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Imprint of the Reguibat Promontory (West Africa) on the Appalachian, Mauritanide and Souttoufide Belts During the Assembly of Pangaea

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Abstract

In the course of the Carboniferous to Permian assembly of Pangaea, large parts of eastern Laurussia and northern Gondwana were affected by the Variscan Orogeny. Here, we particularly focus on the Appalachian belt of eastern Laurentia and the Mauritanide of western Gondwana. Owing to the irregular shapes of the craton margins, the collision between the Laurentia and the West African Craton provides several conjugate promontories and embayments alongside both cratons. Among others, the coupled pair formed by the African Reguibat promontory and its counterpart in North America, the Pennsylvania embayment is the principal subject of this study. The western movement of the Reguibat Shield had initially imprinted the West African belts but finally also affected the Appalachians. Forming such a "punch mark" producing two specific lobes (stacks of nappes) on both sides of the promontory. The southern NW-SW lobe (e.g. Akjoujt nappes) is known since a long time. However, the northern lobe of the "Adrar Souttouf Massif" has not been identified previously owing to its partially covering and also by its N-S alignment instead of an expected symmetrical SW-NE direction. Furthermore, the Adrar Souttouf Massif is partially covered by allochthons terranes (WTB or Appalachians). This new discovery supports a classical impingement model for the deformation of the North American and African belts by westward moving of the Reguibat Shield.

Keywords: impingement; gondwana plate margins; variscan orogeny; reguibat shield; West African and North American belts

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1. Introduction

The associated Variscan sutures between Laurussia and Northern Gondwana was formed during the assembly of Pangea and has an irregular, curved shape (Figure 1). This results in several promontories and embayments. The embayments on the Laurentian side correspond to promontories on the West African Craton (WAC) and vice-versa.

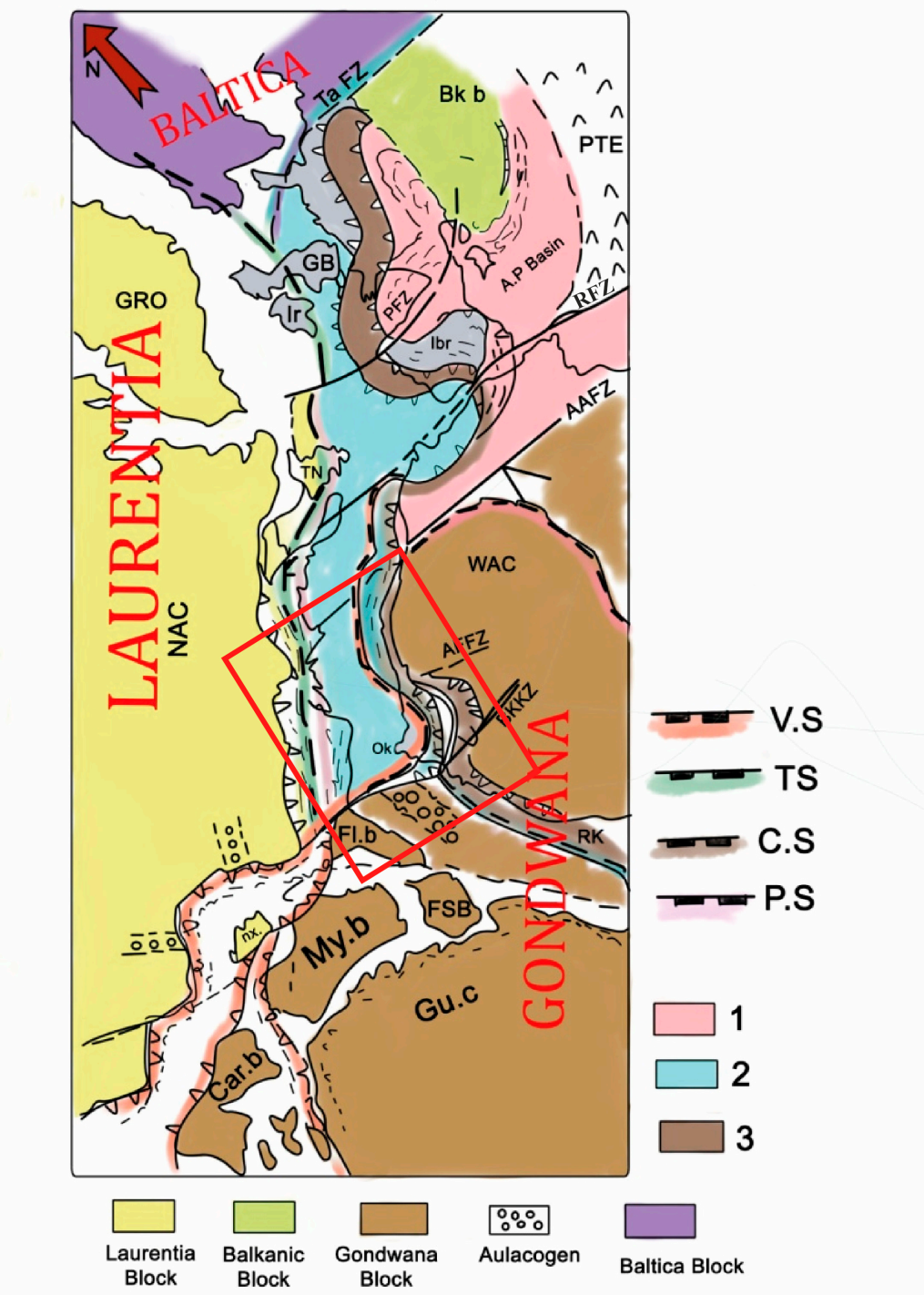

Figure 1. Sketch map of the Variscan belts in the collision zone between Gondwana, Laurentia, and Baltica blocks after [45]. Studied area is in the red frame**.** Legend: 1-Southern European Variscan belts, 2-Appalachian and Northern European belts, 3- Anté-Variscan West Gondwana belts (Bassaride, Rokelides, etc.), VS: Variscan suture (Alleghanian?), TS: Taconic, CS: Caledonian suture, PS: Panafrican suture. NAC: North American Craton, WAC: West African Craton, Bk b: Baltic block, GB: Great Britain, TN: Terra nova, GRO: Greenland, PTE: Peri-Thetys, Flb: Florida block, RK: Rokelide Belt, Car.b: Caribbean Block, My.b: Maya block, Gu.c: Guyana Shield,

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TaFZ: Tornquist fault zone, PFZ: Portuguese fault zone, AAFZ: Anti-Atlas fault zone, AFFZ: Aouker Fault zone, BKKF Bissau–Kidira fault zone.

Here, the focus is on the impact of the West African Reguibat promontory and the corresponding Pennsylvania embayment in the Laurentia (Figure 2). These two regions are bordered by Senegalese-Mauritanian embayment and the corresponding Virginia promontory, to the south and to by the Moroccan-Iberian embayment that corresponds to the New York or Avalonian promontory to the north (Figure 2). The southern limit of the Reguibat Shield is marked by the Aouker Fault Zone (AKFZ) to the south and by the Anti-Atlas Fault zone to the north (AAFZ). While only the southern parts of the Reguibat Shield crop out, its northern parts are concealed underneath the sedimentary rocks of the Tindouf Basin. The latter has often resulted in underestimations of the importance of the Reguibat Shield (northern outcrop of the WAC) in constraining reconstructions of Pangea.

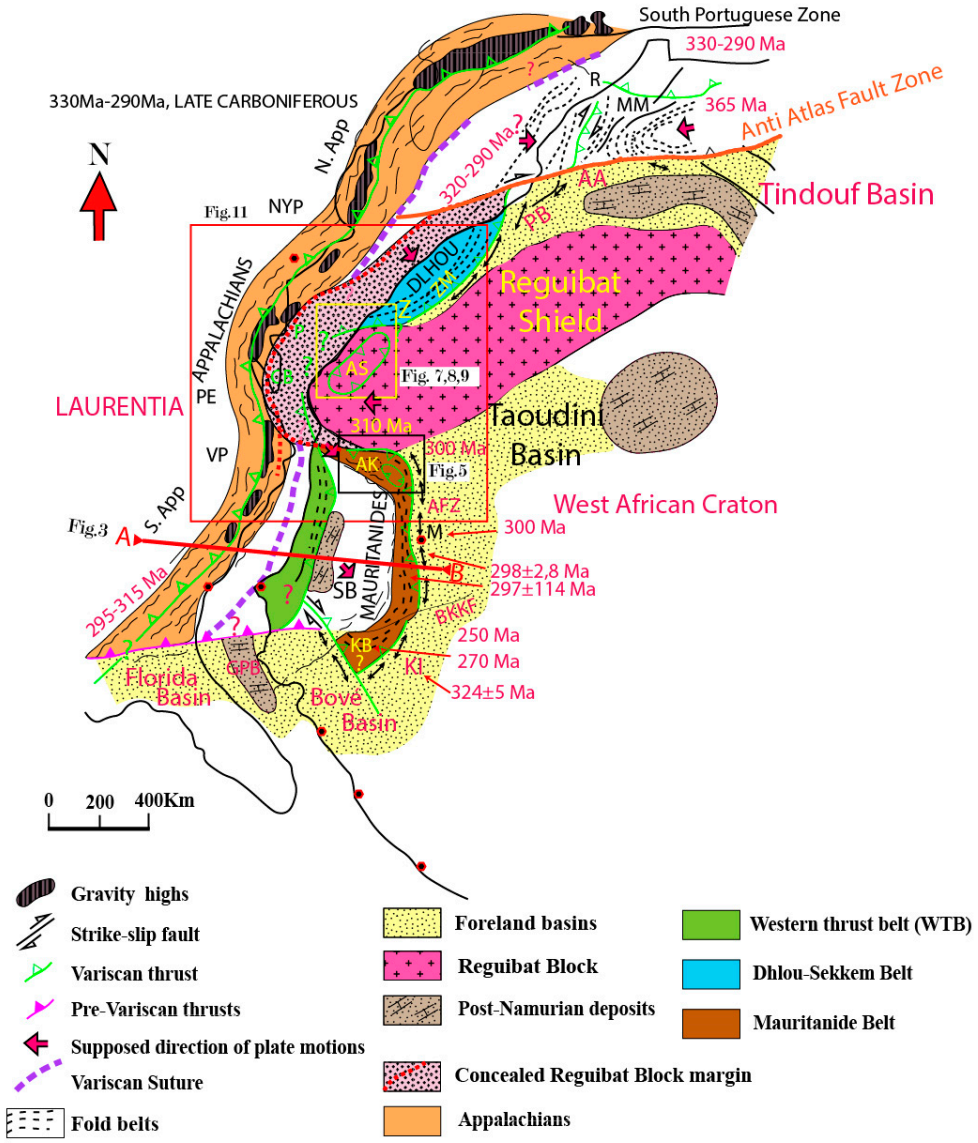

Figure 2. Geological sketch map of the Variscan belts in West Africa and North America modified after [1] with indication of local geological schemes of this study. Legend: AA-Anti-Atlas Belt, AS-Adrar Souttouf Massif, SB-Senegalese Block, MM-Moroccan Meseta, PB-Plage Blanche, ZM –Zemmour massif, TIB-Tindouf Basin, TB-Taoudeni Basin, KB-Koulountou Block, BB-Bové Basin, GPB-Guinean Paleozoic Basin, FL-SB–Florida or Suwanee Bassin, SApp-Southern Appalachians, NApp. Northern Appalachians, VP-Virginia promontory, PE-

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Pennsylvania Embayment, NYP-New York Promontory , AK-Akjoujt , D-Dakar, CX- Conakry , F-Freetown, Mo-Monrovia, CH-Charlotteville, NY- New York. 360-Ages of deformations presented in Ma [46].

The Reguibat Shield is tripartite: (1) a concealed convex western element, (2) more distal element now preserved in the Appalachians and (3) the Souttoufide Belt to the north. The latter includes, from the south to the north: The Adrar Souttouf Massif, the Zemmour Massif including the adjacent Dhlou-(Sekkem) Belt and, finally, the "Plage Blanche" Belt [2]. The Reguibat promontory only concerns the southwesternmost part of the Reguibat Shield and is limited to the south by the Mauritanide Belt and to the north by the Adrar Souttouf Massif. Thus, the northern and southern parts of this Reguibat Shield are not symmetric (Figure 2). This asymmetry which does not fit with the classical impingement model induced a controversial interpretation of the Adrar Souttouf Massif [2,23–25,28,33,37]. This controversial interpretation opposed the supporter of a central synform of sheets thrusted on the Reguibat basement from the East [28,37] and the supporters of a stack of nappes thrusted from the West to the East [2,30,31]. These elements and taking into account the dissymmetry in the orientation of structures, prevent to apply directly the Lefort model [4,5] of impingement. Our new interpretation reconciles the different points of view and allows us to propose a better "imprinting" model for both sides of the Palaeozoic Rheic Ocean.

2. Geological Framework

The collision of West Africa and North America during the assembly of Pangaea resulted in the formation of Variscan Orogen is shown in Figure 2. The Variscan has a mainly N-S trend and can be followed from Morocco to Senegal. Furthermore, this suture is linked to the E-W-directed Brunswick magnetic anomaly that is located between the Appalachians and the Florida Basin. Furthermore, the North American part includes large portions of basement and presumably the Appalachians rest upon the older cratonic basement. The eastern part of the Variscan suture is more complex. It includes the WAC basement surrounded by three Variscan belts: the Adrar Souttouf and Dlhou-Sekkem belts, both representing parts of the Souttoufide Belt to the north and the Western Thrust Belt (WTB), the Mauritanide Belt that are separated by the Senegalese Block including the foreland basins to the south. The foreland basins of the Reguibat Shield and the mentioned orogenic belts comprise the poorly deformed Tindouf, Taoudeni and Bové basins in Africa and the Guinean Palaeozoic Basin (GPB) and Suwannee basins (or Florida basin) in the subsurface of Florida. A geological cross section from the Appalachians to the Mauritanides indicated in Figure 2 and presented in Figure 3, shows a double vergence between the Appalachians and the WTB [3]. We note a vergence to the east for the Mauritanide Belt that is separated from the WTB by the rigid Senegalese Block (SB in Figure 3). Taking the lack magmatic arc in the WTB and some evidence of magmatic arc in the Appalachians [7–9] a westward slab vergence is considered [3] given way to the Appalachian backthrusting.

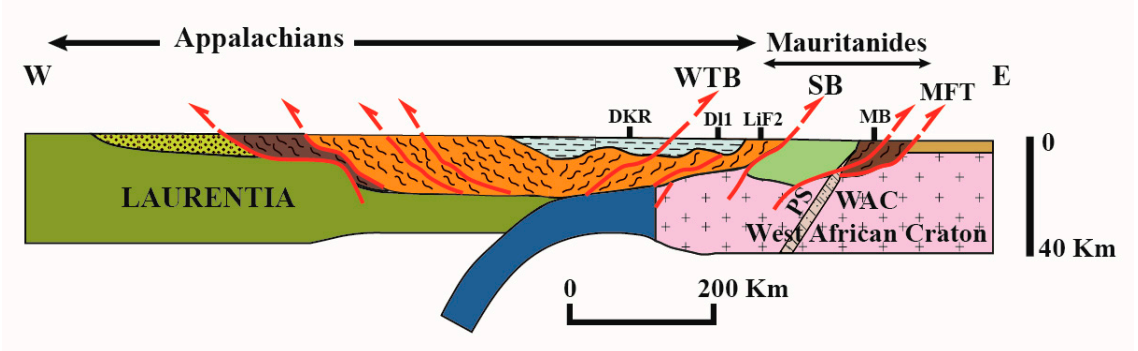

Figure 3. Schematic cross-section along line A-B in figure 2. Legend: as in figure 2. Slab in blue, DKR-Dakar, Dl1-Diourbel well, LiF2-Linguere well, WTB- Western Thrust Belt, SB- Senegalese Block, MB-Mauritanide Belt, MFT-

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Mauritanide Front thrust, PS- Precambrian suture associated to the Bassaride and Rokelide belts. External formations correspond to a melange with pre-Variscan and Variscan formations.

3. The Reguibat Promontory Model of Lefort

A model of the Reguibat imprinting in the Laurentia has been proposed by Lefort [4,5] and presented in Figure 4. This model only considers the southwestern part of the Reguibat Shield as a prong acting as a promontory. According to Figure 4, the westward motion of the southern part of the Reguibat Shield is squeezing the Appalachian and Mauritanide belts, giving way to the "nappes" that are now stacked on both sides of the promontory (areas in green in Figure 4). These areas are furthermore characterised by dextral strike-slip motions along the northern fault and sinistral strike-slip motions along the southern fault that can also be found in the Appalachians. The "nappes" motion is antithetic to the direction of plate convergence.

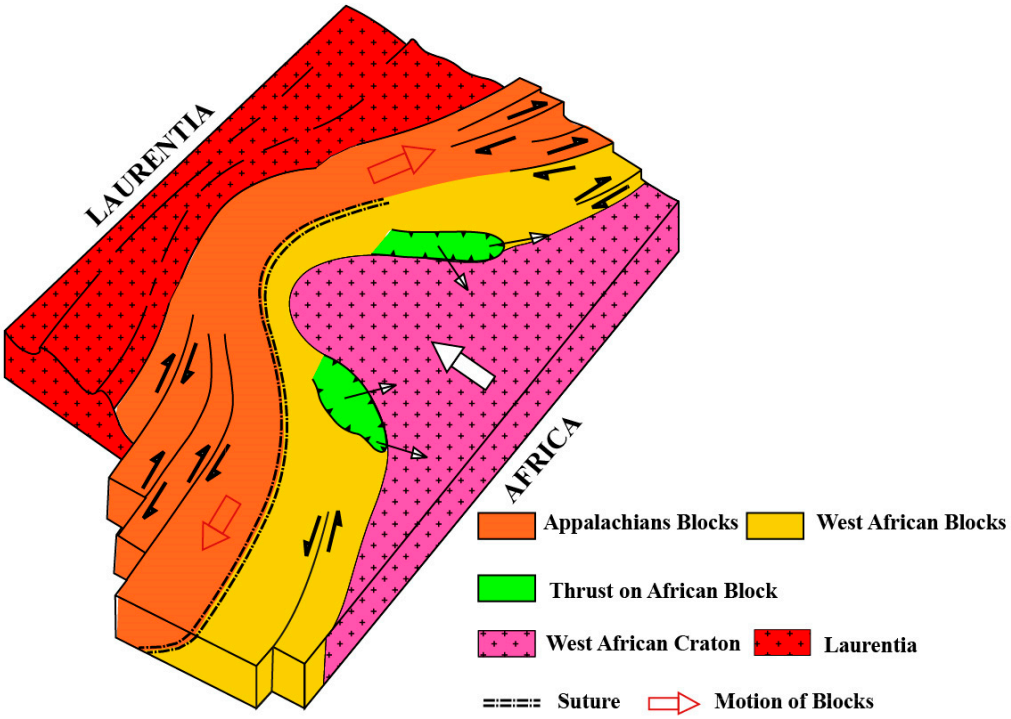

Figure 4. Block diagram that illustrates the tectonic model for the imprint of the Reguibat shield onto the Southern and Central Appalachians (modified after [4]). West African Blocks include the Mauritanide belt, the Senegalese block and the WTB (Western Thrust Belt).

Although the southern part of the Reguibat promontory can be observed in the field, its northern continuation is likely concealed under thick sedimentary sequences. The aim of this paper is to compare the model with field observations.

4. Field Observations

Field observations have been undertaken in the central Appalachians [6–13], in the Akjoujt area of the northern Mauritanides [16] and in the southern Souttoufides (Adrar Souttouf Massif), [2,33–39].

4.1. The Appalachians

The Reguibat promontory caused the separation of the southern Appalachians (S.App) from the northern Appalachians (N.App) by the Pensylvania embayment (PE in Figure 2). According to

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Hibbart et al. [6], the Appalachians can be divided in three parallel belts: the Laurentian terranes to the West, the Iapetian terranes in the middle and the peri-Gondwanan terranes to the East. In the southern Appalachians, there are several strike-slip faults parallel to the three zones. The strike-slip movements along these faults are dextral [7–9]. In the Northern Appalachians, the geological structures are more complex, noticeably with three peri-Gondwanan terranes of Ganderia, W-Avalonia and Meguma. However it is generally agreed that dextral strike-slip motion occurred along the major faults which can be also ascribed to the last oblique collisional event between Laurentia and Gondwana [10–13].

4.2. The Northern Mauritanides (See Figure 5 Indicated in Figure 2)

This part of the Mauritanide Belt is located between the Aouker Trough (AFZ in Figure 2) and the Reguibat Shield. It has been well studied in the course of the prospecting activities and is well known owing to mining company activities around Akjoujt City. The main tectonic event in the Akjoujt series was finally ascribed to the Variscan Orogen by Teissier et al. [14] and Sougy [15] as well as Lecorché [16] and Bradley et al. [17]. Detailed mapping of these units is provided by from Martyn and Strickland [18] as well as Pittfield et al. [19]. The geological map in Figure 5 presents a Reguibat basement (Archaean and Palaeoproterozoic) covered by Neoproterozoic and Palaeozoic sedimentary rocks. These basal formations are capped by the Reg Unit, which contains various rocks resembling those of the Cambro-Ordovician foreland cover. This Reg Unit is dismembered and thrusted over the foreland units. The mainly allochthonous Akjoujt terrane is stratigraphically above them and includes a mix of sheets composed of various rocks such as quartzite, siltstone, migmatite and porphyritic granite. The Akjoujt Unit is considered as a nappe stack (Figures 5 and 6) that was emplaced from the NW to the SE [20] and partially covered by the Agualilet Unit, which crops out in the south-western part of this area and which consists of siliciclastic and volcanic rocks such as basalt, gabbro, prasinite (not interpreted by authors but likely related to ophiolitic remnants) and silicitic tuff thrusted over the previously mentioned units during a Carboniferous tectonic event.

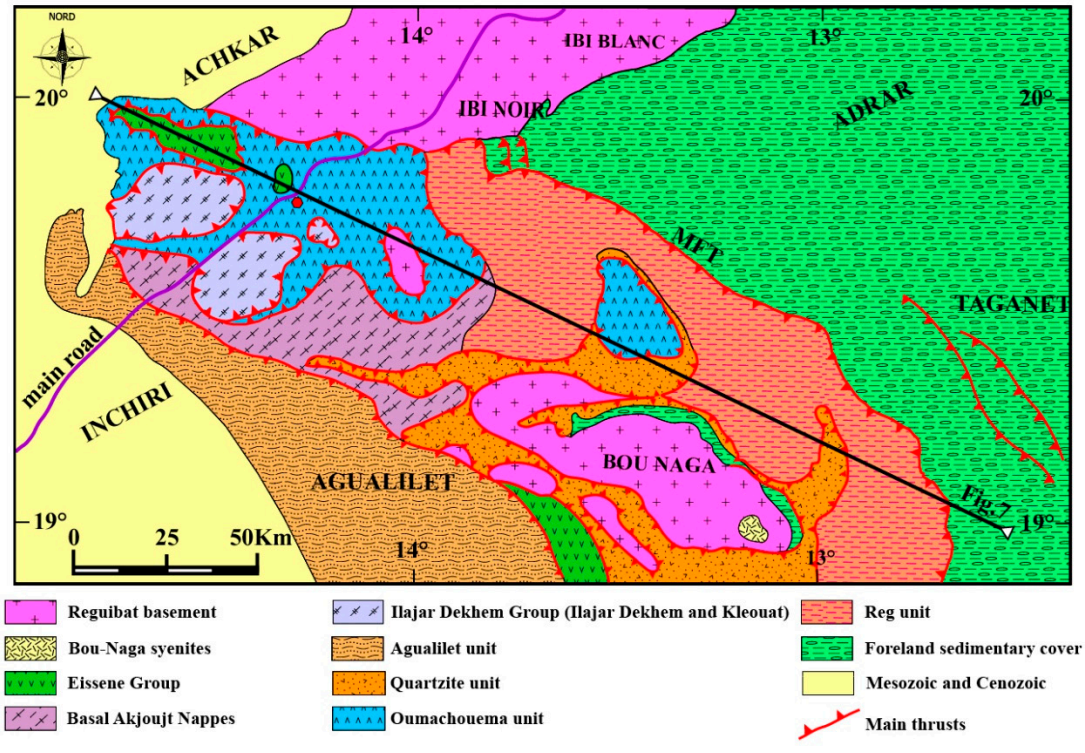

Figure 5. Geological map of the northern Mauritanide area (indicated in Figure 2).This Akjoujt area is surrounded by the Senegalese Block (to the South), the Taoudeni basin (to the East and the Reguibat shield to the North. (Modified after Lecorché et al. [21]).

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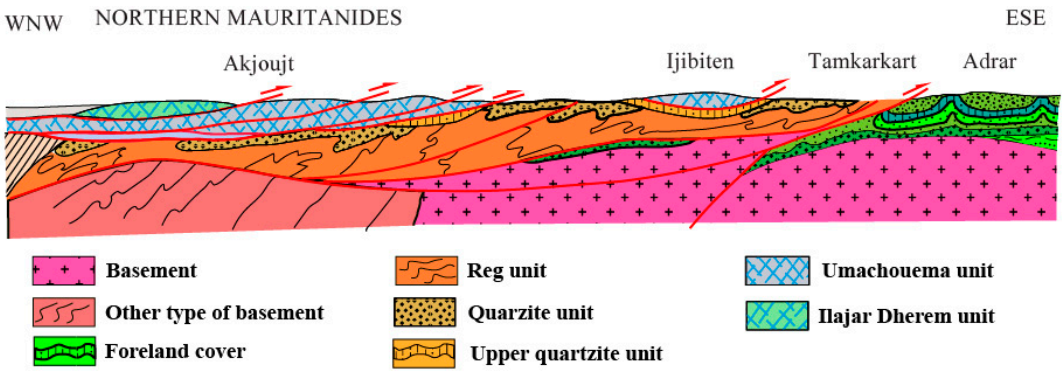

Figure 6. Cross section illustrating the structure from Akjoujt to the Taoudeni foreland (modified after Lecorché et al. [21]).

4.3. Souttoufide Belt

The Souttoufide Belt [2] includes three separate parts: The "Adrar Souttouf Massif", the "Dhlou Belt and Zemmour Massif" and the "PlageBlanche" Belt (located in fig.2)

4.3.1. Adrar Souttouf Massif (Figure 7 Located in Figure 2)

This large and controversial area has been studied by many geologists since 1949. Initial studies were conducted by the Spanish geological Survey [22–26], who considered this massif as the western part of the Reguibat Shield with remnants of Palaeozoic covers. Then, Sougy [27] proposed the thrusting of this massif onto the Reguibat Shield and its thin Palaeozoic cover. Bronner, et al. [28] interpreted aerial photographs and considered this metamorphic massif as a pile of sheets in synform with gabbro thrusted on top of the Reguibat basement and its Palaeozoic cover (Figures 7A and 7B). Le Goff et al. [29] discovered a Neoproterozoic basement with radiometric ages of Variscan metamorphic overprint. Villeneuve et al. [2,30] and Gärtner et al. [31,32] distinguished several units stacked from the West to the East during the Carboniferous Variscan tectonic event (Figures 8A and 8B) without evidence of "nappe synforms". The eastern units are ascribed to the autochthonous Neoproterozoic belts reworked by the Variscan event [2]. Meanwhile the western units are ascribed to exotic terranes likely related to the Appalachians or oceanic remnants and thrusted over the previous autochthonous terranes [31,33,34]. Further geochronological ages by U-Pb on zircon and K/Ar on whole rock and several mineral phases supported this interpretation [32–36]. Recently, Bea et al. [37] according to new radiometric age determination ascribed a part of the western units to the Reguibat Shield basement supporting the Bronner et al. [28] interpretation, which is in contrast to Villeneuve et al. [2].

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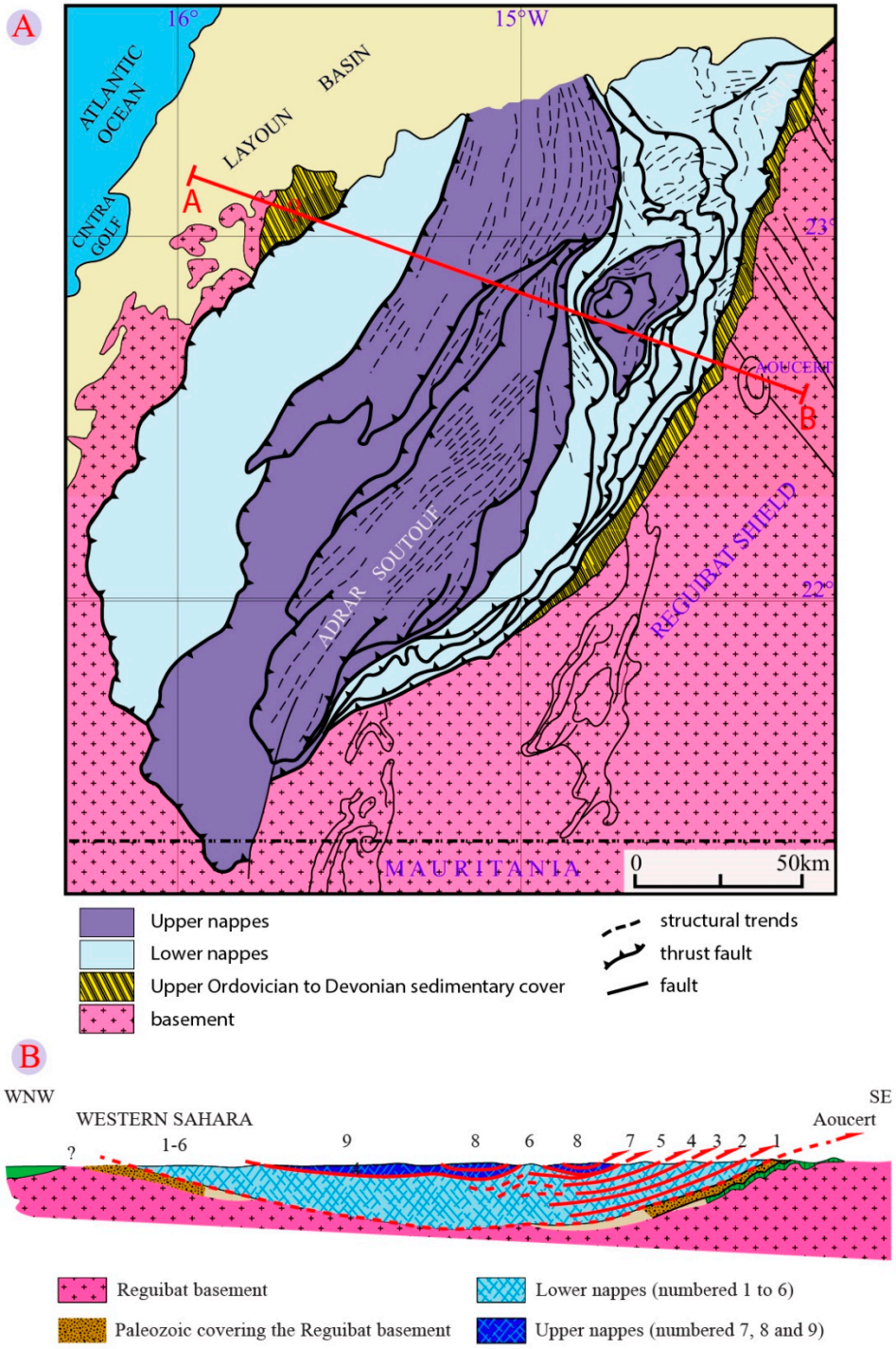

Figure 7. A. Sketch map of the Adrar Souttouf Massif after Bronner et al. [28]. Figure 7B: Geological section across the Adrar Souttouf Massif interpreted as a synform of "nappes" by Lecorché et al. [21].

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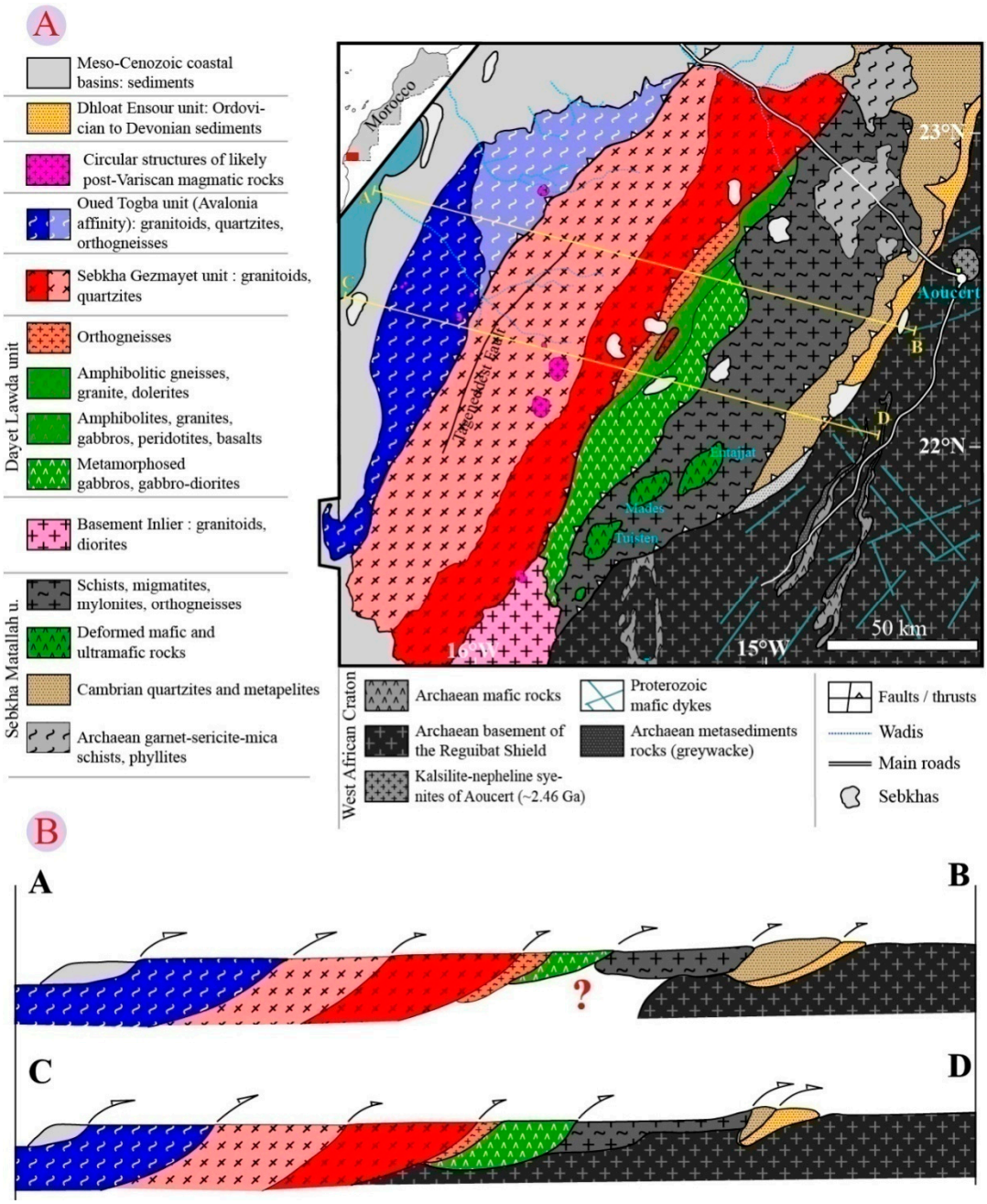

Figure 8. A: Geological scheme of the Adrar Souttouf Massif (modified after Gärtner et al. [31]) with location of cross-sections AB and CD in fig.8A. Figure 8B: Schematic cross-sections AB and CD in the Adrar Souttouf Massif (modified after Gärtner et al. [31].

Until now, there was two opposite interpretations, but the study of the Landsat imagery (Figure 9a) shows that the two previous different interpretations are compatible since we are interpreting (Figure 9b) the central black unit as the thrusted "synform" of Bronner et al. [28] partially covered by thin and peculiar units, which could be related to those mapped in the field by Rjimati and Zemmouri [38] and Villeneuve et al. [30]. Thus, the outcrop of parts of the Reguibat basement in the fore-western units [37] is consistent with an incorporation of a basement sheet into the exotic pile in the course of the thrusting to the east during the late Variscan tectonic event.

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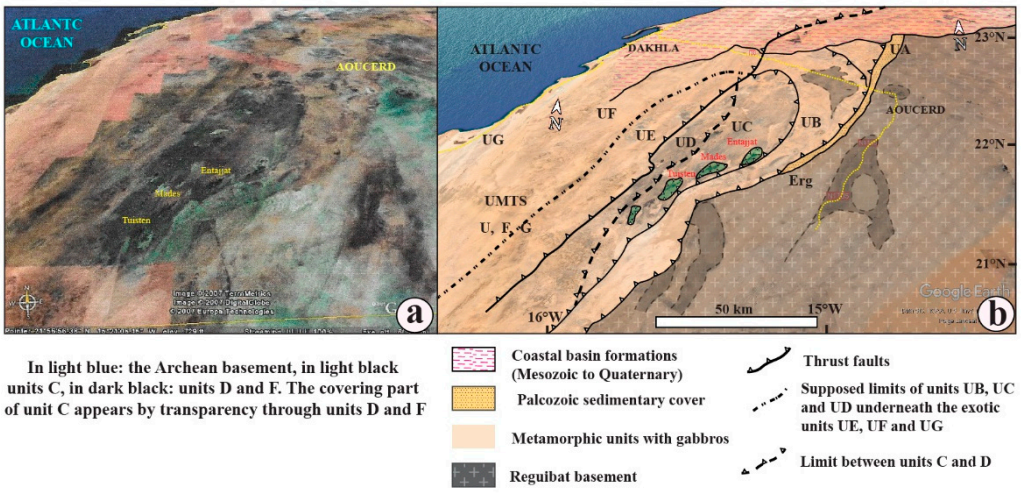

Figure 9. a: Adrar Souttouf Massif photographed from space (NASA photo). Figure 9b: New Interpretation of the Adrar Souttouf Massif with the central gabbroic and metamorphic "nappe synforms". The African units (UB, UC and UD) are covered by the allochthonous units (UE, UF and UG). These units are described in Villeneuve et al. [2].

The seismic profile across the Adrar Souttouf Massif (Figure 10a) after Fateh [39] suggests that the central gutter (unit C in Figure 10b) could be interpreted as the stack of African units ("stacked nappe units") partially covered by exotic units (Figure 10b).

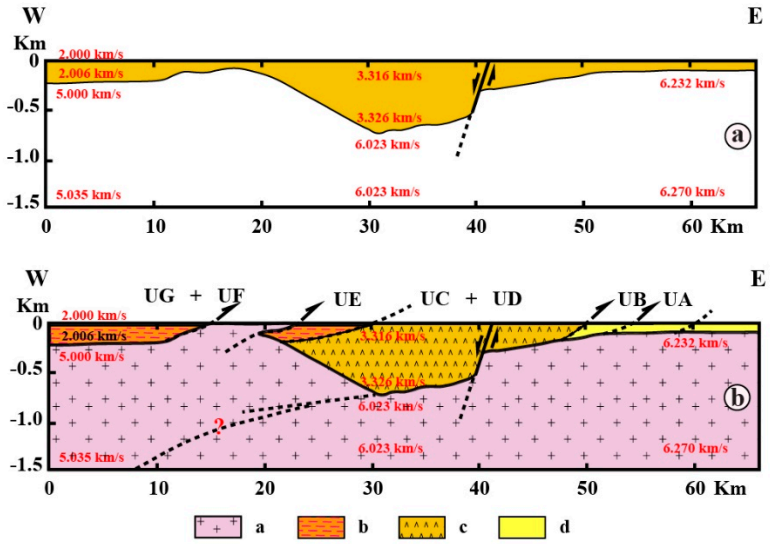

Figure 10. a: W-E Seismic profile across the Adrar Souttouf Massif (Fateh [39]). Figure 10b: Geological interpretation of the seismic profile in Adrar Souttouf Massif. Legend: Allochthonous or exotic terranes (Units E, F and G), African terranes (Units B, C and D), Palaeozoic cover (Unit UA).

The section displayed in Figure 10b could explain why some parts of the Reguibat basement could be allochthonous units like UE, UF or UG during the Variscan tectonic event, in the western part of the massif as it is hypothesised by Bea et al. [37]. We think that parts of the Reguibat basement have been incorporated within the allochthonous units during the last tectonic event.

4.3.2. ZemmourMassif and Dhlou-Sekkem Belt

The Zemmour area studied by Sougy [40] corresponds to the western part of the Tindouf Basin and consists of a sedimentary succession ranging from Ediacaran limestones to the Late Devonian. The Dhlou and Sekkem belts, located to the West, consist in parts of Tindouf Basin sediments folded,

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sheared and thrusted to the east over the western part of the Zemmour Massif. The Dhlou and Sekkem belts were studied by Dacheux [41], Rjimati and Zemmouri [38]) and Belfoul [42].The western part of these belts is concealed underneath the Palaeo- and Neogene sedimentary cover of thecoastal basin.

4.3.3. Plage Blanche Belt (Located in Figure 2)

Recent works by Belfoul [42] and Soulaimani and Burkhard [43] extend the main Variscan Front Thrust (HFT) located in fig.2 in green line (with triangular symbols) until "Plage Blanche", which is located to the west of the Anti-Atlas (AA in fig.2). A W-E cross-section shows a succession of shales, quartzites and argilites deformed and oriented from N-S to NE-SW with dipping to the West. These sediments ascribed to the Ordovician [2] exhibits many westward thrusts linked to the Variscan tectonic event [2]. According to Villeneuve et al. [44] this part belongs to an N-S Cadomian/Variscan belt, cross-cutting the E-W pan-African Anti-Atlas belt in this area.

5. Structure of the Reguibat Impingement

5.1. Structure of the Mauritanian-Appalachian Fold Belts and the Reguibat Impingement

According to Figure 11, the main structural units are from the east to the west:

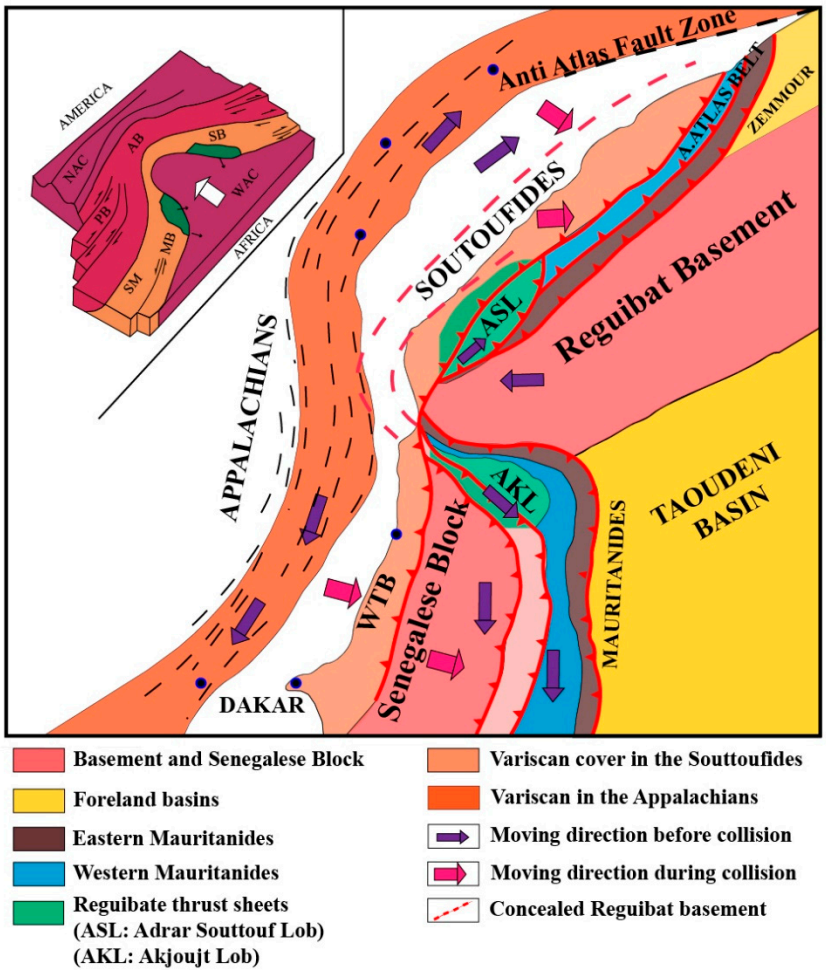

Figure 11. New interpretation of the Reguibat Shield imprint within the Mauritanide and Appalachian systems during the Variscan Orogeny and comparison with the impingement model of the craton (see model in Figure 4).

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- The Reguibat basement (in red) covered by the sedimentary Tindouf (here represented by the Zemmour massif) and Taoudeni foreland basins with Neoproterozoic and Palaeozoic formations (in yellow).
- The Variscan front thrust in the Mauritanides and Souttoufides with remnants of Precambrian Belt (in brown).
- -An eastern Unit with remnants of Neoproterozoic and Early Palaeozoic belts (in blue).
- Two lobes of nappes on both sides of the Reguibat promontory: Adrar Souttouf lobe (ASL) and Akjoujt lobe (AKL) in green. AKL is partially covered by the early Palaeozoic Agualilet Belt (in light pink).
- -The Senegalese Block (in pink).
- -The exotic terranes (allochthons units), which are partially covering the northern lobe and are linked to the Western Thrust belt (WTB) to the West of the Senegalese Block (light orange).
- -The Appalachian domain (dark orange).

5.2. Comparisons with the Previous Model

In summary, the evidence of a "lobe of nappes" in the Adrar Souttouf Massif and the movement of terranes in the Appalachians as well as in the African belts show that the deducted Reguibat imprint model (Figure 11) is similar to the previous model of Lefort [4,5]. The main difference between the two models consists in the asymmetry in the orientation of the lobes which are oriented NW-SE in the northern Mauritanides (to the south of the Reguibat promontory) and SSW-NNE to N-S in the Adrar Souttouf Massif (to the north of the Reguibat promontory). Meanwhile, they are symmetric in the model of Lefort (fig.4). This discrepancy could be explained by the N-S oriented shape of western margin of the Reguibat Shield and the NNE-SSW orientation of the gutter in which the northern lobe (ASL) is infilled. The covering of the Adrar Souttouf lobe by the allochthonous units prevented to validate the similarities between the field observations and the theorical model. Thus, the previously geologic scheme of the Variscan assemblage between the Appalachians on the West African fold belts presented in Figure 2 (Villeneuve et al. [1]) should be modified taking into account the partially capping of the West African structures by the late Variscan Orogeny.

6. Evolution of the Southern Variscan Belts During the Assembly of Pangea

According to Figure 12, three main stages have been distinguished in this assembly process: a pre-collisional stage, a collisional stage and a post-collisional stage.

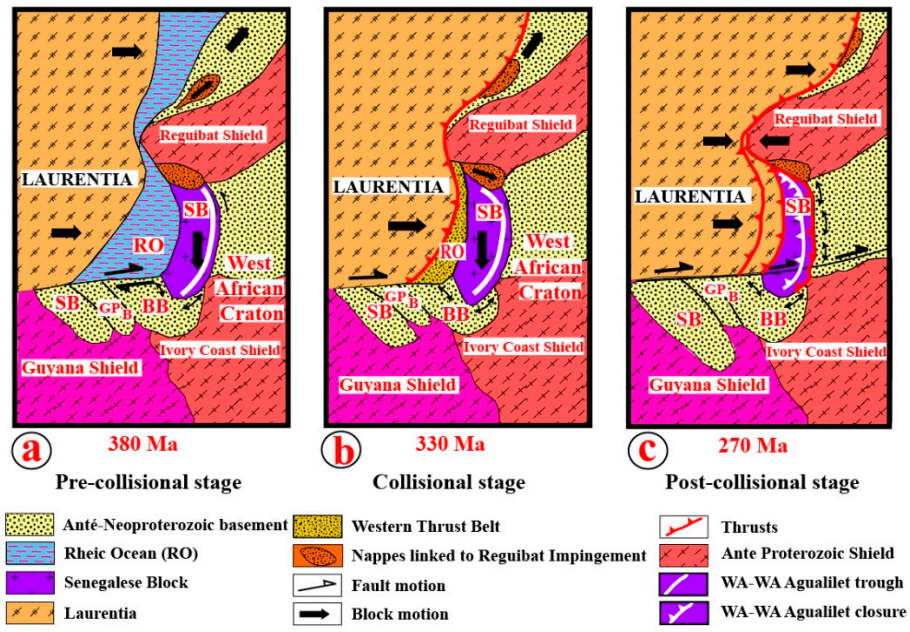

Figure 12. a, b and c illustrate the three different stages of the collision between the Laurentia and the West African Craton during the last period of the Variscan Orogeny (modified after Villeneuve et al. [45]. Legend: FB-

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Suwannee (or Florida) Basin, GPB-Guinean Palaeozoic Basin, BB-Bové Basin, SB-Senegalese Block, RO- Rheic Ocean.

6.2.1. The Pre-Collisional Stage (Figure 12a)

The westward shifting of the Reguibat Shield forced a southward movement of the Senegalese Block, which consequently folded the northern part of the Bové Basin. The northward movement of the Adrar Souttouf terranes occurred coevally. In the Senegalese Block, the N-S-trending Wa-Wa trough (Southern part of the Agualilet unit) which was infilled by post-Cambrian Palaeozoic sediments does not show any signs of strong deformation. The shift of the Reguibat Shield to the west induced the "lobes of nappes" on both sides of the Reguibat promontory. The northwards shift of the Adrar Souttouf Massif is recorded by dextral strike-slip along the meridian faults in the field [45]

6.2.2. The Collisional Stage (Figure 12b)

In this collisional stage the Rheic Ocean was already closed. To the north the exotic terranes that are of WTB or peri-Gonwana origin, are thrusted over the western parts of the Adrar Souttouf "lobe". Meanwhile to the south, the Appalachian belts and the WTB were reunited. At this stage the main strike-slip faults in the Appalachians may have been active.

6.2.3. The Post-Collisional Stage (Figure 12c)

At this stage, the WTB is thrusted over the Senegalese Block which, itself, is thrusted onto the Taoudeni Basin. The Wa-Wa and the Agualilet Units were folded and the Agualilet Unit already covered the southern part of the Akjoujt "lobe". The southern Bissau-Kidira Fault Zone (BKKF in Figure 2) is extended from the Brunswick Fault (BF in fig.2) to the –Bissau Kayes fault BKKF). This dextral strike-slip has separated the southern Koulountou part from the northern Wa-Wa/ Agualilet units.

The whole collisional processes, which have a temporal extension of more than 74Ma (At least between 324 and 250 Ma) is likely simplified at the current stage of knowledge and deserves to be enhanced by new geochronological and tectonic investigations.

7. Conclusion

After several decades of research and controversial debates, we are proposing a new hypothesis reconciliating most of the previous interpretations by the superposition, in the Adrar Souttouf, of lobes of African origin by a sheet of exotic terranes. The thrusting of exotic terranes over the northern "lobe" hampers the recognition and correlation of features similar to the hitherto applied hypothetical model of imprinting. New data from the parts of the Adrar Souttouf lobe which are covering the Reguibat Shield allow us to reconstruct the promontory imprint. Our hypothesis is consistent with the currently available data. The collisional process between Laurentia and the West African Craton has lasted more than 74Ma, perhaps 100 Ma? Owing to complex geometries of the cratonic margins with marginal blocks like the Senegalese Block and owing to the covering of the WTB by the Palaeo- to Neogene sedimentary successions in the Senegalo-Mauritanian basin, a complete reconstruction of the proposed processes is quite complicated. The main driver of these processes was the westward movement of the Reguibat Shield, which imprinted the belts setting on the western tip of the craton.

Author Contribution: MV: conceptualization, writing, supervision, OG: figure drawing, methodology, original draft preparation, AG: formal analysis, investigation, supervision, AE: validation, investigations, AM: data curation, HB: formal analysis, P.A.M: original draft preparation, PMN: visualization, NY: validation, UL: validation, review and editing, MC: supervision. **MV** : All authors have read and agreed to the published version of the manuscript.

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