IGCP PROJECT 683: PRE-ATLANTIC GEOLOGICAL CONNECTIONS AMONG NORTHWEST AFRICA, IBERIA AND EASTERN NORTH AMERICA

MOROCCAN FIELD TRIP GUIDE
OCTOBER 14 TO 20, 2024

# THE SAGHRO DOMAIN OF THE ANTI-ATLAS (CENTRAL AND EASTERN ANTI-ATLAS): EXPLORING GLOBAL CORRELATIONS

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Bleida region (Bou Azzer inlier, Central Anti-Atlas, Morocco)

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## Acknowledgments

We would like to begin by expressing our heartfelt gratitude to all those who have advanced our understanding of Moroccan geology, particularly the geology of the Anti-Atlas. This contribution is a tribute to those who are no longer with us but whose work remains a vital reference in Moroccan geology.

This excursion was organized as part of the IGCP683 annual meeting. We extend our thanks to the IGCP and UNESCO for their financial support, which has been instrumental in facilitating the successful organization of the three meetings of our project. We are grateful to the other co-leaders of the IGCP683 project for their commitment and dedication throughout its four-year duration: Sandra Barr, Yvette Kuiper and Pilar Montero.

Our sincere appreciation goes to MANAGEM Group for granting us access to and a tour of the Imiter and Bou Azzer Mines. Additionally, we thank everyone who contributed at any stage of organizing this meeting, including El Hassane Beraaouz, Mohammed Bouabdellah, Atik El Majid, Núria Pujol Solà and James Pearce.

# Summary

This 5-day field trip marks our final annual meeting for IGCP683, succeeding the post-conference field trip in 2022, held in Nova Scotia, Canada, and the Iberian field trip in Spain in 2023. These events are organized to gather senior and young geoscientists from various countries, including Morocco, Spain, the USA, Canada, Germany, and more. They aim to create a platform for the exchange of ideas, foster interactions, and facilitate potential collaborations among participants. The mean objective is to explore and discuss potential correlations among crustal blocks (eastern North America, northwestern Africa, Iberia) by analyzing the geological, geochronological, and stratigraphic characteristics of select key outcrops.

The Moroccan field trip 2024 will enable participants to explore and appreciate the geology of the central and eastern Anti-Atlas, here referred to as the Saghro domain. This domain is a segment of the Neoproterozoic Pan-African belt system located on the northern edge of the West African craton (WAC). In this area, the oldest rocks consist mainly of Neoproterozoic units recording several geodynamical stages of the Pan-African orogeny: (1) rifting and break-up of Rodinia (>800 Ma) with the development of passive margins, (2) oceanic crust development (770-720 Ma) where island arcs were generated, (3) ocean closure (660-640 Ma) with polyphase accretions and (4) the post-collisional period (630-539 Ma) evolving from a transpressive setting to a transtensive one, during which huge high-K calc-alkaline to shoshonitic volcanism and granitoids were emplaced. In the Saghro domain, the late Ediacaran magmatism is accompanied by pervasive hydrothermal activity giving rise to the several world-class precious metal deposits, base–metal porphyry-epithermal and SEDEX-type occurrences.

During the Cambrian Period, the whole Anti-Atlas constituted a subsident basin characterized by the deposition of thick sedimentary formations, commencing with immature clastics (Série de base) and carbonate (Adoudou Formation) in a subsident basin within a post-orogenic extensional environment. From the Middle Cambrian to the Silurian period, siliciclastic deposition dominated, with environments alternating between fluvial, shallow-marine, and open-marine shelf settings.

This field trip provides a unique opportunity to explore a series of geological outcrops that span a vast period from the Paleoproterozoic to the Upper Ordovician. During this time, the Saghro domain experienced significant geological and biological events, including episodes of glaciation, magmatic activity, metamorphism, and the formation of mineral resources, as well as the appearance and diversification of early life forms, which are preserved in the fossil record within the region's stratigraphy.

# General Information and logistical details

Just like any ordinary geological excursion in the wilderness, the field trip may involve hazards to leaders and participants. Thus, participants are asked to take care and follow the instructions provided by the leaders.

The logistical details for the field trip include accommodation in a mix of hotels, guesthouses and tents, all selected for their proximity to key geological outcrops. Transportation will be arranged using private 4x4 vehicles capable of handling rugged terrain, with professional drivers familiar with the region. Meals will include breakfasts and dinners at the hotels or guesthouses, with packed lunches provided during fieldwork days. Dietary requirements can be accommodated with advance notice. Participants should be in good physical condition, as the trip involves moderate hiking. They may bring essential field equipment, such as hammers, hand lenses, and any other field tools.

Necessary items to bring include sturdy hiking boots, weather-appropriate clothing (in October, temperatures in the Anti-Atlas can vary significantly between warm days and cooler nights), sunscreen, hats, sunglasses, rain gear...

Travel insurance is strongly recommended to cover medical emergencies. Participants should be prepared for varying weather conditions and ready for fieldwork in remote areas. This preparation will ensure a safe and successful field trip experience for everyone involved.

# Introduction

The Kingdom of Morocco is a mountainous country situated in the northwestern corner of Africa, covering an area of 712,550 km². It is bordered to the north by the Strait of Gibraltar, which separates it from Spain and Europe, with Algeria to the east and Mauritania to the south. Morocco has coastlines along both the Mediterranean Sea to the north and the Atlantic Ocean to the west. This strategic location places the country at a triple junction, bridging a continent (Africa), an ocean (the Atlantic), and an active plate collision zone (the Alpine belt system), while spanning the Mediterranean to Sub-Saharan climatic zones.

Geographically, Morocco is distinguished by its vast plains and the highest mountain ranges in North Africa, belonging to the Mediterranean, oceanic, and Saharan domains, with mountains covering more than a third of its territory.

Geologically, Morocco can be divided into five structural domains (***Figure 1***): (i) the Rif domain in the north along the Mediterranean coast, (ii) the domain of elevated plateaus or Mesetas, including intramontane basins, (iii) the Atlas system (High and Middle Atlas), which extends eastward into Algeria and Tunisia, (iv) the Anti-Atlas domain and its surrounding basins (Souss and Ouarzazate), and (v) the Saharan domain to the south, corresponding to the West African craton.

Morocco hosts nearly all the Paleozoic and Precambrian outcrops of northwestern Africa, recording over 3 billion years of Earth's geological history. This history includes the accretion of Paleoproterozoic shields (e.g., Zenaga and Igherm inliers), the formation of the Pan-African belt (e.g., Anti-Atlas) and the Variscan belt (e.g., Meseta), the opening of the Central Atlantic (e.g., High Atlas), and the more recent geological developments of the Alpine chain (e.g., Rif, High Atlas). This extensive geological history is also associated with the formation of diverse mineral deposits, including phosphates, world-class precious metal deposits, base-metal porphyry, and SEDEX-type occurrences. These mineral resources are vital to Morocco's economy, contributing 10% of the national GDP, with phosphates accounting for 90% of this contribution. Notably, minerals, rocks (especially meteorites), and fossils from Morocco are exhibited in museums worldwide.

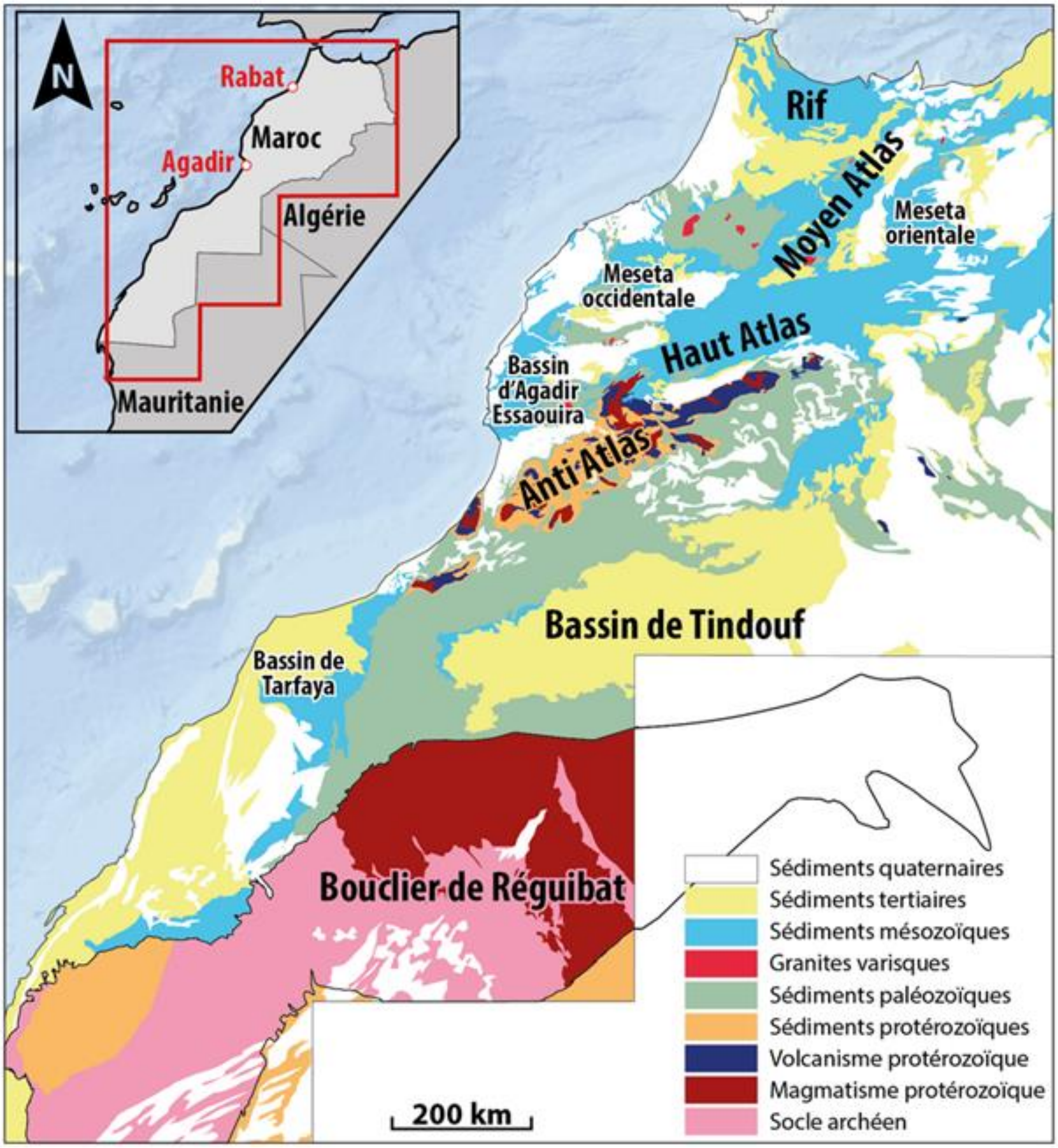


***Figure 1.*** *Simplified map showing the main structural domains of Morocco (Saadi, 1985)*

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# The Anti-Atlas belt: geological and metallogenic background

Located in the south of Morocco, the Anti-Atlas Mountain range stretches from the Atlantic Ocean in the west to the Tafilalt basin in the east (***Figure 2***). It extends in an east-northeast to west-southwest direction over more than 700 kilometers in length and approximately 150 kilometers in width. The Anti-Atlas is bordered to the north by the Cenozoic High Atlas Mountain range, from which it is separated by the crustal-scale South Atlas Fault (SAF). To the south, the Anti-Atlas gradually merges into the expansive desert regions of southern Morocco.

The Anti-Atlas belt exhibits a Precambrian crystalline basement beneath a slightly folded Late Ediacaran and Early Paleozoic volcanic and sedimentary sequences (***Figure 2***). The Proterozoic basement crops out through erosion of its cover in several inliers (Bas Drâa, Ifni, Kerdous, Tagragra of Akka, Tagragra of Tata, Igherm, Siroua, Zenaga, Bou Azzer, Saghro, and Ougnat). It should be noted that Precambrian rocks are not confined to the Anti-Atlas domain, as they are also exposed in the eastern block of the High Atlas Paleozoic massif (The Ouzellagh promontory), in the Western High-Atlas and in the Western and Eastern Mesetas (Pereira et al., 2015; Ouabid et Garrido, 2023). Moreover, both the Anti-Atlas and Atlas-Meseta belts are covered by a Lower Cambrian carbonate platform and share Ordovician glacial sediments, suggesting that they were adjacent at least during the late Ediacaran-Cambrian period (Le Heron, 2007; El Kabouri et al., 2023).

In the Anti-Atlas, the Paleoproterozoic rocks crop out to south of the Anti-Atlas Major Faults (AAMF) running across the Bou Azzer and Sirwa inliers running across the Bou Azzer and Sirwa inliers, in the western Anti-Atlas (known also as the cratonic domain), while the central and eastern Anti-Atlas (known as the mobile domain) belong to the Pan-African mobile belt located to the north of the AAMF (Choubert,1963). This Pan-African domain was recently identified as a single terrane edged to the north by the South Atlas Fault (SAF), and referred to as the Saghro Domain (Schulte et *al*., 2022). However, inherited magmatic zircons and isotopic data indicate the contribution of cratonic material during the genesis of Ediacaran magmatism, indicating that the cratonic crust might be buried deep beneath the entire Anti-Atlas (Ennih and Liégeois, 2001; Soulaimani et al., 2006; Errami et al., 2009) and extend into the Meseta domain as also supported by the presence of 2 Ga cratonic outcrop in Western Meseta (Pereira et al., 2015).

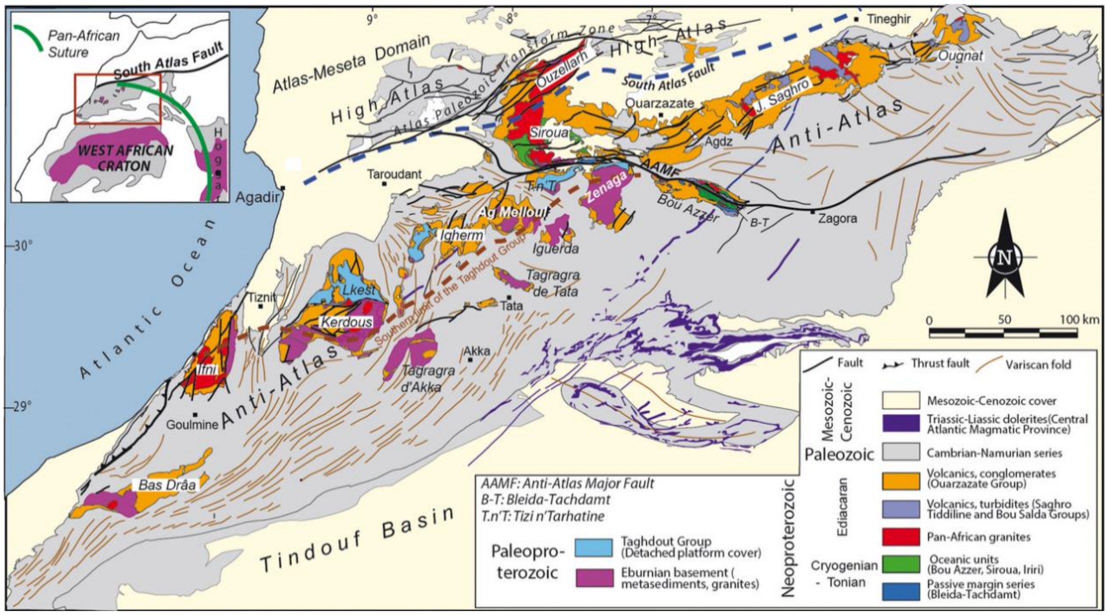



***Figure 2.*** *The Anti- Atlas Mountain range modified after Gasquet et al. (2008)*

The Paleoproterozoic rocks of the cratonic domain (i.e. the Zenaga complex) consist of migmatite, dolerite and metamorphic rocks that are intruded by widespread granitic to granodioritic intrusions (***Figure 3***; Hassenforder, 1987; Walsh et al., 2002; Thomas et al., 2004; Gasquet et al., 2005; Piqué et *al*., 2007). Geochronological dating using the U-Pb method on zircons from batholiths indicate a long-lived Eburnean magmatic event between 2026 ± 7 and 2106 ± 12 Ma (Aït Malek et al., 1998; Walsh et al., 2002; Blein et al., 2022). Overlying this crystalline basement is the Taghdout Group, which consists of a thick series of silico-carbonate rocks with mafic sills cropping out continuously along the northern edge of the Zenaga, Agadir Melloul, Ighrem, and Kerdous inliers (Hassenforder, 1987; Bouougri and Saquaque., 2004; Blein et al., 2014). U-Pb (baddeleyite) ages from doleritic sills in the Taghdout Group indicate crystallization from 1710 Ma to 1650 Ma (Kouyaté et al., 2013; Ikenne et al., 2017), and detrital zircons from these sandstone samples only show Late Paleoproterozoic youngest zircons, supporting the establishment of an epi-cratonic platform during the Late Paleoproterozoic (Abati et al., 2010; Errami et al., 2021b).

The Mesoproterozoic was formerly considered as absent in Morocco. However, further geochronological assessment indicates that the Anti-Atlas records a Mesoproterozoic magmatic event depicted by the emplacement of doleritic dykes dated between ca. 1384 and 1450 Ma (El Bahat et al., 2013; Kouyaté et al., 2013; Youbi et al., 2013). Additionally, no sedimentary evidence of Mesoproterozoic has been reported from the Anti-Atlas.

The Neoproterozoic successions overlie the old Paleoproterozoic crystalline basement. These rocks record different stages of the Pan-African orogeny (***Figure 3)*** represented by: (i) Rifting and breakup (>800 Ma) of an unknown continent to which belonged the WAC with the development of passive margin (Tachdamt Group; Thomas et al., 2004; Bouougri et al., 2020) accompanied by rift-related magmatism (Alvaro et al., 2014b). (ii) Development of an ocean and formation of island arcs at 770–650 Ma and associated back-arc basin sediments of Bleida Group (Samson et *al*., 2005; Blein et *al*., 2014a; Triantafyllou et *al*., 2016, 2020; Bouougri et al., 2020; Arenas et al., 2021). (iii) Ocean closure (650-640 Ma), characterized by polyphase accretion of intra-oceanic rocks forming a varied assemblage of ophiolitic complexes and island arcs associated with minor amounts of calc-alkaline magmatism, the whole being accompanied by amphibolite- to greenschist-facies metamorphism (Thomas et *al*., 2002; Samson et *al*., 2004; D'Lemos et *al*., 2006; Blein et *al*., 2014a; Triantafyllou et *al*., 2015). (iv) Post-collisional period (630–539 Ma), which characterized by a shift from a transpressive to a transtensive tectonic setting (Thomas et *al*., 2002, 2004; Ennih and Liégeois, 2001, 2008; Gasquet et *al*., 2008; Blein et *al*., 2014b, Belkacim et al., 2017), during which huge high potassium calc-alkaline to shoshonitic magmatism occurred, accompanied by sedimentary successions deposited in pull-apart basins (Pouclet et al., 2007; Walsh et al., 2012; Toummite et al., 2012; Alvaro et al., 2014b; Blein et al., 2014b).

During the early Ediacaran period, the Saghro domain recorded the development of a very subsistent basin extending between the AAMF and the SAF, where the turbiditic series of the Saghro Group was deposited (***Figure 3,*** ca. 630-600 Ma; Fekkak et al., 1999; Errami et al., 2009; El Kabouri et al., 2023). These sequences were deformed at greenschist facies metamorphic grade (Thomas et al., 2002; Errami et al., 2009; Abati et al., 2010; Errami et al., 2020). The precursors Anzi, Bou Salda, Tiddiline and M'gouna-Dadès groups were deposited between 600 and 580 Ma (Thomas et al., 2002; Gasquet et al., 2008) in narrow, tectonically active, strike-slip pull-apart rift basins with intrusion of high-K calc-alkaline granitoid batholiths (Thomas et al., 2004; Walsh et al., 2012; Schulte et al., 2020). These groups are overlain in the whole Anti-Atlas by the Ouarzazate Group (580-539 Ma) dominated by potassic calc-alkaline volcanic, volcaniclastic and plutonic rocks (Belkacim et al., 2017; Linnemann et al., 2019; Youbi et al., 2020). This huge silicic magmatic activity of the Ouarzazate Group is thought to belong to a continental silicic large igneous province (SLIP) emplaced in the whole Anti-Atlas, especially in the Saghro domain during the Late Ediacaran times (Tuduri et al., 2018; Belkacim et al., 2021; Schulte et al., 2022; Ferraq et al., 2024).

The emplacement of the Ouarzazate SLIP during the final Pan-African orogenic stage corresponds to orogenic collapse invoked to explain the hydrothermal and metallogenic activity in the Saghro domain as well as a shift in the magma source from crustal recycling to juvenile in the Late Ediacaran (Gasquet et *al*., 2005; Tuduri et al., 2018; El Kabouri, 2023). Indeed, several ore deposits are suggested to be related with the magmatic pulses of the Ouarzazate SLIP and the associated hydrothermal system, such as: Qal'at M'Gouna district Au-Ag (Cu, Mo, Bi, Te), including the Ismlal Au(-Cu-Mo) porphyry, Zone des Dykes Au-base metal, Thaghassa Au-Ag, Imiter Ag-Hg-Pb, Bouskour Ag-base metal, Tiouit Au-Ag-Cu, Sidi Flah Cu-Au-Ag, Tagmout Cu-Ag, Bou Madine Au-Ag-base metal deposits and Imourkhssen Cu-Mo-Au-Ag porphyry (Tuduri et *al*., 2018; Ferraq et *al*., 2024). Subsequently, the Saghro domain could be considered as a porphyry-epithermal metallogenic province (Ferraq et *al*., 2024), including the entirety of porphyry and epithermal ore deposits associated with the emplacement of the multi-pulsed Ouarzazate SLIP (Gasquet et al., 2005; Tuduri et al., 2018; Belkacim et al., 2021; Ferraq et *al*., 2024).

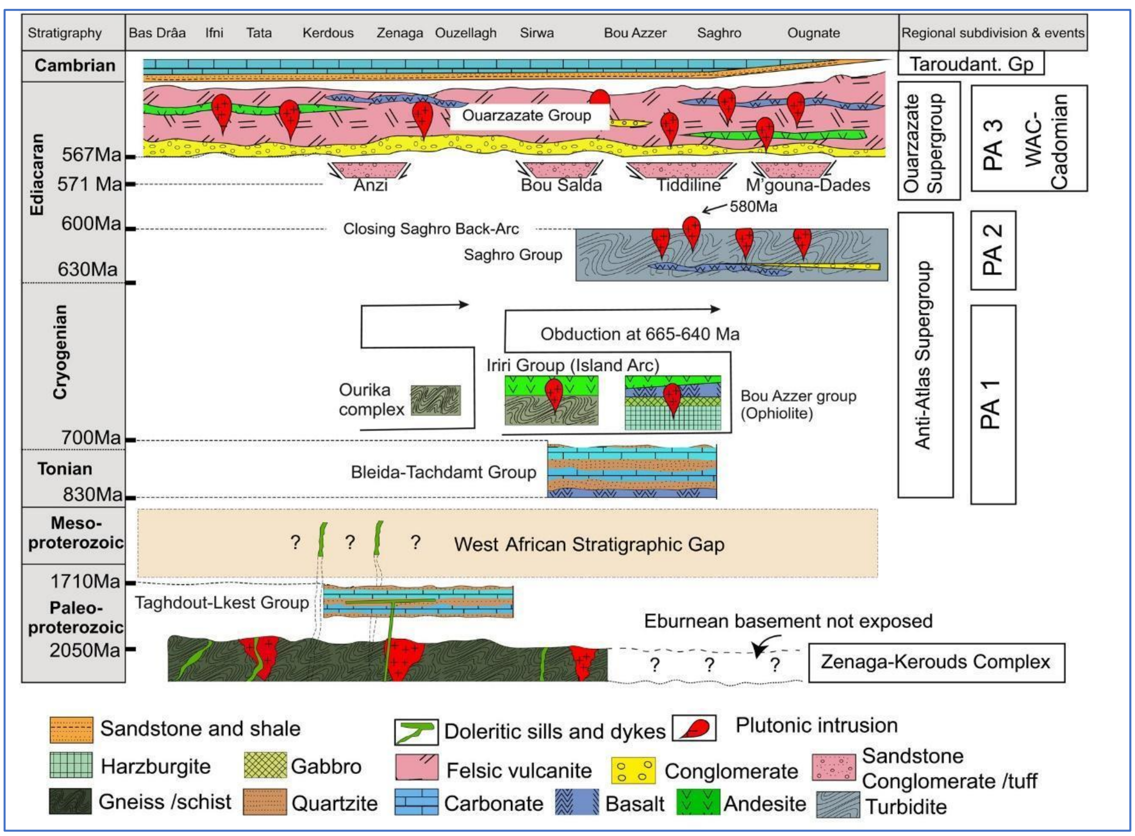



***Figure 3.*** *Generalized lithostratigraphic column for the Anti-Atlas Pan-African orogen (after Errami et al. (2021b))*

## Paleozoic series and Variscan orogeny

After the final stage of the Pan-African orogeny, the Anti-Atlas was dissected into intra-continental basins into which the entire Paleozoic series was deposited and associated volcanic episodes of tholeiitic and alkaline nature (***Figure 4***; Piqué, 2001; Alvaro et al., 2014; Pouclet et al., 2018). Across the whole Anti-Atlas, the Ouarzazate Group volcano-sedimentary rocks are followed by the deposition of thick sedimentary formations (Taroudant and Tata groups) in a post-orogenic extensional environment related to the opening of the Rheic Ocean (Gasquet et al., 2005, 2008; Alvaro et al., 2014a; Soulaimani et al., 2014). This extensional period is concomitant with the emplacement of volcanic flows during the lower Cambrian between 531±5 Ma (Gasquet et al., 2005) and 522 ± 2 Ma (Maloof et al., 2005, 2010; Landing et al., 2021).

During the Lower Cambrian, the transgression started with the deposition of the carbonate-dominated Taroudant and Tata groups (dolomites, limestones and siliciclastic sediments), which evolved towards detrital-dominated deposits during the Middle Cambrian as a result of a marine regression (Choubert, 1963, Soulaimani and Burkhard, 2007). The Upper Cambrian is significantly reduced or even absent in the Anti-Atlas, likely due to an uplift episode in the central and eastern Anti-Atlas, which was located along the basin shoulder (***Figure 4***, Alvaro et al., 2014; Soulaimani et al., 2014).

The shale-dominated sedimentation of the Lower Ordovician marks a short transgression period allowing the deposition of the Fezouata Formation with its distinctive shale-Lagerstätten (Martin et al., 2016). This is followed by a regressive series consisting mainly of shales, silts and mudstones with sandy-quartzitic intercalations (Piqué, 2001; Alvaro et al., 2014). The Middle-Upper Ordovician highlights a hydrothermal magmatic activity portrayed by felsic dykes in the Siroua Massif (***Figure 4,*** Huch, 1988). The Upper Ordovician is characterized by glaciogenic deposits as a record of the Hirnantian glaciation (Clerc et al., 2013).

The post-glacial sediments of the Silurian correspond to a transgressive sequence resulting from the melting of the Saharan Ice-sheet. These deposits consist of sandstone and evolve to shales, mudstones and clayey-limestones along with graptolite fossils (Piqué, 2001; El Maazouz and Hamoumi, 2007; Loi et *al*., 2010).

The Devonian detrital sequences closely follow the Silurian strata comprising alternating mudstones and limestones, together with reef-mounds and mud mounds that spread during the Middle Devonian (Michard et *al*., 2008). The Upper Devonian and the Lower

Carboniferous consists of alternating sandstones, limestones and green silts (Michard et *al*., 2008). On these, shales and sandstones of the Middle and Upper Carboniferous are superposed (Bourque, 2016). At the end of the Carboniferous, sedimentation becomes progressively more continental from west to east, with red sandstones and clays (Burkhard et *al*., 2006; Soulaimani and Burkhard, 2007).

The 10 km thick Paleozoic series accumulated in the intracratonic basin record the Variscan uplift (***Figure 4***; Baidder et al., 2008; Ouanaimi et al., 2008; Soulaimani et al., 2014). Indeed, the Variscan deformation is heterogeneous and weakly expressed in the Anti-Atlas with a very low grade of metamorphism (Hoepfner et al., 2005; Burkhard et al., 2006, Soulaimani et al., 2014).

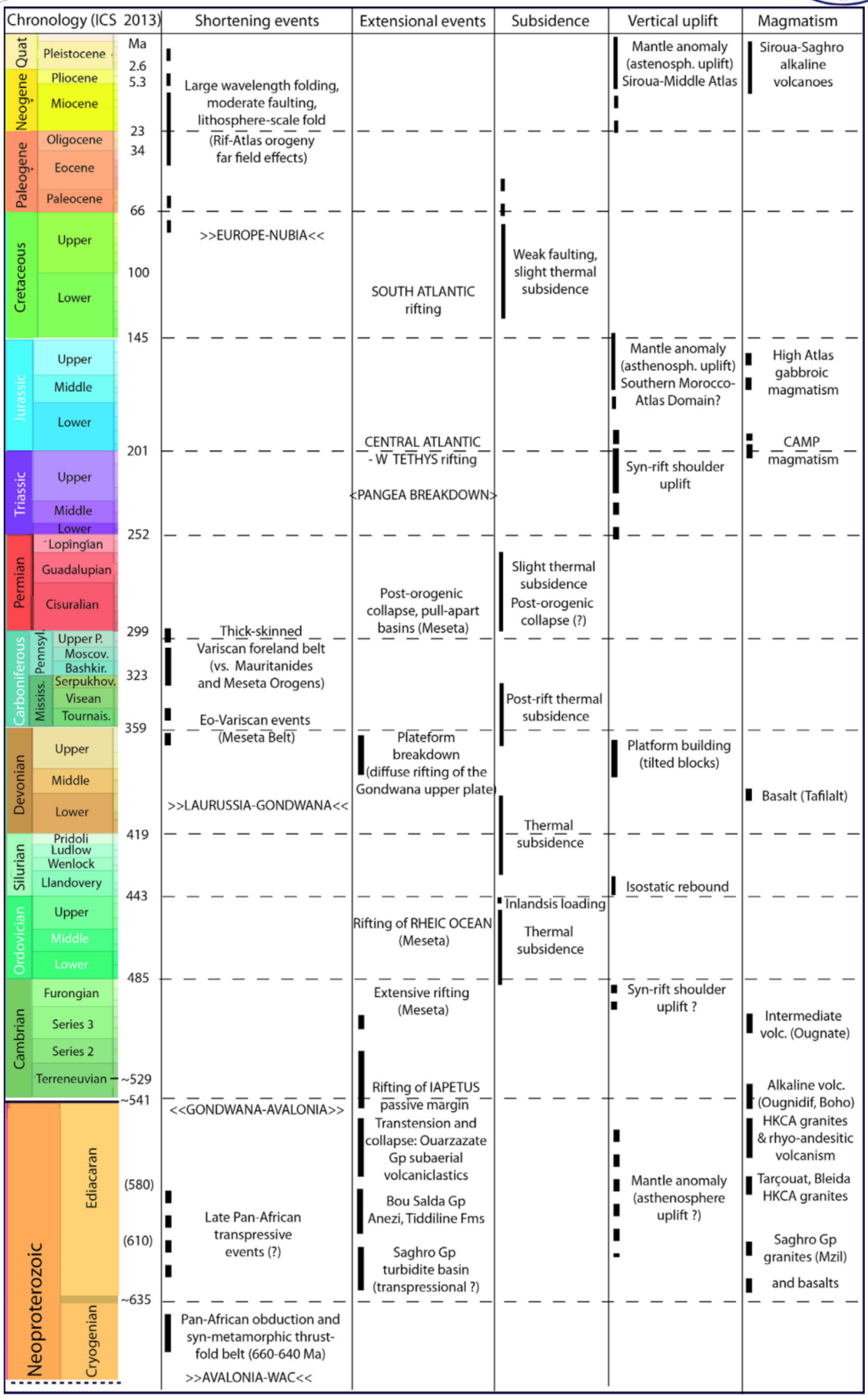



***Figure 4.*** *Tectonic chart of the Anti-Atlas (Soulaimani et al., 2014)*

# The Pan-African Anti-Atlas belt: connections with Peri-Gondwanan crustal blocks

During the Ediacaran period (635-538 Ma), the closure of the Pan-African Ocean led to the formation of the Gondwana supercontinent as a result of large-scale amalgamation of continents and microcontinents located within East and West Gondwana (***Figure 5;*** Murphy, 1989). Within the framework of this amalgamation, the West African craton (WAC) was surrounded by Pan-African terranes including island arcs or continental active margin, the WAC being in the position of a passive margin (Ennih and Liégeois, 2008 and references therein). From the northwestern margin of Gondwana, peri-Gondwanan terranes split off during Paleozoic time leading to the opening of the Rheic Ocean (Linnemann et al., 2012; Nance et al., 2012; Herbosch et al., 2016), as a continuation of Neoproterozoic orogenic activity. Therefore, certain peri-Gondwanan terranes show marked similarities in age, tectonic history, and facies development to the Pan-African belts of the West African Craton (Nance et al., 2012).

The position of the Anti-Atlas belt of Morocco during the Neoproterozoic makes this region a key in understanding the interactions among crustal blocks that are now in the Appalachians and the Pan-African orogen. The original position of these blocks is still debated and it is uncertain whether they belong to a hypothetical North Moroccan continent (Villeneuve and Cornée, 1994), to Avalonian terranes (Ennih and Liégeois, 2001, Keppie et al., 2003), or to Iberian terrane (Piqué, 2003). In a tectonic model proposed by Hefferan et al. (2000), the Anti-Atlas Major Fault (AAMF) considered as a large area of ophiolitic suture contains to the north the Siroua-Saghro arc on which the Avalonia-Cadomia blocks would have been accreted. More recently, the compilation of geochronological and tectonic data on the Neoproterozoic series of the Anti-Atlas led Hefferan et al. (2014) to split the Pan-African Orogeny into three orogenic pulses: Iriri-Tichibanine orogeny (760–700 Ma), Bou Azzer orogeny (680–640 Ma) and the WA Cadomian orogeny (620–555 Ma), and time-equivalent events also are recognized in the Appalachian orogen, especially in the terranes grouped together as Avalonia (Van Staal et al., 2021).

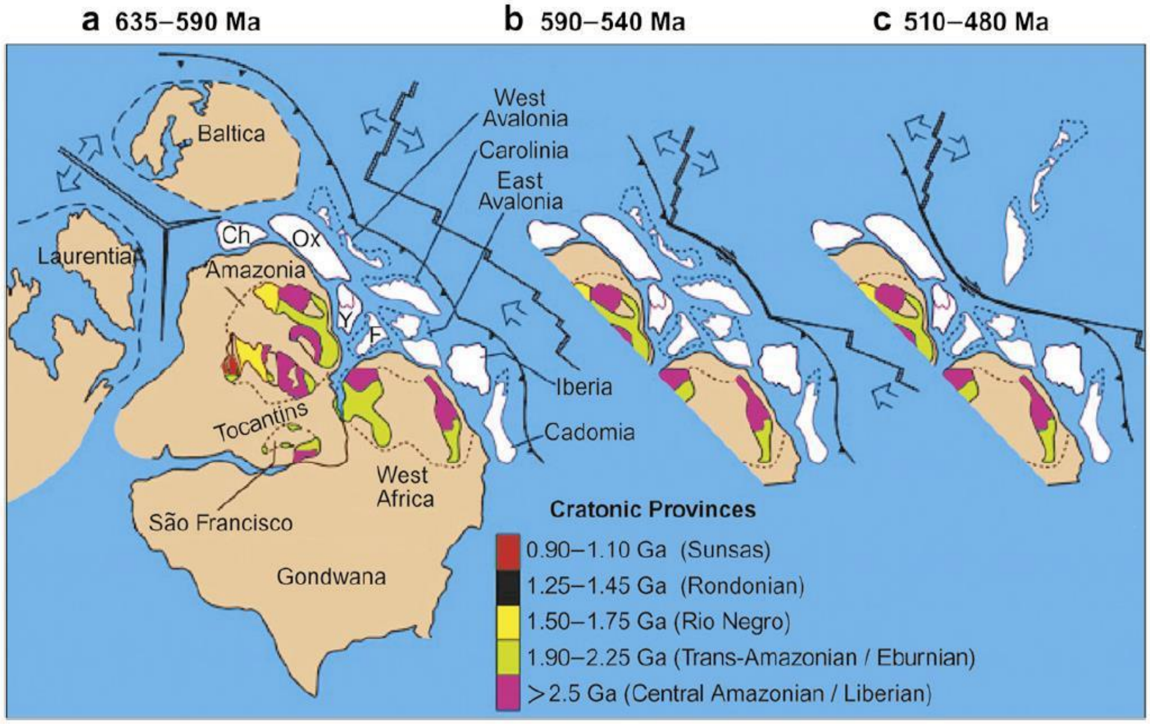



***Figure 5.*** *Paleogeographic situation of the northern margin of Gondwana and neighboring related major peri-Gondwanan terranes during the Ediacaran (Nance et al., 2012)*

# The field trip Program

**October 14th**: Arrival in Agadir airport. Night in Agadir at "Hotel Hamilton" is part of the field trip and included in the field trip cost.

**October 15th**: Departure from Agadir to Taznakhte village (270 km from Agadir). The day will be devoted mainly to the stratigraphy of Lower Cambrian units (Terreneuvian), known as the Taroudant Group (Adoudou and Taliwine formations). These sequences are indicative of the onset of rift-passive margin conditions on the northern boundary of the West African Craton. Night at "Bab Sahara Hotel" in Taznakhte.

**October 16th**: The day will focus on Precambrian rocks from Zenaga and Bou Azzer inliers. We begin by visiting the passive margin sequences of the Taghdout Group (Early Mesoproterozoic). This group is crossed by the Anti-Atlas Major Fault (AAMF) which represents a Pan-African suture zone. We continue the day by visiting the Zenaga inlier Paleoproterozoic rocks, representing a record of the Eburnean orogeny. The Jbel Boho volcanic ashes and flows of the southern Bou-Azzer inlier represent one of the preserved magmatic suites occurred in Lower Cambrian host rocks, which triggered a post-orogenic extensional environment that led to the opening of the Rheic Ocean. We finish the day by visiting the Neoproterozoic Bou Azzer Co-Ni-Fe-As (±Au±Ag) mine. Night in Agdez village in "Kasbah Itrane hostel".

**October 17th**: This day will be exclusively dedicated to Neoproterozoic and Cambrian rock of the Bou Azzer inlier. The area is mostly known by its dismembered ophiolitic complex, and its rich mineral potential including a variety of ore deposits (e.g. the Bleida stratiform copper deposit, the Jbel Laasel Gold–palladium mineralization, and the Bou Azzer Co-Ni-Fe-As (±Au±Ag) district). The inlier exhibits Late Neoproterozoic outcrops of diamictite (Teddiline Group) and banded iron formations (BIF) that may form an important role in global correlations. Night in Agdez at the same hostel (Kasbah Itrane).

**October 18th**: This day will be dedicated to the Ediacaran succession of the Saghro massif to observe the field evidence of the transition from a back-arc basin of the Pan-African-Cadomian orogeny to Cambrian rifting. Our primary focus will be on the Ediacaran-Cambrian boundary in the Id Bab N'Ali area. The second stop will be in the Tizi N'Tzazart region to observe the Intra-Ouarzazate Group unconformity, representing evidence of the collapse of the Pan-African-Cadomian crust and the emplacement of the Silicic Large Igneous Province. Following that, we'll visit the Iknioun village to observe the early Ediacaran sedimentary fill of the Saghro Group. The uppermost Ordovician (Second Bani Group) units of the Alnif region contain a glaciogenic sedimentary deposit related to the Hirnantian glaciation known throughout the world. Night in Merzouga in a campsite **offering <u>only double-occupancy tents.</u>**

**October 19th**: The day will begin with a visit to the Arfoud Fossil Museum where several important fossil specimens of the region are exhibited. On the way to the city of Tinghir, we will pass by an outcrop representing the transition from the Asrir Formation sequences (Tata Group, Lower Cambrian) to the Jbel Wawrmast Formation (Feijas Internes Group, Middle Cambrian). We continue the day with a visit to the giant epithermal Ag–Hg deposit of Imiter in the Tinghir region and with outcrops of late Ediacaran stromatolites and the Ouarzazate Caldera system in the Ouarzazate region. In the afternoon, we will dedicate time to a sightseeing visit to the Ait Benhaddou kasbah, listed as a UNESCO World Heritage site. Night in Ouarzazate at "Perle du Sud Hotel".

**October 20th**: Travel back to Agadir from Ouarzazate and end the field trip.

# The field trip itineraries and stops

October 15th, 2024

## Day 1 Lower Cambrian sequences of the eastern Anti-Atlas

***Itinerary:*** From Agadir, departure at 8 o'clock, drive towards Taznakhte via the P1719 road (***Figure 6***, 270 km).

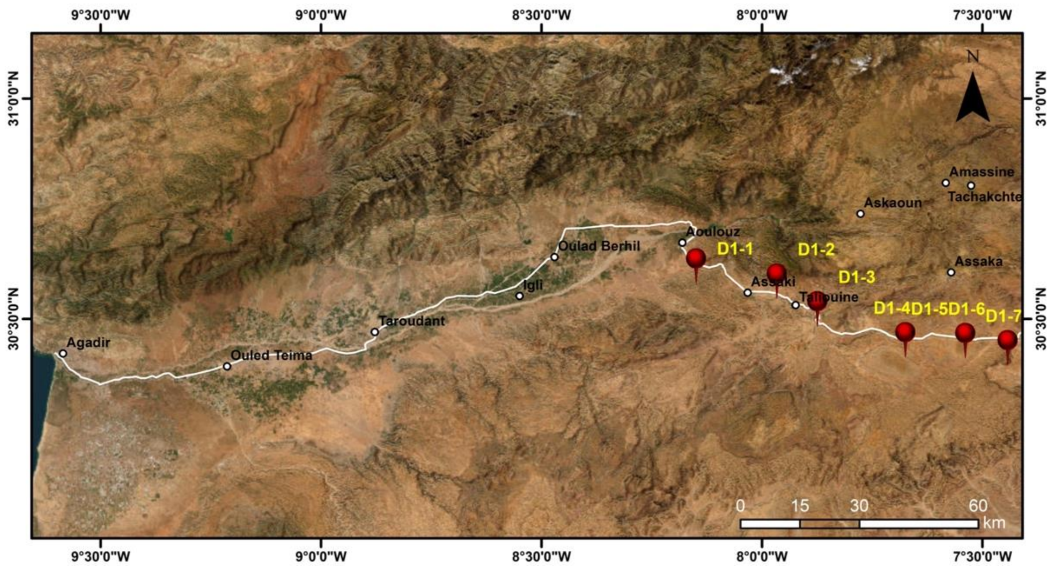


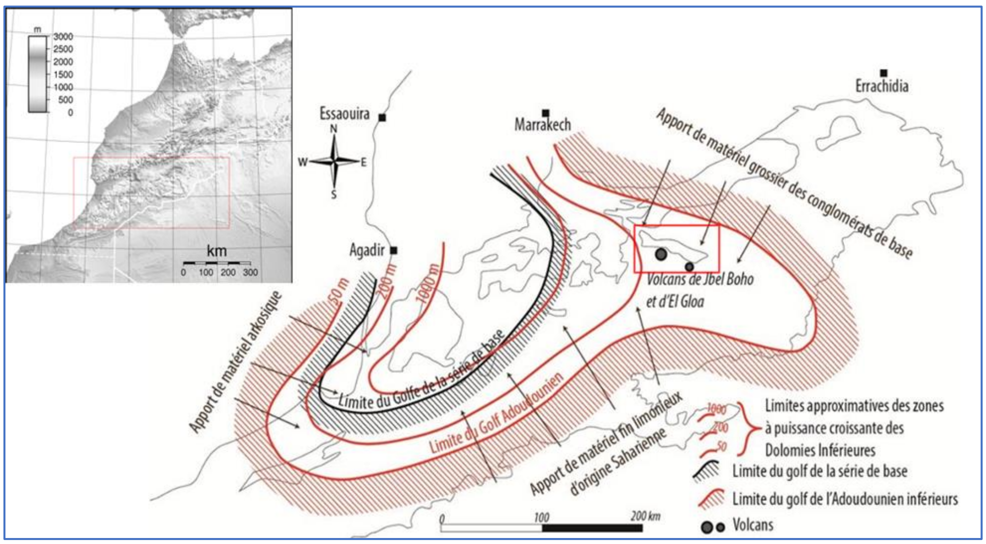

***Figure 6.*** *Itinerary and stops of the 1st day*

The Cambrian rocks in Morocco are subdivided into four groups (***Figure 7***): the Taroudant Group, the Tata Group, the Feijas Internes Group, and the Tabanite Group. During this day, only the first two groups will be the focus of our visit, mostly in the Ihouna syncline (Central Anti-Atlas).

In the Saghro domain, the Paleozoic sequences start with the Lower Cambrian deposits of the Taroudant Group including the Adoudou Formation (calcaires inférieurs, Choubert, 1963), superposed by thick purple to reddish, fine-grained siliciclastic rocks of the Lie-de-Vin Formation (Alvaro et al., 2014). The Tata Group contains six formations: the Igoudine, Amouslek, Lemdad, Tislit, Issafen and Asrir formations (**Figure 7**; Geyer, 2006; Alvaro et al., 2014).

The Cambrian succession of the Ihouna syncline is highly significant from a paleogeographic perspective as it represents a key link between the western Anti-Atlas and its central counterpart.

Specifically, in the western part of the Anti-Atlas, the Cambrian succession begins with the Tabia Member of the Adoudou Formation (formerly 'la série de base' of Choubert et al., 1963), which indicates the inundation of the Proterozoic basement by the first marine incursions (Maloof et al., 2010). On the other hand, the detrital component of the Lie-de-Vin Formation is often subtle, making it sometimes difficult to distinguish from the overlying limestones of the Igoudine Formation. However, in the central Anti-Atlas (particularly in the Ouarzazate region), the Tabia Formation is entirely absent, indicating that this area was affected by the marine transgression also, but at a later stage. This area displays clear evidence of both a gradual eastward advance of the Cambrian transgression (Adoudou Formation; **Figure 7**) and a westward regressive retreat (Taliwine Formation; **Figure 8**). This same scenario will later recurs with the transgressive limestone formations of Igoudine and Issafène, followed by the regressive sandstone of the Tatelt Formation.




*F**igure 7.** Paleogeographic sketch of the Adoudounian sedimentary cycle in the Anti-Atlas (modified from Boudda et al., (1979))*

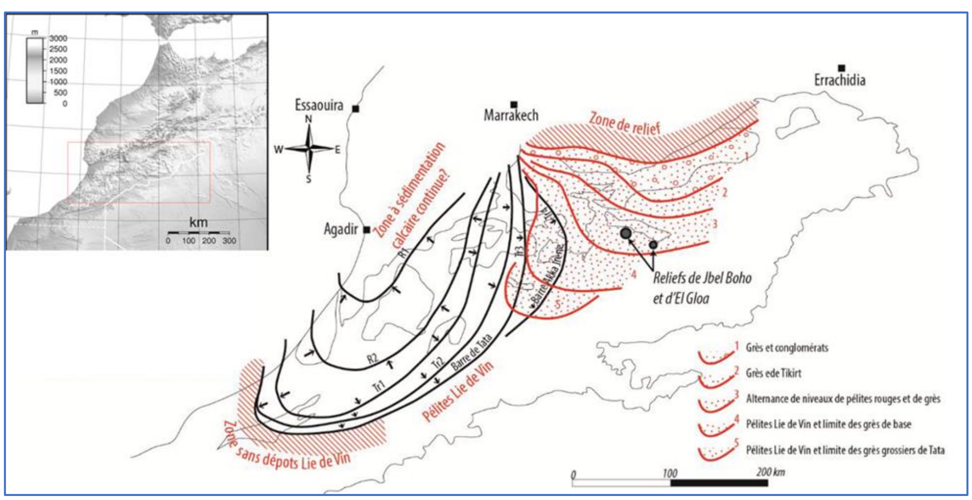



***Figure 8.** Paleogeographic sketch of the Adoudou basin during deposition of the Lie-de-Vin and Tikirt formations (Boudda et al., 1979)*

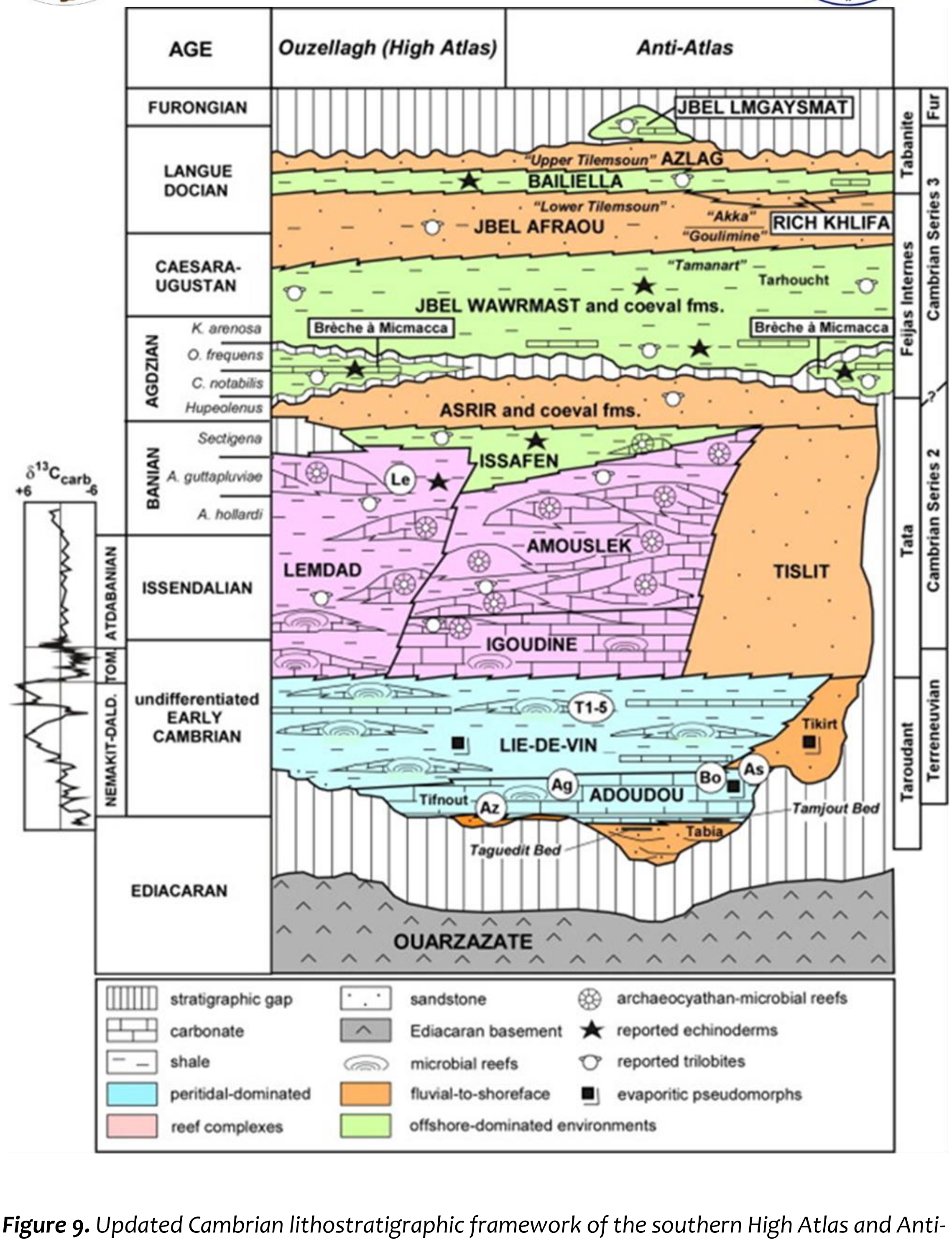



***Figure 9.*** *Updated Cambrian lithostratigraphic framework of the southern High Atlas and Anti-Atlas regions (Alvaro et al., 2014)*

## *Stop D1-1* *Panoramic view of the Souss plain*

**30°37'17"N; 8°09'01"W**

This stop, located in the far west of the Souss Plain (160 km from Agadir), offers a panoramic view of the plain, bordered to the north by the High Atlas and to the west and south by the Cambrian cover of the Anti-Atlas. At the level of the plain itself, the upper strata of the Cambrian cover are deeply buried under recent Quaternary sequences.

During this stop, a quick overview of the Moroccan geology will be given by the leaders.

## Stop D1-2 The Adoudou and Lie-de-Vin formations

**30°33'18.51" N; 07°58'2.2"W**

This stop is located 5 km southeast of Assaki village and 6 km northwest of Taliwine village. This is the area where the stratotype section of the Lie-de-Vin Formation was defined by Choubert, (1952). The term 'Lie-de-Vin' refers to the reddish-purple color of the constituent facies (***Figure 8***). Later, Boudda and Choubert (1979) assigned this formation to the Taliwinian, naming it after the nearby village of Taliwine. Recent stratigraphic subdivisions propose the Taliwine Formation as a synonym for the Lie-de-Vin Formation (Alvaro et al., 2014), which would be equivalent to the summit member of the Daldenian Neymakit of Siberia and the Fortunian stage of the Terreneuvian (Maloof et al., 2005, 2010). This clay-sandstone series allowed Choubert et al. (1963) to define two carbonate units, namely: "les calcaires supérieurs" (Upper limestones) and "les calcaires inférieurs" (Lower Limestones). The first unit corresponds to the Adoudou Formation (Fortunian) and the second one to the Igoudine Formation (Cambrian Series 2). The purpose of this stop is to examine these three units as they appear sequentially in the landscape.

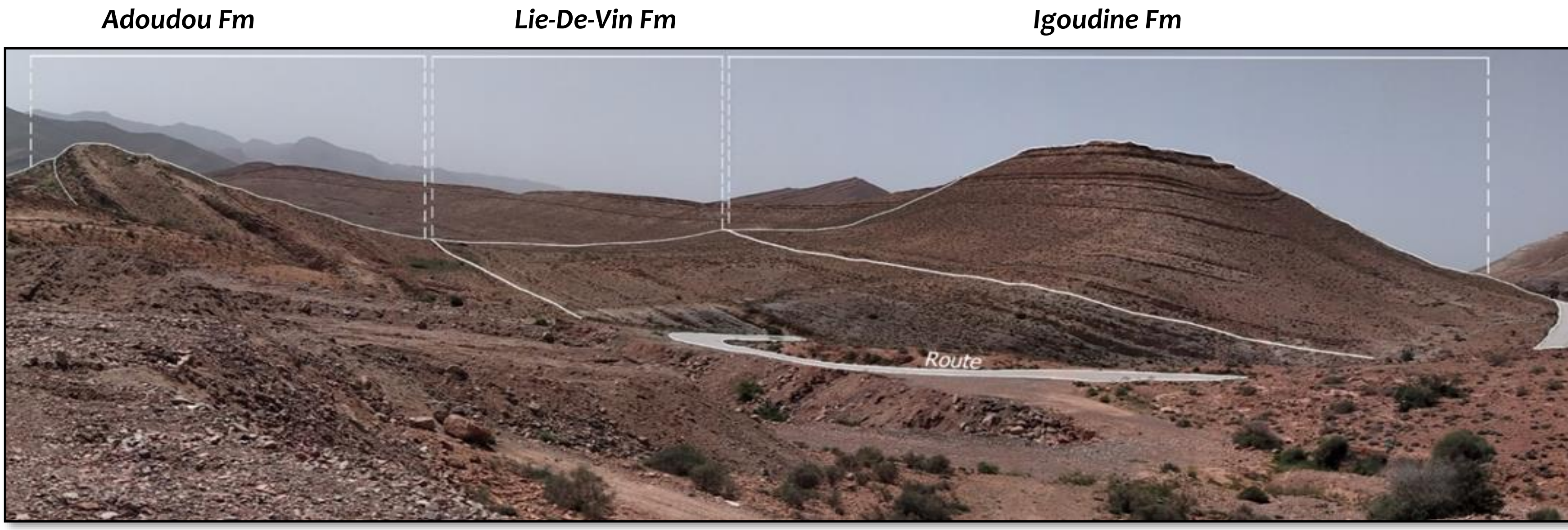



***Figure 10***. *NW-SE view showing the stratigraphic superposition of the Adoudou, Lie-de-Vin and Igoudine formations*

## Stop D1-3 Thrombolites of the Lie-de-Vin Formation

**30°31'28"N; 7°52'31"W**

This stop is located on a cliff along the national road leading to Tazenakhte, where microbialite structures, ranging from decimetric to pluridecimetric bioherms, are exposed. These are thrombolites that form within the carbonate banks. These carbonates alternate with argillites and red sandstones with planar laminations, and in places exhibit desiccation cracks. Thrombolites are microbial structures that differ from stromatolites by their granular texture (clotted accretionary structures). This texture results from the aggregation of clumps of microbial origin with irregular contours. Microscopically, the texture reveals a mosaic of irregular dark micrite patches and distinctly lighter rhombohedral dolosparite spots, which may contain clastic particles (Bensaou et Hamoumi, 2004). This appearance can be explained by the simultaneous presence of a phase built by microbial communities, represented by the micritic phase, and a non-built phase consisting of chemical carbonates and silico-clastic particles (Clausen et al., 2014; Bensaou and Hamoumi, 2004). The building microorganisms are likely calcified cyanobacteria, which appear as individual coccoid forms organized and preserved in irregular colonies. The presence of calcified cyanobacteria at the base of the Lie-de-Vin Formation in the western Anti-Atlas was demonstrated by Latham and Riding (1990).

***Figure 11.*** *Field photo showing the thrombolitic construction on the bedding plane (Lie-de-Vin Formation).*

## Stop D1-4 Double unconformity of Tizi N'Taghatin

**30°27'16"N; 7°40'32"W**

This outcrop is located along the N10 national road heading towards Taznakhte, approximately 26 km east of Taliwine village. It shows double unconformities between: (i) the Taghdout Group (Upper Paleoproterozoic-Tonian) and the highly metamorphosed schists of the Zenaga Complex (Paleoproterozoic), (ii) the whole is unconformably overlain by the Adoudou Formation. This outcrop is one of the most well-known in the Anti-Atlas, where this double unconformity was first documented by Nelthner, (1938). This stop represents a witness of two tectonic deformation events during the Eburnean and Pan-African orogenies, respectively. In addition, the carbonate rocks of the Adoudou Formation preserve copper-mineralization associated with the hydrothermal activity of the Cambrian rifting.

## Stop D1-5 The Adoudou Formation of the Ihouna syncline

**30°27'09"N; 7°32'23"W**

Located approximately 36 km southeast of Taznakhte, this outcrop represents the northern flank of the Ihouna syncline where the sequences of the Adoudou Formation record a relatively late transgression evidenced by the absence of the Tabia Member, well developed to the west. The upper Member of the Adoudou Formation (Tifnoute Member), which rests directly on the Proterozoic basement, notably accumulates angular quartzite pebbles at its base. These pebbles gradually give way to carbonate layers with microbialites and reddish siliceous intercalations (Bensaou and Hamoumi, 2004). The pebble-rich carbonate facies at the base of the sedimentary succession indicate the beginning of marine transgression over a continental area covered with loose pebbles, likely originating from the still-exposed quartzites of the Taghdout Group. The disappearance of these pebbles within the stromatolite and thrombolite carbonates reflects a full submersion of the area by marine waters. Therefore, the sea from the west only reached this region during the deposition of the Tifnoute Member of the Adoudou Formation.

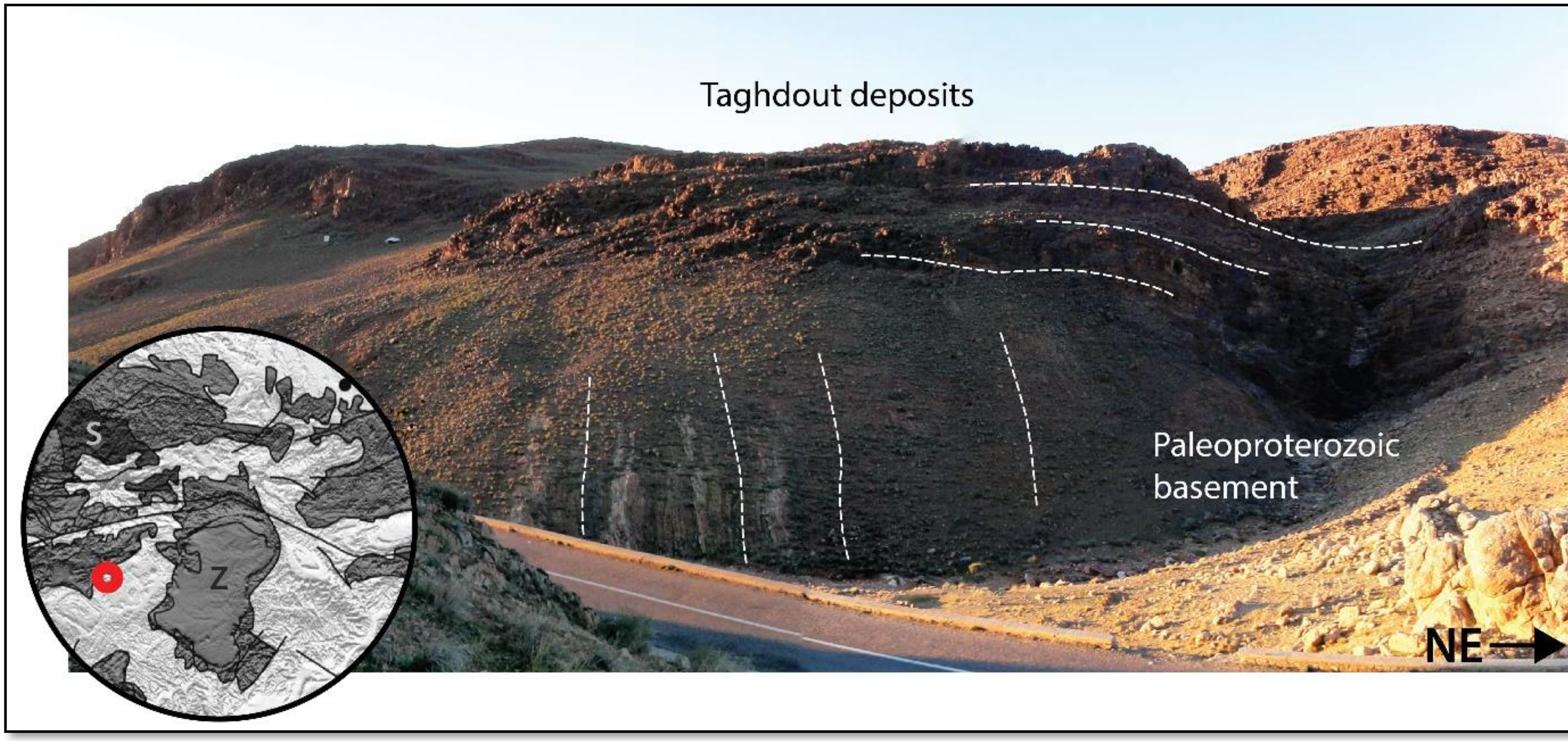



**Figure 12.** Field photo showing the discordant contact between the verticalized Paleoproterozoic basement (Zenaga Complex) and the quartzite of the Taghdout Group (Triantafyllou, 2018)

## Stop D1-6 Igoudine, Amouslek, Issafène and Tatelt formations

**30°27'09"N; 7°32'23"W**

This stop is dedicated to the upper formations of the Lower Cambrian in the Ihouna succession, which occupy the core of the syncline. Except for the Tatelt Formation ("Grès terminaux" terminal sandstones), which forms a topographic rise, the other two formations (Igoudine and Issafène) display a gentle tilt and create a nearly flat plateau, leading to poor outcrop visibility. Typically, the Igoudine Formation (Tommotian) consists of thick limestone layers rich in stromatolites and thrombolites, interlayered with thin clayey or marly strata. Conversely, the Amouslek and Issafène formations (which are challenging to differentiate in outcrop) are characterized by metric-thick black limestone beds separated by dark-colored clay layers.

The Tatelt Formation, also known as "Grès terminaux" (formerly the Asrir Formation), consists of a vertical succession of metric to plurimetric amalgamated sandstone beds. This formation, attributed to the Agdzien (Alvaro et al., 2014), likely represents the final part of Cambrian Series 2.

Following the regression marked by the Lie-de-Vin Formation, carbonate sedimentation resumes after a second transgression, which shifts the detrital sediments toward the east.

The major transgression occurs in stages, with each period of rising sea levels being succeeded by a phase of local sediment accumulation. During the transgressive intervals, carbonate facies are present, while regressive intervals are marked by detrital facies, which appear as interbeds ranging from decimeters to meters in thickness.

## Stop D1-7 Panoramic view of the Zenaga Inlier

**30°27'09"N; 7°32'23"W**

Geologically, the Zenaga inlier is mainly composed of a Paleoproterozoic basement with a Late-Paleoproterozoic-Cambrian cover. The basement includes schists, mica schists, and granites with rare migmatites. The cover consists of a limestone and quartzite series of the Taghdout Group affected by the Pan-African orogeny. The whole is topped by a Late Neoproterozoic to Early Cambrian calcareous and dolomitic series. This inlier shows a comprehensive record of the Eburnean and Pan- African orogenies.

***Figure 13.*** *Panoramic view of the Zenaga inlier*

October 16th, 2024

# Day 2 Precambrian rocks of the Zenaga inlier and Early Cambrian volcanism of Jbel Boho

***Itinerary***: From Taznakhte, drive northwest towards Taghdout via the N10 national road (10 km). Head back to Taznakhte and take the R108 east towards Bou Azzer. About 14 km before reaching Bou Azzer, turn south onto Route R111 towards Zaouiet Sidi Belal.

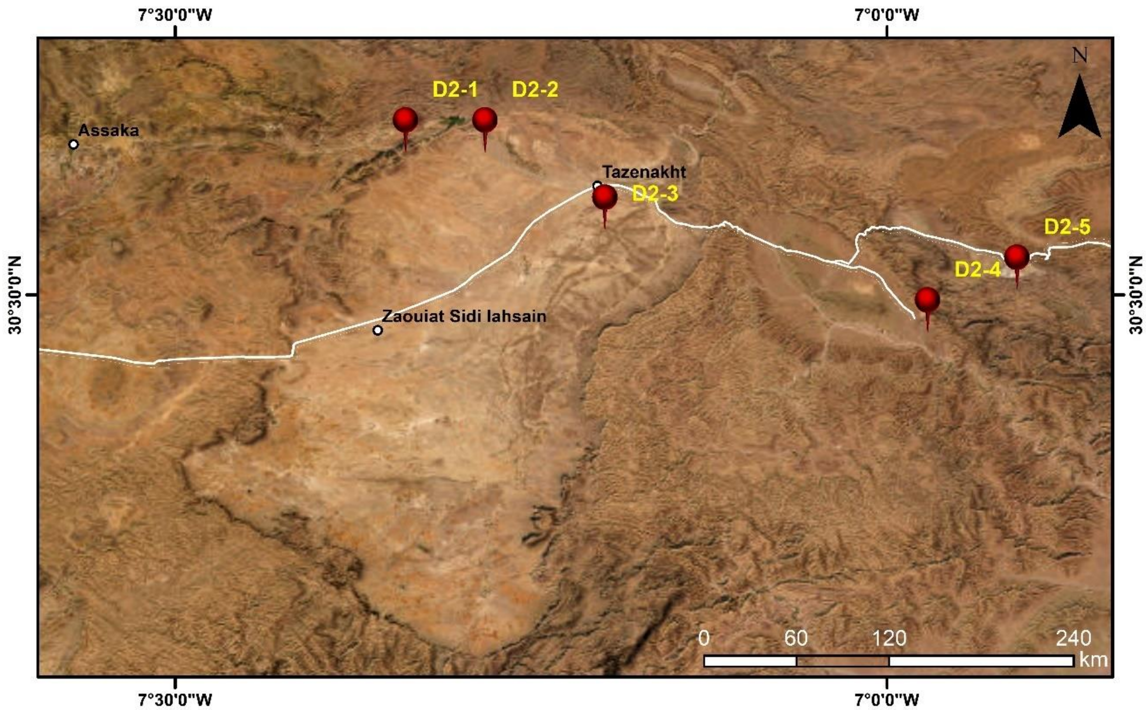



***Figure 14.*** *Itinerary and stops of the 2nd day*

The oldest, Paleoproterozoic Eburnean, orogeny in the Anti-Atlas domain is characterized by syn-metamorphic deformation accompanied by significant magmatic activity, mainly expressed through Paleoproterozoic granitoids of predominantly granitic to granodioritic compositions (Choubert, 1963; Hassenforder, 1987; Ennih and Liégeois, 2008). The metamorphic basement (Zenaga Complex) consists of schists, mica schists, gneisses, and migmatites with intercalation of felsic tuffs dated at 2040± 6 Ma U-Pb (Walsh et al., 2002) and metabasites. In the Zenaga inlier, the basement is intruded by a number of calc-alkaline plutonic rocks, dolerite dykes and sills, dated (U-Pb method) by Thomas et al. (2002): the Assourg Tonalite (2037±7 Ma), the Azguemerzi Granodiorite (2032±5 Ma) and the Tazenakhte Granite (2037±9 Ma = Tamazzarra Granite). The Zenaga dyke swarm yielded U-Pb (zircons and baddeleyite ages range from 2040±2 Ma, 1656±9 Ma to ca. 1655 Ma (Kouyaté et al., 2013).

The Zenaga Complex is unconformably covered by a typical shallow marine siliciclastic sequence of the Taghdout Group (Late Paleoproterozoic), which consists of quartzites and stromatolitic carbonates deposited during a rifting event related to the fragmentation of the earlier Nuna-Columbia supercontinent (Ikenne et al., 2017). The Zenaga Complex and the Taghdout Group sediments are intruded by abundant dykes and sills of dolerites and gabbros (Kouyaté et al., 2013).

The whole is unconformably overlain by a volcano-sedimentary sequence of the Ouarzazate Group consisting of coarse volcanic conglomerates, ignimbritic rhyolites, trachytes, andesites, basaltic trachyandesites, tuffites, and rare interbedded stromatolitic layers and fault scarp breccias (Kouyaté et al., 2013). This Group also includes various types of intrusions, such as granitoid massifs, necks and dolerite dykes.

The Ouarzazate Group is conformably to unconformably overlain by transgressive marine successions of Cambrian age (Taroudant and Tata groups), which contain in their base volcanic ashes and flows related to the opening of the Cambrian Atlas rift in Morocco (Alvaro et al., 2014; Pouclet et al., 2018).

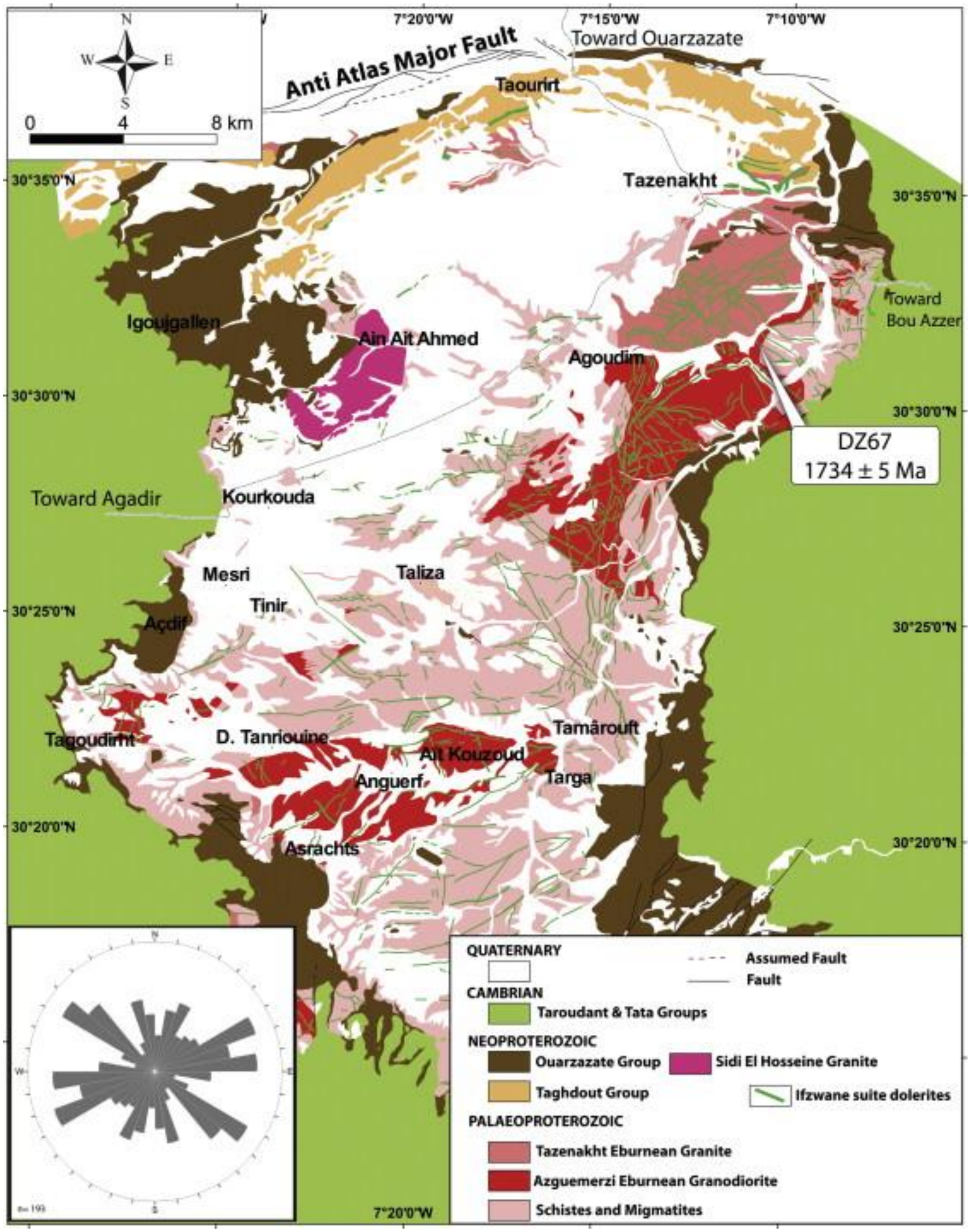



***Figure 15***. *Simplified geologic map of the Zenaga inlier modified after Choubert (1963), Gresse et al. (2000), Thomas et al. (2004) and Kouyaté et al. (2013)*

This outcrop is located less than 1 km to the northeast of Taghdout village, which is situated 9 km to the northwest of Taznakhte (***Figure 14***).

The stop features an outcrop where epicontinental platform sequences are represented by quartzites with ripple marks and ripple-like structures, which may be of either sedimentary or tectonic origin. The deposition of this group was previously thought to be Tonian (788 ± 9 Ma; Clauer, 1976), based on the Rb–Sr method applied to clay fractions from the Taghdout metasediments. However, new detrital zircon ages (Abati et al., 2010; Soulaimani et al., 2019) only yielded youngest detrital zircon populations, ca. 2.2–1.78 Ga. Additionally, a doleritic sill within this series has been dated to ca. 1710 Ma (U–Pb on baddeleyite; Ikenne et al., 2017), supporting a Late Paleoproterozoic depositional age for this group.

Basement rocks from drill core below the Georges Bank, offshore Massachusetts (USA), have recently been correlated with the Taghdout Group, based on new detrital zircon data (Kuiper et al., 2017). The zircon populations from the Georges Bank well exhibit signatures similar to those of the Taghdout Group, leading the authors to propose that these basement rocks represent a fragment of Paleoproterozoic West African crust now situated within the eastern North American continental margin (Kuiper et al., 2017). Similar detrital zircon signatures have since been found in rocks in coastal Maine, USA (Reusch et al., 2018) and Grand Manan Island, Canada (Barr et al., 2019).

***Figure 16.*** *Field photo showing quartzite of the Taghdout Group displaying exceptional sedimentary structures characteristic of proximal facies of passive margins*

## Stop D2-2 Middle Ediacaran Imdgher Izdar Diamictites (Tiddiline Group)

**30°37'00"N; 7°20'18"W**

Located north of Imdghir village, 3.5 km east of the Taghdout Dam, this glacial formation provides compelling evidence of Middle Ediacaran glaciation in the Central Anti-Atlas. The glaciogenic sediments are prominently visible in a panoramic view on the northern foot of the Paleoproterozoic Taghdout Quartzite. These sediments consist of a reddish, matrix- and clast-supported, chaotic conglomerate with pebbles and cobbles ranging in size from 2 cm to 2 m. Most of the cobbles are composed of quartzite and limestone of Paleoproterozoic origin. In many places, the pebbles are striated, supporting a glacial origin. U-Pb dating from the matrix of this conglomerate yields a maximum depositional age of 592 Ma (Letsch et al., 2018), and the entire formation is overlain by an ignimbritic sheet dated to 574 ± 4 Ma (Letsch et al., 2018). This constrains the glaciation to be between 592 Ma and 574 Ma, coinciding temporally with the ca. 580 Ma Gaskiers glaciation (Pu et al., 2016).

## Stop D2-3 The Paleoproterozoic Azguemerzi granite

**30°33'45"N; 7°11'54"W**

The Paleoproterozoic Azguemerzi Augen granite occurs mostly at the western part of the Zenaga inlier. It is a dark-colored, garnet-bearing porphyritic granodiorite, distinguished by the presence of ilmenite, the lack of basic enclaves, and very rare gneissic xenoliths (Chappell and White, 1974; White and Chappell, 1977). Its composition varies between granodiorite and monzogranite, including quartz, K-feldspar and oligoclase (both as augen up to 4 cm in length and in the groundmass), biotite (partly altered to chlorite) ± hornblende± muscovite± garnet with accessory zircon, apatite, opaques and sporadic fibrous sillimanite (Ennih et al., 2001).

Alumina saturation indices (ASI: molar Al2O3/ [Na2O/K2O/CaO]) highlight their peraluminous and S-type nature (Thomas et al., 2002). U-Pb geochronological dates yield an age of 2032 ± 5 Ma with the evidence of older dates of ~ 2170 Ma possibly inherited from the Zenaga schists (Thomas et al., 2002). This intrusion was emplaced diapirically during the Eburnean Orogeny, leading to localized thermal metamorphism (Ennih et al., 2001). The pluton was deformed during the Eburnean orogeny, exhibiting pervasive structures such as mylonite with S-C fabrics, and migmatite (Ennih et al., 2001).

***Figure 17.*** *Field image showing augen of K-feldspar in the Azguemerzi pluton, deformed by a ductile left-lateral shear zone*

| Stop D2-4 | Lower Cambrian volcanism of Jbel Boho |
|---|---|
| | 30°29'25"N; 6°58'18"W |

This stop focuses on an example of Lower Cambrian magmatism on the southern side of the Bou Azzer inlier. After significant calc-alkaline magmatic activity during the Late Ediacaran (Ouarzazate Group), the Anti-Atlas evolved into a platform environment with the deposition of thick silico-carbonate sedimentary piles (Gasquet et al., 2005; Ezzouhairi et al., 2008; Alvaro et al., 2014). This extensional event is associated with the emplacement of alkaline magmatism, represented by the Jbel Boho volcanic complex (Pouclet et al., 2018). This rifting event had occurred also in the Ossa Morena and North Armorican zones, and identified as a single rifting episode referred to as ‘’AOMNA Rift’’, that fringed the West Gondwana after the Pan-African and Cadomian orogenies (Alvaro et al., 2024).

The Jbel Boho volcanism consists of up to 400 m of pyroclastic deposits (coarse tuffs and ignimbrites) and basaltic lava flows, which were active from the early stages of the Adoudou Formation deposition and continued until being capped by the later carbonate beds of the Adoudou and the sandstones of the Tikart Formation (Alvaro et al., 2006). The age of this volcanism has been constrained to 541 ± 6 Ma (Blein et al., 2014) from the lower volcano-sedimentary levels intercalated within the Adoudou carbonates and to 531 ± 5 Ma for the Jbel Boho syenite (Gasquet et al., 2005).

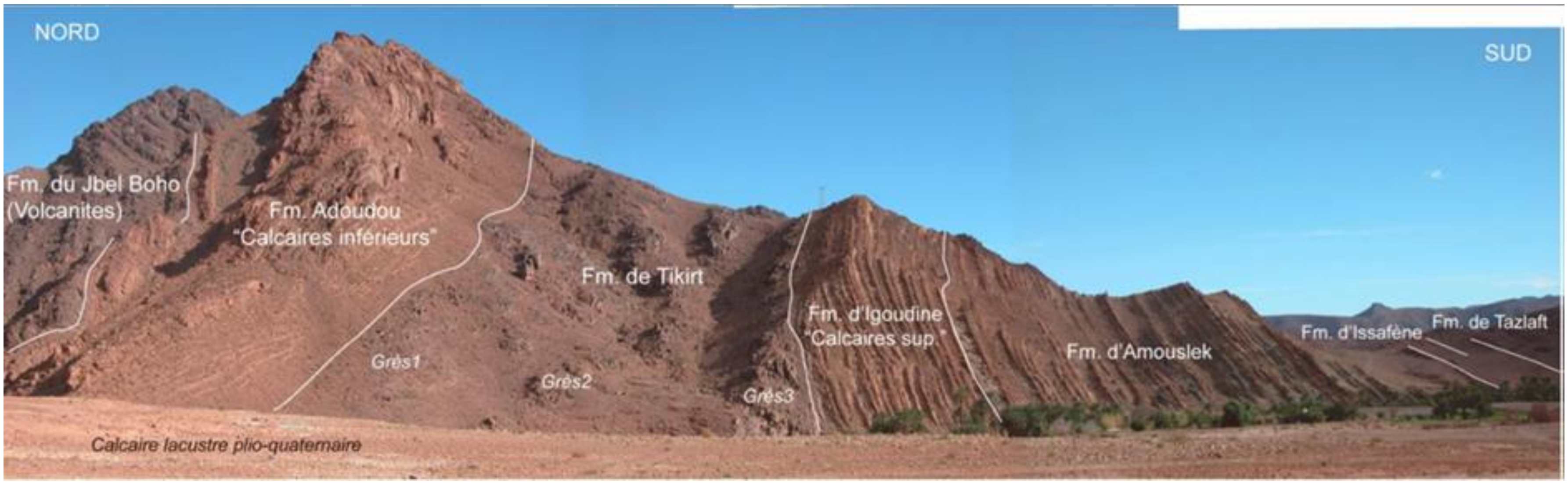



***Figure 18.*** *Lower Cambrian stratigraphic succession on the southern flank of the Bou Azzer inlier, Sidi Blal syncline, central Anti-Atlas (Admou et al., 2013)*

## Stop D2-5 The Neoproterozoic Bou Azzer Co-Ni-Fe-As (±Au±Ag) district

**30°31'13"N; 6°54'32"W**

Located about 80 km southwest of Ouarzazate city in the Bou Azzer inlier, the Neoproterozoic Bou Azzer Co-Ni-Fe-As (±Au±Ag) district hosts the only mine in the world where Co is produced as a primary commodity directly from Co- and As-bearing arsenide minerals (Bouabdellah et al., 2016).

Major orebodies are developed either within serpentinite or more importantly along the contact between serpentinite and quartz-diorite rocks. Field and textural relationships record three hydrothermal stages characterized by mineral assemblages of pre-arsenide auriferous stage I, (Co, Ni, Fe)-arsenide and sulpharsenide stage II, and sulphide-sulphosat ± Au ± Ag epithermal stage III; one post-ore supergene stage IV characterized by secondary Co minerals (erythrine, roselite, talmessite).

Ore mineralogy is dominated by diarsenide, triarsenide, and sulpharsenide minerals accompanied by various generations of intergrown calcite, dolomite, and quartz. Gold- and silver-bearing assemblages mainly comprise native gold and electrum, polybasite, proustite, xanthoconite, argyrodite, stromeyerite, and freibergite. Similarity of structural orientations of the veins that formed during the three stages suggests a common mechanism of ore formation.

Mining activities are presently managed by the Tifnout Tiranimine company (CTT) producing an average of 100,000 tons of ore annually, with an average grade of approximately 1% Co, 1% Ni, 3–42 g/t Ag, and 3–4 g/t Au.

The mineralization is suggested to be sourced from both magmatic and metamorphic fluids regarding sulfur, oxygen and hydrogen data (Dolansky et al., 2007). However, fluid inclusion and mineralogical features indicate an epithermal and porphyry-style gold deposits (Wafik et al., 2024). The superimposed mineralization episodes and its estimated age spanning from Neoproterozoic to late Triassic period highlight the role of the regional tectonic activities related the orogenic cycle from the Pan-African to Alpine events (Bouabdellah et al., 2016; Wafik et al., 2024).

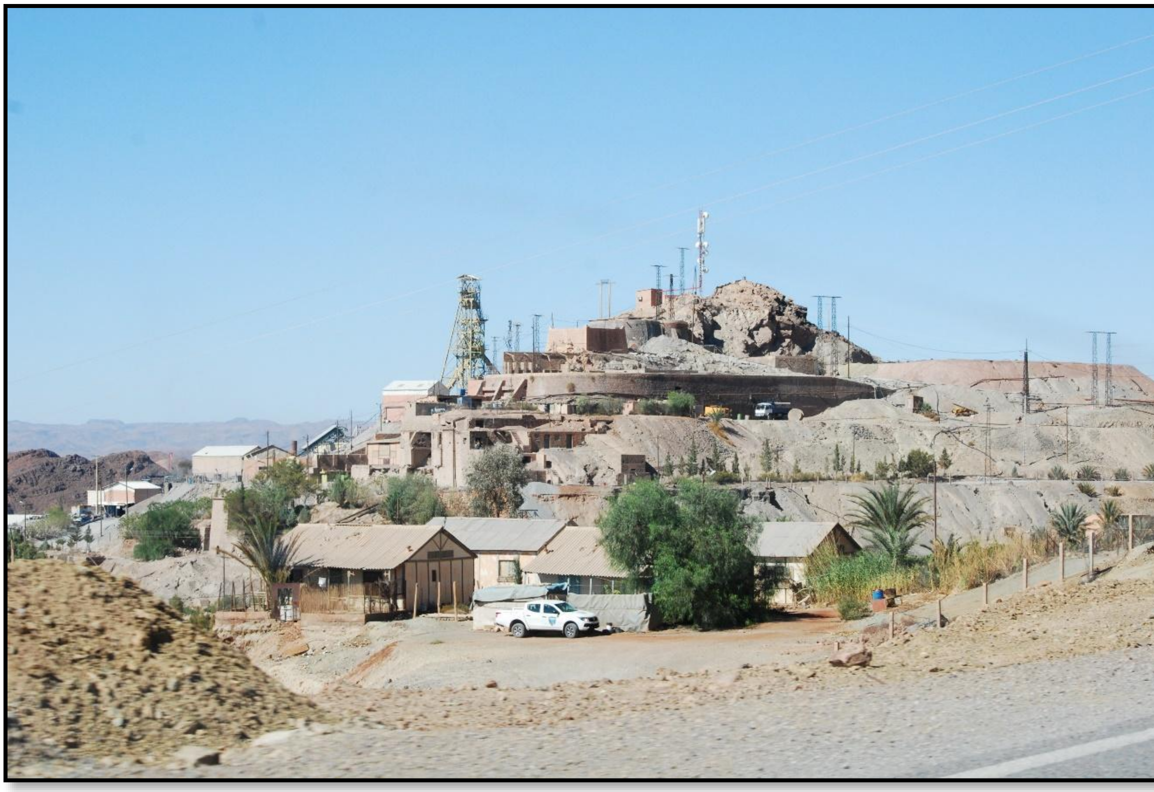


***Figure 19.*** *General view of the Bou Azzer mine*

## Day 3 The Bou Azzer inlier: from Neoproterozoic to Cambrian

***Itinerary***: From Agdez, drive southeast towards the Bou Azzer inlier via the R108 national road (66 km). Start the first stop at the village of Ait Hmane.

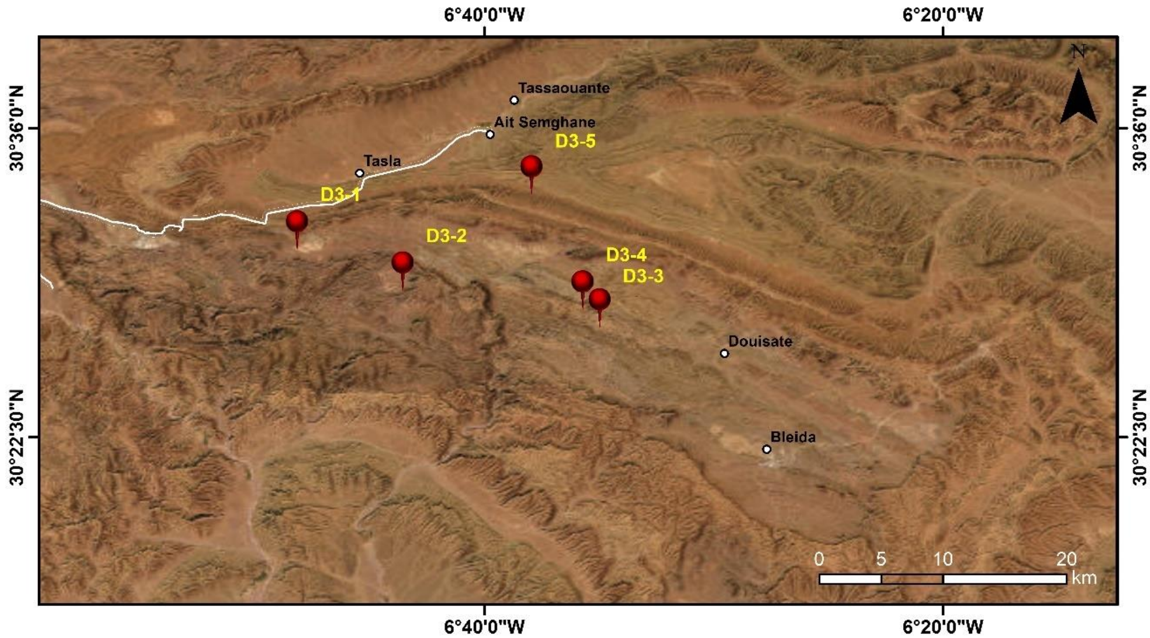



***Figure 20****. Itinerary and stops of the 3th day*

The Bou Azzer inlier located in the western part of the central Anti-Atlas is one of the most documented inliers of the Anti-Atlas (**Figure 18**). It is considered a key area for appreciating the lithostratigraphy of Precambrian rocks and for better understanding the Pan-African geodynamic and metallogenic evolution of the Anti-Atlas belt.

The Proterozoic basement is composed of: (1) Gneissic rocks distributed in two parallel bands aligned with the elongation of the inlier (Triantafyllou, 2016). This unit is mostly represented by former plutonic rock marking mafic to felsic bimodal magmatism dated between 755 Ma and 730 Ma (Thomas et al., 2002; Blein et al., 2014; Triantafyllou et al., 2016). (2) A platform sequence of a continental margin, referred to as the Tachdamt-Bleida series (Leblanc, 1975; El Hadi et al., 2010), deposited during the Tonian rifting event in the WAC margin. (3) The ophiolitic complex of Ait Hmane, that tectonically overlies the continental margin sequences. (4) Intrusive syn-kinematic dioritic to granodiorite plutons cut across both gneissic and ophiolitic units (Triantafyllou et al., 2018; Ikenne et al., 2023). These arc-like rocks with adakitic affinity were emplaced in an intra-oceanic context between 660 and 640 Ma (Triantafyllou et al., 2018 and references therein). (5) An Ediacaran cover composed of a clastic unit (Tiddiline Group) and a volcanic and volcanoclastic one (Ouarzazate group). (6) The whole is covered by Lower Cambrian rocks.

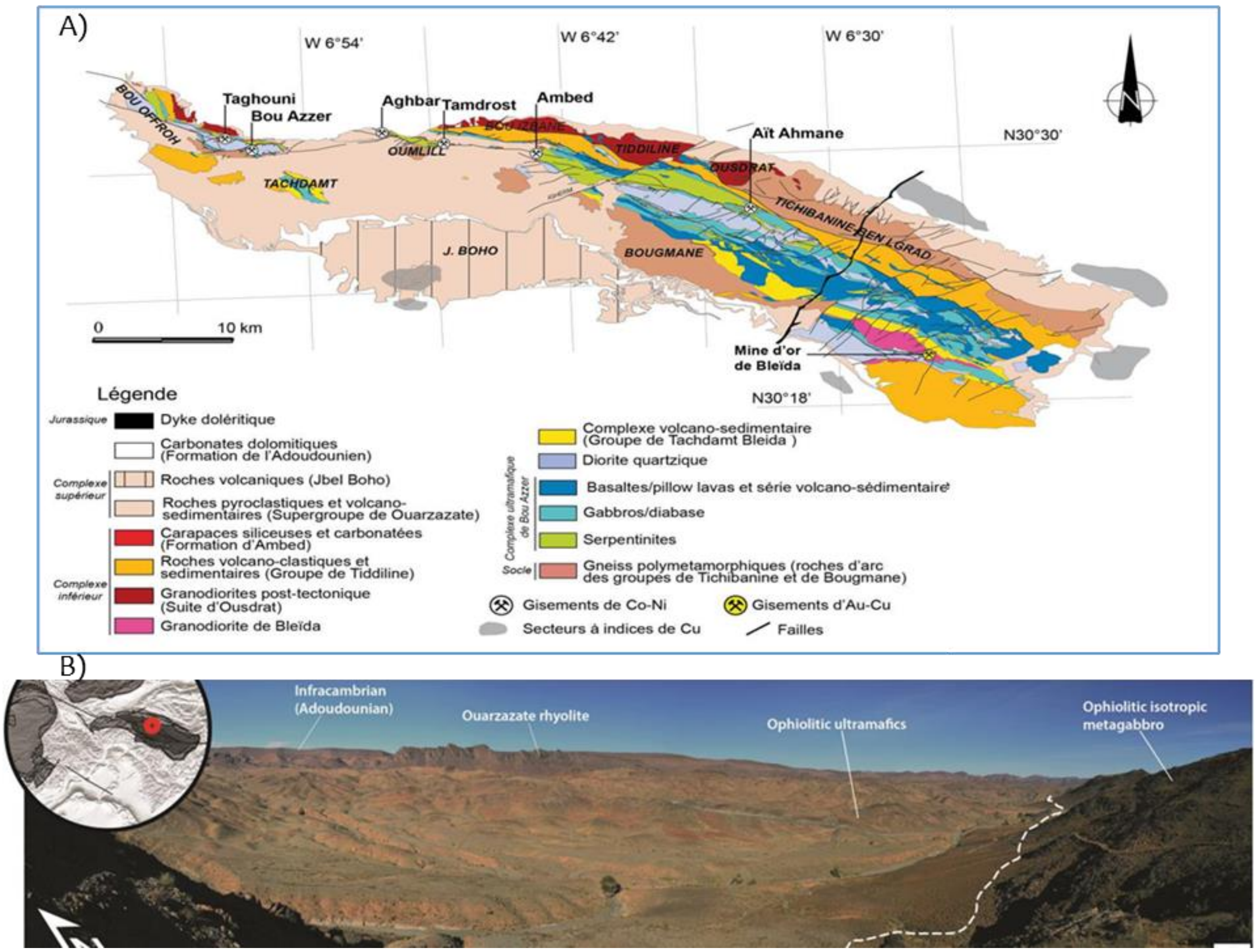



***Figure 21.*** *A) Sketch map of the Bou Azzer inlier (modified after, Leblanc (1975), Admou et al. (2013), Blein et al. (2013) and Tourneur, 2019. B) Field photograph illustrating the main lithologies (Triantafyllou, 2016)*

| Stop D3-1 | Diamictites of the Tiddiline Group |
|---|---|
| | 30°31'13"N; 6°54'32"W |

The Neoproterozoic glaciations had a major impact on the evolution of life on Earth and recorded some of the most extreme climate episodes in Earth's history. They played a significant role as a bottleneck for the rise of Ediacaran biota (Pu et al., 2016; Xiao and Narbonne, 2020). The Neoproterozoic Snowball Earth-related glaciogenic diamictites occur worldwide and attest to two major glacial periods that Earth experienced during this time: (i) the Sturtian, at ca. 717–660 Ma, and (ii) the Marinoan, at ca. 639–635 Ma. The Middle Ediacaran also recorded another high-latitude glaciation known as the Gaskiers, at ca. 580 Ma (Rooney et al., 2015; Linnemann et al., 2021).

In the Bou Azzer inlier, sedimentological evidence of this Middle Ediacaran glaciation is preserved within the Tiddiline Group (Thomas et al., 2004). The glaciogenic sediments consist of diamictite characterized by centimetric pebbles and cobbles floating within green to brown siltstone (Figure 19). The dominant pebbles are quartzites, sourced from the Taghdout Group of the Zenaga inlier (Letsch et al., 2018).

U–Pb dating of these sediments yields a maximum depositional age of 592 Ma (Letsch et al., 2018). Additionally, based on lithostratigraphic relationships, the entire Tiddiline Group has been inferred to be intruded by the 580 Ma Bleida granodiorite, providing a maximum depositional age for the group. Consequently, the diamictite within the Tiddiline Group was deposited between 592 and 580 Ma.

It should also be noted that other glaciogenic sediments were found within the Ouarzazate Group of the Bou Azzer inlier (Varnet et al., 2012) and contemporaneous glaciogenic sediments have also been reported from the Armorican Massif and Bohemian Massif (Linnemann et al., 2019; 2021).

***Figure 22.*** *Massive diamictite with well-rounded quartz sandstone clasts*

| **Stop D3-2** | **Ait Hmane ophiolite** |
|---|---|
| | **30°28'11"N 6°35'00"W** |

Located 32 km east of the Bou Azzer district, the Ait Hmane village exhibits an outcrop where the remains of an ophiolitic complex are exposed.

This stop is dedicated to visiting the ophiolitic sequences of Ait Hmane, an example of Middle Neoproterozoic oceanic crust formed north of the West African Craton during the break-up of Rodinia (Ennih and Liégeois, 2001).

This ophiolitic sequence can be observed along the Ait Ahmane valley, where the entire sequence outcrops, including serpentinite, sheeted dykes, dunite, gabbro, and pillow basalt. The formation age of this ophiolitic sequence has been determined by U-Pb dating of gabbro and plagiogranite, commonly yielding ages ranging from 760 to 690 Ma (El Hadi et al., 2010; Hodel et al., 2020). This portion of oceanic crust was obducted onto the northern margin of the WAC during the accretion of an island arc (Iriri and Boulmane arcs) during the main Pan-African orogeny at approximately 650 Ma (Thomas et al., 2002; Ingles et al., 2004). The obduction of the ophiolitic sequences was accompanied by the intrusion of several calc-alkaline plutons, including the Ait Ahmane granodiorite, which also crops out across the valley.

## Stop D3-3 A Paleomagnetic Study from the Bou Azzer inlier: Implications for paleogeography, the geodynamo, and the appearance of complex life on Earth (by James Pearce)

30°29'48"N 6°43'35"W

The outcrop is at the northwest edge of the Bou Azzer inlier and accessible from road R108 to the east of the Bou Azzer mine. Turn south on a dirt road toward Oued Tazigzaout, which should be marked. Stop near the first small village on the left side of the road.

The outcrop consists of 240+ meters of predominantly volcanic rocks that are between 568 and 566 million years old. Lithologies are primarily tan to red, and silicic to intermediate pyroclastic deposits that vary from poorly consolidated tuffs to welded ignimbrites. Most flows are a few, to tens of meters thick. The exception is the basal rhyolite, which is at least 70 meters thick and represents one of the few true lava flows in the region. This rhyolite is precisely dated to 567.94 Ma using U-Pb CA-ID-TIMS.

About 100 meters above the rhyolite is an exquisitely preserved striated erosional surface that is exposed laterally for several hundred meters. The exact mechanism that scoured and shaped this curious surface is debated, but is likely glaciogenic. This should not be controversial given the evidence for other Ediacaran glaciations in the Bou Azzer inlier (Vernhet et al., 2012) and recent paleomagnetic evidence that places the West African Craton near the south pole at this time (Pierce et al., in review).

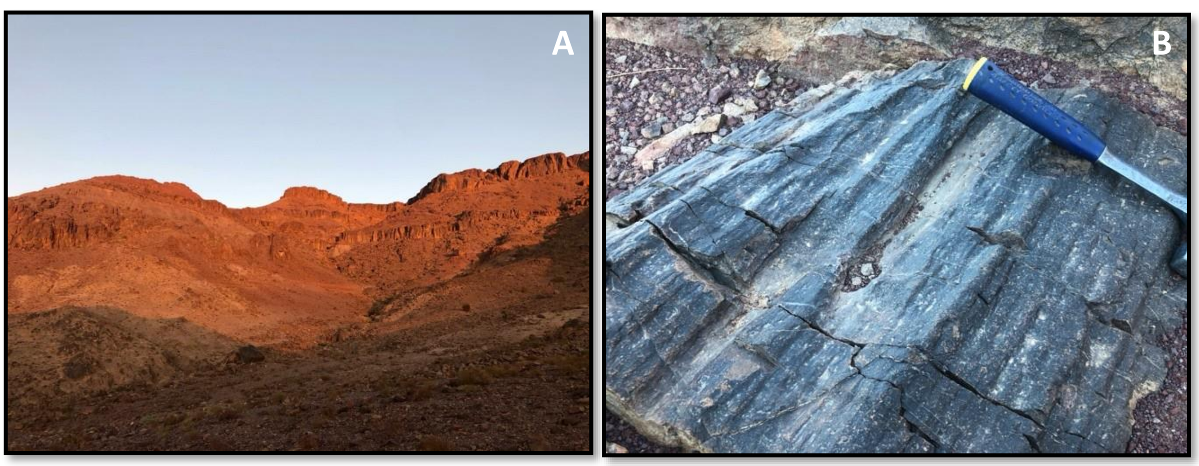



***Figure 233***. *Genral view showing a succession of volcanic and volcoclastic rocks of the Ouarzazate Group (A) and rhyolite with striated erosional surface.*

Zaouite Ouzdine is a small village which is administratively related to Zagora province approximately 48 km southeast of Ouarzazate. Geologically, Zaouite Ouzdine is built on the Cambrian cover of the Bou Azzer inlier, and precisely in the southern front of the Zaouite Ouzdine syncline.

A north-south cross section of nearly 3 km long shows a series that begins from the Tatelt Formation (Tata Group) in the south to the Jbel Wawrmast Formation (Feijas Internes Group, Middle Cambrian) in the north.

The Tatelt Formation consists of fractured fine- to coarse-grained sandstone deposited in a low-energy open shallow margino-littoral hollow. This lithology shows stream channel structures, with ferruginous sandstone lenses of about 100m thick and up to 6 km along strike. These lenticular structures are easily recognized even from satellite images owing to their dark color. Additionally, many spectacular sedimentary structures occur in this unit such as ripple marks, cross-bedding and rip-up clasts.

The Jbel Wawrmast Formation is composed of fairly monotonous successions of greenish-grey, fine-grained sandstones with occasional carbonate levels and nodules. The formation is very attractive for its high content of preserved faunas, particularly trilobites and hyoliths that portray typical early Middle Cambrian fossil associations. The base of this Formation (Brèche à Micmacca Member: BMM) is marked by carbonate levels containing Micmacca fossils, which belong to a particular biozone called "Moroccunus notabilis zone” (Geyer and Vincent, 2014). These carbonates indicate the beginning of a strong marine incursion in a platform with low energy conditions (Geyer and Vincent, 2014). In the upper part of the BMM, numerous trilobite species from the Kingaspidoidae and Ellipsocephalidae families were also identified and belong to the so-called the Ornamentaspis frequens Zone (Geyer and Landing, 2020). This Formation exhibits diverse sinuous trails of ichnofossils that provide evidence of invertebrate activity in early Middle Cambrian.


***Figure 244.*** *Typical fauna from the Brèche à Micmaca Member of the Zaouite Ouzdine Jbel Wawrmast Formation. The specimens belong to the Morocconus notabilis biozone (Stage 4, Series 2, Middle Cambrian) and the Ornamentaspis Frequens biozones (Wuliuan Stage, Miaoligian Series, Middle Cambrian). (A), (B) Cranidium of the trilobite Protolenus densigranulatus (Geyer, 1990). (C): Posterior thorax and part of the pygidium of the trilobite Conomicmacca alta. (D-F): Cranidium of a species of Kingaspidoides trilobite. (E): Large pleura of a thoracic segment of a paradoxides*

***Itinerary***: From Agdz, drive towards Merzouga via the R108 and N10 roads (384 km).

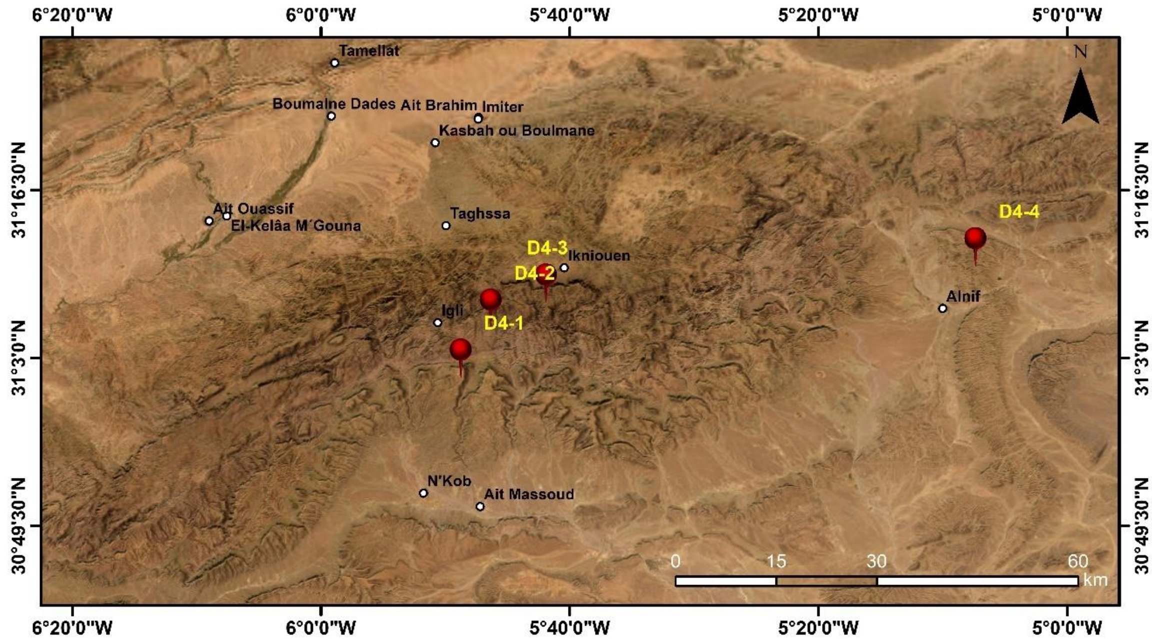



***Figure 255****. Google Earth image showing the locations of the targeted stations in the Saghro Massif*

The Saghro Massif extends over an area of 180 × 32 km, from the Bou Azzer inlier in the west to the Ougnat inlier in the east. The Saghro Massif belongs to the Eastern Anti-Atlas (or Saghro domain), which is separated from the Central Anti-Atlas (the orogenic portion of the Pan-African orogeny) by the Anti-Atlas Major Fault.

The Saghro Massif consists of an Ediacaran basement formed during the later stages of the Pan-African orogeny (temporally contemporaneous with the Cadomian orogeny; Michard et al., 2016; Soulaimani et al., 2018; El Kabouri, 2023). It is composed of three unconformable stratigraphic groups, overlain by the Lower Cambrian transgressive series. The Saghro Group crops out in many sub-inliers, including the Boulmane inlier, which we will visit (D4-3). It consists of a thick siliciclastic turbiditic sequence, thin carbonate lenses, cherts, and basaltic flows deposited between approximately 640-600 Ma (Gasquet et al., 2008). The Saghro Group is intruded by syn-tectonic intrusions dated to around 600 Ma (D4-3, Errami et al., 2021).

Overlying the Saghro Group is the Ouarzazate Supergroup, which is subdivided into the M'gouna Group, unconformably overlain by the Ouarzazate Group (Walsh et al., 2012; Alvaro et al., 2014). The M'gouna Group consists of volcano-sedimentary rocks deposited in small basins in Imiter, Kelâat M'gouna, and Sidi Fellah. M'gouna Group began to deposit at approximately 572 Ma, unconformably above the Saghro Group, indicating a significant sedimentary gap of 30 Ma (Errami et al., 2021). The M'gouna Group is unconformably overlain by the Ouarzazate Group, which is extensively exposed in the Saghro Massif. Older U-Pb geochronological ages from the basal part of the Ouarzazate Group range from 572 Ma to 567 Ma (Walsh et al., 2012; Errami et al., 2021). This group consists of a widespread volcano-sedimentary succession of rhyolite, ignimbrite, basalt, andesite, and conglomerates with vertical and lateral thickness variations. Recently, an intra-Ouarzazate Group has been detected, which is contemporaneous with a shift in the geochemical and isotopic fingerprint of magma (D4-2; El Kabouri, 2023).

The Ediacaran volcano-sedimentary rocks are unconformably to slightly conformably overlain by the siliciclastic sediments of the Lower Cambrian Taroudant Group (D4-1, O'Connor et al., 2010). At the scale of the Anti-Atlas, the Taroudant Group is divided into the Adoudou and Lie-de-Vin formations (Boudda et al., 1979; Geyer and Landing, 1995; Maloof et al., 2005). In the Western Anti-Atlas, the Adoudou Formation is very thick and comprises the Tabia Member, which consists of siliciclastic sediments overlain by a thick carbonate platform of the Tifnout Member (Choubert, 1952; Maloof et al., 2005). However, in the Central and Eastern Anti-Atlas, the thickness of the Adoudou Formation is reduced, and the correlation between the two members is not straightforward (stop D4-1). Furthermore, the carbonate lithology of the Tifnout Member disappears east of Ait Saouen village in the Central Saghro Massif as a result of a progressive eastward transgression (Alvaro et al., 2008; Letsch et al., 2019).

## Stop D4-1 Ediacaran–Lower Cambrian contact in the Saghro Massif

**31° 3'2.49"N; 5°48'47"W**

This outcrop is located on the right side of the road running from Agdz to the Iknioune villages. The outcrop is famous for the Id Bab N'Ali, a butte-like touristic viewpoint. This stop is dedicated to observing the marginal basin of the transgressive Taroudant and Tata Groups. At this stop, we will observe the stratigraphic contact between the Late Ediacaran Ouarzazate Group and the Lower Cambrian sediments of the Taroudant Group. Here in the Saghro Massif, the lower sediments of the Cambrian transgressive series consist of a thick conglomerate known as the Id Bab N'Ali Formation (O'Connor et al., 2010), which crops out in the form of steep cliffs. The stratigraphic contact with the conglomerate of the underlying Ouarzazate Group is progressive, and its lower boundary is marked by the dominance of rounded pebbles. The age of the Id Bab N'Ali Formation is not well known due to the absence of fossils, but lithostratigraphic correlation suggests it is equivalent to the Tikirt Member of the Lie de Vin Formation. Id Bab N'Ali Formation represents the basin margin succession deposited shoreward of the shallow marine peritidal-dominated Lie de Vin of the Taroudant Group, which is more typical of the sequence in the Western Anti-Atlas region (D1-2 stop).

The Id Bab N'Ali Formation is overlain by the siliciclastic sediments of the Tata Group. In the Id Bab N'Ali area, the Tata Group begins with the Tislite Formation, which consists of a 30 m thick series of alternating siltstone and sandstone with thin lenses of conglomerate (Ouhezza Member, O'Connor et al., 2010), grading upward to an alternation of sandstone and stromatolitic dolostone (Lokaman Mb, O'Connor et al., 2010). In turn, the Tislite Formation is overlain by the Asrir (Tazlaft) Formation, which consists of a 12 to 170 m thick series of cross-bedded and rippled siltstone, sandstone, and microconglomerate deposited in a fluvial environment. The first transgressive sediments in the eastern Anti-Atlas are represented by the Feijas Internes Group. The transgressive surface is overlain by a 20 cm to 1 m thick dolostone marker bed known as the Brèche à Micmacca Member, which is then overlain by the siltstone-dominated Jbel Wawrmast Formation and the sandstone-dominated Jbel Afraou Formation (O'Connor et al., 2010).

***Figure 266.*** *Panoramic view showing the Id Bad N'Ali Formation deposited above the volcanic conglomerate of Ouarzazate Group.*

| Stop D4-2 | Intra-Ouarzazate unconformity |
|---|---|
| | 31° 7'3.45"N ;5°46'22"W |

In the Iknioune inlier, intra-Ouarzazate Group unconformity is well exposed in two areas. The first is in Gharghiz village (31° 6'36.20"N, 5°40'56.57"W), accessible only on foot, where the lower part of the Ouarzazate Group is affected by E-W normal faults, leading to its collapse and unconformably overlain by the Upper Ouarzazate Group. The second outcrop is located on the right side of the road between Iknioune and Nkob villages at

Tizi N'Tzazart (31° 7'8.11"N, 5°46'11.39"W). Here, the lower Ouarzazate Group is represented by thick rhyolitic ignimbrite sheets tilted at 25° to the south, becoming slightly folded towards the west. The unconformity is highlighted by the differing dip of the Upper Ouarzazate Group, which dips 5-10° to the south and is dominated by conglomerate, sandstone, and siltstone. The lower part of the Upper Ouarzazate Group is formed by fluvial conglomerates deposited on an irregular erosional surface above the andesite and rhyolite of the Lower Ouarzazate Group.

Based on a regional geochemical and Nd isotopic compilation, a significant geochemical shift in magma source is observed: from recycling of continental crust during the deposition of the M'gouna Group and Lower Ouarzazate Group (average εNd of -5) to a more juvenile source during the deposition of the Upper Ouarzazate Group (average εNd of +4). This shift highlights the collapse of the Pan-African-Cadomian crust and the progressive transition to Cambrian rifting (El Kabouri, 2023).

## Stop D4-3 — Saghro Group: A Cadomian back-arc basin fills

**31° 9'5.22"N; 5°41'55.86"W**

Within the Boulmane inlier, this stop is dedicated to visit the location where recent U-Pb ages of detrital sediments from the Saghro Group and the syn-tectonic Iknioune granodiorite have been reported.

In the Iknioune inlier area, the Saghro Group comprises three distinct formations:

1) The Izemgane-Anou N'Izeme Formation, characterized by a fining-upward volcaniclastic sequence of mudstone, siltstone, and sandstone (Benkirane, 1987; Benziane, 2007), with intercalations of thin limestone and chert beds, as well as volcanic layers such as the Anou N'Izeme basalt (Fekkak et al., 2002; Errami et al., 2009);

2) The Schist Formation consists mainly of fine-grained sediments, dominated by approximately 300 meters of well-laminated black shale.

3) The Tiboulkhirine Formation predominantly consists of volcanic-origin pebbly sandstone, medium sandstone, and siltstone. This succession was affected by southeast-verging folds with associated schistosity under greenschist facies.

On the southern side of Iknioune village, the Iknioune pluton intrudes the sedimentary deposits of the Saghro Group, inducing thermal metamorphism. A new U-Pb age dating of the Iknioune granodiorite yields an age of ca. 603 Ma. The anisotropy of magnetic susceptibility (AMS) (Errami and Olivier, 2012) and the arrangement of Mafic Microgranular Enclaves (Outaaoui et al., 2024) indicate its emplacement was syn-kinematic during the closure of the Saghro Group back-arc in a transpressive dextral regime (Errami et al., 2021).

31° 8'19.18"N; 5° 7'48.59"W

This stop is dedicated to visiting an example of glacial sediments deposited during the Hirnantian Glaciation in the Anti-Atlas belt of Morocco. This outcrop is located near the road connecting Alnif and Arfoud, approximately 15 km east of the village of Alnif.

The stratigraphic succession of the Upper Ordovician consists of the Ktaoua Group overlain by the Second Bani Group. The Ktaoua Group is subdivided into three formations: the lower Ktaoua, the Tiouririne, and the upper Ktaoua Formations (Villas et al., 2006). The Second Bani Group is subdivided into Lower and Upper Formations. In the visited area, the Lower Formation of the Bani Group is completely absent, having been removed by the glaciation, with glacial sediments preserved within the Upper Formation of the Second Bani Group. The glacial unconformity incises deeply into the preglacial lower Ktaoua Formation (Clerc et al., 2013).

This outcrop shows prominent evidence of glacial deposits, including matrix-supported conglomerates and diamictite. The matrix-supported conglomerate is up to 15 m thick and is formed by angular to subangular pebbles and cobbles ranging in size from 2 cm to 3 m, within coarse to very coarse sandy matrix (Clerc et al., 2013). These pebbles and cobbles are composed of sandstone and widespread carbonate. Notably, the carbonate still preserves microbialite fabric of the "Brèche à micmama" Member (Middle Cambrian). Locally, this conglomerate is incised by small, well-bedded levels, consisting of channel-fill sediments (up to 40 cm thick and 4–8 m wide) with erosive basal parts.

***Figure 277.*** *Field photo showing glacial deposits of the Hirnantian Glaciation (Alnif region, Saghro massif, Eastern Anti-Atlas).*

October 19th, 2024

## Day 5 Fossil collection to giant Ag-Hg Imiter ore deposits

***Itinerary***: From Merzouga, drive towards Ouarzazate via the R108 and N10 roads (384 km).

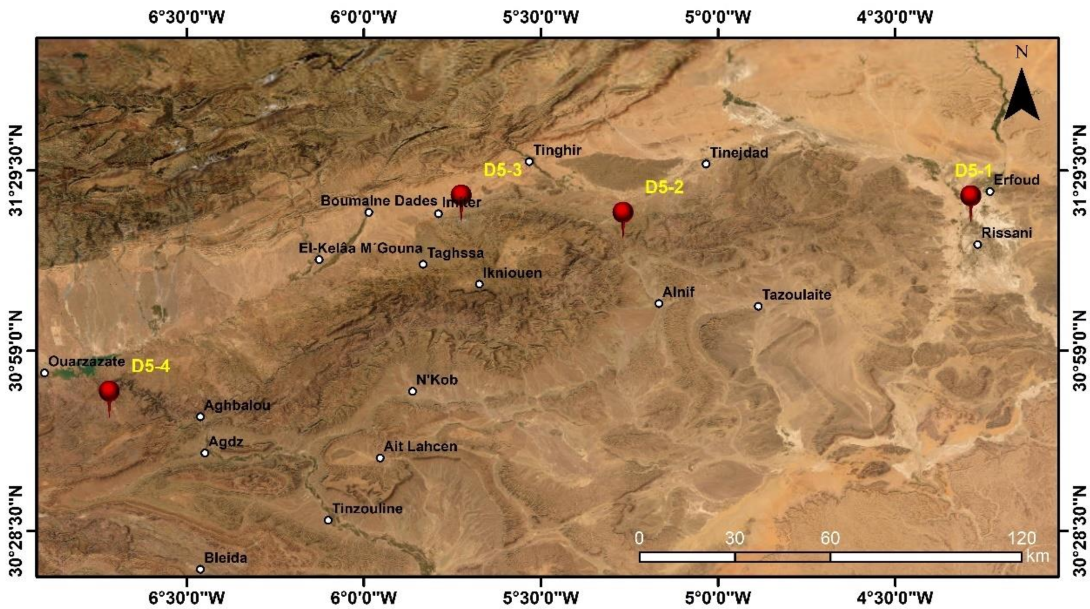



***Figure 288****. Locations of the targeted stops of the 5th day*

The eastern Anti-Atlas, with its well-preserved sedimentary archive spanning from the Ediacaran to the present, records evidence of numerous geological events, including biotic turnover, evolutionary innovation, and the formation of global mineralization. Many academics and amateurs are involved in promoting and showcasing this rich geological heritage, leading to the creation of museums and the development of mines and quarries.

This day is dedicated to visiting some prominent geological sites that illustrate the paleontological and mineralization potential of the eastern Anti-Atlas.

First, we will visit a paleontological and mineral museum in Erfoud, which includes fossils ranging from the late Ediacaran to Cenozoic including many species of trilobites, specimens from the famous *Fazouata* biota, and dinosaur bones. Then, we will drive to Tinghir to visit the marker bed of Brèche à Micmac, known for its characteristic carbonate composition, located in the Tizi N'Boujou area. Next, we will proceed to the world-renowned Ag-Hg epithermal mineralization at the Imiter mine. Afterward, we will drive to Ouarzazate to see an example of Ediacaran terrestrial life, represented by freshwater stromatolites. The day will conclude with a touristic visit to the Ait Ben Haddou tower.

## Stop D5-1 Tahiri Museum of Fossils and Minerals-Erfoud

31°21'03"N; 4°17'15"W

The paleontological content of the eastern Anti-Atlas, especially the Early Paleozoic fossils, is renowned worldwide and has been instrumental in the conceptualization of Cambrian-Ordovician biozones (Hupé 1952; Boudda and Choubert, 1972). In addition, the Cenozoic fossils of the *Hamada de Kem-Kem* are well known for revealing the biodiversity of ecosystems that coexisted with the dinosaur world.

At this stop, we will visit the Tahiri Museum, a personal museum that offers a near-natural collection of fossils from the Early Paleozoic biota.

## Stop D5-2 Imiter Ag-Hg epithermal ore-deposit

31°20'53"N; 5°43'37"W

The Imiter Ag-Hg mineralization is regarded as a giant Neoproterozoic epithermal ore deposit occurred in the Saghro inlier (Cheilletz et al., 2002). It is located at the northeast of the Saghro massif, and 32 km at the south west of the Tinghir city. It is mined by the Society Metallurgic of Imiter (SMI) with a production capacity of 115 to 120 tons of silver (700 g/t) and 15 to 20 tons of mercury per year (Leistel and Qadrouci, 1991; Tuduri et al., 2006). Archeological investigations were undertaken in many of the ore enrichment tanks of the Imiter mine, which radiocarbon dates obtained on the tanks place their final use before the Islamic period. These studies document the first time an ancient silver mining site in the southern regions of Morocco displaying archaeological evidence of ancient mining and metallurgical works (Fauvelle et al., 2021)

The Imiter epithermal ore deposit consists of mineralized quartz–carbonate veins hosted by meta-greywackes (Tuduri, et al., 2018). The mineralization is related to the felsic magmatic rocks emplaced around 550 ±3 Ma (Levresse, 2001). Nevertheless, a discrete base metal episode was recognized and associated with granodiorite intrusions dated at 572 ±5 Ma (Levresse, 2001).

The mineralization is strongly controlled by a E-W trend faulting related to the Imiter fault (Laftouhi et al., 2007). Tuduri et al. (2006) proposed a genetic model of three stages of which the first stage is the responsible of the development of the most productive structures coeval with the main trend structures of Thaghassa, Kelâa et de la Zone des Dykes ore deposits.

The Imiter mineralization is an example of ore deposit related to the Late Neoproterozoic magmatism emplaced in the extensional tectonic setting occurred at the Precambrian–Cambrian transition (Levresse et al., 2004; Tuduri et al., 2006).

***Figure 299.*** *Photo showing an open-pit within the old quarry (Imiter district, Saghro massif, Eastern Anti-Atlas)*

## Stop D5-3 Amane Tazgart stromatolites

30° 47' 34'' N, 6° 43' 17'' W

The Amane Tazgart stromatolites consist of several carbonate outcrops covering an area of about 204000 m², located 25 km southeast of Ouarzazate close to the Ouarzazate-Agdez national road, at the western edge of the Saghro inlier (**Figure 24**). They consist of 10–20 m thick units, embedded in the late Ediacaran volcanics and volcaniclastic (rhyolites ignimbrites, tuffs, sandstones, and conglomerates), which belong to the Ouarzazate Group (Alvaro et al., 2010, Beraaouz et al., 2017, Chraiki et al., 2020). These microbial and laminated rocks were deposited in a shallow sedimentary basin, most likely in a lacustrine environment, and record the interactions between late Ediacaran volcanic activity, terrigenous sedimentation, and local microbial carbonate productivity (Alvaro et al., 2010, Beraaouz et al., 2017).

***Figure 30.*** *General view of the Amane Tazgart stromatolites (left). Close-up view showing laminated stromatolite (right).*

## Stop D5-4 Visit to the Ait Ben Haddou Ksar

**31°02'48"N; 7°07'33"W**

Located 30 km northwest of the city of Ouarzazate, the Kasbah (or Kser) of Ait Ben Haddou is a group of earthen buildings surrounded by defensive walls and towers. It is a historic figure build in the 17$^{th}$ century and served as an important hub for trading caravans between Marrakech and Sahara.

Known for its striking architecture and traditional Moroccan design, the Kasbah was classified in 1987 by the UNESCO as a World Heritage Site. Today the Kasbah is a popular tourist destination admired for its beauty and authenticity.

***Figure 301.*** *Ait Ben Haddou Village, UNESCO World Heritage Site since 1987*

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