as reference to link the sections one to the other. Fig. 4 shows the lateral distribution of the sedimentary bodies around the Saghro and Ougnat massifs.

The analysis of the lithostratigraphic sections, indicates that the Lower Cambrian deposits are absent in the western and eastern region of the Saghro and Ougnat massifs, respectively. While the Middle Cambrian sediments show a tendency to thin from east to west and from west to east in Saghro and Ougnat, respectively. This phenomenon was produced by active tectonics related to the Neoproterozoic-Lower Cambrian rifting that transformed the Anti-Atlas domain into low

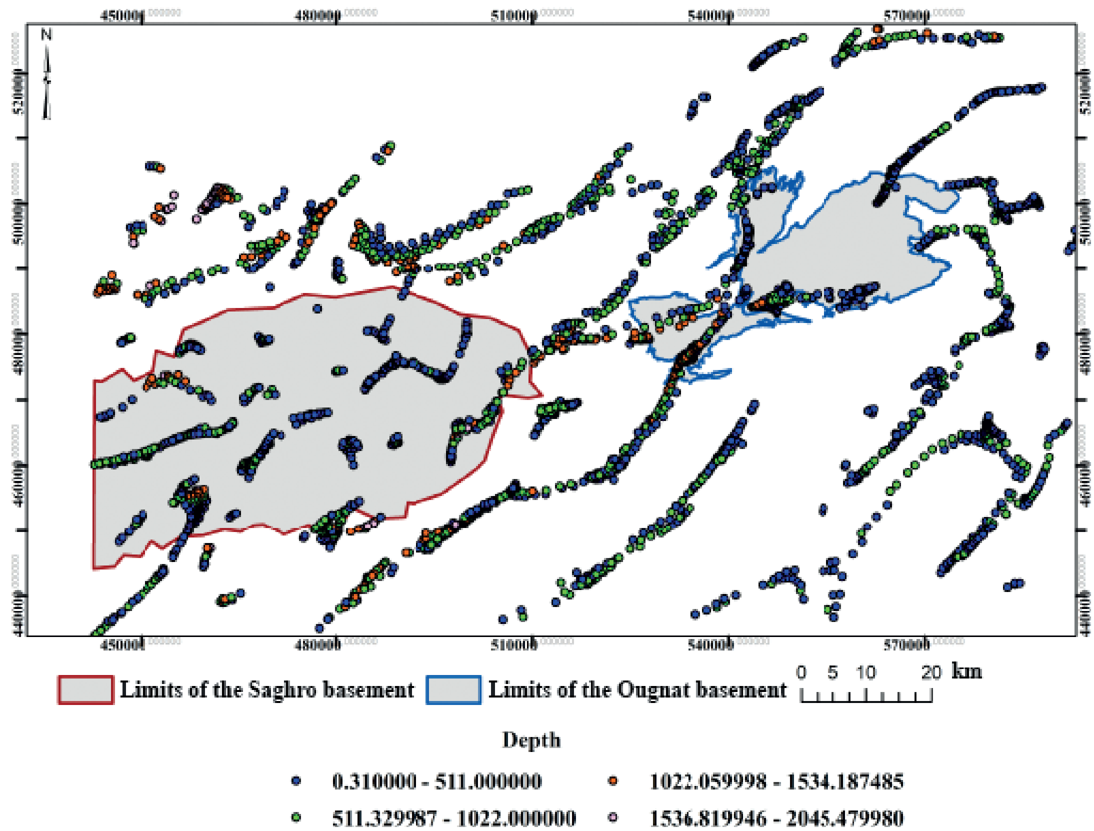

Fig. 3 - Map of the ED solutions showing the depth of the detected faults of the study area.

and high areas. During the Lower Cambrian transgression (Choubert, 1946), the subsided areas of the north-eastern and southern part of the Saghro Massif and the southern and western region of Ougnat received significant sedimentation. The rest of the study area remained emerged. After the Middle Cambrian transgression, the entire Anti-Atlas was immerged (Choubert, 1946). The structural architecture of the basement influenced the distribution of Middle Cambrian sedimentation, where grabens recorded greater sedimentation than horsts.

5.2. Geophysical context

The faults that we assume responsible for this sedimentological architecture are hidden by the later sedimentation, henceforth, it was necessary to use aeromagnetic mapping to expose the subsurface structures. The application of ED processing has provided valuable insights into the direction and depth estimation of faults within the study area. The majority of the detected lineaments are trending NE-SW within a depth of 0.3 m to 1022 m. Previous works linked these directions to the upper Neoproterozoic and Lower Cambrian rifting event, that structured the study area into horsts and grabens (Soulaimani *et al.*, 2003; Burkhard *et al.*, 2006; Raddi *et al.*, 2007; Gouiza *et al.*, 2017; Pouclet *et al.*, 2018; Hejja *et al.*, 2020; Idrissi *et al.*, 2021). Fig. 4C exposes the graben structure found between the Saghro and Ougnat, which explains the lateral variations of the facies, and the E-W thinning of the Lower and Middle Cambrian sedimentary series in Saghro and the W-E thinning in Ougnat.

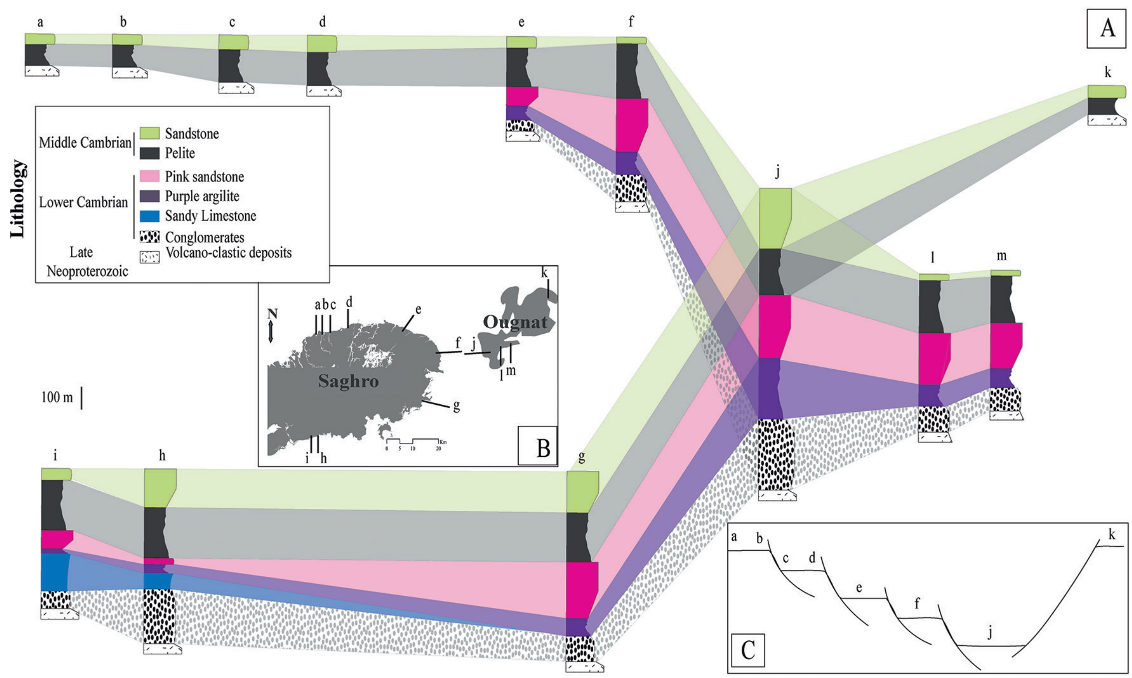

Fig. 4 - Lateral correlation between the lithostratigraphic sections of the Lower and Middle Cambrian series in the Saghro and Ougnat massifs (A); position of the sections in relation to the Saghro and Ougnat massifs (B); position of the sections in relation to the graben (C) and its depocentre (section J). Sections a, b, c, d, e, and f are after Idrissi *et al.* (2022).

Based on the superposition of the ED solutions and the SPI map (Fig. 5), the NE-SW trending faults appear to be mainly located in the basement depth variation areas and also coincide with the boundaries of the outcropping basement. This observation prompts an intriguing hypothesis regarding the influence of these faults on the elevation of the basement in the study area. It is reasonable to assume that the presence and activity of these faults have played a significant role in shaping the topography of the basement and its elevation variations.

5.3. Structural context

Further investigation and analysis are warranted to establish a causal relationship between the identified faults and basement elevation, potentially shedding light on the tectonic processes governing the geodynamic evolution of the region. Therefore, it was necessary to compare the outcomes of the geophysical processing with the structural data of the Saghro-Ougnat area (Fig. 6).

By comparing the geophysical processing results with the structural data available, notable similarities in the fault patterns and orientations are observed. This analogy between the two data sets proposes a robust correlation, reinforcing the reliability and accuracy of the geophysical findings.

Using the structural data of Saghro and Ougnat (Fig. 6), we were able to produce a rose diagram for each edifice (Fig. 7). The comparison between the Saghro and Ougnat structural maps illustrates the main trending faults in both areas. The main faults in Saghro are trending E-W and NE-SW to ENE-WSW while in Ougnat the main faults are trending NE-SW, N-S, and NW-SE. The difference between the main trending directions is explained by the very heterogeneous geometry and kinematics of the deformation in the study area, as mentioned in the structural context above.

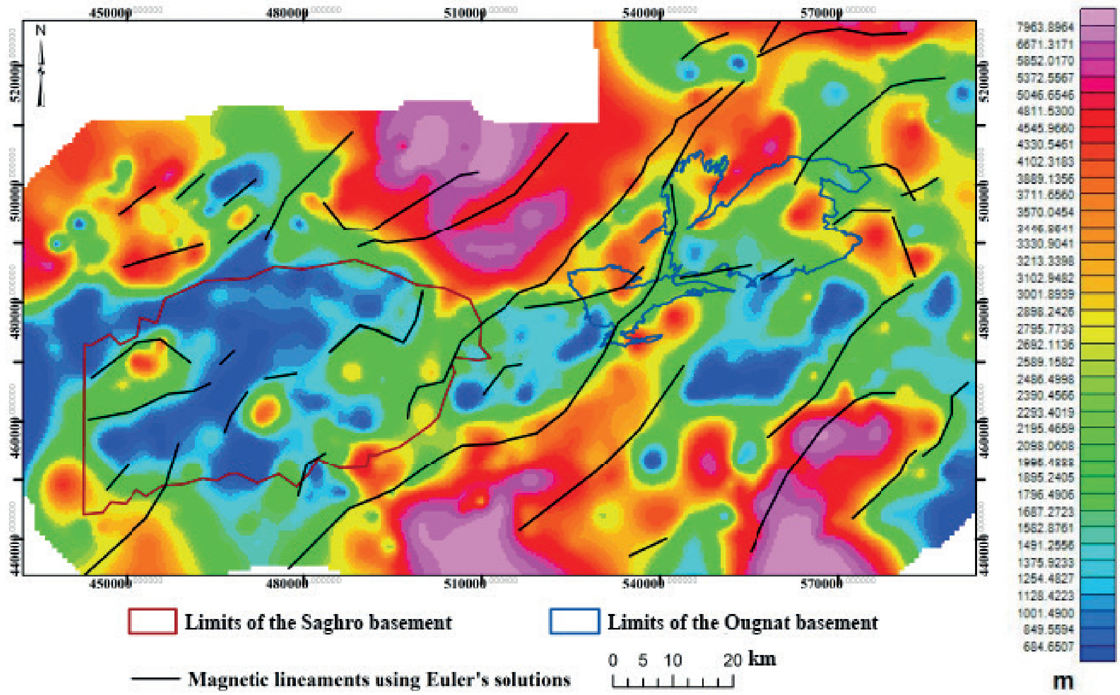

Fig. 5 - Superposition of the SPI map and the ED magnetised lineaments of the study area.

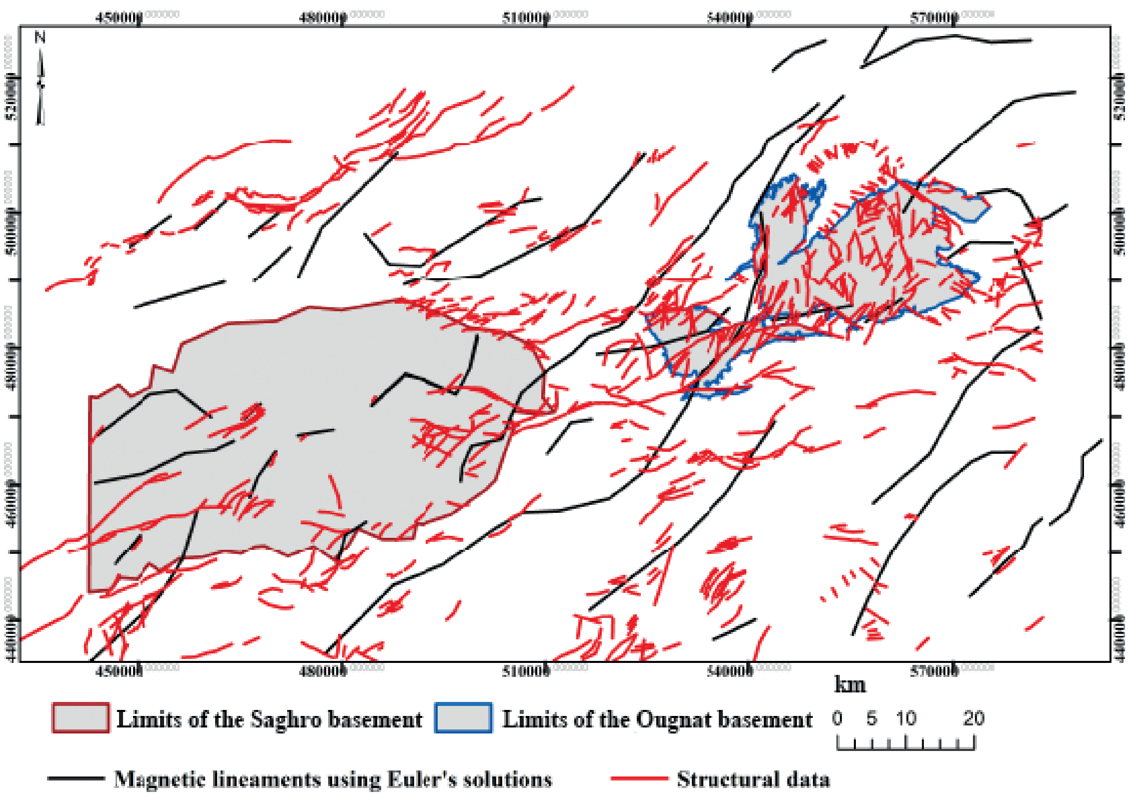

Fig. 6 - Superposition of the ED magnetised lineaments and the structural data of the study area.

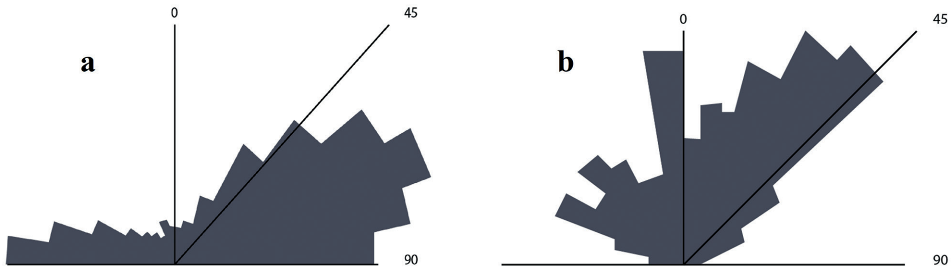

Fig. 7 - Rose diagrams of the studied edifice based on structural data: the rose diagram of the Saghro Massif (a), and of the Ougnat Massif (b).

The tectonic event between the upper Neoproterozoic and the Cambrian epoch, led to a rifting initiation in the study area. Rifting causes uneven distribution of substratum components, consequently creating high and low landscapes. Using SPI processing, we were able to confirm this distribution. The Neoproterozoic basement in the eastern Anti-Atlas terrains have been differentially uplifted, which in turn led to subsided and uplifted zones in the study area. The uplifted areas recorded less sedimentation and, in some places, they remained outcropping.

5.4. Implication of the study

This study analyses the geological evolution of the Saghro and Ougnat massifs from the Neoproterozoic to the Cambrian period, providing new insights into sedimentation, tectonics, and structural development. The findings contribute to the understanding of the sedimentation evolution during the Neoproterozoic to Cambrian period and have important implications. They enhance the current understanding of the tectonostratigraphic evolution of the Saghro-Ougnat region by identifying the mechanisms that control the thickness of sedimentary sequences. The results suggest that regional tectonic stresses played a crucial role in determining the sedimentation patterns observed in the area. By highlighting the relationships between tectonics, sedimentation, and structural development, this study offers a valuable contribution to both academic research and practical applications in geoscience.

6. Conclusions

The current work presents the outcomes of field surveys and geophysical processing to describe the influence of tectonics on the Cambrian sedimentary framework. The field work facilitated the establishment of multiple lithostratigraphic sections that highlighted the thickness variation of the Cambrian deposits along the study area. Conversely, geophysical processing consists of reducing to the pole the residual map, then applying several filters to extract the geological structures represented by the brutal changes of magnetisation.

The sections logged revealed thickness contrast along the Saghro and the Ougnat massifs. The Saghro Massif sections showed that the northern area deposits are thinner than those of the southern and eastern zones. Whereas, the Ougnat Massif sections indicated that the western and southern area deposits are thicker than the eastern and northern zones. Firstly, this confirms the presence of a differential distribution of basement uplifts and, secondly, the existence of a graben structure between the two massifs.

The uneven distribution of the basement has been proven using SPI transformation. The results of SPI highlighted the spatial distribution of the anomalies, thus, indicating the spatial organisation of the basement uplifts, which, in turn, affected posterior sedimentation.

As the tectonic factor influenced sedimentation emplacement, subsidence was not homogeneous in the whole study area, so the western part recorded a hiatus of the Lower Cambrian and a significant reduction in thickness of the Middle Cambrian deposits.

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