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# Example of post-Ediacarian complex volcanism emplaced during the Cambrian rifting in the Western High-Atlas, Morocco: Geochemical study and geotectonic significance

## *Exemple d'un volcanisme complexe post-Ediacarien mis en place durant le rifting cambrien dans le Haut-Atlas occidental, Maroc : Etude géochimique et signification géotectonique*

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**Abstract**. The Moroccan Variscan domain contains relics of the "Cambrian rift" developed from the Anti-Atlasic to the mesetian domain. Distinct volcanic activities, effusive and explosive, are related to this event, and are encased in the Cambrian deposits of the Western High Atlas from both sides of the Tizi-N-Test fault system. We have focused our work on a particular explosive volcanic conglomerate, referred here as V2 event. It's $La_n/Yb_n$ ratios (>8) and low ratios of Nb/Y (<1), added to Nb, Ta and Ti-negative anomalies are comparable to the calc-alkaline orogenic rocks. The $(Gd/Yb)_C$ ratios (>2) confirm that the volcanic conglomerate V2 was generated by the melting of a deep garnet bearing mantle and would have inherited their orogenic signature from the partial melting of previously metasomatized mantle. The spatial extend of such volcanic rocks in different blocks of the Western High-Atlas supports their use it as a potential stratigraphic marker for the correlation of the Cambrian terranes deposited during this major extensive event.

**Keywords**: Explosive Calc-alkaline volcanism, Early Cambrian, Western High Atlas, Cambrian rifting, Morocco.

**Résumé**. Les domaines varisques marocains contiennent les reliques du « Rift Cambrien » qui s'est développé depuis le domaine Anti-Atlasique jusqu'au domaine mésétien. Des activités volcaniques distinctes, effusives et explosives, sont liées à cet événement, et sont encaissées dans les dépôts cambriens du Haut Atlas occidental de part et d'autre du système de failles de Tizi-N-Test. Notre travail est focalisé sur un volcanisme conglomératique explosif particulier, que nous avons dénommé événement V2. Les rapports $La_n/Yb_n$ >8 et les rapports faibles en Nb/Y (<1), en plus des anomalies négatives en Nb, Ta et Ti sont comparables à ceux des roches orogéniques calco-alcalines. Les rapports $(Gd/Yb)_C$ (>2) confirment que les conglomérats volcaniques V2 sont générés par la fusion d'un manteau profond à grenat et ont hérité la signature orogénique de la fusion partielle d'un manteau antérieurement métasomatisé. L'extension spatiale de telles roches volcaniques dans les différents blocs du Haut Atlas occidental est favorable à leur utilisation en tant que marqueur stratigraphique potentiel pour la corrélation des dépôts du Cambrien durant cette phase extensive majeure.

**Mots-clés** : Volcanisme explosif calco-alcalin, Cambrien inférieur, Haut Atlas occidental, Rifting Cambrien, Maroc.

## INTRODUCTION

During Ediacaran to Cambrian times, the Northwestern border of the WAC has been the subject of a major crustal extensional tectonic event (Bernardin *et al*. 1988, El Archi *et al*. 2004, El Attari *et al*. 1997, Piqué 2003, Piqué *et al*. 1990, 1995, Soulaimani *et al*. 2003, 2004). In the Anti-Atlas, above the thick post-orogenic Ediacaran volcanoclastic deposits have been initiated faulted basins during the Lower Cambrian, filled with siliciclastic and carbonates deposits (Bensaou & Hamoumi, 2003). This event is associated with an important effusive and intrusive magmatism which evolved from Ediacaran calc-alkaline late to post-orogenic magmatism ( Belkacim *et al*. 2017, Youbi 1998), toward tholeitic (Soulaimani *et al*. 2004) and alkaline lava during the Early Cambrian (J. Boho syenite dated at 534 (Alvaro *et al*. 2006, Blein *et al*. 2014a, Ducrot & Lancelot 1977). The geodynamic significance of this crustal extension and its relation with the previous Ediacaran event are still a matter of debates (Blein *et al*. 2014b, Oudra *et al*. 2006, Soulaimani & Piqué 2004). Overall, there is a consensus that the Lower Cambrian extension is a Cambrian rifting phase, which affects not only the Anti-Atlas but also the other northern areas of Morocco (Fig. 1a). Further north, in the Mesetian domain, the high metamorphic grade generated by the Variscan deformation makes difficult any attempt to date the flows hosted in the Middle Cambrian formations. Geochemical data from these flows revealed an alkaline signature in the Western, Central and Eastern Meseta (Ouali *et al*. 2003) and a calc-alkaline signature in the Oued Rhebar- Bouznika (El Hadi *et al*. 2006).

In the Western High Atlas (WHA), Ediacaran basement is covered, in apparent conformity or an angular unconformity (Pouclet *et al*. 2007), by the Lower Paleozoic cover. This domain consists of two distinct parts (Fig. 1b) the Eastern Paleozoic Massif known as the Marrakech High Atlas (MHA), and the Western Paleozoic massif (WPM). The WPM consists of three zones, axial zone bounded by the Northern and Southern subatlasic zones, limited by several longitudinal faults (Fig. 1b). By its variscan

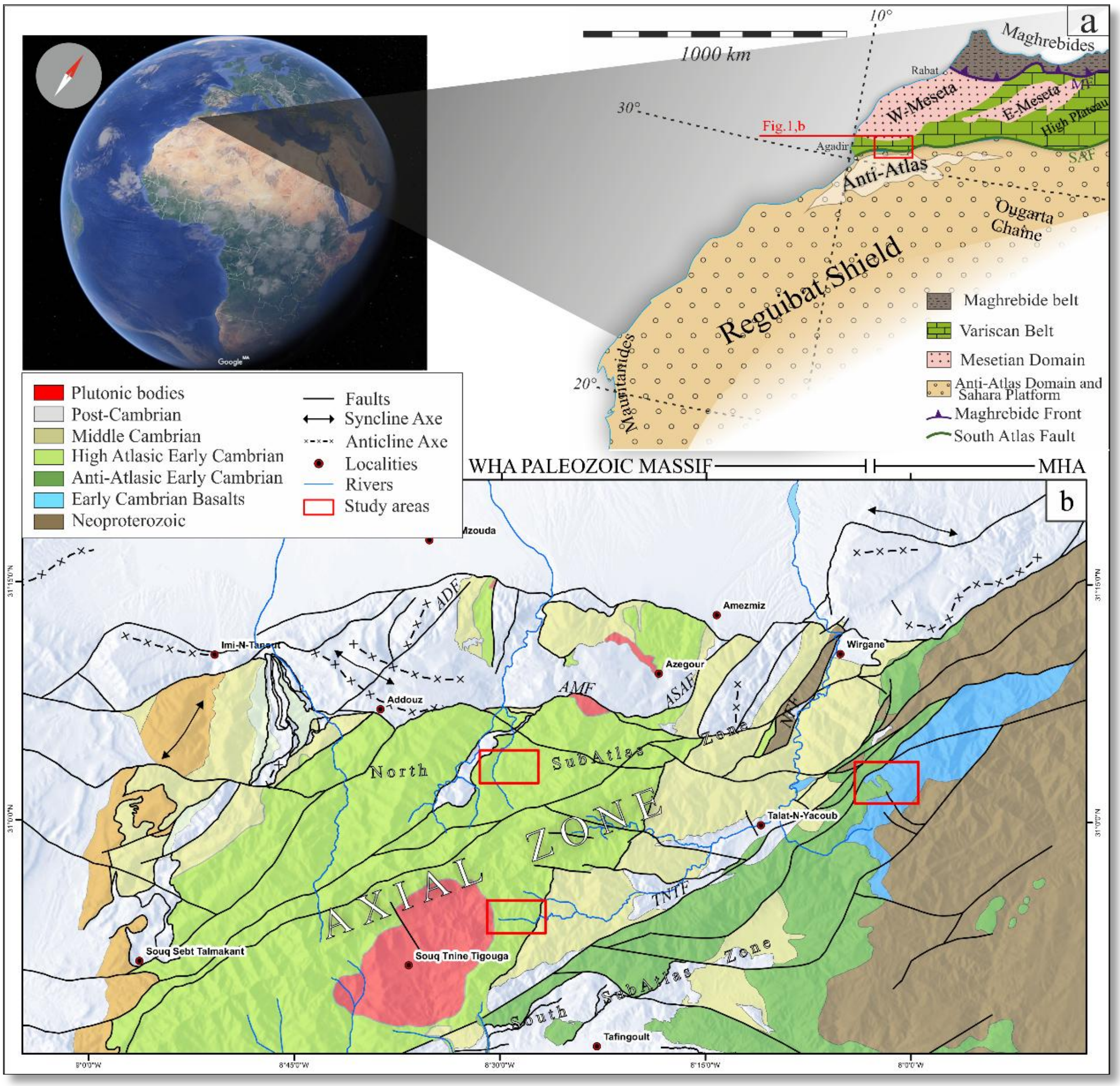


Figure1. a. Major Domain of the Variscan Belt in Morocco (after Michard *et al*. 2008); b. Geological sketch map of the Western High Atlas (adapted from Fekkak et al. 2018). AAMF – Anti Atlasic Main Fault; AEMF – Assif El Mal Fault; AMF – Adassil Medinet Fault ; ASAF – Assif Anougal Fault; ERF – Erdouz Fault; NFF – N-Fis Fault and TNTF – Tizi-N-Test Fault.

deformation and the syn-to late orogenic granitic intrusion this domain is considered as part of the mesetian domain (Lagarde & Roddaz 1983, Lagarde 1985; Mabkhout *et al*. 1988, Ait Ayad 1987, Rosé 1987, Lagarde 1987, Lagarde & Roddaz 1987, Gasquet 1991, 1992). The MHA consist of two zones, the Northern zone, belonging to the North subatlas zone, and the Ouzelagh promontory, considered as the northern continuity of the Anti-Atlasic domain (Ouanaimi 1989, Ouanaimi & Petit 1992, Soulaimani & Ouanaimi 2011). Accordingly, it is important to distinguish two Cambrian domains in terms of lithology and tectonic stress.

In the WHA, the Cambrian deposits are essentially composed of silico-clastic and carbonates deposits, coeval to an important volcanic activity. El Archi *et al*. (2004) recognized two magmatic events: the first one consists of calc-alkaline rocks, extends from Neoproterozoic (Sequence IA) to the Early Cambrian (Sequence IB), and the second is represented by the Middle Cambrian basalt (Sequence II) with tholeiitic signature. The signature of the calc-alkaline rocks led these authors to propose a setting up in a convergent margin for the sequence 1A and a major shear zone for the sequence 1B. According to these authors, the tholeiitic signature of the Middle Cambrian sequence is consistant with the dominant Cambrian extensional event that started in the WHA after the Early Cambrian. Pouclet *et al.* (2007) describes five volcanic events (From V1 to V5) in the Agoundis-Ounein area. The V2 volcanic activity is particularly interesting as far as it differs from (V1, V3, V4 and V5) by its explosive character. In addition, its stratigraphic position and age are very controversial. Indeed, Ouazzani *et al*. (1998, 2001) demonstrate the calc-alkaline signature of this V2 volcanism and compared it to the Ediacaran Anti-Atlas arc volcanism and therefore attributed it to Neoproterozoic age. El Archi *et al*. (2004) and Jouhari *et al*. (2001) confirm the calc-alkaline signature and propose an emplacement in shear-zone basin context. Pouclet *et al*.

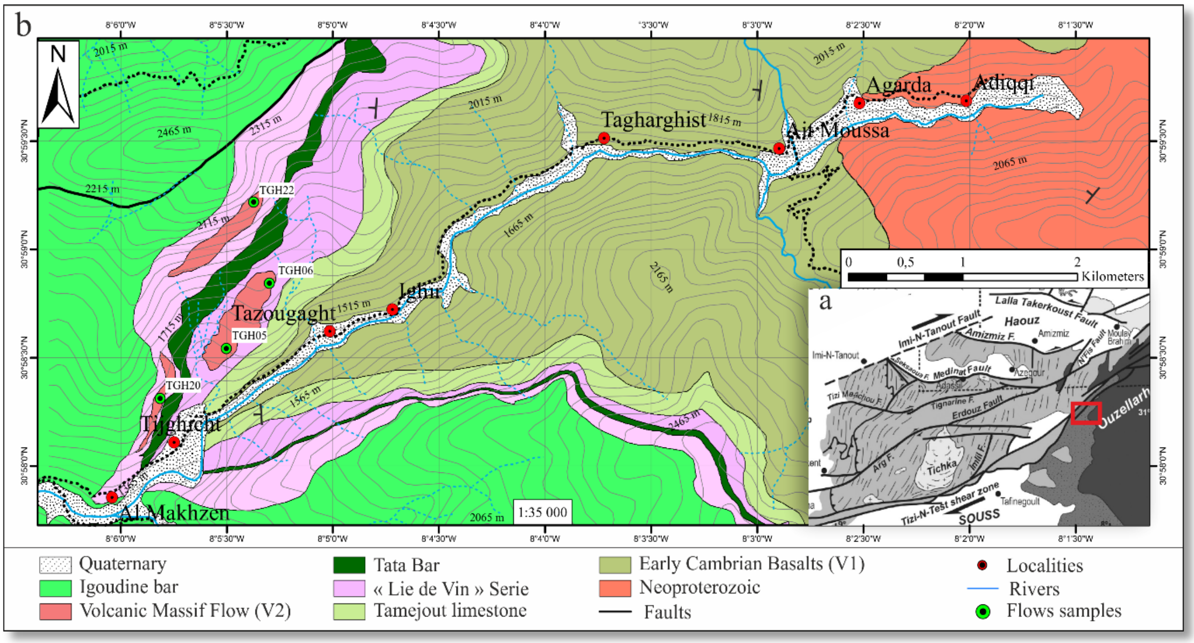


Figure 2. a. Simplified geological map of the Western High Atlas and geographic location of Agoundis-Ounein area; b. Geological map of Agoundis-Ounein area (adapted from Geological map of Talat-N-Yacoub 1/50 000).

(2007) evoke a calc-alkaline signature and exclude the active margin context. These authors also gave an Atdabanian age to this volcanism.

All these works underestimate the real importance of the V2 “Calc-Alkaline” volcanic activity considered only as an anomaly compared with the predominant tholeiitic volcanic activity related to the rifting environment. In this paper, we perform (i) a detailed study of the V2 explosive volcanic activity compared to the WHA other volcanic activities (ii) Stratigraphic constraint is used to specify the age of this volcanism. All data are then compiled to discuss a new geodynamic model of the Western High Atlas during the lower Cambrian.

## REGIONAL GEOLOGY

From Ediacaran to Early Cambrian Morocco was submitted to an important extensive event (Piqué 2003). It started at the end of the Proterozoic in the Anti-Atlas (Soulaimani *et al*. 2004) and aborted in the middle Cambrian in the western Meseta (Ouali *et al*. 2003). This extensive event reached the Iberian Ossa-Morena zone during the late Cambrian (Alvaro *et al*. 2014) and evolved to the opening of the Rheic Ocean (Linemann *et al*. 2007). It therefore seems logical to connect Morocco to the Avalonian and Cadomian zone at this time (Nance *et al*. 2002). By the location of the WHA between the Moroccan Meseta and the WAC, these domains certainly reveals relics of this extensive event and thus represent a key area that should be investigated to understand the complex evolution of the Gondwana margin during this period.

Due to the superposition of several orogenic events, the Cambrian rifting is evidenced in the Moroccan domains by lateral stratigraphic variations, intense volcanic activity and rare syn-sedimentary deformations. In the western Anti-Atlas, the “Cambrian Rifting” corresponds to conglomeratic deposit characterized by a brutal variation in thickness and associated with High-Ti tholeiitic volcanism (Soulaimani *et al*. 2004). As noticed above, a tholeiitic volcanism hosted in carbonate and detrital formation attributed to the lower Cambrian has been described in the Agoundis-Ounein and in the Ouezellagh promontory (Pouclet *et al*. 2007). Also, El Archi *et al*. (2004) noticed several magmatic occurrences in the WHA. El Hadi *et al*. (2006) described a calc-alkaline volcanism emplaced, within the “Schistes à Paradoxydes” series of Oued Rhebar in the western Meseta, during the Cambrian extensive event. They related the calc-alkaline signature, in a distensive context, to partial melting of a metasomatized mantle, probably during previous subduction (Morris *et al*. 2000, Ikenne *et al*. 2007, Pouclet *et al*. 2007).

## METHODS

This study was supported by the National Program of Geological Mapping (Fekkak *et al*. 2018, Jouhari *et al*. 2018, Ouanaimi *et al*. 2018) and by the Faculty of Science of El Jadida (Chouaib Doukkali University). This study includes geological mapping, sampling of volcanic rocks and detailed stratigraphic analysis focused on the exposures linked to deeply incised rivers of several valleys of the WHA especially Agoundis, Aghbar and Iounsektene. More than 50 samples of volcanic and volcano sedimentary rocks have been collected. Macroscopic observations during mapping and thin-section observations of these rocks have simplified both identification and characterization of the rock types. Eighteen (18) samples representing the V2 rocks have been selected for geochemical analyses. They represent the best exposed and freshest outcrops of this volcanic event. The analyses of major, trace and rare-earth elements (Table 1) were carried out by the inductively coupled plasma mass

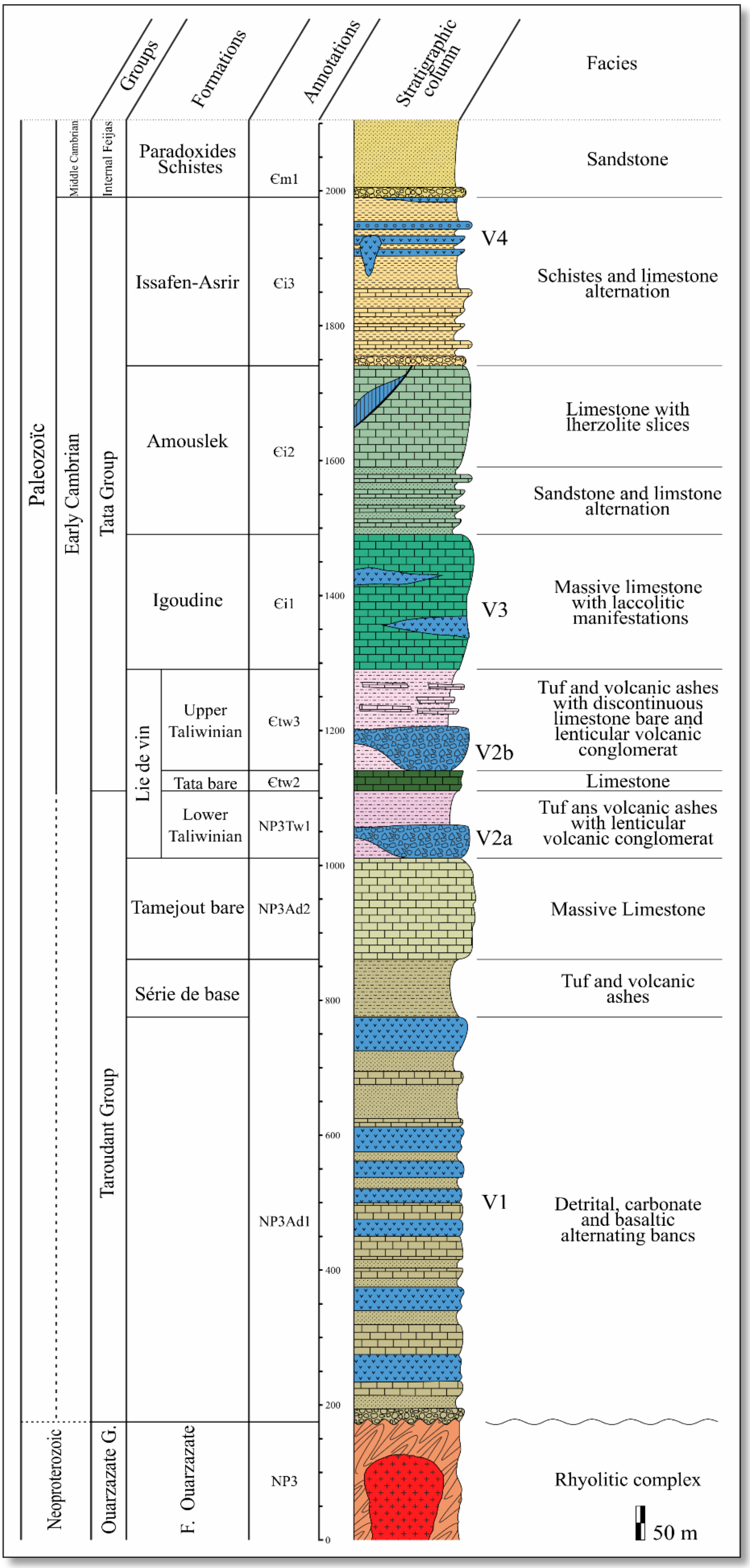


Figure 3. Synthetic lithostratigraphic column of the Anti-Atlasic block of the Western High Atlas.

Table1. Chemical analyses of the V2 volcanic conglomerate of the Anti-Atlasic block and High Atlasic blocks of the Western High Atlas. (* Sample from Fekkak *et al*. 2018, Jouhari *et al*. 2018, Ouanaimi *et al*. 2018).

| Block | Anti-Atlasic | | | | High Atlasic | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Location | Agoundis | | | | Aghbar | | | | |
| Sample number | TGH05 | TGH06 | TGH20 | TGH22 | TC2 | TC3 | TC4 | TC5 | TC6 |
| (Wt%) | | | | | | | | | |
| SiO2 | 54,11 | 60,08 | 60,68 | 61,25 | 57,68 | 68,07 | 64,19 | 64,44 | 60,18 |
| Al2O3 | 16,97 | 17,29 | 15,63 | 14,67 | 20,49 | 15,81 | 17,58 | 17,78 | 16,96 |
| Fe2O3 | 4,71 | 3,43 | 4,01 | 5,34 | 8,02 | 3,67 | 4,11 | 3,59 | 3,8 |
| MgO | 3,68 | 1,42 | 3,35 | 5,34 | 1,14 | 1,21 | 1,5 | 1,62 | 2,2 |
| CaO | 4,45 | 2,89 | 0,81 | 1,32 | 1,4 | 4,31 | 2,31 | 2,05 | 5,67 |
| Na2O | 6,11 | 6,91 | 0,08 | 3,94 | 2,56 | 2,33 | 6,75 | 7,37 | 7,7 |
| K2O | 3,04 | 3,36 | 10,72 | 2,7 | 6,39 | 2,47 | 1,81 | 1,42 | 0,53 |
| TiO2 | 1,26 | 1,23 | 0,94 | 1,1 | 0,84 | 0,58 | 0,65 | 0,65 | 0,73 |
| P2O5 | 0,39 | 0,31 | 0,28 | 0,3 | 0,24 | 0,11 | 0,29 | 0,18 | 0,15 |
| MnO | 0,05 | 0,03 | | 0,04 | 0,04 | 0,1 | 0,05 | 0,03 | 0,08 |
| LOI | 5 | 2,8 | 3,2 | 3,8 | 0,9 | 1,1 | 0,5 | 0,6 | 1,8 |
| Total | 99,85 | 99,85 | 99,9 | 99,83 | 99,88 | 99,86 | 99,87 | 99,86 | 99,86 |
| ppm | | | | | | | | | |
| Ba | 1051 | 646 | 1401 | 230 | 1543 | 1254 | 1276 | 1140 | 346 |
| Cs | 1 | 1,2 | 1,8 | 1,3 | 6,2 | 0,6 | 0,6 | 0,7 | 0,2 |
| Hf | 3,5 | 3 | 2,9 | 3 | 4,6 | 3,1 | 3,6 | 3 | 3,4 |
| Nb | 19,3 | 13,6 | 14,6 | 15,5 | 7,1 | 3 | 2,6 | 2,1 | 2,7 |
| Rb | 20,4 | 26,5 | 77,8 | 39,2 | 167 | 40,4 | 23,8 | 21,7 | 10,8 |
| Sn | 0,5 | 0,5 | 0,5 | 0,5 | 2 | 0,5 | 0,5 | 0,5 | 3 |
| Sr | 410,7 | 519,7 | 44,5 | 315,3 | 123,6 | 341,2 | 255,5 | 541,9 | 321,8 |
| Ta | 1,2 | 0,8 | 1 | 0,9 | 0,5 | 0,3 | 0,2 | 0,2 | 0,3 |
| Th | 2,4 | 2 | 1,9 | 1,7 | 5,2 | 1,8 | 2 | 1,7 | 1,6 |
| U | 1,1 | 0,7 | 0,6 | 0,6 | 1,6 | 1,4 | 3,1 | 1 | 1,5 |
| W | 62 | 83,2 | 40,5 | 36,9 | 180,8 | 262,1 | 149,9 | 132,1 | 164 |
| Zr | 125,3 | 114,1 | 109 | 112,2 | 165,6 | 115,6 | 138,3 | 120,7 | 131,5 |
| Y | 11,2 | 11,7 | 10,8 | 11,2 | 18,6 | 8,5 | 13,3 | 10 | 12,1 |
| La | 20,8 | 18,9 | 14 | 12,4 | 21,5 | 8,4 | 17,7 | 13,4 | 11,3 |
| Ce | 42,1 | 38,9 | 31,5 | 26 | 52 | 22,7 | 41,3 | 32,2 | 26,1 |
| Pr | 4,92 | 4,85 | 3,86 | 3,38 | 6,4 | 2,95 | 5,62 | 4,21 | 3,57 |
| Nd | 21,2 | 20,5 | 15,4 | 14,3 | 25,9 | 12,1 | 23,8 | 16,9 | 15,4 |
| Sm | 4,31 | 4,19 | 3,1 | 2,92 | 5,35 | 2,5 | 4,73 | 3,54 | 3,22 |
| Eu | 1,58 | 1,42 | 0,9 | 0,94 | 1,47 | 0,86 | 1,37 | 1,03 | 1,15 |
| Gd | 4,07 | 4,08 | 2,94 | 2,74 | 4,47 | 2,29 | 3,96 | 2,97 | 3,15 |
| Tb | 0,47 | 0,49 | 0,36 | 0,36 | 0,6 | 0,27 | 0,46 | 0,35 | 0,4 |
| Dy | 2,49 | 2,55 | 2,02 | 2,22 | 3,43 | 1,67 | 2,5 | 1,97 | 2,4 |
| Ho | 0,39 | 0,43 | 0,38 | 0,41 | 0,67 | 0,29 | 0,41 | 0,3 | 0,4 |
| Er | 1,08 | 0,95 | 0,96 | 1,1 | 1,99 | 0,82 | 1,21 | 0,88 | 1,22 |
| Yb | 0,94 | 0,76 | 0,9 | 0,93 | 1,78 | 0,76 | 1,12 | 0,77 | 1,13 |
| Lu | 0,13 | 0,11 | 0,12 | 0,1 | 0,25 | 0,09 | 0,14 | 0,09 | 0,14 |

| Block | High Atlasic | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Location | Aghbar | Iounsektene | | | | | | | |
| Sample number | TC8 | AZFJE 11* | AZFJE 11b* | AZ 15a* | AZFJE 15b* | ADFJE 62b* | ADFJE 63a* | ADFJE 69* | ADAF 105* |
| (Wt%) | | | | | | | | | |
| SiO2 | 57,21 | 58,08 | 58,82 | 55,35 | 56,32 | 54,97 | 47,8 | 60,55 | 52,04 |
| Al2O3 | 17,33 | 17,82 | 18,42 | 20,74 | 19,64 | 16,47 | 16,55 | 16,35 | 16,82 |
| Fe2O3 | 8,48 | 5,35 | 5,29 | 9,36 | 5,71 | 9,76 | 7,8 | 6,63 | 7,75 |
| MgO | 2,02 | 3,66 | 2,96 | 1,8 | 2,83 | 3,6 | 3,13 | 3,25 | 5,31 |
| CaO | 3,05 | 3,48 | 2,97 | 0,5 | 5,39 | 2,43 | 9,2 | 1,86 | 4,54 |
| Na2O | 3,51 | 6,01 | 4,82 | 7,68 | 3,97 | 5,7 | 4,44 | 4,14 | 4,76 |
| K2O | 2,79 | 1,06 | 1,8 | 0,61 | 1,34 | 0,58 | 1,31 | 1,24 | 1,76 |
| TiO2 | 0,84 | 0,81 | 0,91 | 0,7 | 0,7 | 1,64 | 1,26 | 0,85 | 1,52 |
| P2O5 | 0,31 | 0,16 | 0,17 | 0,01 | 0,12 | 0,59 | 0,22 | 0,15 | 0,24 |
| MnO | 0,08 | 0,07 | 0,08 | 0,15 | 0,06 | 0,1 | 0,13 | 0,09 | 0,1 |
| LOI | 4,2 | 3,1 | 3,4 | 2,9 | 3,6 | 3,9 | 7,7 | 4,6 | 4,7 |
| Total | 99,86 | 99,63 | 99,6 | 99,76 | 99,69 | 99,79 | 99,54 | 99,75 | 99,59 |
| ppm | | | | | | | | | |
| Ba | 524 | 572 | 515 | 260 | 523 | 90 | 1821 | 239 | 1905 |
| Cs | 2,4 | 0,2 | 1,3 | 0,4 | 1 | 0,4 | 1,3 | 0,6 | 2,6 |
| Hf | 4,5 | 3,4 | 4,1 | 4,2 | 3 | 5,7 | 3,1 | 3,5 | 3,6 |
| Nb | 10,9 | 3,3 | 3,8 | 2,6 | 2,7 | 8,1 | 11,5 | 2,5 | 15,8 |
| Rb | 53,3 | 10,8 | 29,7 | 11,5 | 19,8 | 13,2 | 16,6 | 22,9 | 29,9 |
| Sn | 1 | 27 | 39 | 17 | 25 | 10 | 7 | 18 | 0,5 |
| Sr | 226,9 | 854,1 | 805,3 | 645,1 | 530,4 | 140,4 | 753,9 | 580,7 | 389 |
| Ta | 0,6 | 0,2 | 0,2 | 0,1 | 0,2 | 0,6 | 0,9 | 0,2 | 1 |
| Th | 3 | 1,4 | 1,8 | 1,9 | 1,4 | 2,8 | 1,6 | 2,1 | 1,9 |
| U | 1,2 | 0,8 | 1,7 | 0,4 | 1,8 | 1,4 | 0,6 | 1,2 | 0,9 |
| W | 62,6 | | 0,5 | | | 0,7 | | 2,1 | |
| Zr | 184,6 | 137,3 | 166,3 | 159,6 | 114,2 | 226,1 | 128 | 141 | 160,1 |
| Y | 22,4 | 14,1 | 19 | 7,5 | 13,3 | 36,8 | 14,9 | 14,7 | 16 |
| La | 26,8 | 0,687 | 11,1 | 5,2 | 11,7 | 18,8 | 16,3 | 14,2 | 17,3 |
| Ce | 68,6 | 1,775 | 31,4 | 12,2 | 24,3 | 43,8 | 34,4 | 33,8 | 39,1 |
| Pr | 7,52 | 0,276 | 3,99 | 1,52 | 3,26 | 5,92 | 4,27 | 4,41 | 4,83 |
| Nd | 29,7 | 0,444 | 17,7 | 6,8 | 14,4 | 25,6 | 17,8 | 18 | 19,3 |
| Sm | 6,35 | 0,444 | 3,9 | 1,57 | 3,17 | 6,15 | 3,98 | 3,82 | 4,24 |
| Eu | 1,92 | 0,168 | 1,21 | 0,44 | 1,01 | 1,91 | 1,4 | 1,1 | 1,39 |
| Gd | 5,89 | 0,596 | 3,71 | 1,65 | 3,04 | 7,1 | 3,77 | 3,78 | 4,21 |
| Tb | 0,83 | 0,108 | 0,56 | 0,26 | 0,47 | 1,14 | 0,53 | 0,56 | 0,61 |
| Dy | 4,71 | 0,737 | 3,26 | 1,57 | 2,71 | 7 | 2,86 | 2,9 | 3,24 |
| Ho | 0,81 | 0,164 | 0,77 | 0,3 | 0,51 | 1,46 | 0,55 | 0,59 | 0,62 |
| Er | 2,25 | 0,48 | 2,15 | 1,04 | 1,37 | 4,15 | 1,54 | 1,45 | 1,71 |
| Yb | 1,76 | 0,493 | 2,11 | 1,08 | 1,48 | 3,92 | 1,38 | 1,03 | 1,38 |
| Lu | 0,25 | 0,074 | 0,33 | 0,19 | 0,23 | 0,63 | 0,22 | 0,2 | 0,21 |

spectrometry (ICP-MS) at the ACMELAB laboratory (Canada). Precision for major and trace elements are usually better than 1% and 1-5%, respectively. Geochemical affinity and geodynamic evolution are proposed based on petrographic and geochemical comparison with data in the literature. The use of geochemical data of the Agoundis-Ounein volcanic rocks (Pouclet *et al*. 2007) allow us to attribute the explosive volcanic conglomerates to the V2 volcanic event. While the comparison with other works in the Western High Atlas has enabled us to identify the spatial extent of the V2 volcanic rocks. (El Archi *et al*. 2004, Jouhari 2001, Pouclet *et al*. 2008, 2018, Ouazzani *et al*. 1998, 2001). In addition to data presented above, works on other extensive areas besides the Western High Atlas helped us to propose geodynamic model during the Cambrian extensive event.

## RESULTS

### Stratigraphic succession of the Early Cambrian

In the WHA, the Early Cambrian formations outcrop on both sides of the TNTF (Fig. 1). In the southern block (Anti-Atlas block), Variscan deformation is weak and stratigraphic surveys are possible. In the northern block (High-Atlas block), the Variscan deformation is very intense and the stratigraphic reconstructions are very uncertain. This distinction is due to the different levels of exhumation of these two blocks during alpine orogeny. The latter is influenced by different paleogeographic positions of these blocks during the Lower Cambrian and the Carboniferous Variscan deformation. In order to understand the paleogeography of the Western High Atlas blocks during the Early Cambrian extension, it’s important to distinguish two Cambrian.

#### *Anti-Atlasic block*

In this block located SW of the TNTFZ, the synthetic stratigraphic column shows Ediacran basement overlain by thick Early Cambrian deposits (Figures 2 and 3). The Edicaran basement consists of rhyolite, andesite and volcano-clastic breccia, that may be assumed to be the equivalent of the Ouarzazate Group. The Cambrian deposits start by “Basal Conglomerates”, followed by an important basaltic stacking flows (>500m), representing the product of the V1 volcanic event, they are covered by tuffs formation. The entity represents the equivalent of the “série de base” of the Anti-Atlas. This assemblage is capped by 150 m thick of massive limestone escarpment. This latter is the lateral continuity of the Tommotian Tamjout dolomitic formation (Pouclet *et al*. 2007). Above, comes next the equivalent of “Lie de Vin” formation. The different reference levels described in the Anti-Atlas are recognizable here (reddish detrital facies and limestone Tata Barre) but are associated with an important volcanic activity in the form of tuffs and mudflows (V2 from Pouclet *et al*. 2007). The upper limestones represent the Igoudine formation; it contains magmatic occurrences related to the V3 volcanic event. Micritic layers are rich in *Archeaocyatha* (Pouclet *et al*. 2007). The Amouslek formation is composed of a basal part consisting of alternating layers of silty clay and limestone beds; and a thick-bedded limestone formation at the top. The upper part of this formation is affected by normal faults responsible of the ascension of lherzolite slices (Pouclet *et al*. 2007, Aarab 2007). The Early Cambrian ended by the Issafen-Asrir formation which consists of conglomerate and breccia followed by the alternation of decimetre-sized beds of clay, silty clay, and argillaceous limestones. The upper part of the formation contains relics of the V4 volcanic event. The detrital upper formations are attributed to the Middle Cambrian.

#### *High-Atlasic block*

The High Atlasic synthetic stratigraphic column consists of volcano-detrital and carbonate formations affected by numerous overlapping Variscan faults reactivated during alpine orogeny (Fekkak *et al*. 2018b) and hosted several Variscan intrusive bodies. The stratigraphic marker recognized is the limestone bar equivalent to the Early Cambrian Igoudine bar of the Anti-Atlasic block (Figures 4, 5 and 6). Under this bar we recognize an epiclastic formation which consists of volcanic ashes overlain schists and sandstone alternations (Fig. 6). Due to their position under the Igoudine bar, those formations both belong to the upper Taliwinian “Lie de Vin” series and contains Lahars and debris flows similar to these recognized by the Agoundis Valley in the Anti-Atlasic block. Tuff and limestone alternation constitute the basal part of the stratigraphic column; they represent the equivalent of the Early Cambrian Tata bar. The lahars of the High-Atlas block differ from those of Anti-Atlas block by increasing grain diameter, important exposure and thickness. The real thickness of this unit cannot be defined because its basal part is consumed by intrusions or remains submerged.

### Petrography of the magmatic occurrences

Early Cambrian Volcanic activity of the western High Atlas is represented by four magmatic occurrences (V1 to V4) emplaced during the “Cambrian Rifting” (Pouclet *et al*. 2007, 2018, Aarab 2007). These four magmatic events have been distinguished on the basis of their emplacement levels within the stratigraphic coulumns. The V2 is distinguished from the others by its distinctive explosive character and its lateral geographic extension. In order to assesses the characteristics, the evolution and the affinity of the V2 volcanic activity; eighteen (18) samples from several areas of the Western High Atlas have been analyzed, and compared with previous geochemical data (Pouclet *et al.* (2007) and others) on this volcanic activity of the Western High Atlas. The V1 basaltic flows overlies Ouarzazate group complex. In Tizi-N-Isdid area, close to Major Anti-Atlasic Fault (Fig. 1), the V1 thickness does not exceed 130m, gradually increases to the NE and reached more than 500m at Agoundis area. The youngest similar event is highlighted in the Eastern of the Anti-Atlas (Gasquet *et al.* 2005, Levresse 2001, Thomas *et al.* 2002, Walsh *et al.* 2002) and was dated to 550 to 552 Ma and 559 to 565 in the Western Anti-Atlas (Thomas *et al*. 2002, Walsh *et al*. 2002). The V1 basaltic flows are surmounted

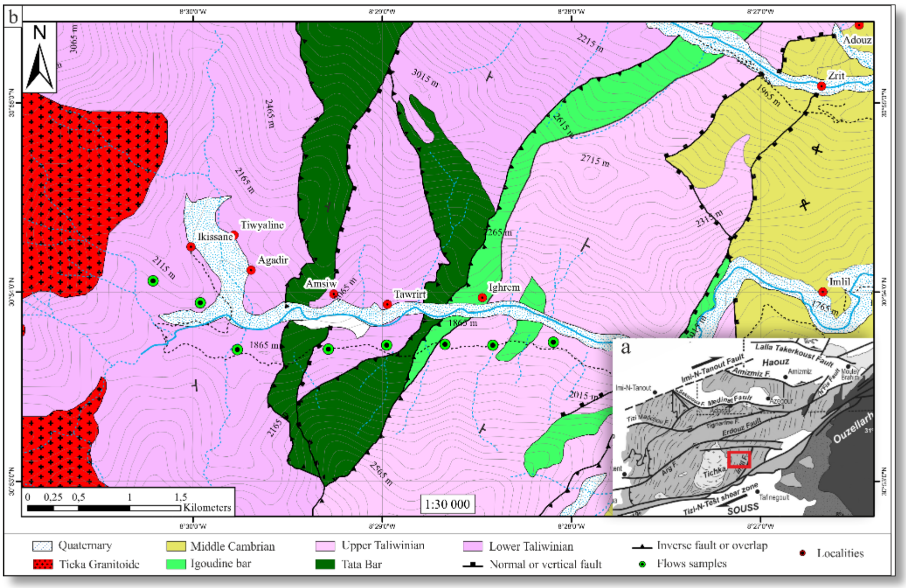


Figure 4. a. Simplified geological map of the Western High Atlas and geographic location of Aghbar Valley; b. Geological map of Aghbar area (adapted from Geological map of Tafingoult 1/50 000).

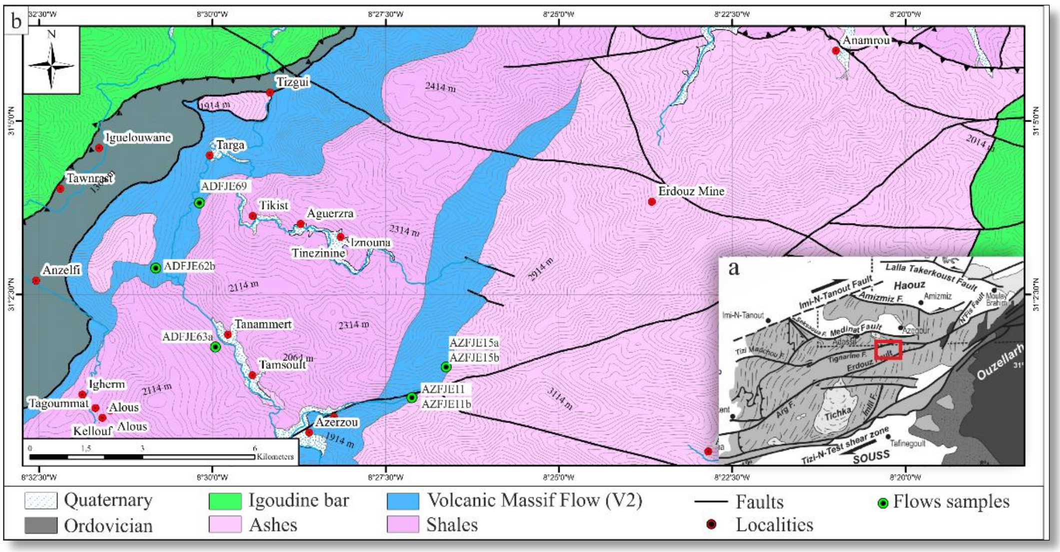


Figure 5. a. Simplified geological map of the Western High Atlas and geographic location of Iounsektene Valley; b. Geological map of Iounsektene area (adapted from 1/50 000 Geological map s of Jouhari *et al*. 2018, Ouanaimi *et al*. 2018).

by sedimentary formations correlated to the Early Adoudounian formations of the Central Anti-Atlas (Pouclet *et al*. 2007). The absence of this magmatic event in the High-Atlasic block of the Western High Atlas is related to the high subsidence level in this area.

Volcanic products of the V2 event outcrops in several areas in the Western High Atlas. This magmatic activity is highlighted by several authors and considered anomalous due to its Calc-Alkaline signature. In the Agoundis Valley, the V2 lenticular shapes deposits lead Aarab *et al*. (2005) to interpret them as laccolites. Actually, in details, they correspond to massive volcanic flows (MVF) that consist of volcano-conglomeratic deposit which grain and cement present same volcanic lithology (Fig. 7). The V2 MVF which overlies the Early Tommotian Tamejout limestone (Pouclet *et al*. 2007), are interbedded within the Tata limestones and surmounted by the Igoudine limestones. Similar MVF deposits are recognized in the Aghbar and the Iounsektene valleys in the High Atlas block and are thicker and more extended (Figures 4 and 5).

The V3 volcanic event is materialized by a lacoolitic deposit hosted in the Igoudine limestone (Pouclet *et al*. 2007, Aarab 2007). *Archaeocyatha* are noticed in the massive part of the limestones and thus implies Atdabanian age to this formation (Debrenne & Debrenne 1978).

The V4 volcanic unit consists of several magmatic layers interstratified with Issafen-Asrir limestones (Pouclet *et al*. 2007, Aarab 2007). It's an intense effusive spilitic activity, with chimneys and flows. The last two magmatic events are not very developed in the High Atlasic block of the Western

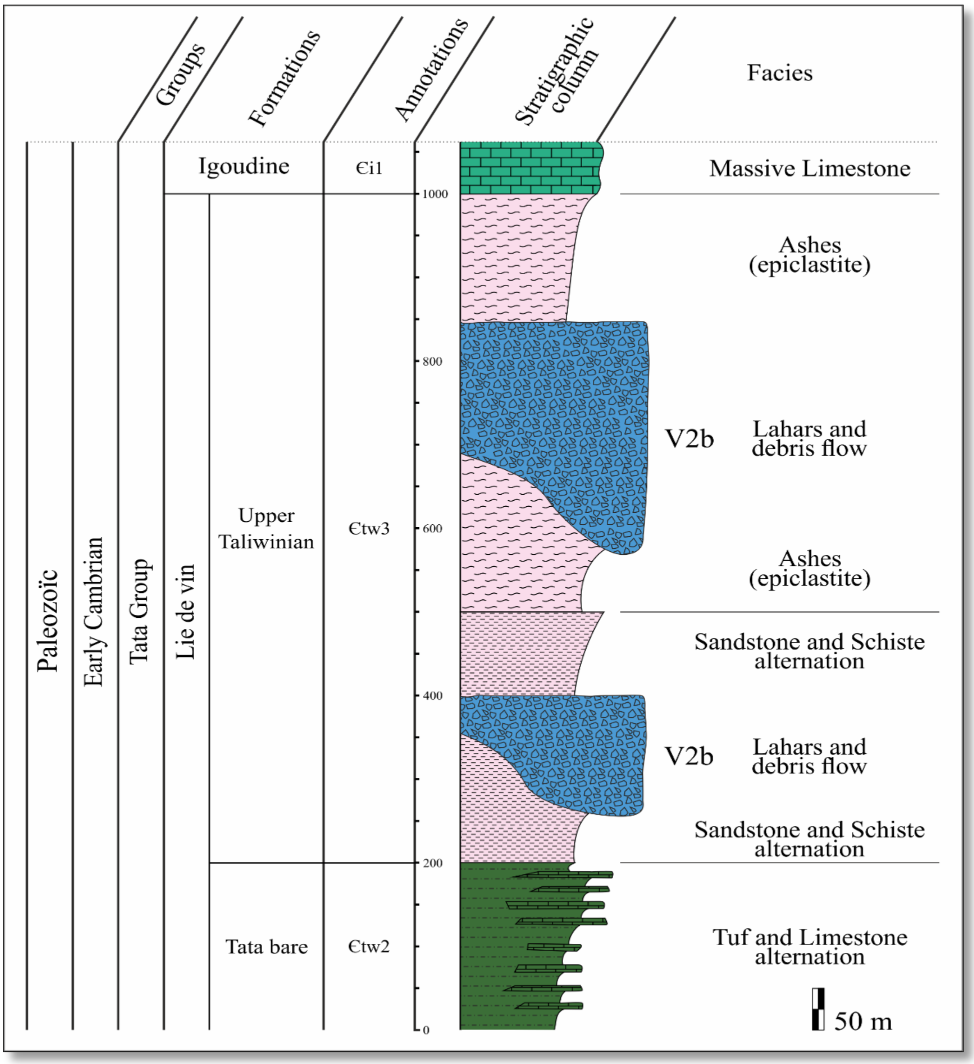


Figure 6. Synthetic lithostratigraphic column of the High-Atlasic block of the Western High Atlas

High-Atlas, some V3 relicts are associated to the Igoudine limestones in the Azegour area.

Petrographically, the V2 explosive rocks include a volcanic conglomerate which grain and cement present the same volcanic lithology (Fig. 8). In Agoundis area, they consist of dominant microliths of plagioclase and opaque in the groundmass and hornblende phenocrysts (Fig. 8a). In Aghbar Valley, phenocrysts are essentially plagioclases and clinopyroxenes (Fig. 8b). The Iounsektene V2 conglomerate has the same mineralogy as the Aghbar ones but with angular forms of plagioclase minerals (Fig. 8c) testifying the explosive attitude of this magmatic activity. The mineral assemblage indicates that the Agoundis volcanic conglomerate corresponds to basaltic composition and the volcanic conglomerate of the other areas shows an andesitic composition.

## Geochemical Affinity

We have collected 18 samples of the V2 rocks from several areas of the Western High Atlas (Figures 2, 4 and 5). The volcanic Massif flows of the Anti-Atlasic block underwent low-grade metamorphic conditions while those of the High Atlasic block are affected by high-grade metamorphic transformation. Thus, the nomenclature and the chemical characterization have been conducted using only elements assumed immobile (Nb, Zr, Y, V and Ti) during the secondary processes and showing consistent trends (Floyd & Winchester 1975, Wood *et al*. 1979, Pearce 1983, Rollinson 1996). The remaining analyses are given in Table 1. The studied rocks display mafic to intermediate composition, their SiO2 contents range from 47.8 to 64.44, TiO2 from 1.26 to 1.64 and MgO from 1.14 to 5.34. In the Zr/TiO2–Nb/Y diagram of Winchester & Floyd (1977) (Fig. 9) the volcanic rocks of the Agoundis-Ounein area, represented by the set of V3 to V4 through V1 (Pouclet *et al*. 2007) define series from andesite/basalt to rhyodacite/dacite, including andesite, suggesting a sub-Alkaline series. While the analysed V2 rocks define a subalkaline series. The V2 volcanic conglomerate of Agoundis area plots in the Alkali-basalts field while the others plot on the andesite range. The affiliation to the calc-alkaline series can also be

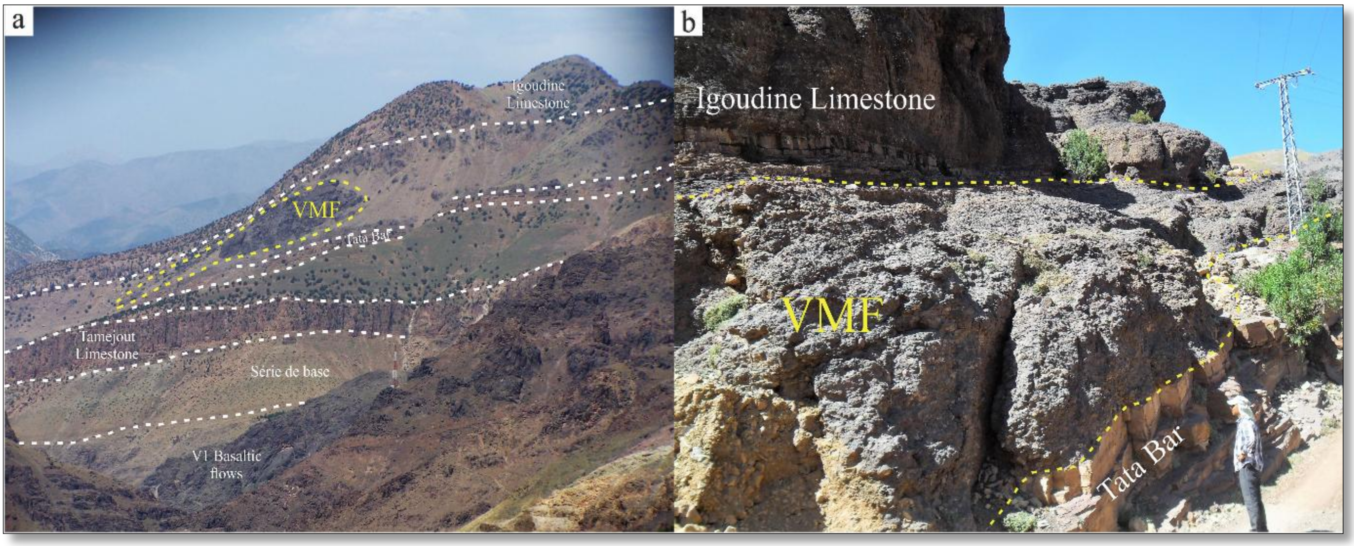


Figure 7. a. View looking South of the Agoundis Valley showing stratigraphic column with lenticular shapes of volcanic conglomerate (V2); b. Volcanic massif flow within the "lie de vin" series in the Tagdirt-Izder. Person as scale.

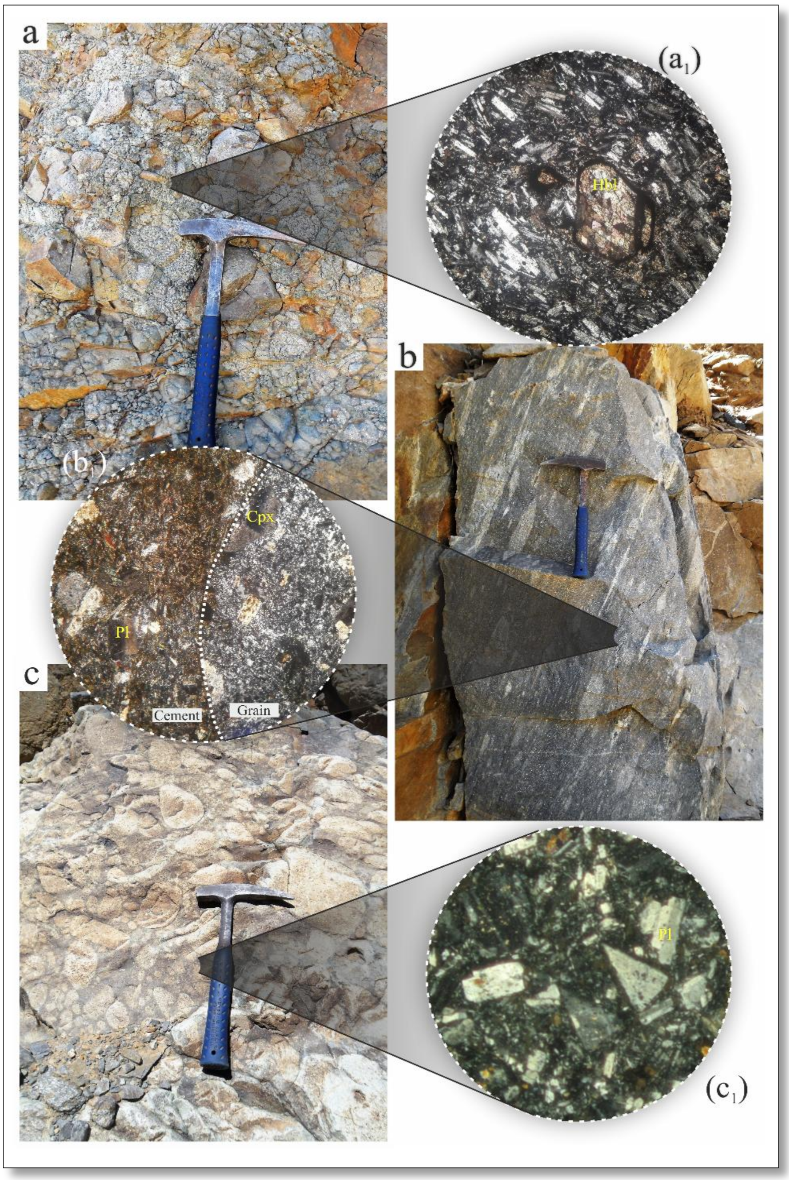


Figure 8. Field pictures and microphotographs (x40) of the V2 volcanic conglomerate. (a) Field pictures showing the aspect of the volcanic conglomerate of the Agoundis valley. ($a_1$) Microphotograph focused on the boundary between grains and cement. (b) Field picture of Aghbar volcanic conglomerate. ($b_1$) Microphotograph of the Aghbar volcanic conglomerate. (c) Field picture showing the Iounsektene volcanic conglomerate. ($c_1$) Microphotograph zooming on plagioclase minerals with angular forms of Iounsektene volcanic conglomerate. Am - Amphibole; Cpx - Clinopyroxene; Hbl - Hornblende; Pl - Plagioclase; Ol - Olivine; Ox - iron oxide.

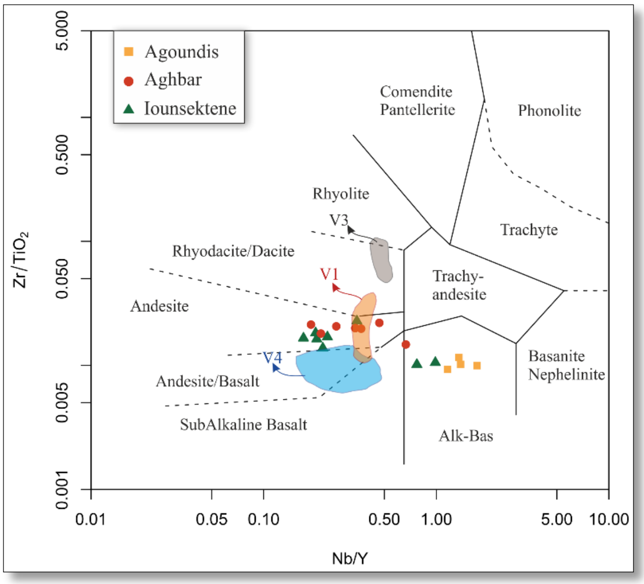


Figure 9. V2 Volcanic Massif Flows plotted in the Winchester & Floyd (1977) diagram compared to reference rocks. From Pouclet *et al.* (2007).

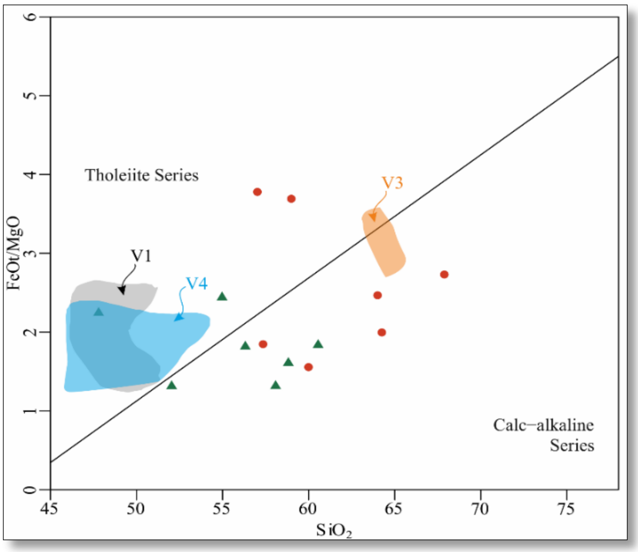


Figure 10. V2 Volcanic Massif Flows plotted SiO2 Vs FeOt/MgO diagram After Miyashiro (1974) compared to reference rocks from Pouclet *et al*. (2007) and El Archi *et al.* (2004). Same symbols as for Fig. 9.

demonstrated in the SiO2 vs FeOt/MgO diagram after Miyashiro (1974, Fig. 10) for Aghbar and Iounsektene volcanic conglomerate. However, the V2 fractionated pattern of different areas shows different aspects. The Agoundis V2 volcanic conglomerate shows a very fractionated profile with $La_n/Yb_n$ ratios ranging from 9.56 to 17.83. This high fractionation profile of the Agoundis V2 rocks is the result of a low fractionation of LREE (La to Gd) and a high fractionation in HREE (Tb to Lu) (Fig. 11a). While those of Aghbar Valley are relatively fractionated ($7.17<La_n/Yb_n<12.48$) (Fig. 11c). The V2 of the Iounsektene Valley are moderately fractioned with $La_n/Yb_n$ ratios ranging from 3.44 to 9.88, with a moderately Eu-negative anomaly (Fig.11e). The $La_n/Yb_n$ ratios (>8) and the low ratio of Nb/Y (<1) of the Iounsektene and Aghbar volcanic conglomerate are similar to calc-alkaline orogenic rocks.

The incompatible elements profiles, Primitive Mantle normalized after (Sun & McDounough 1989) are used to approach the geotectonic signature of the volcanic rocks. N- and E-MORB signature are excluded based on the heavy REE depletion and the more incompatible element enrichment of the V2. The Continental tholeiite signature must also be excluded relating to their LILE/HFSE>10 ratio. By its positive Nb and Ta anomalies, the Agoundis V2 volcanic conglomerate fit with alkaline series (Fig. 11b). While the Iounsektene and Aghbar volcanic conglomerate fit with the orogenic calc-alkaline series by their Nb, Ta and Ti negative anomalies and High fractioned profile (Fig. 11d, f). The geotectonic settings displayed in the Y/15-LA/10-Nb/8 diagram of Cabanis & Lecolle (1989) shows that Iounsektene and Aghbar V2 Volcanic conglomerate has a calc-alkaline basalt signature while those of the Agoundis

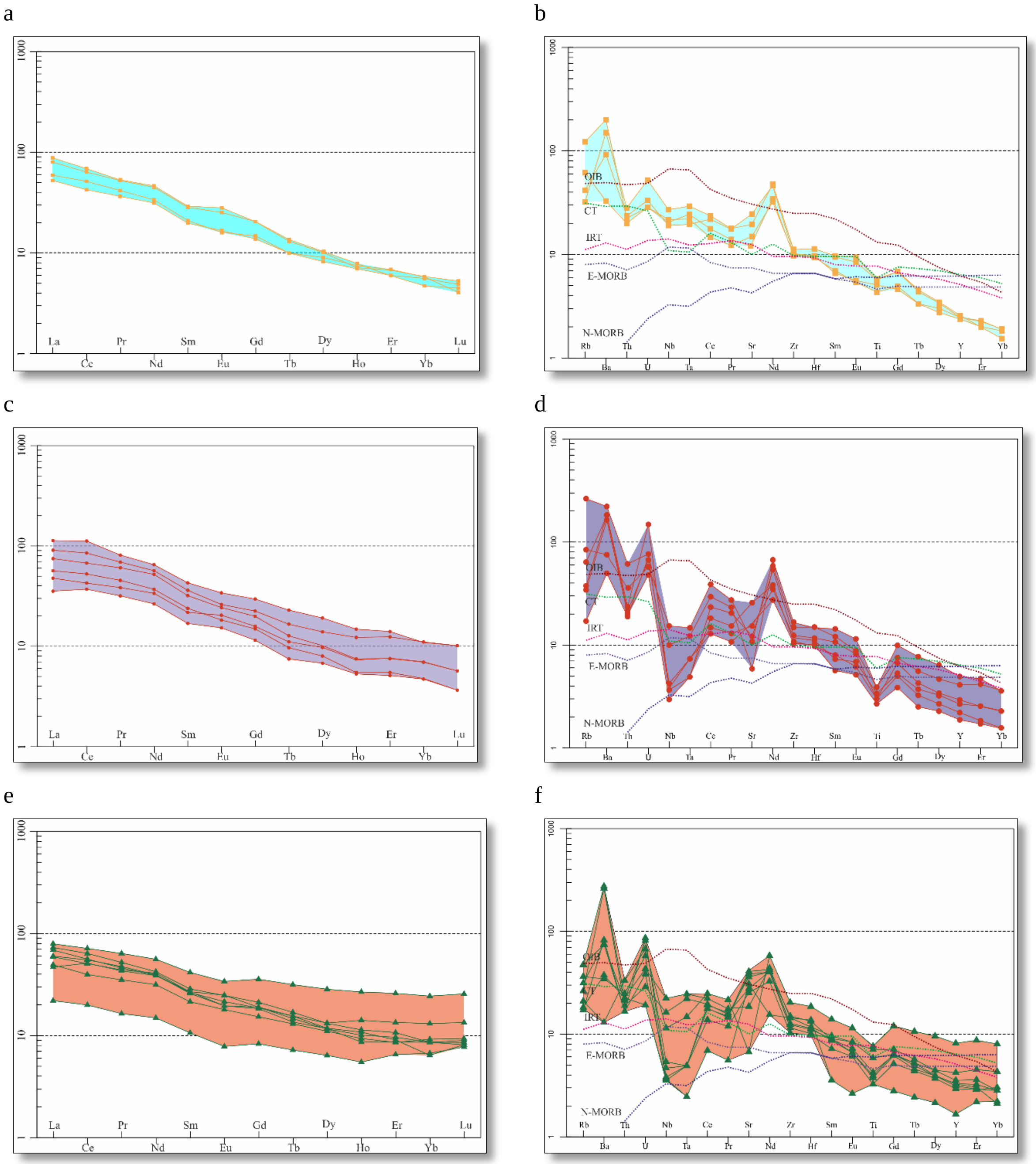


Figure 11. Chondrite-normalized diagram (Sun & McDonough 1989) for REE for V2 volcanic conglomerate of the Western High Atlas. (a) Agoundis, (c) Aghbar et (e) Iounsektene.; b. Primitive Mantle normalized incompatible element diagram of the V2 volcanic conglomerate of the western High-Atlas Normalization values of Sun & McDounough (1989). (b) Agoundis; (d) Aghbar and (f) Iounsektene.

area are located in the range of Continental tholeiite (Fig. 12). In addition, the $(La/Sm)_C$ vs $(Gd/Yb)_C$ diagram (Fig. 13) clearly shows that the V2 Volcanic conglomerate are originated from a garnet bearing source while the other V1, V3 and V4 originated from a spinel bearing sources.

## DISCUSSION

During the Ediacaran time, the northwestern part of Paleo-Gondwana was marked by the final suture of the Anti-Atlas Pan-African mobile belt and the West African Craton, followed by the accretion of the Mesetian-High Atlasic domain. An extensive regime began during latest Proterozoic in the Anti-Atlas and ended in this area at the end of the Early Cambrian, while in the High Atlas it is operating during Early Cambrian and aborted at the end of the Middle Cambrian (Piqué 2003). This transition from an orogenic to anorogenic environment is reflected in the geochemical affinities of the igneous rocks and account for the discordance observed between the Neoproterozoic basement and its lower Paleozoic cover.

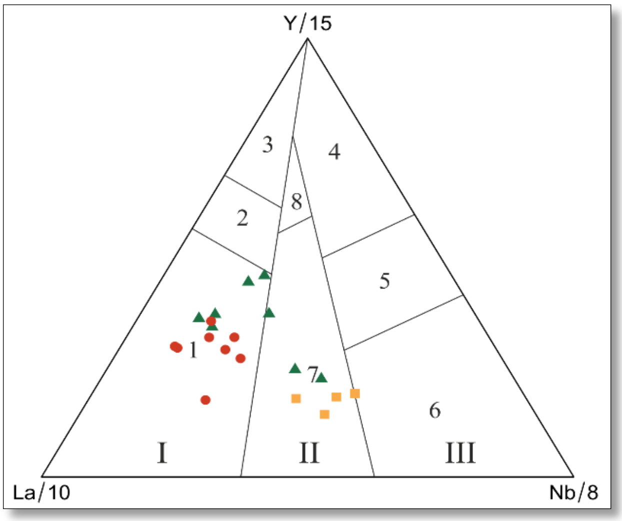


Figure12. V2 volcanic conglomerate plotted in the Geodynamic diagram of Cabanis & Lecolle 1989. Same symbols as for Fig.9. 1. Calc-Alkali Basalts , 2.Intermediary , 3.PIAT , 4.N-MORB; 5. E-MORB;.6.Alkali Basalts; 7.continental Tholeiite; 8.Back Arc Basalts. I. Orogenic domain; II.Intra-continental Domain; III.Anorogenic domain

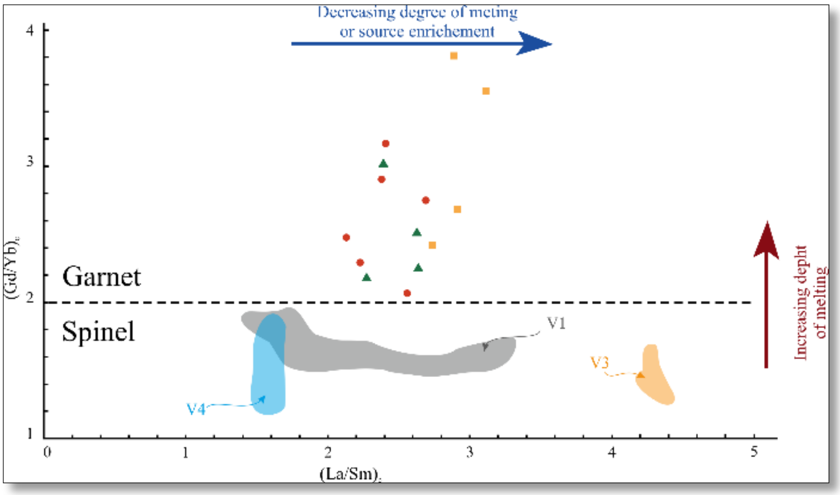


Figure.13: V2 volcanic conglomerate plotted in $(La/Sm)_C$ vs $(Gd/Yb)_C$ diagram. Same symbols as for Fig. 9.

The Early Cambrian volcanic activity of the WHA displays a great rock types diversity, ranging from effusive to explosive. The difference of the implementaion modes reflects the diversity of sources and the emplacement process. In fact, the effusive rocks described in the Agoundis-Ounein area (V1, V3 and V4), are related to the "Cambrian rifting" that occurs on the Western High Atlas (Pouclet *et al*. 2007). This reality may appear controversial with the calc-alkaline signature obtained by some diagrams. According to LILE/HFSE ratio the continental tholeiite signature is the convenient profile of this magmatic occurrence. This calc-alkaline signature is inherited from the melting of a metasomatized mantle during ancient subduction that occurred probably at the Pan-African orogeny (El Hadi *et al*. 2006, Pouclet *et al*. 2007).

The V2 volcanic event is contemporaneous with the deposition of the detrital deposits assigned to the "Lie de vin" series (Fig. 14). It consists of explosive volcanic conglomerate whose grains and cement presents the same lithology. The compilation of petrographic and geochemical data compilation reveals some differences between the three studied areas. The V2 outcrops in the Aghbar and Iounsektene valley consist of huge conglomerates deposit, while in the Agoundis Valley they are limited to large lenticular shapes. The incompatible elements profiles and the geotectonic diagrams of this volcanic conglomerate lead to the same result, the Agoundis volcanic conglomerate are comparable to the alkaline rocks emplaced in anorogenic context, they are contemporaneous to Iounsektene and Aghbar calc-alkaline volcanic conglomerate whose signatures are similar to calc-alkaline rocks emplaced in orogenic context. The alkaline signature fit with the extensive event that occurs in this domain during this epoch. It seems impossible to link the calc-alkaline signature to any oceanic subduction in this part of Morocco especially during Early Cambrian (Piqué 2003, Pouclet *et al*. 2007, 2008, Aarab 2007). The bimodal rocks (alkaline and calk-alkaline) are related to the source effect or crust partial melting. Otherwise, the calc-alkaline signature is probably inherited from melting of a remnant rocks related to the Ediacaran Cadomian arc subduction event (Linnemann *et al*. 2008, El Hadi *et al*. 2006). According to the stratigraphic emplacement of the V2 Volcanic Massive Flows between the Tommotian Tamejout limestone, and the Atdabanian Igoudine limestone, we confirm a c.a. 530 to 510 Ma age for this event as proposed by Pouclet *et al*. (2008).

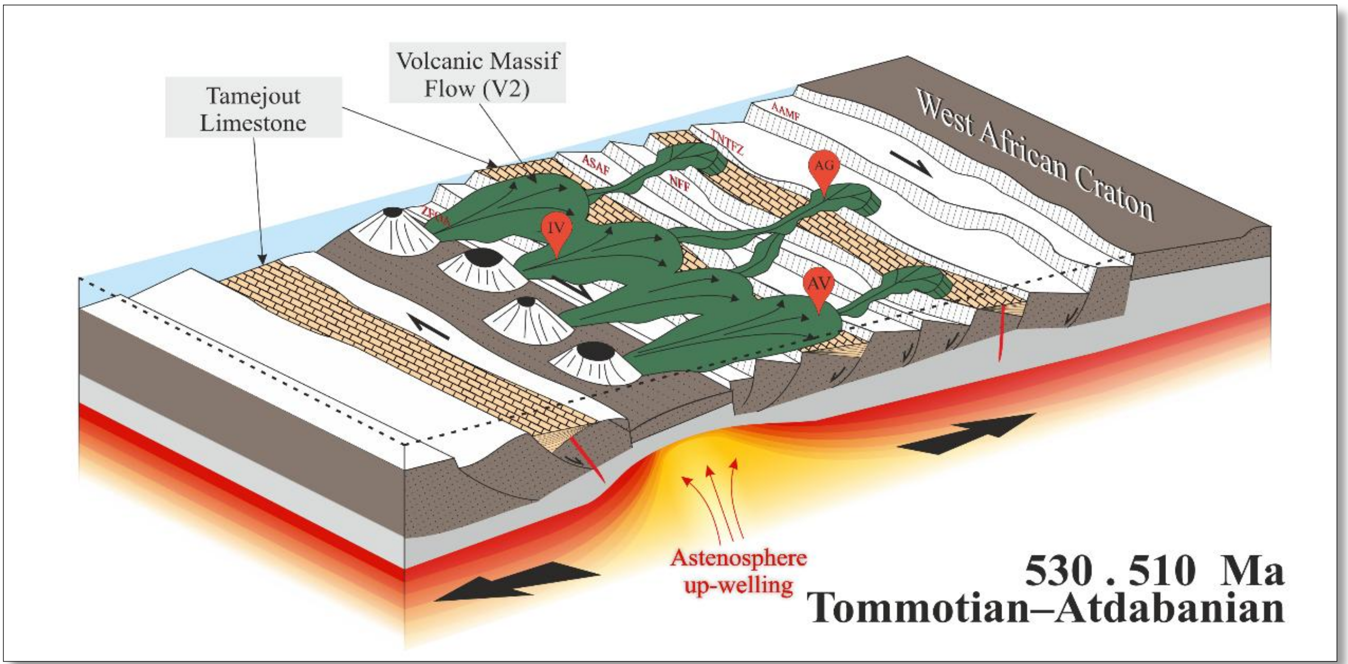


Figure.14. Model for the emplacement of the V2 volcanic massif flow on the Western High Atlas.

The geographical spread of the V2 to the two blocks of the High Atlas (Anti-Atlasic and High Atlasic blocks) on the one hand and its different geomorphological expressions on the two blocks, on the other hand, are favourable assets to develop a paleogeographic reconstitution of the studied area in the Lower Cambrian (Fig. 14). According to our model, the V2 provenance has been located far to the West, gave large mud-flows in the High-Atlas block and reduced to lenticular fans in the Anti-Atlasic block to disappear completely to the East in the Anti-Atlas. This states that the High Atlas and the Anti-Atlas were side-by-side at least from the Lower Cambrian.

## CONCLUSION

The abundance of volcanic activity throughout the WHA contributes to reconstitute the evolution of this domain. The nature and signature of the WHA magmatic rocks reflect the stress inversion, from compressive during the Pan-African orogeny, to extensive during the Cambrian extensive event. The effusive rocks of the Agoundis-Ounein area, related to the “Cambrian rifting”, consist of basalt and andesitic basalt with orogenic calc-alkaline signature. This exposed signature results from the melting influence of a previous orogenic component.

The explosive V2 volcanic massive flows represent a potential new stratigraphic marker in the Cambrian terranes of Morocco by its relation with the “Lie de Vin” series. The Conglomeratic aspect, morphology and bimodal signature of this volcanic activity result from different sources generated by the dominant extensive stress during the Early Cambrian. It’s a particular volcanic event resulted from melting a deeper remnant rock related to Cadomian arc subduction event. This volcanic diversity resulting from a heterogeneity of the lithospheric source composition and probably also different degrees and depth of partial melting of the mantle. The westward-to-east lateral evolution of V2 magmatism is favorable to a westward-located Aerian volcanic source and an eastward spread that involves the placement of large flows in the High-Atlasic block and fans in the Anti-Atlasic block of the High Atlas and a complete disappearance in the Anti-Atlas. This scheme states that the High Atlas and the Anti-Atlas have been side-by-side at least from the Lower Cambrian.

Similar volcanic diversity is highlighted further north, in the Mesetian domain during the Middle Cambrian. The Oued Rhebar calc-alkaline volcanic activity (El Hadi *et al*. 2006) is probably the continuity of the V2 volcanic event in time and space. This volcanic event is also contemporaneous with tholeiitic magmatism at Bou Acila (Ouali *et al*. 2003) and alkaline basalt at Sidi Said Maachou and Haute Moulouya (Ouali *et al*. 2000, 2001).

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