The Mesozoic Margin of the Maghrebian Tethys in the Rif Belt (Morocco): Evidence for Polyphase Rifting and Related Magmatic Activity

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Abstract The Rif belt (northern Morocco) is a mountain chain located at the junction between the Mediterranean and Central Atlantic Domains. Although the Rif belt underwent important Cenozoic (i.e., Alpine) shortening, remnants of the Mesozoic North African rifted margin are preserved in its external zones. This contribution aims to characterize the Mesozoic architecture and polyphase rifting history of this rifted margin. We present detailed field evidence and geochronological data from two palaeogeographic zones (Mesorif and Intrarif) preserving remnants of the former North African distal margin. The Mesorif conserves lithostratigraphic associations characterized by mafic intrusive rocks overlain by dismembered and discontinuous blocks of Lower Jurassic carbonates covered by Middle to Upper Jurassic sediments. U-Pb zircon dating of four samples from this gabbroic complex shows ages close to the Triassic-Jurassic boundary (195–200 Ma). The gabbros were emplaced within the continental crust at the end of the first Triassic rift event and exhumed shortly after during a second Middle Jurassic rift event, which presents exceptional rift-related structures. The most distal part of the margin is exposed in the Intrarif. In this unit, the Beni-Malek serpentinized peridotites exhibit ophicalcites with uppermost Jurassic limestones resting conformally on top, suggesting that exhumation of the mantle occurred at the distal part of the North African margin at this time. When integrated, these new evidences enable us to discuss the evolution of the western part of the North African rifted margin and its relations with the Moroccan Atlantic margin and Tethys system.

1. Introduction

Rifting processes leading to continental breakup are commonly the result of polyphase rift systems evolving in space and time (Ziegler, 1992; Ziegler & Cloetingh, 2004). Polyphase rift systems are often associated with magmatic events occurring before, during, or after rifting (Frizon de Lamotte et al., 2015; Merle, 2011; Şengör & Natal'in, 2001). Complex interplays between tectonism and magmatism are well documented in the Moroccan Rif belt, which corresponds to the westernmost termination of the Alpine-Himalaya orogenic system. In particular, the Rif belt (Figure 1) preserves evidence of polyphase Mesozoic rift systems developed at the junction between the Central Atlantic and the Tethys along the so-called Maghrebian Tethys (Figure 1c; Ricou, 1994; Sahabi et al., 2004; Labails et al., 2010; Frizon de Lamotte et al., 2011; Sallarès et al., 2011; Leprêtre et al., 2018).

The Rif belt, an element of the Tell-Rif or Maghrebides orogenic system (Durand-Delga & Fontboté, 1980), is a mountain belt resulting from the collision between the Alboran Domain of European origin and the North African rifted margin (Leprêtre et al., 2018, and references therein). Although the deep structure of the Rif belt remains poorly constrained, modeling of gravity data indicates a maximum crustal thickness of 30–35 km in the Central Rif and only 25 km in the Eastern Rif (de Lis Mancilla & Diaz, 2015; Petit et al., 2015). The lack of significant crustal thickening is puzzling in such a collisional context. In the absence of generalized late orogenic extensional collapse (except in the core of the system, i.e., the Alboran Sea), the African continental crust likely was already initially thinned as a consequence of the polyphase Mesozoic rifting. This rifting, leading finally to the opening of the Maghrebian Tethys, has been previously studied
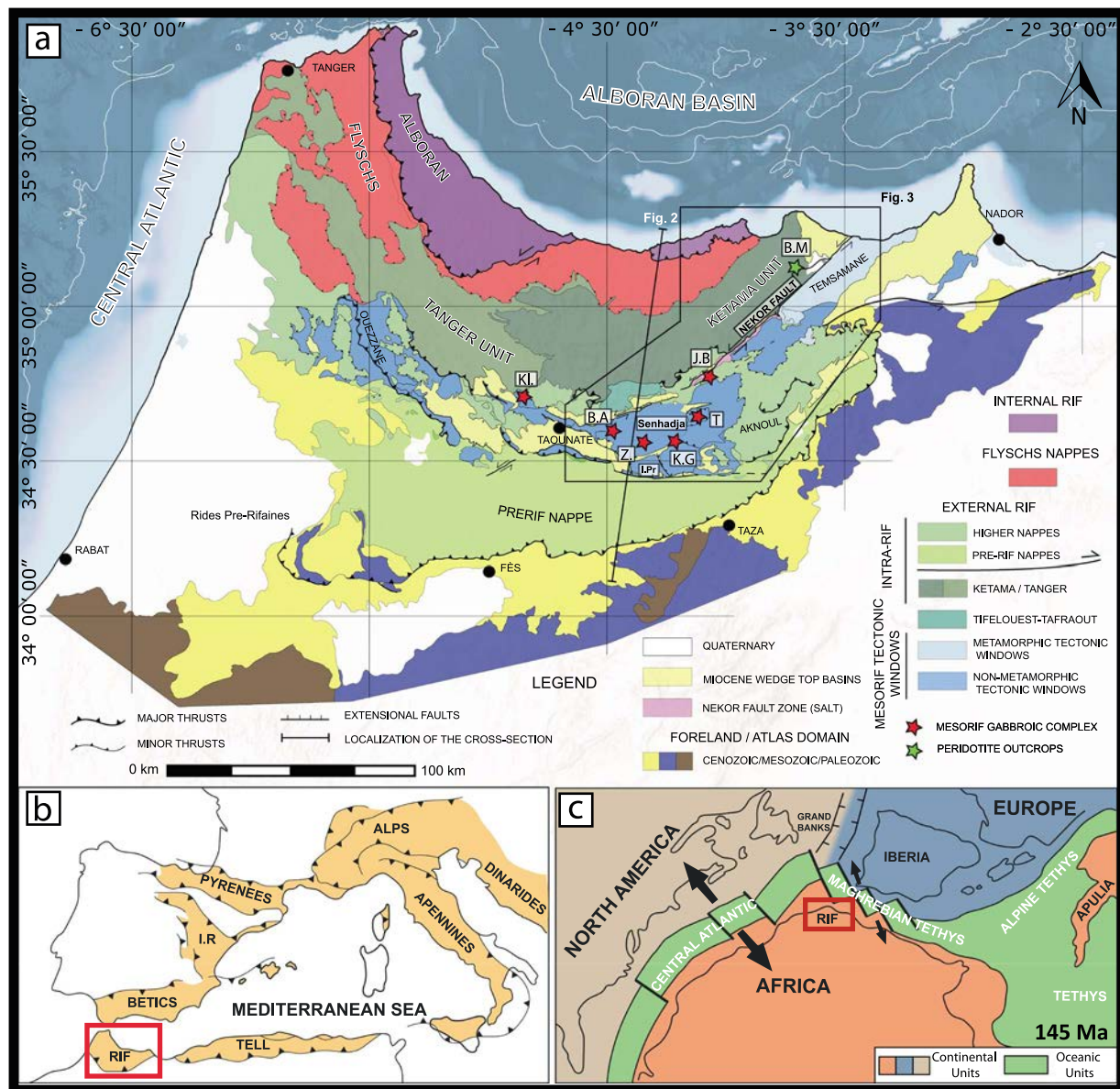
Figure 1. (a) Structural map of the Rif belt in the North of Morocco (after Suter 1980a, 1980b; Chalouan et al., 2008). Principal tectonic units are shown with special emphasis on the External Rif. The location of Figures 2 and 3 are indicated. (b) Map of the western Mediterranean region showing the Alpine belt with the location of the Rif (modified after Vergés & Sàbat, 1999). (c) Paleogeographic reconstruction summarizing the geodynamic setting between Europe-Iberia, Africa, and North America during the Upper Jurassic. The Rif belt samples the remnants of the former Mesozoic North African rifted margin (modified after Sallarès et al., 2011). B. A = Bou Adel; B. M = Beni Malek; I. Pr = Internal Prerif; J. B = Jebel Baïo; K. G = Kef el Ghar; Kl = LaKlaaia; T = Taïneste; Z = Zitouna.

in the external parts of the Rif belt by Ph. Favre (Favre, 1992; Favre, 1995; Favre et al., 1991) using mainly sedimentologic and stratigraphic data. This author revealed Late Triassic to Middle Jurassic (i.e., Bathonian) extensional activity and proposed a drift onset during the late Middle Jurassic (i.e., Callovian) in this westernmost branch of the Tethys. The same timing was subsequently extended to the Algerian Tell (Bracène & Frizon de Lamotte, 2002).

Since this pioneering work, the attention in the External Rif has been mainly focused on remnants of mafic and ultramafic rocks defining a hypothetical "Mesorif Suture" (Benzaggagh, 2011; Benzaggagh, 2016; Benzaggagh et al., 2014; Michard et al., 2014; Michard et al., 2018). Among these rocks, the Beni Malek serpentinite (Michard et al., 1992), located in the Eastern Rif (Figure 1), has been interpreted as exhumed subcontinental mantle (Michard et al., 2007) derived from a continent-ocean transition along the

Mesozoic African rifted margin. Evidence for mafic intrusive rocks scattered across the Central Rif (hereafter named the Mesorif gabbroic complex) has been interpreted as elements of an ophiolitic assemblage (Michard et al., 2018). Recent U-Pb zircon dating of one sample of this complex at 190 ± 2 Ma (Michard et al., 2018) needs to be reconciled with the younger rift event (i.e., Middle Jurassic in age) described by Favre et al. (1991) in exactly the same area.

To investigate these polyphase rift events in relation to the mafic magmatism, we propose a reassessment of the External Rif rifting history based on new geological mapping, field observations, and U-Pb zircon dating of the Mesorif gabbroic complex. Based on this data set, we show that the External Rif underwent two main rifting events during the Late Triassic and Middle Jurassic. A restoration of the former Mesozoic North African rifted margin of the Maghrebian Tethys preserved in the Rif segment is proposed. This study enables us to identify the main rift domains and to propose a tectonosedimentary scenario for the formation of this hyperextended rifted margin. Together, these new data allow us to portray the evolution of the western part of the Mesozoic North African rifted margin as well as its connexions with the Moroccan Atlantic margin and Tethys system.

2. Geological Setting: General Architecture of the Rif Belt and Definition of the Main Palaeogeographic Domains

The Rif belt architecture consists of stacked thrust sheets, classically subdivided into three structural-palaeogeographic domains from north to south (Figure 1): the Internal, the Flyschs, and the External Domains (Chalouan et al., 2008; Durand-Delga et al., 1960; Suter, 1980a, 1980b). The Internal Domain corresponds to units derived from the AlKaPeCa (Alboran-Kabylies-Peloritan-Calabria) microcontinent (Bouillin, 1986) or Meso-mediterranean Terrane (Guerrera et al., 1992) and more precisely from the western part of this realm (the "Al" of AlKaPeCa). This domain is composed of metamorphic terrains of Variscan and Alpine ages (see reviews in Chalouan et al., 2008 and Rossetti et al., 2010). Associated with these terrains, the "Dorsale Calcaire" complex represents the former northern margin of the Maghrebian Tethys, which connected the Central Atlantic and the Alpine Tethys from the Jurassic to the Palaeocene. The Flyschs Domain ("Bassin des Flyschs" of Bouillin, 1986) corresponds to the original cover of the Maghrebian Tethys from the Cretaceous to the late Burdigalian (De Capoa et al., 2007; Zaghloul et al., 2007). The closure of the Maghrebian Tethys during the Langhian-Serravallian (Vitale, Zaghloul, Tramparulo, El Ouaragli, Garcia, 2014; Vitale, Zaghloul, Tramparulo, El Ouaragli, 2014; Vitale et al., 2015), ultimately leading to collision between the AlKaPeCa and the Mesozoic North African margin, resulted in the formation of a nappe stack ("accretionary prism") formed essentially by turbidite sequences ("flyschs") accumulated within the Maghrebian oceanic basin.

The External Domain, topic of our study, consists of a nappe stack composed of Upper Triassic to Cenozoic deposits. The tectonic transport is southwestward at the scale of the whole orogenic system. However, along the Nekor Fault zone, acting since the Miocene as a transfer zone for the SW translation of the Central Rif, a partitioning of the deformation occurs. Therefore, southeast of the Nekor, the movement is basically perpendicular to the strike of the structures (Frizon de Lamotte et al., 1991; Figure 2). The External Rif derives from the inversion of the Mesozoic North African margin during the late stages of the collisional processes. Classically, the External Rif is divided into several palaeogeographic/palaeotectonic domains, from south to north: the Prerif, the Mesorif, and the Intrarif (Suter, 1965; Suter, 1980a, 1980b). We keep this terminology for the palaeogeographic zonation from the proximal to the distal parts of the Mesozoic North African rifted margin throughout the text, completed by additional terms required to describe the architecture of the system as illustrated on cross sections (Figure 2).

The foreland of the Rif belt is the Atlas System where the Upper Miocene foredeep developed (Figure 1). This foredeep basin is tectonically covered by allochthonous materials made of marls and clays, corresponding to the "Nappe Prérifaine" (Levy & Tilloy, 1952), and by better organized units (Aknoul, Tsoul and Ouezzane Nappes) forming the "Higher Nappes" of the system (Andrieux, 1971; Crespo-Blanc & Frizon de Lamotte, 2006; Frizon de Lamotte, 1987; Frizon de Lamotte et al., 1991; Leblanc, 1979; Suter, 1965; Vidal, 1977). These far-traveled allochthonous materials (Cretaceous to Miocene in age) are considered the former top stratigraphic sequences of the Intrarif (i.e., Ketama-Tanger Units) (see below).
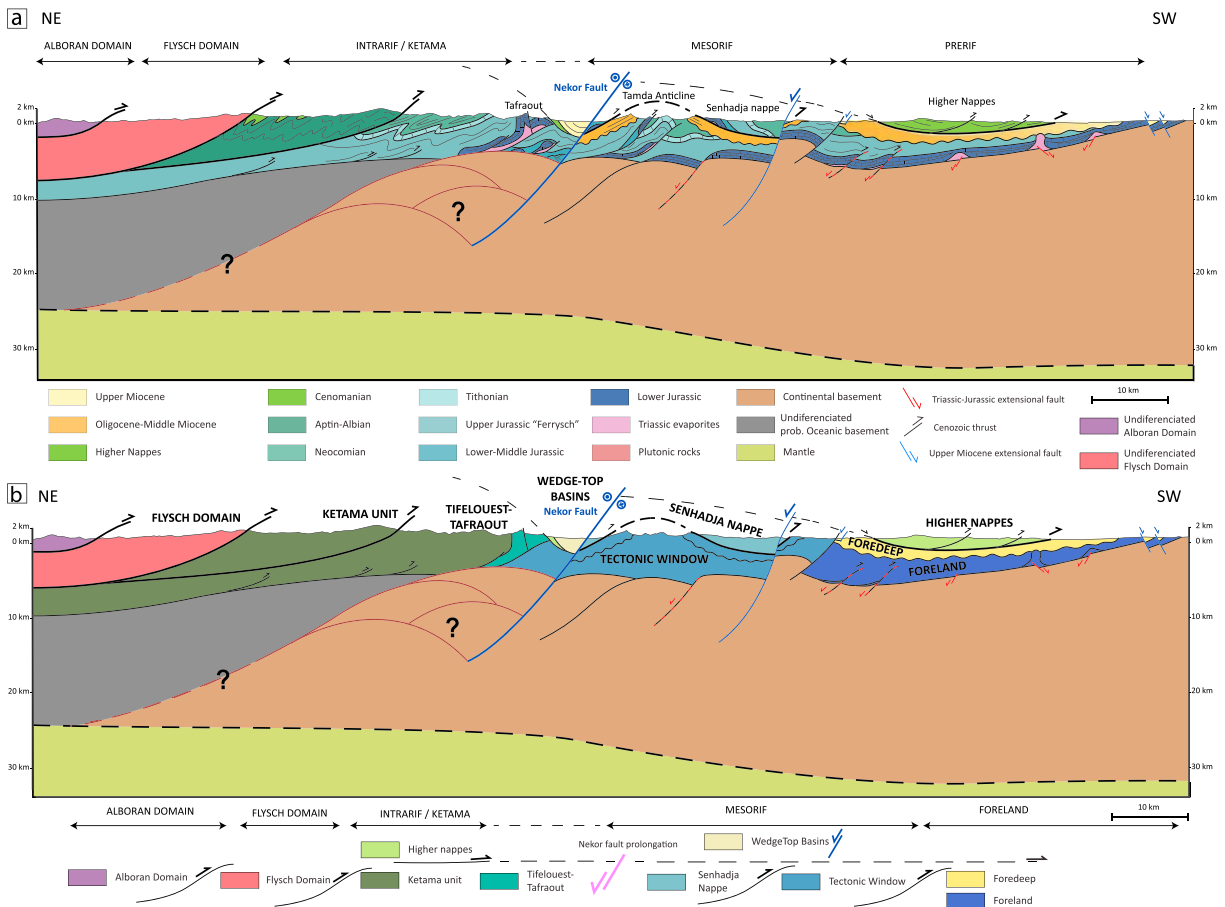
Figure 2. (a). General geological and (b) structural cross sections of the Rif belt along the eastern external Rif (see location in Figure 1) based on Moroccan geological maps (Geological maps of the Rif 1/50,000 Dhar souk and Beni Frassene), subsurface data in the southern part and own observations.

The Upper Miocene sedimentary successions of the foredeep lie unconformably over the early Mesozoic sequence and, occasionally, directly over the Atlas foreland Palaeozoic terranes (Figure 1). This unconformity seals an earlier tectonic inversion occurring during the middle-late Eocene, before the main collisional event (see a review in Leprêtre et al., 2018). The Rif foredeep is narrow and deep, suggesting low lithosphere rigidity (Favre, 1995; Leprêtre et al., 2018). Industrial seismic lines image a regular slope (flexure) of a Lower to Middle Jurassic carbonate platform completed by Upper Jurassic turbidites (the "ferrysch" formation; Wildi, 1981; Figure 2). Due to pre-Miocene erosion, the Cretaceous sediments are generally not preserved. The stratigraphic pile is poorly deformed and locally cut by weakly inverted extensional faults (Figure 2). Exceptions are observed in the "Rides Prérifaines" (Figure 1), where large ramp-related folds are exposed (Zizi, 2002 and references therein). The presence of diapiric structures involving Upper Triassic salt and red clay is frequent in the Prerif foredeep basin. The Triassic salt flows as salt plugs piercing the Miocene sediments of the foredeep and even the Higher Nappes. It is worth noting that part of the salt present in the basin is allochthonous and corresponds to the sole of the Higher Nappes.

To the north, new structural elements appear below the Higher Nappes due to late antiformal stacking. This tectonic pile comprises the following units from bottom to top: (1) large so-called Tectonic Windows covered by (2) allochthonous sequences exhibiting an apparent chaotic aspect: the "Senhadja Nappe" (Marçais in Durand-Delga et al., 1960; Papillon, 1989; Favre, 1992). Among the Tectonic Windows, we include not only the ridges (Kouine, Tamda, Izzarene, and Temsamane massifs among others) located at the bottom of the structural pile (Marçais and Suter in Durand-Delga et al., 1960) but also the large culminations cropping out just north of the foredeep basin and referred to as the "Internal Prerif" (Bulundwe Kitongo, 1986; Favre, 1992; Suter, 1980a, 1980b). From a lithostratigraphic point of view, the Tectonic Windows display a

Jurassic sequence similar to that existing below the foredeep but completed by a Cretaceous to Palaeogene marly sequence. A spectacular "Oligocene unconformity" seals folds and thrusts that developed before an Oligo-Lower Miocene sequence of conglomerate and clastic sediments (Favre, 1992; Figure 2). The Tectonic Windows show no evidence for metamorphism except for the easternmost one, the Temsamane unit (Andrieux, 1971; Booth-Rea et al., 2012; Frizon de Lamotte, 1987; Frizon de Lamotte & Leikine, 1985; Jabaloy-Sánchez et al., 2015). This unit records MP-LT metamorphic conditions (7–9 kbar and 330–430 °C) during Oligocene time (Negro et al., 2007; Negro et al., 2008).

On top of the Tectonic Windows and resting directly over the Oligo-lower Miocene is the Senhadja Nappe. This unit comprises an Upper Triassic evaporitic sole and Jurassic to Lower Cretaceous sediments and magmatic rocks (the so-called Mesorif gabbroic complex; Figure 3). The Mesorif gabbroic complex was initially wrongly described as a granite (the "Taïneste granite") and considered the only evidence of basement rock involvement in the belt (Marçais in Durand-Delga et al., 1960). The origin of the Senhadja Nappe has historically been a matter of debate. Many authors (Marçais in Durand-Delga et al., 1960; Suter, 1965; Leblanc, 1979; Frizon de Lamotte, 1985) proposed a root zone in the Nekor Fault Zone and its southwestward prolongation, which is marked by a megabreccia (containing clasts of marble, gabbro, and ophite) mixed with a large accumulation of Triassic evaporites (Figures 1 and 3). Other authors (Mattauer in Durand-Delga et al., 1960; Andrieux, 1971; Vidal, 1977] considered that all allochthonous elements currently located south of the Ketama Unit (Figures 1 and 2) have a common origin somewhere between the Ketama Unit and the Flyschs Domain. However, the convincing palaeogeographic affinities between the observed sequence in the Tectonic Windows and the Senhadja Nappe strongly suggest a closer origin (i.e., the Nekor Fault Zone; Figures 1 and 2; Wildi, 1981; Papillon, 1989; Favre, 1992).

North of the Nekor root zone, the Tifelouest and Tafraout Units (Figure 3) correspond to tectonic windows with the typical Oligocene unconformity, although in a different structural position regarding the previously described Kouine, Tamda, Izzarene, and Temsamane Units. They preserve the transition with the Ketama Unit (Mattauer in Durand-Delga et al., 1960; Andrieux, 1971; Frizon de Lamotte, 1985), which comprises a thick and continuous stratigraphic sequence from Late Triassic to Cenomanian. The younger stratigraphic sequence (Cenomanian to Miocene) has been detached and currently constitutes either the Tanger Unit to the west or the Higher Nappes to the south and southwest; in both of them, the absence of the Oligocene unconformity is a typical feature. The Triassic to Upper Jurassic sedimentary rocks are exposed only in the southernmost part of the Ketama Unit, while in its northeastern part, the Upper Jurassic sediments rest directly on the Beni-Malek serpentinite (Michard et al., 1992; Michard et al., 2007; Figure 3). The serpentinite corresponds to the former ocean-continent transition of the Mesozoic North African margin (Michard et al., 2014). The Ketama Unit was intensively folded and foliated during the Miocene, recording low-grade greenschist facies metamorphism in its southern and eastern parts (Andrieux, 1971; Frizon de Lamotte & Leikine, 1985).

A first-order restoration of the presented cross section (Figure 2) allows us to reveal the initial palaeogeographic configuration:

(1) To the south, the Prerif Domain composed of the Mesozoic sequence is buried below the Miocene foredeep; (2) In the middle, the Mesorif Domain comprises, from south to north, the Tectonic Windows (including the former Internal Prerif of Suter, 1980a, 1980b; Figure 3), the Senhadja Nappe, and the Tifelouest-Tafraout Unit; (3) To the north, the Intrarif Domain comprises the Ketama Unit, the Tanger Unit, and the Higher Nappes.

In the following section, the geodynamic significance of these different palaeogeographic domains is associated with the former architecture of the Mesozoic North African margin.

3. A revised Structural Architecture of the Rif Segment of the North African Mesozoic Margin

In the External Rif, the major palaeogeographic domains (viz., Prerif, Mesorif, and Intrarif) were well recognized in the work of G. Suter (1980a, 1980b). The description of the distinct deformation and stratigraphic evolution of the Prerif, Mesorif, and Intrarif enables us to identify former rift domains of the Mesozoic African margin. Rift domain recognition relies on the thickness variations in the distinct sedimentary
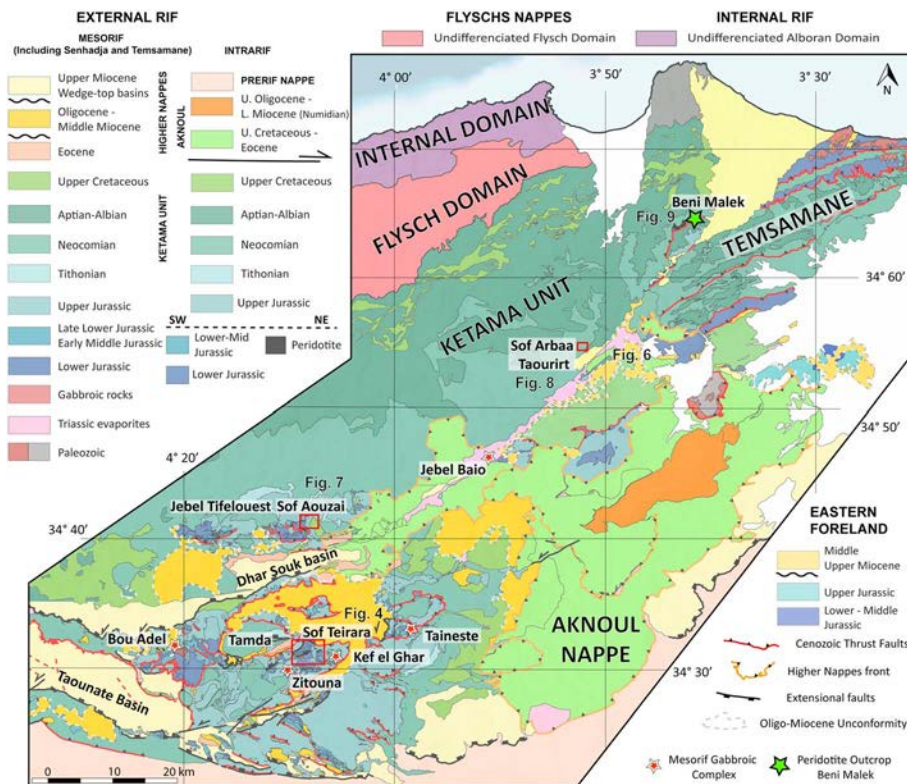
Figure 3. Detailed geological map of the Central and Eastern External Rif. Map compiled from the Geological maps of the Rif at 1/500,000 after G. Suter 1980a, 1980b, at 1/50,000 (Al Hoceima, Boudinar, Kebdani, Midar, Moyen Ouergha, Dhar souk, Taïneste, Aknoul, Beni Frassene, and Taza) (Vidal, 1979; Leblanc, 1983; Frizon de Lamotte et al., 1984; Choubert, Faure-Muret, Hilali, et al., 1984; Choubert, Faure-Muret, & Housay, 1984; Faure-Muret et al., 1994), the map of the Central Rif by J. Andrieux, the "Carte structural du Rif oriental" by d. Frizon de Lamotte et al., and own observations. The described outcrops are indicated in the map as well as the location of the main Mesorif gabbroic complex and peridotite outcrops in the Central and Eastern External Rif.

sequences (and associated accommodation space), the nature of the basement, and the geometry of extensional structures (see Tugend et al., 2015, for details on the methodology).

3.1. The Prerif: The Former Mesozoic Proximal Margin

Below the Higher Nappes and the Miocene deposits of the foredeep, the Mesozoic sequence is preserved. This sequence starts with a Triassic succession, reaching a local thickness of 500 m (Sani et al., 2007; Zizi, 2002). It exhibits a sequence with red continental sandstones at the base (Buntsandstein facies) and evaporites at the top (Keuper facies). The succession is overlain by a Lower Jurassic carbonate platform. This carbonate platform is exposed in the Rides Prérifaines (Figure 1; Faugères, 1981; Zizi, 2002) and is known elsewhere from seismic data. It is a thick (locally reaching more than 800 m) and continuous platform, only weakly affected by extensional faulting. These faults are often associated with Triassic salt-related structures such as salt diapirs crossing the whole foredeep and even the Higher Nappes (Leblanc, 1979; Sani et al., 2007; Zizi, 2002). The Middle to Upper Jurassic sequence resting on top of the carbonate platform is relatively thin without major structural complexities. It comprises siliciclastic materials with a southern origin. The occurrence of sporadic extensional faults, the thick and continuous carbonate platform (>800 m thick), and the thin Middle to Upper Jurassic succession (~300 m thick) are characteristic elements of a domain that did not undergo significant crustal thinning during Mesozoic rifting events. Such observations led us to interpret the Prerif as the proximal domain of the North African Mesozoic margin.

3.2. The Mesorif: From the Necking Zone to the Distal Margin

The Mesorif palaeogeographic domain comprises two structural units, which are from south to north in their restored position, the Tectonic Windows (including the former Internal Prerif) and the Senhadja Nappe (Figure 3). The continuous Lower Jurassic carbonate platform observed in the Prerif is still observed.

However, in this domain, the carbonate platform displays a different architecture; it is less continuous and shows the presence of many extensional faults (Figures 2 and 3).

In the Tectonic Windows, no basement rock is observed. In this area, the stratigraphically lower unit is made by Lower-Middle Jurassic sediments and is restricted to a few areas (the so-called "Sofs" [alignment of blocks in Arabic] of the former Internal Prerif). The reverse faults producing the antiformal stack at the origin of the Tectonic Windows (Figure 2) are likely reactivated former Mesozoic extensional faults.

In general, the transition from the Prerif to Mesorif is characterized by a significant increase in thickness (from 500 to 1,500 m) of the Middle to Late Jurassic successions. Such variation documents an increase in the accommodation space associated with a general deepening of sediments toward the Mesorif. Together, these elements suggest that the Prerif-Mesorif transition may correspond to the necking zone of the former Mesozoic African margin, recording a decrease in the crustal thickness and an increase in the accommodation space.

The Senhadja Nappe represents an unrooted allochthonous unit overlying the Mesorif Tectonic Windows. This nappe is far traveled; however, the primary rifting structures are exceptionally preserved. In contrast to the Tectonic Windows, the Senhadja Nappe exposes basement rocks consisting of mafic intrusions (hereafter referred to as "the Mesorif gabbroic complex"). This complex is widely exposed along the Mesorif Domain from Laklaaia to the west to Jebel Baïo to the east (Figure 1). It occurs as discontinuous magmatic bodies typically kilometer size in length. The outcropping bodies thickness (e.g., Bou Adel) does not exceed 100 m, while its extension at depth is unknown but likely larger. The nature, age, and significance of these mafic intrusions have been the subject of several interpretations. First, they were described as "Palaeozoic granite" within the Senhadja Nappe (Suter, 1965). Only after the geological mapping of the External Rif (Leblanc, 1979; Vidal, 1983) were they finally recognized as gabbroic rocks and interpreted as Lower Cretaceous intrusive bodies within a "melange" (Vidal, 1983). The latter interpretation was influenced by the magmatism described in the Atlas system, Middle-Late Jurassic to Early Cretaceous in age (Hailwood & Mitchell, 1971; Laville & Piqué, 1992). Finally, recent U-Pb zircon dating by Michard et al. (2018) on one sample from the Bou Adel locality (Figures 1 and 3) reported an Early Jurassic age (190 ± 2 Ma). In detail, the Mesorif gabbroic complex consists of various lithologies, such as gabbros, dolerites, and leucocratic segregations (i.e., "trondhjemitic levels") showing E-MORB affinities as reported by Benzaggagh et al. (2014). The country rock in which the gabbroic complex was initially emplaced has never been observed in the field and remains unknown. On top, the gabbroic complex is overlain by a sedimentary succession that starts in the Triassic and continues to the Early Cretaceous.

The Sof Teirara area, southeast of the Tamda window (Figure 4), exemplifies the main structural elements and lithostratigraphic associations of the Senhadja Nappe (Figure 3). The base of the outcrop consists of the Mesorif gabbroic complex, which is tectonically covered by Lower Jurassic carbonates, showing no evidence for contact metamorphism. The limit between these two lithologies is a subhorizontal contact, truncating the steep bedding of the Lower Jurassic carbonates with a clear "cutoff" relationship (Figure 4). This subhorizontal contact is characterized by a less than 5-m-thick tectonic breccia, made essentially of centimeter-sized Lower Jurassic carbonate clasts within a fine-grained matrix and showing a cataclastic structure (Figure 4d). These observations highlight the tectonic origin of the contact between the Mesorif gabbroic complex and the Lower Jurassic carbonates. In addition, along the contact, discontinuous occurrence of Upper Triassic evaporates is observed. These evaporites are often associated with carbonate breccias, showing a vacuolar aspect related to the preferred dissolution of dolomite with gypsum-derived sulfate (i.e., cargneule). Within the Triassic evaporites, highly sheared, folded, and marmorized blocks of unknown age are locally reported.

Northwest of Jebel el Harra (Figure 4), the tectonic contact is cut by a major high-angle extensional fault (Figure 4c). The hanging wall is composed of Middle Jurassic marls (Toarcian-Aalenian) showing growth strata thickening toward the extensional fault (Figure 4). This depositional architecture confirms the synrift depositional setting of the Middle Jurassic sequence. The fault zone shows evidence for ductile-brittle deformation characterized by gouge and cataclasite with elongated carbonate clasts as well as S-C type fabrics (Figures 4c and 4e). This extensional structure is sealed by the Upper Jurassic to Lower Cretaceous sequence (Figure 4b) consisting of a turbiditic succession (Favre, 1992; Papillon, 1989). Compared with the sequence
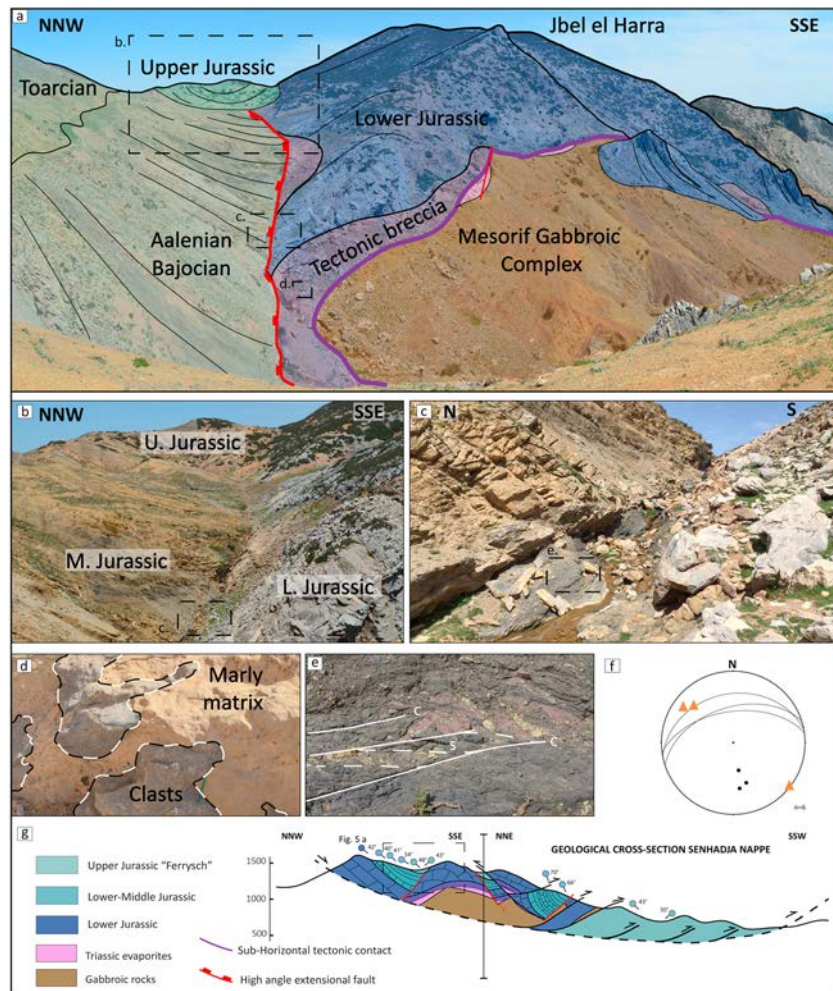
Figure 4. (a) Panoramic view of Sof Teirara outcrop showing the Lower Jurassic sediments on top of the Mesorif gabbro. In purple is the tectonic breccia located at the contact between these two units. In red is a Middle Jurassic high-angle extensional fault separating the Lower Jurassic carbonate and Mesorif gabbro (footwall) from the Toarcian-Aalenian sediments (hanging wall). The latter are characterized by growth strata toward the footwall of the fault. (b) Detail of the Upper Jurassic sediments, sealing the extensional fault. (c) Detail of the extensional fault between the Lower Jurassic and the Middle Jurassic. (d) Tectonic breccia at the contact between the gabbro and the Lower Jurassic carbonates. (e) S-C structures observed in the high-angle extensional fault zone. (f) Lower hemisphere Schmidt projection plot showing high-angle extensional fault plane orientation and associated slikenlines expressed as orange triangles. (g) Geological cross section across the Senhadja nappe highlighting its present-day architecture (See Figure 3 for the location of the photograph).

observed in the Prerif, a deepening and thickening in relation to an increase in the accommodation space of the basin is shown from the Middle Jurassic to the Upper Cretaceous in the Senhadja Nappe.

Additional observations are provided from other key localities for the Senhadja Nappe. In Zitouna (Figure 5a), Bou Adel (Figure 5b), and Taïneste, Lower Jurassic carbonate blocks appear extremely dismembered and discontinuous, ranging from a few meters to some kilometers, showing clear cutoff relationships with the underlying mafic intrusions (Figures 5a and 5b). As a result, the Middle to Upper Jurassic sediments can locally rest conformably on the tectonic contact at the top of the gabbroic complex (Figure 5c). As in Jebel el Harra, the subhorizontal contact between the Jurassic sediments and the gabbroic complex is characterized by tectonic breccias of variable thickness (up to 5 m) containing clasts of Lower Jurassic carbonates and to a lesser extent of mafic rocks, especially in Taïneste. Along this tectonic contact, the breccias are often associated with Upper Triassic evaporites.
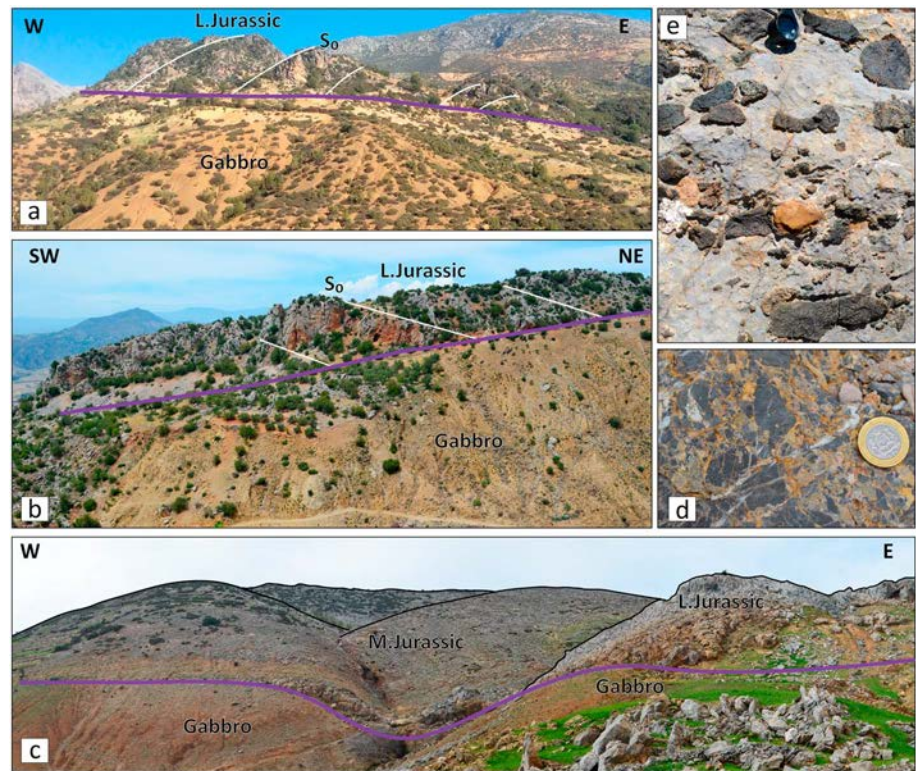
Figure 5. Compilation of field photographs showing (a, b) discontinuous blocks of Lower Jurassic carbonates showing cutoff of the bedding (S_0) over the Mesorif gabbro, (c) Middle Jurassic sediments overlaying both stretched block of Lower Jurassic carbonates and the Mesorif gabbro, (d) tectonic breccia at the contact between the gabbro and the Lower Jurassic carbonates, and (e) sedimentary breccia reworking the Mesorif gabbro and the Lower Jurassic carbonates. In Purple is the subhorizontal tectonic contact.

In some places, Lower to Middle Jurassic sedimentary breccia directly reworked the mafic rocks (Figure 5e). This sedimentary breccia contains clasts (less than 30 cm in size) of gabbros, ophites, and Lower Jurassic carbonates, suggesting that the Mesorif gabbroic complex was already exhumed during the Middle Jurassic (Figure 5d).

As indicated above, the root of the Senhadja Nappe is likely located in the Nekor Fault Zone (Andrieux, 1971; Frizon de Lamotte, 1985; Leblanc, 1979). This zone is underlined by a megabreccia including various blocks and megablocks of gabbro, marble, and basement rocks embedded within a Triassic evaporitic matrix (Figure 6). Such a massive accumulation of Triassic salt and evaporites is currently observed along the Moroccan and Canadian segments of the Central Atlantic at the bottom of the necking zone (Hafid et al., 2008; Tari et al., 2017; Deptuck & Kendell, 2017). Therefore, the Senhadja Nappe preserves evidence of the fragmentation of the Lower Jurassic carbonate platform accommodated by extensional structures interacting with Upper Triassic evaporites during the Middle Jurassic. This extensional deformation is sealed by a thick Upper Jurassic to Early Cretaceous postrift sequence. The significance of the Mesorif gabbroic complex remains a puzzling point, which is discussed in the next section combined with U-Pb zircon dating.

3.3. The Intrarif: From the Distal Margin to the Exhumed Mantle Domain

North and west of the Nekor Fault Zone (Figure 6), two tectonic units are recognized: the Tifelouest-Tafraout and the Ketama-Tanger Units. The Tifelouest-Tafraout Unit shares several features with the Senhadja Nappe and the Mesorif Tectonic Windows, including large exposures of Jurassic sedimentary rocks deformed and uplifted before the deposition of a thick Oligo-Miocene sequence (Andrieux, 1971; Favre, 1992). In contrast, the pre-Cretaceous rocks of the Ketama Unit are poorly exposed, and the Eocene-Oligocene transition, preserved in the Higher Nappes, does not show any unconformity (Leblanc &
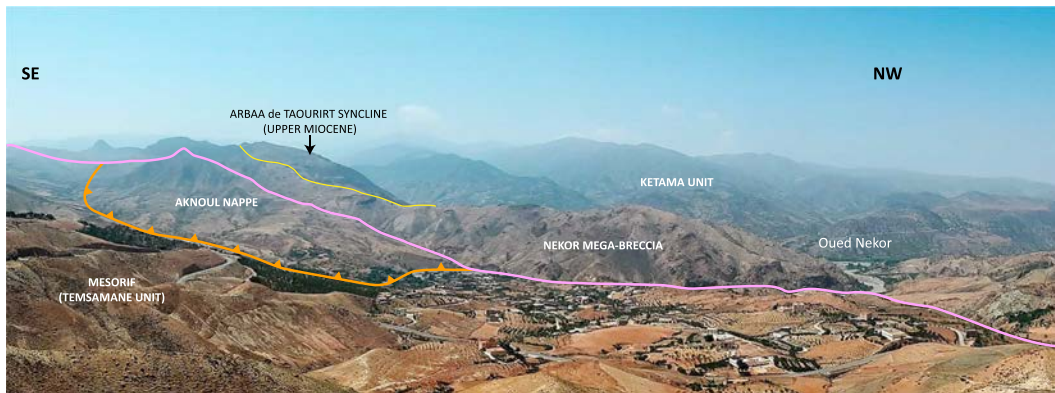
Figure 6. Panoramic view illustrating the Nekor megabreccia and the structural relationship between the Ketama Unit, the Higher nappes (Aknoul), and the Mesorif (South Temsamane).

Feinberg, 1982). Therefore, from a tectonic point of view, the Tifelouest-Tafraout Unit constitutes the transition from the Senhadja Nappe to the Ketama Unit and from palaeogeographical point of view, the transition from the Mesorif to the Intrarif Domains. Among the few outcrops exposing the Lower-Middle Jurassic rocks in the Ketama Unit, two are exceptionally interesting: the Sof Aouzzai and Sof Arbaa de Taourirt.

The Sof Aouzzai (Figure 7), located at the very south of the Ketama Unit (Figure 3), exemplifies the general features of this domain as previously described by Favre (1992). In this area, the lower stratigraphic succession is made of highly tectonized Upper Triassic evaporites. The evaporitic sequence thickness remains difficult to evaluate due to postdepositional reactivation of this level during both the rifting and compressional stages. However, in areas where the evaporites have been less mobilized, such as in the Prerif and the foreland, they can reach thicknesses ranging between 500 and 800 m (Et-touhami (2000)). Several lithologies are embedded within the evaporites, such as gabbroic rocks, ophites, and Triassic subsalt clasts, such as Buntsandstein-like red beds and Muschelkalk-like limestones. The Upper Triassic evaporites are steeply dipping and involved in a diapiric structure. In the southern flank, the Upper Jurassic turbiditic sequence is directly juxtaposed against the diapir through an extensional fault. In contrast, its northern flank is characterized by verticalized and highly brecciated Lower Jurassic carbonates. As in the Senhadja Nappe (Sof Teirara; Figure 4), the Middle Jurassic marls show significant thickness variations recording rapid growth strata thinning southward, approaching the diapir. Such wedge geometry in the Middle Jurassic succession indicates salt movement during the formation of the diapiric structure. Up section, the thick Upper Jurassic to Lower Cretaceous succession does not show thickness changes. The lithological and geometrical changes across the two diapir flanks may record the activity of a normal fault accommodating the salt movement in its footwall, describing a typical salt-cored normal fault geometry (i.e., a salt roller) (Brun & Mauduit, 2009; Quirk & Pilcher, 2012).

The Sof Arbaa Taourirt (Figure 8) is located along the NE border of the Ketama Unit close to the Nekor fault zone (Frizon de Lamotte, 1985; Figure 3). This outcrop exposes a Lower Jurassic carbonate platform block, similar to those observed in the Tifelouest-Tafraout Unit, in contact with a well-preserved Triassic sequence comprising evaporites and subsalt material. The subsalt lithology consists of steeply dipping continental red beds (Buntsandstein facies). Immediately on top, the Upper Triassic evaporites are highly deformed, especially at direct contacts with the Lower Jurassic carbonates. Both Triassic sediments and the Lower Jurassic carbonate platform are tilted together. The latter are unconformably overlain by Middle Jurassic sediments (Figure 8b). This geometric relationship illustrates a tilted block geometry of Lower Jurassic carbonates and Triassic materials controlled by a system of extensional faults. The timing and the general geometrical relationship are remarkably similar to those observed at Sof Teirara in the Senhadja Nappe, showing the tectonic juxtaposition of Lower Jurassic carbonates with subsalt lithologies (i.e., Mesorif gabbro in Sof Teirara and red beds in Sof Arbaa de Taourirt) subsequently crosscut by high-angle extensional faults.
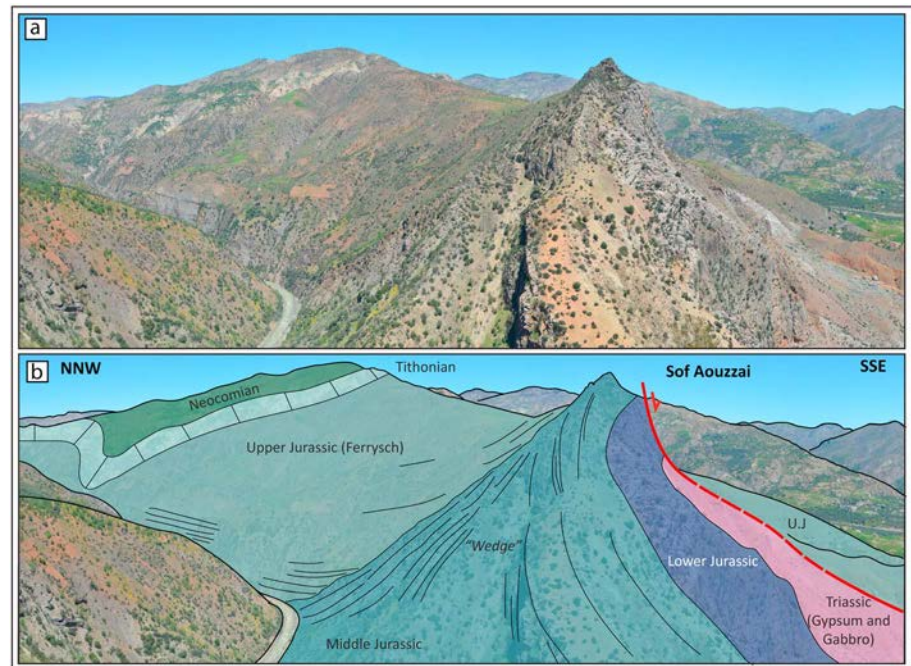
Figure 7. (a) Photograph and (b) Line drawing of the Sof Aouzzai Outcrop illustrating the southern part of the Ketama Unit. Photograph and line drawing document a Triassic diapiric structure associated with tilting the Lower Jurassic carbonate, as well as a wedge of the Middle Jurassic marls showing evidence of salt movement. (See Figure 3 for the location of the photograph).

The subsequent sedimentary succession of the Ketama Unit is characterized by a thick (locally 2.5 km) Upper Jurassic to Albian-Cenomanian alternation of sandstones and pelitic layers (Andrieux, 1971; Figures 9a and 9b). This succession is significantly thicker in the Intrarif than in the previously described palaeogeographic domains. In particular, the Oxfordian to Berriasian sediments are characterized by decimeter- to meter-thick (0.5 to 20 m) volcaniclastic levels composed of basalt clasts associated with some lava flows (Benzaggagh, 2011). Such observations are interpreted as evidence for submarine volcanic activity during the Late Jurassic-Early Cretaceous (Benzaggagh, 2011; Benzaggagh, 2016; Benzaggagh et al., 2014). Close to the Nekor Fault Zone and at a short distance from Arbaa de Taourirt, the basement of the Ketama Unit changes dramatically, passing to serpentinized peridotites (i.e., the Beni Malek massif) (Figure 9).

Figure 8. (a) Panoramic view of Arbaa de Taourirt showing a rotated fault block consisting from base to top of subsalt Triassic red beds (buntsandstein facies), Triassic evaporites, and Lower Jurassic Carbonates. In purple, a major subhorizontal tectonic contact is observed between the carbonates and the evaporites. In red is the high-angle extensional fault bounding the tilted block. (b) Close up photograph of the high-angle fault with the Triassic red beds in the footwall and the Middle Jurassic sediments in the hanging wall. (See Figure 3 for the location of the photograph).
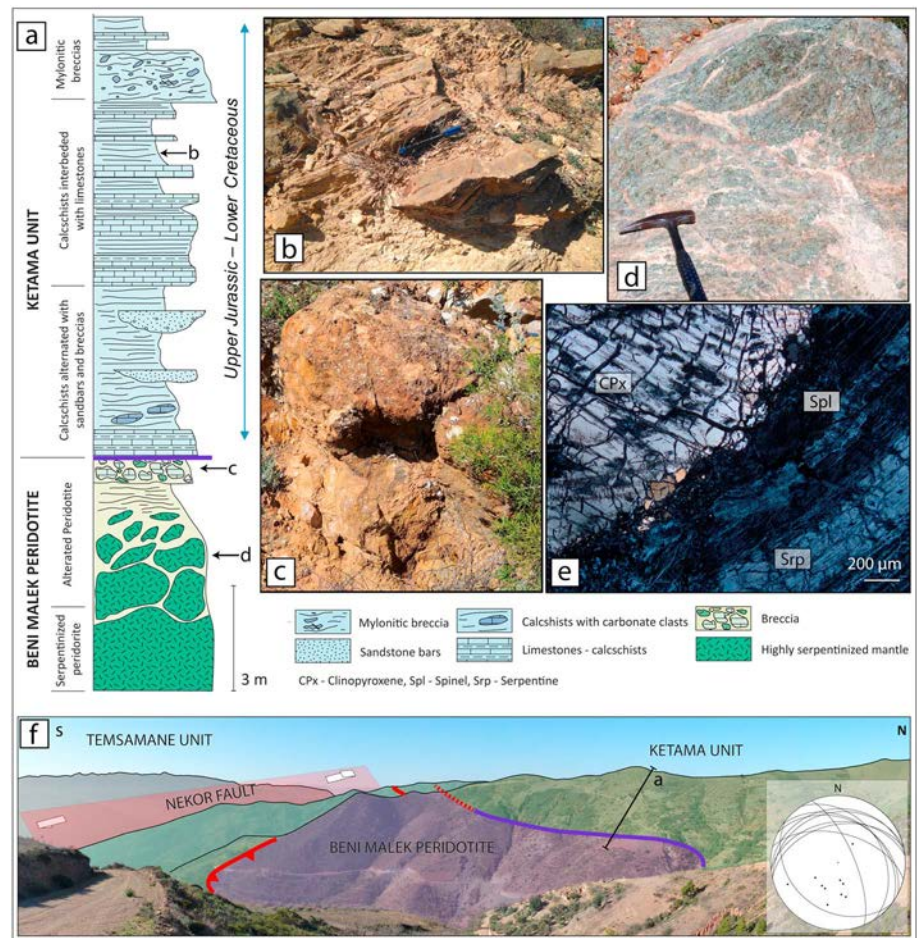
Figure 9. (a) Stratigraphic section representing the lithologies observed at Beni Malek. (b) Turbiditic succession of Ketama Unit showing alternation of calc-schist and limestone bars. (c) Breccia resting directly over the mantle documenting fluid circulation between the mantle and the sediments. (d) Deformed serpentinized peridotite with calcite veins. (e) Thin section photography showing the highly serpentinized mantle, locally preserving its primary mineralogy. (f) Panoramic view with geological interpretation of the Beni Malek outcrop. (g) Lower hemisphere Schmidt projection plot of the main thrust planes on the Ketama Unit. (See Figure 3 for the location of the figure).

The Beni Malek massif results from the exhumation of mantle during the Mesozoic rifting in the distal domain of the North African rifted margin (Michard et al., 1992). This peridotite body is observed in the NW part of the Ketama Unit over 12 km with a NE-SW trend between the villages of Beni Malek and Skifat. During the Cenozoic, it was involved in compressional deformation as shown by a succession of thrust sheets with top-to-the-SW shear (Figure 9g). A detailed description of the overlying lithostratigraphic associations combined with structural observations enables us to identify the following succession (Figure 9f):

1. *The Beni Malek serpentinized peridotite.* The serpentinized peridotite essentially consists of spinel lherzolites. Despite pervasive serpentinization (>80%), the initial mineralogical association and texture can still be observed. Although the rocks exhibit typical mesh and hourglass textures in relation to serpentinization, pyroxene and, to a lesser extent, olivine and spinel are recognized (Figure 9e). Locally, meter-thick garnet pyroxenite dykes are observed, while no other magmatic rocks have been identified. Approaching the top and the contact with the first overlying sediments, the serpentinized mantle shows evidence for brittle deformation, with serpentinite cataclasites and breccias. This deformation is associated with a network of carbonate veins showing generally anastomosing geometries and ophicarbonates (Figure 9d). All these lithologies attest to important fluid circulation at the top of the mantle.

2. *Sedimentary cover succession*. The first sediments resting directly on top of the mantle are composed of a yellowish breccia several meters thick (Figure 9c). This breccia is characterized by a fine-grained matrix of quartz associated with carbonates, frequently presenting calcite veins. The texture of this breccia suggests significant silica-rich fluid circulation at the contact with the ultramafic rocks. Above, the sedimentary succession of the Ketama Unit starts with an alternation of calc-schist, sandstone, and breccias in the lower part, while the upper part of the succession is characterized by meter-thick limestone strata (0.5 to 2 m thick) alternating with calc-schists. The stratigraphic succession is variably deformed under greenschist-facies conditions (Andrieux, 1971; Frizon de Lamotte & Leikine, 1985); calc-schist intervals are heterogeneously folded and foliated, while the limestone strata locally display a pervasive mylonitic fabric. Michard et al. (2014) describe the occurrence of spinel and serpentine clasts within these sediments, confirming the mantle exhumation at the seafloor and its reworking into neighboring sediments. The precise age of this sedimentary succession remains poorly constrained. Nevertheless, based on facies analogy, a Late Jurassic age for this succession is supposed.

Therefore, the lithostratigraphic association implies that the Ketama Unit and subsequently the Intrarif preserved distinct palaeogeographic domains. On the one hand, the Sof Aouzzaï and Arbaa de Taourirt represent the distal part of the margin and likely developed over a hyperextended continental basement, as shown by the occurrence of Triassic red beds. The salt tectonism was intense during the rifting, allowing almost complete decoupling between the cover and the basement. The subsalt continental basement is not exposed in the field except for the Arbaa de Taourirt Triassic red beds. However, the substratum of the northern part of the Ketama Unit corresponds to the Beni Malek peridotites. A minimum Late Jurassic age for the unroofing of the mantle can be proposed based on field observations. This interpretation is consistent with an exhumation occurring at the end of the Middle Jurassic rifting observed in the Mesorif Units at Sofs Aouzzaï and Arbaa de Taourirt.

From the Proximal Domain in the Prerif through the Necking Domain in the Mesorif and the distal Domain in the Mesorif and Intrarif, the stratigraphic and structural evolution of the External Rif enables us to determine the different rift domains of the North African Mesozoic margin in Morocco. In the following section, we describe the petrology and the geochronological data obtained from the Mesorif gabbroic complex in order to later discuss its significance in margin reconstruction.

4. Petrography and Geochronology of the Mesorif Gabbroic Complex

To investigate the petrography and emplacement age of the Mesorif gabbroic complex, we selected four samples for zircon U-Pb dating across the identified and mapped gabbroic bodies from west to east: Laklaaia, Bou Adel, and Kef el Ghar. (Figures 1–3; GPS coordinates are provided in supporting information Table S1).

4.1. General Petrography of the Mesorif Gabbroic Complex

Fieldwork in the Mesorif yielded the discovery of new outcrops of mafic magmatic rocks, which are described and studied for the first time. This work particularly concerns the Zitouna, Laklaaia, and Jebel Baïo outcrops. Other outcrops, such as Bou Adel, Kef el Ghar, Taïneste, and Harrara, have already been characterized, and the petrography and geochemistry of Bou Adel and Kef ef Ghar are reported in Benzaggagh et al. (2014) and Benzaggagh (2016). Additional geochemical analyses on the Mesorif gabbroic complex are provided in the supporting information (Figure S1).

We summarize below the most important petrographic characteristics of these mafic rocks. Along these outcrops, a variety of lithologies are observed, such as dolerites, gabbros, and leucocratic segregations called trondhjemitic levels. A well-preserved magmatic breccia has been observed in the Zitouna outcrop only. A gradual transition from gabbroic to fine-grained dolerites has been observed in almost all outcrops.

Dolerites and gabbros display different textures, from microdoleritic to gabbroic (coarse to medium grained to pegmatitic; Figure 10c). Most outcrops show various degrees of alteration, and the primary magmatic mineralogy can be completely replaced by secondary phases. Evidence of low-grade hydrothermal metamorphism (prehnite-pumpellyite facies) is observed in almost all outcrops.

Dolerites and gabbros are the most abundant lithologies. In some localities (Laklaaia and Zitouna), dolerites can represent the most abundant facies. They generally display ophitic texture showing fine grain sizes from
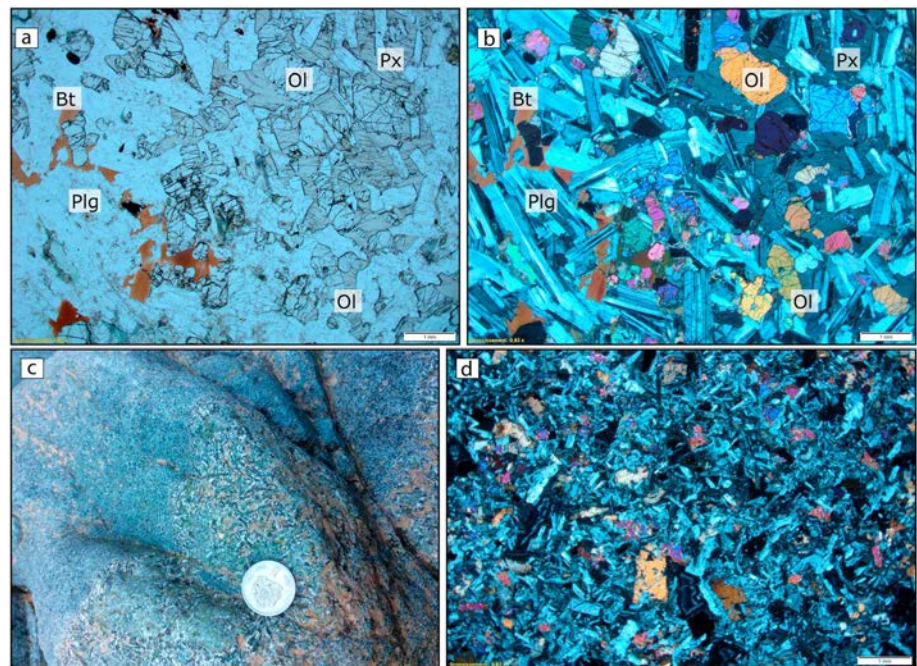
Figure 10. Thin sections photograph of the Mesorif Gabbro in Bou Adel in (a) plane-polarized light and (b) in cross-polarized light, showing peculiar heteracumulate texture with poikilitic clinopyroxene enclosing olivine and euhedral crystals of plagioclase. The mineralogical assemblage consists of olivine+plagiolclase ± orthopyroxene and also secondary Biotite. (c) Photograph of Zitouna gabbro showing distinct grain sizes (coarse to medium grained). (d) Thin section photograph of a Dolerite sample from Zitouna showing an ophitic texture. Presence of plagiolcase ± orthopyroxene and biotite, in this case without olivine.

200 to 500 μm with the presence in some cases of phenocrysts of clinopyroxene (and rarely of olivine). The main assemblage is clinopyroxene-plagioclase (the most abundant phases) + scarce olivine (<6%) ± orthopyroxene ± Fe-Ti oxides ± apatite. Minor biotite is present in some samples as a product of secondary alteration. Olivine is scarce (sometimes absent) in most of the samples except in Taïneste and Bou Adel. Secondary alteration phases are systematically observed (iddingsite, serpentine, calcite, sericite, chlorite, epidote, amphibole [mainly as rims around clinopyroxene], and talc). In some samples, only pseudomorphs of clinopyroxene, olivine, and plagioclase are recognized due to their shape, and very small portions of the minerals have been preserved. Prehnite also occurs in some samples from Laklaaia and Zitouna.

Gabbros display variable mineral grain sizes and different abundances of olivine. Medium- to coarse-grained or even pegmatitic textures are observed (Figure 10d). Medium-grained gabbro is observed in the Jebel Baïo outcrop with abundant olivine and clinopyroxene phenocrysts embedded in a fine-grained matrix composed of clinopyroxene-olivine-plagioclase-oxides amphibole. A coarse-grained gabbro with abundant olivine is also observed in Bou Adel (olivine + plagioclase ± orthopyroxene [very scarce, if present] + Fe-Ti oxides + biotite + minor amounts of amphiboles). This gabbro shows a peculiar heteracumulate texture with poikilitic clinopyroxene enclosing olivine and euhedral crystals of plagioclase (Figures 10a and 10b). At Bou Adel, Zitouna, and Kef el Ghar, gabbros display pegmatitic texture with plagioclase + clinopyroxene + Fe-Ti oxides. Olivine is absent or very scarce (<1%), and minor amphibole rims around clinopyroxene, epidote, apatite, sphene, and prehnite are also observed.

The leucocratic bodies, generally called trondhjemitic levels, are mostly made of clinopyroxene + plagioclase ± K-feldspar ± quartz ± amphibole ± oxides ± apatite.

4.2. U-Pb Dating Results

U-Pb geochronology of zircons extracted and separated from four samples was conducted using Laser Ablation Inductively Coupled Plasma Mass Spectrometry at the Laboratoire Magmas et Volcans (Clermont Ferrand, France). The selected samples represent different observed magmatic facies and
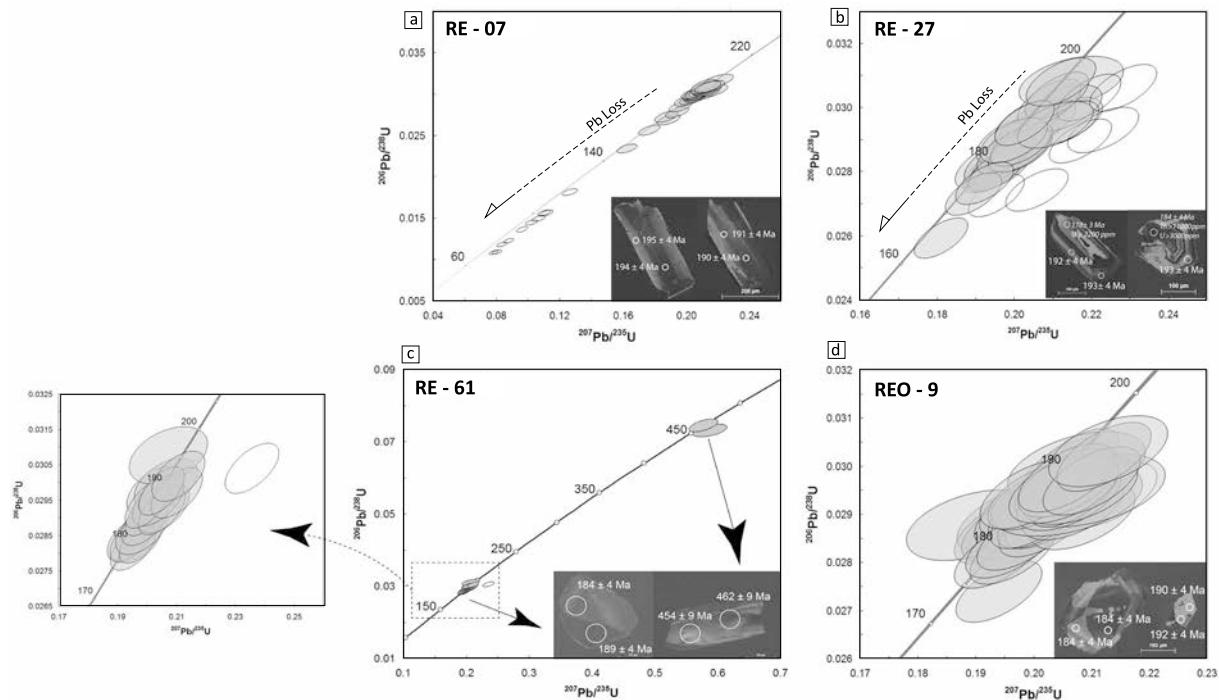
Figure 11. Concordia diagram and cathodoluminescence images of dated zircon crystals from Laklaiaa (a), Bou Adel (b), and Kef el Ghar (c) and (d) with spot location with the related U-Pb ages (Ma).

different outcrops: two dolerites from Laklaiaa (RE-07) and Kef el Ghar (RE-61), one pegmatitic gabbro from Bou Adel (RE-27), and one leucocratic facies sample (REO-09) from Kef el Ghar. Analytical conditions are described in detail in the supporting information (supporting information Text S1 and Table S5).

The separation of zircon grains was accomplished using conventional heavy liquids and Frantz magnetic separation techniques. Zircon grains were then hand-picked under a binocular microscope, mounted in epoxy blocks, and polished for analysis. Prior to analytical work, the internal structure of the grains was investigated using cathodoluminescence microscopy. Zircon grains are elongated, subhedral to euhedral in samples RE-07 and RE-27 and rather large, prismatic grains in samples REO-09 and RE-61. They commonly display oscillatory zoning and, in some cases, sector zoning, with almost no evidence of inherited cores.

Th/U values are extremely high up to 13 (compared to the mean value of <0.5 in igneous zircons; Hoskin & Schaltegger, 2003) in all samples reflecting very high Th as well as U contents (supporting information Tables S1 to S4) compared to what could be expected in zircon (tens to thousands of ppm; Hoskin & Schaltegger, 2003). Such exceptional Th and U compositions may relate from late-stage zircon saturation and growth in these gabbro-dolerite-type rocks. Indeed, in these gabbroic magmas, Zr saturation is reached late in the crystallization history and zircons crystallize from highly fractionated melts enriched in incompatible elements such as U and Th (supporting information Text S2). High concentrations of Th and U are responsible for the distortion of the zircon crystal lattice and induce low retention of the radiogenic Pb. As a consequence in our samples, most of the zircon grains corresponding to the higher U and Th content display younger apparent ages because of Pb loss (Figure 11 and supporting information Tables S1 to S4). In these conditions, only maximum ages can be interpreted as crystallization ages.

A total of 37 analyses was obtained in 29 zircon grains from the pegmatitic gabbro RE-27 (Figure 11b and supporting information Table S1). Concordant $^{206}Pb/^{238}U$ ages (31 analyses) range from 196 ± 4 to 165 ± 3 Ma. Th/U ratios are between 0.2 and 3.6 with Th contents from approximately 40 ppm to 11,150 ppm and U contents from 100 ppm to 3,700 ppm. The lowest U and Th contents (100 and 40 ppm, respectively) correspond to the maximum ages (supporting information Table S1) measured in this sample.

Thus, they are interpreted as the crystallization age of the RE-27 gabbro at approximately 196 Ma. The younger ages, including those obtained in the "cores" of some grains (Figure 11b), correspond to Pb loss.

A total of 26 zircon grains from the RE-07 dolerite sample was analyzed (Figure 11a and supporting information S2). Concordant $^{206}Pb/^{238}U$ ages (33 analyses) range from 200 ± 4 to 149 ± 3 Ma. Th/U ratios are between 0.8 and 3.0 with Th contents from approximately 690 to 9,690 ppm and U contents from 720 to 4,260 ppm. Here again, the lowest U and Th contents are measured in the zircon domains yielding older ages of 200 ± 4 Ma (supporting information Table S2) and corresponding to the age of the dolerite crystallization.

A total of 16 zircon grains was analyzed from the RE-61 dolerite, yielding two groups of concordant ages (19 analyses). The first group was measured in one zircon grain yielding two $^{206}Pb/^{238}U$ ages of 462 ± 9 and 454 ± 9 Ma (Figure 11c and supporting information Table S3) with Th/U ratios of 0.04 and 0.1. This grain was probably inherited from the host rocks and sampled during the dolerite emplacement. The second group corresponds to the main population of zircons, with ages ranging between 195 ± 4 and 179 ± 3 Ma (Figure 11c). Th/U ratios are between 1.4 and 12.6, with Th contents up to 10,600 ppm and U contents between 120 and 3,570 ppm (Table S3). The maximum age of 195 ± 4 Ma has been measured in a domain corresponding to the lowest U and Th contents (supporting information Table S3) and is interpreted as the crystallization age of the dolerite.

In the REO-9 gabbro sample, 20 zircon grains were analyzed. Concordant $^{206}Pb/^{238}U$ ages (36 analyses) range between 192 ± 4 and 174 ± 3 Ma (Figure 11d and supporting information Table S4). Th/U ratios are between 0.7 and 12.7 with Th contents from approximately 170 to 25,750 ppm and U contents from 110 to 9,580 ppm (supporting information Table S4). Most of the lowest Th and U contents are measured in the domain corresponding to the oldest ages. Thus, as previously proposed for the other samples, the younger ages are interpreted as disturbed by Pb loss, whereas the age of the REO 9 gabbro crystallization is estimated at approximately 192 ± 4 Ma.

5. Discussion: The Polyphase History of Mesozoic Rifting and the Opening of the Maghrebian Tethys

The description of the distinct palaeogeographic domains of the External Rif highlights significant variations in the Mesozoic stratigraphic record and in the basement nature, which were used as diagnostic elements to identify and interpret the remnants of the former rifted margin. Based on analogies with present-day rifted margins, we recognized the proximal margin in the Prerif, the necking zone to the distal margin in the Mesorif, and the distal margin to the exhumed mantle domain in the Intrarif.

In particular, the Senhadja Nappe, sampling the former distal margin, preserves evidence of a Middle Jurassic rift event ending with Late Jurassic mantle exhumation in the Intrarif. A puzzling point is the existence of mafic intrusions representing the "basement" of the Senhadja Nappe. Geochemical results from the Mesorif gabbroic complex indicate an E-MORB affinity (Benzaggagh et al., 2014, and supporting information Figure S1). In addition, U-Pb zircon geochronological results show scattered zircon ages from ~170 to 200 Ma. We interpret the younger ages (approximately 170 Ma) as resulting from the loss of Pb and therefore geologically meaningless. The range of the maximum ages measured in the four samples is consistently 195–200 Ma and is assigned to a major magmatic event occurring in the Mesorif during this period. The age retained by Michard et al., 2018 (190 ± 4 Ma) for the emplacement of the gabbro falls in a similar range, showing the same U enrichment and Pb loss. In the following discussion, we successively discuss (1) the occurrence of an initial Triassic rift event associated with the emplacement of the Mesorif gabbroic complex and (2) the geometry, kinematics, and style of a subsequent Middle Jurassic rift event accommodating both the exhumation of the mafic intrusions at the base of the Senhadja Nappe and finally the exhumation of mantle peridotites at the bottom of the Ketama Unit.

5.1. The Emplacement of the Mesorif Gabbroic Complex and Its Relationship With a Late Triassic Rifting Phase

Evidence for mafic magmatism is observed discontinuously at the bottom of the Senhadja Nappe for more than 100 km along the strike. As emphasized above, our new U-Pb zircon dating of four samples documents the emplacement of the gabbroic complex during the Late Triassic and earliest Jurassic (195–200 Ma). The

geodynamic significance of these mafic intrusions has not been widely discussed to date, except in the recent contribution of Michard et al. (2018). Benzaggagh et al. (2014) discussed the E-MORB affinity of the gabbroic complex, suggesting a potential connection with the Mesorif suture zone proposed by Michard et al. (2007). These studies suggest the emplacement of the gabbroic complex in an oceanic domain, now closed and sampled in the Mesorif suture zone. However, the observed lithostratigraphic associations of the gabbroic complex (e.g., tectonic contacts with Lower Jurassic shallow marine carbonates and Upper Triassic evaporites) as well as its geochemical signature (even partly modified by alteration, evidenced by secondary minerals as sericite and iddingsite) indicate rather an emplacement in a continental setting. Moreover, one zircon from a dolerite of the gabbroic complex (RE-61) yields two concordant ages at approximately 450–460 Ma (Figure 11c). This significant older zircon is interpreted as inherited from the host rocks during the magma ascent through the continental crust. Such contamination by crustal materials confirms the emplacement of the magmas in a continental setting.

Continental intraplate basaltic magmatism is generally associated with large igneous provinces. Our geochronological data on zircons from different mafic rocks indicate a 195- to 200-Ma age range, which fits with the peak age of tholeiitic magmatism of the so-called Central Atlantic magmatic province (CAMP). The CAMP represents a large continental igneous province emplaced at the latest stages of the Triassic to Early Jurassic rifting phase associated with the onset of Pangea breakup (Hames et al., 2003; Knight et al., 2004; Marzoli et al., 1999; Verati et al., 2007). This magmatic event occurred along the Central Atlantic Domain from South America to Europe (Denyszyn et al., 2018; Marzoli et al., 1999, and references therein). It records the emplacement of important volumes of mafic volcanic rocks, such as basaltic flows, sills, and dykes (Marzoli et al., 1999). Our geochronological and geochemical data fit well with other CAMP-related sills and dykes from southwestern Europe, mainly Portugal and Spain, with ages of approximately 200 Ma (e.g., Callegaro et al., 2014; Cebriá et al., 2003; Lago et al., 2000; Morata et al., 1997). Therefore, we suggest that the emplacement of the Mesorif gabbroic complex was associated with continental lithospheric thinning, that is, the upwelling of the asthenosphere during the Late Triassic. Based on the comparison with magmas of the CAMP, we infer similar P-T conditions for their emplacement, that is, a shallow depth of crystallization (Marzoli et al., 1999). In the Rif, this magmatism was spatially associated with Upper Triassic evaporites, dolerites, and ophites (Lacoste, 1934; Leblanc, 1979; Suter, 1964a, 1964b). The geochemical and petrographic signatures of the volcanic rocks display approximately the same characteristics as the Mesorif gabbroic complex, suggesting only slight differences such as shallower depth of crystallization for the finer-grained materials. In addition, the CAMP basalts were emplaced at approximately 200 Ma (Blackburn et al., 2013; Marzoli et al., 1999), coinciding exactly with the deposition of the main evaporite packages in Morocco (Late Triassic to Early Jurassic [Hettangian];Tari et al., 2012; Flinch & Soto, 2017; Soto et al., 2017; Figure 12a).

Triassic rifting remains difficult to unravel in the External Rif belt because of the scarcity of pre-Keuper outcrops. However, when exposed, the Triassic sediments record a stratigraphic sequence similar to those in the adjacent rift basins where a Triassic rift event is well established: the Khemisset Basin (Et-touhami, 2000), the Rides Prérifaines (Sani et al., 2007; Zizi, 2002), the Middle Atlas (Frizon de Lamotte et al., 2008; Zizi, 2002), and the Central Atlantic (Hafid et al., 2008; Tari et al., 2012; Biari et al., 2017; Figure 12a). In these basins, the original stratigraphy and tectonic setting of the Triassic sequences are well preserved. The Triassic rift system corresponds to a complex network of northeast trending basins (Et-touhami, 2000; Frizon de Lamotte et al., 2008; Sani et al., 2007; Zizi, 2002). Grabens are filled by a succession of clastic materials (Buntsandstein facies) and finally overlain by Upper Triassic evaporites (Zizi, 2002), reaching a local thickness of 700 m (Et-touhami, 2000) (Figure 12a). This Triassic rifting is also documented along the Central Atlantic Moroccan margin, with a sequence of half-grabens generating isolated basins (Hafid et al., 2008; Tari et al., 2012). These basins are associated with the deposition of continental siliciclastic sediments and locally thick evaporitic sequences emplaced in a late synrift to postrift setting (Leleu et al., 2016; Tari et al., 2012).

Evidence for rift basins of this age has also been described in Nova Scotia (Leleu & Hartley, 2010; Deptuck & Kendell, 2017), the Grand Banks (Balkwill & Legall, 1989), the conjugate margin of the Moroccan Atlantic margin (Biari et al., 2017; Tari et al., 2012), and the southern Iberia margin (Ramos et al., 2016). Finally, this rifting phase led to the opening of the Central Atlantic during the Early Jurassic (Biari et al., 2017; Frizon de Lamotte et al., 2011; Labails et al., 2010; Sahabi et al., 2004). Although the importance and distribution of the
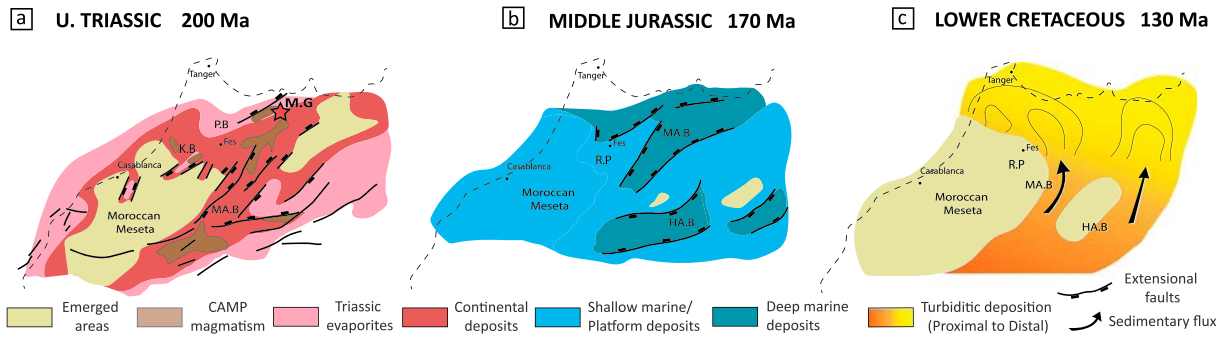
Figure 12. Paleogeographic setting of Northern Morocco through the Mesozoic. (a) Upper Triassic setting showing the localization of the main Triassic basins and the position of the CAMP magmatism. (b) Middle Jurassic setting, representing the major rifting phase in the Rif with a deepening of the basin (modified after El Arabi, 2007). (c) Lower Cretaceous setting showing the infilling of the Maghrebian Tethys margin sourcing from the south (modified after Wildi, 1981). HA. B = High Atlas basin; K. B = Khemisset Basin; P. B = Prerif Basin; MA. B = Middle Atlas basin; R. P = Rides Prerifaines.

Triassic rift event remain difficult to evaluate in the External Rif, the existence of the Mesorif gabbroic complex indicates important thinning and weakening of the continental lithosphere before the Middle Jurassic rifting (Figure 13a). Eventually, this extensional event associated with CAMP magmatism weakened the continental lithosphere of the future Mesozoic North African margin.

5.2. The Middle Jurassic Rifting Phase

After the end of the Triassic rifting, the External Rif recorded a period of relative tectonic quiescence marked by the deposition of Lower Jurassic shallow marine carbonates (Figure 13a). This carbonate platform (locally reaching 800 m) is present throughout the South Tethys realm (Dercourt et al., 1986; Faugères & Mouterde, 1980; Wildi, 1983). Such environments lasted approximately until the Toarcian, when another rifting phase began, associated with a dramatic change in the palaeogeography (Favre, 1992; Papillon, 1989). The Middle Jurassic stratigraphic sequence records a rapid deepening of the basin from Toarcian to Bajocian, associated with important thickness variations and growth strata controlled by extensional faults and related Triassic salt activity (e.g., Sof Teirara, Figure 4; Sof Aouzzai, Figure 7). All these elements, combining the stratigraphic record and the structural evolution, attest to a major extensional phase during the Middle Jurassic (Figures 12b and 13b).

The structural features recorded in the Mesorif, especially in the Senhadja Nappe, show an important partitioning of the deformation along the contact between the suprasalt Jurassic cover and the subsalt basement (i.e., the Mesorif gabbroic complex) accommodated within the Upper Triassic evaporites representing a major décollement level. The tectonic style of deformation of the supra-salt cover is well exposed and characterized by an intense dismembering of the Lower Jurassic carbonate platform. In contrast, the subsalt basement deformation remains poorly constrained due to the lack of exposure (Figure 13b).

Although not directly visible, important crustal and lithospheric thinning is required to accommodate the gabbroic complex exhumation at the base of the Mesozoic cover and finally the serpentinized mantle at the seafloor, as shown in Beni Malek. Indirect evidence of important crustal thinning and exhumation of the lower crust is exposed in the Rif-Tell system, due to the Upper Triassic salt diapirs. In the Rif, a block of high-grade metamorphic rocks (i.e., kinzigite) has been found in the Triassic evaporites at the bottom of the Aknoul Nappe (Frizon de Lamotte, 1982; Morel, 1980). In the Western Tell, Midoun and Seddiki (2016) describe the presence of blocks reworking lower crustal materials and upper mantle xenoliths such as peridotite, gabbro, kinzigite, gneiss, and mica schist embedded in Upper Triassic evaporites. These rocks, sampled during the salt movements, testify to the nature of the basement in the distal part of the Tell-Rif. It is worth noting, as indicated by J. Kornbrobst (in Frizon de Lamotte, 1982), that the kinzigites of the External Rif and Tell define an "external basement" (i.e., basement of the External Rif units), which represents the hyperthinned African crust in the distal margin.

In the field, a major flat-lying tectonic contact underlines the top of the mafic rocks and the bottom of the overlying truncated Lower Jurassic carbonates (Figure 5). This tectonic contact is interpreted as a major crustal extensional detachment fault at least partly accommodating the exhumation of the Mesorif
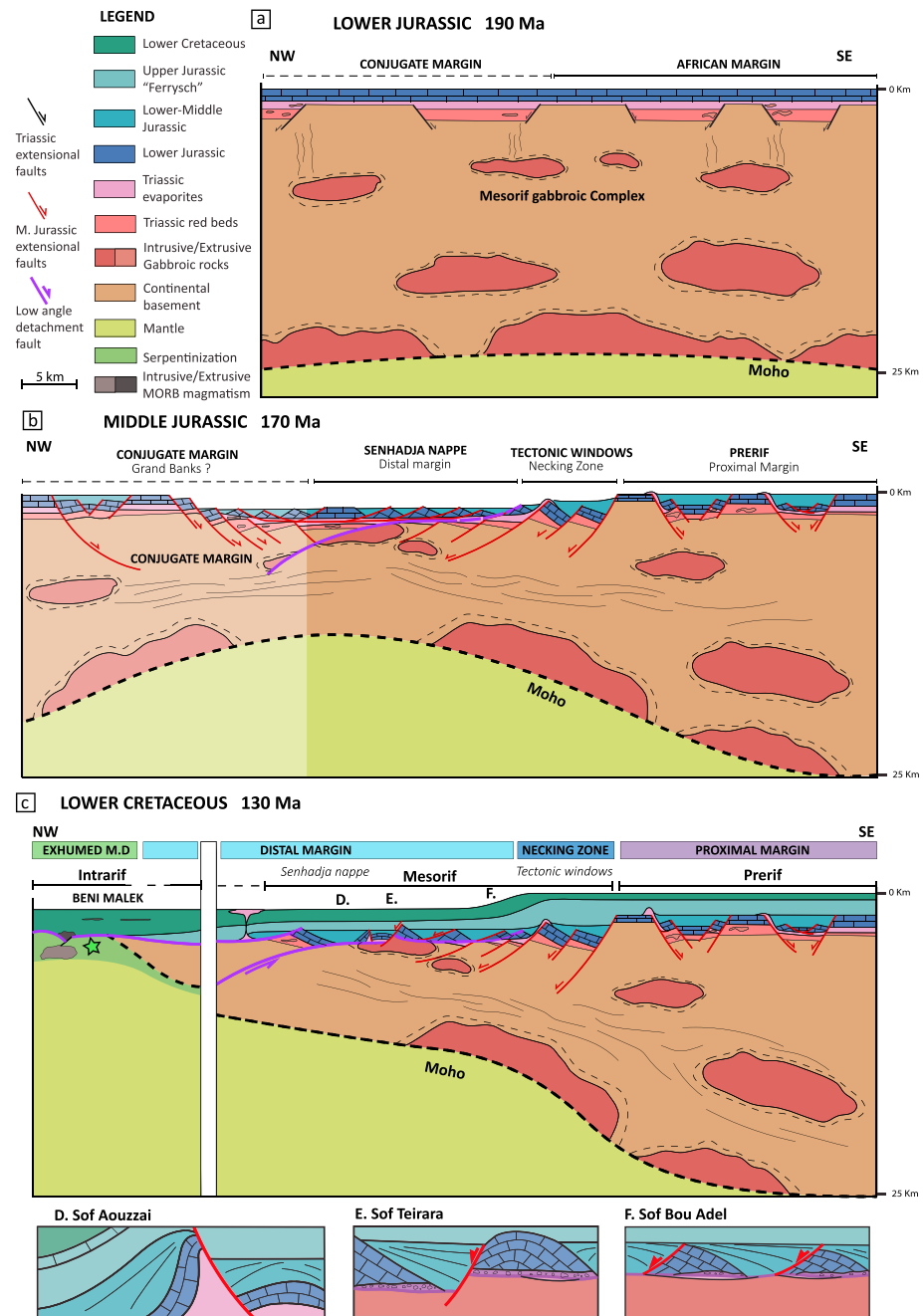
Figure 13. Idealized evolution of the North African rifted margin across the Rif Belt (Morocco) from the Lower Jurassic to the Lower Cretaceous. (a) Schematic cross section of the Rif basin during the Lower Jurassic. This period is characterized by the deposition of shallow marine carbonates, sealing a previous Triassic rifting phase. The potential location of gabbroic intrusions (i.e., Mesorif gabbroic complex) is indicated. (b) Schematic cross section during the Middle Jurassic representing the main rifting phase. Note the partitioning of the deformation between supra and subsalt levels characterized by a major décollement level within the Upper Triassic evaporites. (c) Schematic cross section through the North African rifted margin during the Lower Cretaceous showing the exhumation of the Beni-Malek serpentinized peridotite. Please note that the cross sections result from combination of observations from separate areas; the Beni Malek and Mesorif both merged into the same profile. (d–f) Sketch detail of the Figure 13c representing the position of the main outcrops (d) Sof Aouzzai, (e) Sof Teirara, and (f) Sof Bou Adel.

gabbroic complex toward the surface (Figure 1c). The décollement level associated with the Upper Triassic evaporites will ultimately merge with the detachment fault described previously (Figure 13c). The suprasalt extension of the cover shows a typical "raft-like geometry" (e.g., Bou Adel area) associated with other salt-related structures, such as salt-cored normal faults (e.g., Sof Aouzzai). This deformation is restricted to the cover and likely resulted from the combination of extensional tectonics and gravitational processes.

Sof Teirara (Figure 4) and Sof Arbaa de Taourirt (Figure 8) show that the main detachment fault/ décollement is crosscut by late high-angle normal faults. Such observations highlight that at this stage, the cover, and the basement (i.e. the Mesorif gabbroic complex) were coupled. This coupling likely resulted from Upper Triassic salt expulsion and basinward migration leading to the welding of the lower carbonates over the gabbroic complex. This second step of deformation was accompanied by the deposition of Middle Jurassic sediments between the extended blocks of Lower Jurassic carbonates, locally resting in primary contact over the exhumed mafic rocks. Overall, the salt played an important role in the structural formation of the Mesozoic North African rifted margin corresponding to a major décollement level during the rifting phase. The salt movement generated salt accumulations and diapiric structures, starting from the rifting phase and lasting until the Late Cretaceous (Andrieux, 1971; Frizon de Lamotte, 1985). The second rifting phase ended in the Callovo-Oxfordian. The sedimentary rocks of this age ("Ferrysch Fm.") seal the extensional faults, defining the postrift sequence.

The latest stage of the Mesozoic rifting corresponds to the mantle exhumation observed at Beni Malek (Michard et al., 1992; Michard et al., 2007; Figure 13c). The Beni Malek peridotite corresponds to the original basement of the northern part of the Ketama sedimentary succession. The contact between them is interpreted as primary (i.e., stratigraphic), preserving the original relationships between the exhumed mantle and its sedimentary cover during rifting. The top of the mantle is characterized by brittle deformation associated with ophicarbonates highlighting mantle/seawater interactions. The observed brittle deformation implies the activity of an extensional detachment fault accommodating mantle exhumation to the seafloor. The presence of spinel reworked within the Late Jurassic to Early Cretaceous calc-schist sequence confirms that the mantle was already exhumed before the deposition of these sediments (Michard et al., 1992). Therefore, mantle exhumation occurred at least in the Tithonian (age of the first sediment deposited on top of the peridotite; Michard et al., 1992). It is worth noting that smaller peridotite outcrops in equivalent structural positions have been observed in the Oran region (Oued Madakh Massif, Western Algerian Tell; Fenet, 1975; Ciszak, 1992). According to Michard et al. (2007) and Leprêtre et al. (2018), their exhumation occurred at the same time as that at Beni Malek. Moreover, in the Central Algerian Tell, tilted blocks preserved below the Higher Nappes (equivalent to Aknoul) and the foredeep basin allow us to define an Early to Middle Jurassic age for the rift event associated with spectacular salt activity (Bracène & Frizon de Lamotte, 2002).

Therefore, together, these observations suggest the exhumation of ultramafic bodies along the North African margin during the Late Jurassic in a final rifting stage. Although not directly observed at Beni Malek, mantle exhumation and the opening of the Maghrebian Tethys were likely also associated with mafic magmatism. Indirect evidence is provided by lava flows and reworked basalts within Oxfordian-Berriasian deposits (Benzaggagh, 2011; Benzaggagh et al., 2014; Benzaggagh, 2016) in the Mesorif and Intrarif Domains. This Late Jurassic to Early Cretaceous magmatic event signals the onset of a Tethys ocean floor-type magmatism and must be distinguished from the Late Triassic to Early Jurassic magmatic event previously described.

The Grand Banks, the Gulf of Cadiz, and the Algarve basins represent the conjugate margins of the Rif and Western Tell systems (Fernandez, 2019). They correspond to the triple point where the North American, African, and Iberian plates join. In the Algarve basin and Gulf of Cadiz, Ramos et al. (2016, 2017) described a similar process since the Triassic, with major rifting activity during the late Early Jurassic-Middle Jurassic leading to the opening of the Maghrebian Tethys. The salt activity observed in the Algarve Basin seems similar to that described in the External Rif with important activity from the Late Triassic to the Cretaceous and even the Palaeogene (Ramos et al., 2016). The Late Jurassic onset of the Maghrebian Tethys formation, as evidenced in the External Rif, is similar to the proposed timing (i.e., Late Jurassic to Early Cretaceous) for mantle exhumation in the Gorringe Bank representing the conjugate margin (Conti et al., 2004; Jiménez-Munt et al., 2010). All these elements agree with the timing for the opening of the Maghrebian Tethys (Leprêtre et al., 2018).

6. Conclusion

The Rif basin is a segment of the Mesozoic North African palaeomargin, south of the Maghrebian Tethys. It resulted from a polyphase rifting history with two pulses during the Late Triassic and the Middle Jurassic. The first phase was marked by the development of isolated basins filled with continental deposits and evaporites. This rifting phase was responsible for initial crustal and lithospheric thinning ending with the emplacement of mafic magmatic intrusions. This magmatism is expressed in the External Rif by gabbroic intrusions (i.e., Mesorif gabbroic complex) dated at 195–200 Ma and consequently related to the CAMP. The second rifting phase led to the opening of the Maghrebian Tethys. It is well preserved in the Mesorif and Intrarif Units representing the former distal margin (the current Senhadja Nappe and Ketama Unit, respectively).

The structural style of this second rifting phase was characterized by decoupling between the cover and the basement along an Upper Triassic evaporitic décollement level. In the subsalt, extreme crustal thinning with a major extensional detachment fault allowed the exhumation of gabbroic bodies formerly intruded in the continental crust up to the bottom of the Mesozoic cover. The suprasalt sedimentary cover recorded the stretching of the Lower Jurassic cover over the Upper Triassic décollement level. The net result was the complete dismembering of the sedimentary cover as exposed in the Senhadja Nappe. Locally, high-angle extensional faults were able to crosscut and couple the cover and the basement. These extensional faults controlled the deposition of the Middle Jurassic (Toarcian-Bajocian) sediments, with wedge geometries attesting their synrift setting. This extensional phase was characterized by strong and rapid deepening of the margin from the Middle Jurassic (Toarcian). This second rifting phase ended with the exhumation of the subcontinental mantle occurring at the bottom of the Intrarif during the Upper Jurassic.

Finally, we documented the complex interactions between polyphase rifting, CAMP-related magmatism, and salt tectonics in controlling the architecture and evolution of the Maghrebian Tethys at the junction between the Central Atlantic and Alpine Tethys. The presence of an initial rift event during the Late Triassic, a precursor of a second successful rift event, appears to be a common feature at the scale of North Africa and Western Europe. Further work is required to better understand the impact of this initial rift event in terms of structural and thermal inheritance for the subsequent extensional events leading to the opening of the North Atlantic and Tethys systems.

References

Andrieux, J. (1971). La structure du Rif central: Étude des relations entre la tectonique de compression et les nappes de glissement dans un tronçon de la chaîne alpine. In *Notes et Mémoires du Service Géologique* (Vol. 235, pp. 155). Rabat, Morocco: Service géologique du Maroc.

Balkwill, H. R., & Legall, F. D. (1989). Whale basin, offshore Newfoundland: Extension and salt diapirism. In A. J. Tankard, & H. R. Balkwill (Eds.), *Extensional tectonics and stratigraphy of the North Atlantic margins*, *American Association of Petroleum Geologists Memoir* (Vol. 46, pp. 233–245).

Benzaggagh, M. (2011). Activités volcaniques sous-marines à la limite Jurassique-Crétacé dans le Rif externe (Maroc). Age et relation avec la sédimentation et la paléogéographie du sillon rifain externe. *Comptes Rendus Geoscience*, *343*(4), 302–311. https://doi.org/10.1016/j.crte.2010.12.009

Benzaggagh, M. (2016). Tholeitic basalts and ophiolitic complexes of the Mesorif Zone (External Rif, Morocco) at the Jurassic-Cretaceous boundary and the importance of the Ouerrha Accident in the palaeogeographic and geodynamic evolution of the Rif Mountains. *Boletín geológico y minero*, *127*, 389–406.

Benzaggagh, M., Mokhtari, A., Rossi, P., Michard, A., El Maz, A., Chalouan, A., et al. (2014). Oceanic units in the core of the External Rif (Morocco): Intramargin hiatus or South-Tethyan remnants? *Journal of Geodynamics*, *77*, 4–21. https://doi.org/10.1016/j.jog.2013.10.003

Biari, Y., Klingelhoefer, F., Sahabi, M., Funck, T., Benabdellouahed, M., Schnabel, M., et al. (2017). Opening of the central Atlantic Ocean: Implications for geometric rifting and asymmetric initial seafloor spreading after continental breakup. *Tectonics*, *36*, 1129–1150. https://doi.org/10.1002/2017TC004596

Blackburn, T. J., Olsen, P. E., Bowring, S. A., McLean, N. M., Kent, D. V., Puffer, J., et al. (2013). Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic magmatic province. *Science*, *340*(6135), 941–945. https://doi.org/10.1126/science.1234204

Booth-Rea, G., Jabaloy-Sánchez, A., Azdimousa, A., Asebriy, L., Vázquez-Vílchez, M., & Martínez-Martínez, J. M. (2012). Upper-crustal extension during oblique collision: The Temsamane extensional detachment (eastern Rif, Morocco). *Terra Nova*, *24*(6), 505–512. https://doi.org/10.1111/j.1365-3121.2012.01089.x

Bouillin J.P. (1986). Le "bassin maghrébin": Une ancienne limite entre l'Europe et l'Afrique à l'ouest des Alpes, Bull. Soc. Géol. Fr. (8) p. 547–558.

Bracène, R., & Frizon de Lamotte, D. (2002). The origin of intraplate deformation in the Atlas system of western and Central Algeria: From Jurassic rifting to Cenozoic–Quaternary inversion. *Tectono- physics*, *357*(1-4), 207–226. https://doi.org/10.1016/S0040-1951(02)00369-4

Brun, J. P., & Mauduit, T. (2009). Salt rollers: Structure and kinematics from analogue modelling. *Marine and Petroleum Geology*, *26*(2), 249–258. https://doi.org/10.1016/j.marpetgeo.2008.02.002

Bulundwe Kitongo MK. (1986). Stratigraphie des «sofs» jurassiques du Prérif interne, Maroc: Publications du Département de Géologie et de Paléontologie, Université de Genève, 4, 326 p.

Callegaro, S., Rapaille, C., Marzoli, A., Bertrand, H., Chiaradia, M., Reisberg, L., et al. (2014). Enriched mantle source for the Central Atlantic magmatic province: New supporting evidence from southwestern Europe. *Lithos*, *188*, 15–32. https://doi.org/10.1016/j.lithos.2013.10.021

Cebriá, J. M., LópezRruiz, J., Doblas, M., Martins, L. T., & Munhá, J. (2003). Geochemistry of the Early Jurassic Messejana-Plasencia dyke (Portugal-Spain): Implications on the origin of the Central Atlantic MAGMATIC PROVINCE. *Journal of Petrology*, *44*(3), 547–568. https://doi.org/10.1093/petrology/44.3.547

Chalouan, A., Michard, A., El Kadiri, K., Negro, F., Frizon de Lamotte, D., Soto, J. I., & Saddiqi, O. (2008). The Rif belt. In A. Michard (Ed.), *The Geology of Morocco* (pp. 203–302). Berlin: Springer.

Choubert, G., Faure-Muret, A., Hilali, E. A., Houzay, J. P. & Frizon de Lamotte, D. (1984). Carte géologique du Rif, échelle 1/50 000, feuille Boudinar. Notes et Mémoires du Service géologique du Maroc, 299.

Choubert, G., Faure-Muret, A., & Houzay, J. P. (1984). Carte géologique du Rif, échelle 1/50 000, feuille Kebdani. Notes et Mémoires du Service géologique du Maroc, 301.

Ciszak, R. (1992). *Évolution géodynamique de la chaîne tellienne en Oranie (Algérie occidentale) pendant le Paléozoïque et le Mésozoïque* (Vol. 3). Toulouse, France: Univ. Toulouse.

Conti, M. A., Alteriis, G.d., Marino, M. C., Pallini, G., & Tonielli, R. (2004). Discovery of Late Jurassic fossils inside modern sediments at Gorringe Bank (Eastern Atlantic Ocean) and some geological implications. *Terra Nova*, *16*(6), 331–337. https://doi.org/10.1111/j.1365-3121.2004.00570.x

Crespo-Blanc, A., & Frizon de Lamotte, D. (2006). Structural evolution of the external zones derived from the Flysch Trough and the South Iberian and Maghrebian paleomargins around the Gibraltar Arc: A comparative study. *Bulletin de la Société géologique de France*, *177*(5), 267–282. https://doi.org/10.2113/gssgfbull.177.5.267

De Capoa, P., Di Staso, A., Perrone, V., & Zaghloul, M. N. (2007). The age of the foredeep sedimentation in the Betic–Rifian Mauretanian Units: A major constraint for the reconstruction of the tectonic evolution of the Gibraltar Arc. *Comptes Rendus Geoscience*, *339*(2), 161–170. https://doi.org/10.1016/j.crte.2007.01.003

de Lis Mancilla, F., & Diaz, J. (2015). High resolution Moho topography map beneath Iberia and Northern Morocco from receiver function analysis. *Tectonophysics*, *663*, 203–211. https://doi.org/10.1016/j.tecto.2015.06.017

Denyszyn, S. W., Fiorentini, M. L., Maas, R., & Dering, G. (2018). A bigger tent for CAMP. *Geology*, *46*(9), 823–826. https://doi.org/10.1130/G45050.1

Deptuck, M. E., & Kendell, K. L. (2017). A review of Mesozoic-Cenozoic salt tectonics along the Scotian Margin, Eastern Canada. *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*, 287–312. https://doi.org/10.1016/B978-0-12-809417-4.00014-8

Dercourt, J., Zonenshain, L. P., Ricou, L. E., Kazmin, V. G., Le Pi-Chon, X., Knipper, A. L., et al. (1986). Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *Tectonophysics*, *123*(1-4), 241–315. https://doi.org/10.1016/0040-1951(86)90199-X

Durand-Delga M, Fontboté JM. (1980). Le cadre structural de la Méditerranée occidentale. In 26o Congrès Géol. Intern. Paris, Colloque no. 5, Les chaines alpines issues de la Téthis.

Durand-Delga, M., Hottinger, L., Marcais, J., Mattauer, M., Milliard, Y., Suter, G. (1960-1962). Donnés actuelles sur la structure du Rif. Mdm. h. s&. Soc. géol. Fr., Livre m6m. Prof. Fallot, 1, 399-422.

El Arabi, E. H. (2007). La série permienne et triasique du rift haut-atlassique. Nouvelles datations et évolution tectono-sédimentaire. Thèse Sci., Univ. Hassan II, Casablanca, 220 p. (déposé Univ. Casablanca).

Et-touhami, M. (2000). Lithostratigraphy and depositional environments of Lower Mesozoic evaporites and associated red beds, Khemisset Basin, northwestern Morocco. Epicontinental Triassic International Symposium.

Faugères, J. C. (1981). Evolution d'un bassin Atlantico-mésogéen de la marge Africaine: Les rides sud rifaines (Maroc). *Bulletin de la Société géologique de France*, 7, XXIII, 229–224.

Faugères, J.C. and Mouterde, R. (1980). Affinités des faunes dans le Lias sud-rifain (Maroc): Précisions sur l'évolution des paléoocéans atlantique et mésogéen. 26' Congr. géol. intern., Colloque C5, Mém. Bur. rech. Géol. Min., 115, 188.

Faure-Muret, A., Choubet, G., Braud, J., Morell, J. L., & Frizon de Lamotte, D. (1994). Carte geologique du Rif: Midar (feuille NI-30-XV-3d) Cartes geologi- ques au 1/50.000. Notes et memoires du Service geologique NM, 367

Favre, P. (1992). Géologie des massifs calcaires situés au front S de l'unité de Kétama (Rif, Maroc). Publications du Département de Géologie et Paléontologie, Univ. Genève, 11, 138.

Favre, P. (1995). Analyse quantitative du rifting et de la relaxation thermique de la partie occidentale de la marge transformante nord-africaine: Le Rif externe (Maroc) Comparaison avec la structure actuelle de la chaïne. *Geodinamica Acta*, *8*(2), 59–81. https://doi.org/10.1080/09853111.1995.11105275

Favre, P., Stampfli, G., & Wildi, W. (1991). Jurassic sedimentary record and tectonic evolution of the northwestern corner of Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *87*(1-4), 53–73. https://doi.org/10.1016/0031-0182(91)90130-J

Fenet, B. (1975). *Recherches sur l'alpinisation de la bordure septentrionale du bouclier African: À partir de l'étude d'un élément de l'Orogène nord-maghrébin: Les Monts du Djebel Tessala et les Massifs du littoral oranais*. Nice, France: Univ. Nice.

Fernandez, O. (2019). The Jurassic evolution of the Africa-Iberia conjugate margin and its implications on the evolution of the Atlantic-Tethys triple junction. *Tectonophysics*, *750*, 379–393. https://doi.org/10.1016/j.tecto.2018.12.006

Flinch, J., & Soto, J. (2017). Allochthonous Triassic and salt tectonic processes in the Betic-Rif Orogenic Arc. In J. I. Soto, J. F. Flinch, & G. Tari (Eds.), *Permo-Triassic Salt Provinces of Europe, North Africa and the Central Atlantic: Tectonics and Hydrocarbon Potential* (pp. 243–261). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809417-4.00020-3

Frizon de Lamotte, D. (1982). *Contribution à l'étude de l'evolution structurale du Rif oriental (Maroc). Notes et Mémoires du Service Géologique* (Vol. 314, pp. 239–309). Rabat, Morocco: Service géologique du Maroc.

Frizon de Lamotte, D. (1985). La structure du Rif oriental (Maroc). Rôle de la tectonique longitudinale et importance des fluides. These Doct. Etat, Univ. P. et M. Curie, Paris VI; Sci. Terre Univ. P. et M. Curie n ° 85-03.

Frizon de Lamotte, D. (1987). Un exemple de collage synmétamorphe: La déformation miocene des Temsamane (Rif, Maroc). Bull. Soc. Géol. Fr. (8), III, 337-344

Frizon de Lamotte, D., Andrieux, J., & Guezou, J. C. (1991). Cinématique des chevauchements néogènes dans l'Arc bético-rifain: Discussion sur les modèles géodynamiques. *Bulletin de la Société géologique de France*, *169*, 611–626.

Frizon de Lamotte, D., Faure-Muret, A. Choubert, G. (1984). Carte structurale du Rif oriental. échelle 1/200 000.

Frizon De Lamotte, D., Fourdan, B., Leleu, S., Leparmentier, F., & De Clarens, P. (2015). Style of rifting and the stages of Pangea breakup. *Tectonics*, *34*, 1009–1029. https://doi.org/10.1002/2014TC003760

Frizon de Lamotte, D., & Leikine, M. (1985). Métamorphisme miocène du Rif oriental (Maroc) et individualisation de la nappe gravitaire d'Aknoul. *Revue de Géologie dynamique et de Géographie physique*, *26*, 29–42.

Frizon de Lamotte, D., Raulin, C., Mouchot, N., Wrobel-Daveau, J. C., Blanpied, C., & Ringenbach, J.-C. (2011). The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: Initial geometry and timing of the inversion processes. *Tectonics*, *30*, TC3002. https://doi.org/10.1029/2010TC002691

Frizon de Lamotte, D., Zizi, M., Missenard, Y., Hafid, M., El Azzouzi, M., Maurym, R. C., et al. (2008). The atlas system. In A. Michard, O. Saddiqi, A. Chalouan, & D. F. de Lamotte (Eds.), *Continental evolution: The geology of Morocco* (Vol. 116, pp. 133–202).

Guerrera, F., Loiacono, F., Puglisi, D., & Moretti, E. (1992). The Numidian Nappe in the Maghrebian chain: State of the art. *Bollettino Della Società Geologica Italiana*, *111*, 217–253.

Hafid, M., Tari, G., Bouhadioui, D., Moussaid, I. E., Echarfaoui, H., Salem, A. A., et al. (2008). Atlantic basins. In A. Michard, O. Saddiqi, A. Chalouan, & D. Frizon de Lamotte (Eds.), *Structure, Stratigraphy and Tec- tonics of the Africa–Atlantic–Mediterranean Triple Junction. Lecture Notes in Earth Sciences* (Vol. *116*, pp. 303–329). https://doi.org/10.1007/978-3-540-77076-3_6

Hailwood, E. A., & Mitchell, J. G. (1971). Paleomagnetic and radiometric dating results from Jurassic intrusions in South Morocco. *Eophysical Journal of the Royal Astronomical Society*, *41*(1971), 213–236.

Hames, W., McHone, J. G., Renne, P., & Ruppel, C. (2003). *Introduction. The Central Atlantic magmatic province: Insights from fragments of Pangea, Geophysical Monograph* (Vol. 136). Washington, D.C: AGU.

Hoskin, P. W. O., & Schaltegger, U. (2003). The composition of zircon and igneous and meta-morphic petrogenesis. In J. M. Hanchar, & P. W. O. Hoskin (Eds.), *Reviews in Mineralogy and Geochemistry* (Vol. 53, pp. 27–62). https://doi.org/10.2113/0530027

Jabaloy-Sánchez, A., Azdimousa, A., Booth-Rea, G., Asebriy, L., Vazquez-Vilchez, M., Miguel Martinez-Martinez, J., & Gabites, J. (2015). The structure of the Temsamane fold- and-thrust stack (eastern Rif, Morocco): Evolution of a transpressional orogenic wedge. *Tectonophysics*, *663*, 150–176. https://doi.org/10.1016/j.tecto.2015.02.003

Jiménez-Munt, I., Fernàndez, M., Vergés, J., Afonso, J. C., Garcia-Castellanos, D., & Fullea (2010). Lithospheric structure of the Gorringe Bank: Insights into its origin and tectonic evolution. *Tectonics*, *29*, TC5019. https://doi.org/10.1029/2009TC002458

Knight, K. B., Nomade, S., Renne, P. R., Marzoli, A., Bertrand, H., & Youbi, N. (2004). The Central Atlantic Magmatic Province at the Triassic-Jurassic boundary: Paleomagnetic and ^{40}Ar/^{39}Ar evidence from Morocco for brief, episodic volcanism. *Earth and Planetary Science Letters*, *228*(1–2), 143–160. https://doi.org/10.1016/j.epsl.2004.09.022

Labails, C., Olivet, J. L., Aslanian, D., & Roest, W. R. (2010). An alternative early opening scenario for the Central Atlantic Ocean. *Earth and Planetary Science Letters*, *297*(3-4), 355–368. https://doi.org/10.1016/j.epsl.2010.06.024

Lacoste, J. (1934). *Etudes Geologiques dans le Rif meridional. Notes et Mémoires du Service Géologique* (Vol. 31, pp. 1–660). Rabat, Morocco: Service géologique du Maroc.

Lago, M., Gale, C., Arranz, E., Gil, A., Pocovi, A., & Vaquer, R. (2000). The triassic alkaline dolerites of the Valacloche-Camarena are (SE-Iberian Chain, Teruel, Geodynamic implications). *Estudios Geologicos*, *56*, 211–228.

Laville, E., & Piqué, A. (1992). Jurassic penetrative deformation and Cenozoic uplift in the Central High Atlas (Morocco): A tectonic model. Structural and Orogenic inversions. *Geologische Rundschau*, *81*(1), 157–170. https://doi.org/10.1007/BF01764546

Leblanc, D. (1979). Etude geologique du Rif externe oriental au Nord de Taza (Maroc). Notes et Mdm. Serv. gdol. Maroc, Rabat, n ° 281.

Leblanc, D. (1983). Carte géologique du Rif, feuille de Taïneste au 1/50.000. Notes et Mémoires du Service géologique du Maroc, 305.

Leblanc, D., & Feinberg, H. (1982). Nouvelles données stratigraphiques et structurales sur le Numidien du Rif oriental (Maroc). Implications géodynamiques. *Bulletin de la Société géologique de France*, *7*(4), 861–865.

Leleu, S., & Hartley, A. J. (2010). Controls on the stratigraphic development of the Triassic Fundy Basin, Nova Scotia, Canada: Implications for the interpretation and correlation of ancient fluvial sucessions. *Journal of Sedimentary Research*, *80*(10), 867–883. https://doi.org/10.2110/jsr.2010.080

Leleu, S., Hartley, A. J., van Oosterhout, C., Kennan, L., Ruckwied, K., & Gerdes, K. (2016). Structural, stratigraphic and sedimentological characterisation of a wide rift system: The Triassic rift system of the Central Atlantic Domain. *Earth-Science Reviews*, *158*, 89–124. https://doi.org/10.1016/j.earscirev.2016.03.008

Leprêtre, R., Frizon de Lamotte, D., Combier, V., Gimeno-Vives, O., Mohn, G., & Eschard, R. (2018). The Tell-Riforogenic system (Morocco, Algeria, Tunisia) and the structural heritage of the southern Tethys margin, BSGF. *BSGF-Earth Sciences Bulletin*, *189*(2), 10. https://doi.org/10.1051/bsgf/2018009

Levy, R. G., Tilloy, R. (1952). Maroc septentrional (chaine du Rif), partie B.Livret-guide de excursions A31 et C31. Congres Geologique International, XIX session, Ager, serie Maroc, 8, 65.

Marzoli, A., Renne, P. R., Piccirillo, E. M., Ernesto, M., Bellieni, G., & De Min, A. (1999). Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science*, *284*(5414), 616–618. https://doi.org/10.1126/science.284.5414.616

Merle, O. (2011). A simple continental rift classification. *Tectonophysics*, *513*(1-4), 88–95. https://doi.org/10.1016/j.tecto.2011.10.004

Michard, A., Feinberg, H., El-Azzab, D., Bouybaouène, M., & Saddiqi, O. (1992). A serpentinite ridge in a collisional paleomargin setting: The Beni Malek Massif, external Rif, Morocco. *Earth and Planetary Science Letters*, *113*(3), 435–442. https://doi.org/10.1016/0012-821X(92)90144-K

Michard, A., Mokhtari, A., Chalouan, A., Saddiqi, O., Rossi, P., & Rjimati, E. C. (2014). New ophiolite slivers in the External Rif belt, and tentative restoration of a dual Tethyan suture in the western Maghrebides. *Bulletin de la Societe Geologique de France*, *185*(5), 313–328. https://doi.org/10.2113/gssgfbull.185.5.313

Michard, A., Mokhtari, A., Lach, P., Rossi, P., Chalouan, A., Saddiqi, O., & Rjimati, E. C. (2018). Liassic age of an oceanic gabbro of the External Rif (Morocco): Implications for the Jurassic continent–ocean boundary of Northwest Africa. *Comptes Rendus - Geoscience*, *350*(6), 299–309. https://doi.org/10.1016/j.crte.2018.05.006

Michard, A., Negro, F., Frizon de Lamotte, D., & Saddiqi, O. (2007). Serpentinite slivers and metamorphism in the External Maghrebides: Arguments for an intracontinental suture in the African paleomargin (Morocco, Algeria). *Revista de La Sociedad Geológica de España*, *20*, 173–186.

Midoun, M., & Seddiki, A. (2016). The mafic, ultramafic and metamorphic xenoliths in Triassic evaporite complexes, North West Algeria. *Boletin Geologico y Minero*, *127*(2-3), 333–344.

Morata, D., Puga, E., Demant, A., & Aguirre, L. (1997). Geochemistry and tectonic setting of the "ophites" from the external zones of the Betic Cordilleras (S. Spain). *Estudios Geologicos*, *53*, 107–120.

Morel, J.-L. (1980). *Contribution à l'étude géologique et structurale de la région de Midar (Rif Oriental, Maroc). Thése de 3éme cycle*, (p. 177). Orsay: Université Paris Sud.

Negro, F., Agard, P., Goffé, B., & Saddiqi, O. (2007). Tectonic and metamorphic evolution of the Temsamane units, External Rif (northern Morocco): Implications for the evolution of the Rif and the Betic–Rif arc. *Journal of the Geological Society of London*, *164*(4), 829–842. https://doi.org/10.1144/0016-76492006-112

Negro, F., de Sigoyer, J., Goffé, B., Saddiqi, O., & Villa, I. M. (2008). Tectonic evolution of the Betic-Rif arc: New constraints from 40Ar/39Ar dating on white micas in the Temsamane units (External Rif, northern Morocco). *Lithos*, *106*, 93–108. https://doi.org.10.1016/j. lithos.2008.06.011

Papillon, R. (1989). Stratigraphie des Sofs Lias-Dogger des massifs des Senhadja et de l'Azrou Akchar (Rif, Maroc). Publications du Département Géologie et de Paléontologie de l'Université de Genève, 8, 217.

Petit, C., Le Pourhiet, L., Scalabrino, B., Corsini, M., Bonnin, M., & Romagny, A. (2015). Crustal structure and gravity anomalies beneath the Rif, northern Morocco: Implications for the current tectonics of the Alboran region. *Geophysical Journal International*, *202*(1), 640–652. https://doi.org/10.1093/gji/ggv169

Quirk, D. G., & Pilcher, R. S. (2012). Flip-flop salt tectonics. *Geological Society, London, Special Publications*, *363*(1), 245–264. https://doi. org/10.1144/sp363.11

Ramos, A., Fernández, O., Terrinha, P., & Muñoz, J. A. (2016). Extension and inversion structures in the Tethys–Atlantic linkage zone, Algarve Basin, Portugal. *International Journal of Earth Sciences*, *105*(5), 1663–1679. https://doi.org/10.1007/s00531-015-1280-1

Ramos, A., Fernández, O., Torne, M., Sánchez de la Muela, A., Muñoz, J. A., Terrinha, P., et al. (2017). Crustal structure of the SW Iberian passive margin: The westernmost remnant of the Ligurian Tethys? *Tectonophysics*, *705*, 42–62. https://doi.org/10.1016/j. tecto.2017.03.012

Ricou, L. E. (1994). Tethys reconstructed: Plates, continental fragments and their boundaries since 260 Ma from Central America to South-eastern Asia. *Geodinamica Acta*, *7*, 169–218.

Rossetti, F., Theye, T., Lucci, F., Bouybaouène, M. L., Dini, A., Gerdes, A., et al. (2010). Timing and modes of granite magmatism in the core of the Alboran domain (rif chain, northern Morocco): Implications for the alpine evolution of the western Mediterranean. *Tectonics*, *29*, TC2017. https://doi.org/10.1029/2009TC002487

Sahabi, M., Aslanian, D., & Olivet, J. L. (2004). Un nouveau point de départ pour l'histoire de l'Atlantique central. *Comptes Rendus Geoscience*, *336*(12), 1041–1052. https://doi.org/10.1016/j.crte.2004.03.017

Sallarès, V., Gailler, A., Gutscher, M.-A., Graindorge, D., Bartolomé, R., Gràcia, E., et al. (2011). Seismic evidence for the presence of Jurassic oceanic crust in the central Gulf of Cadiz (SW Iberian margin). *Earth and Planetary Science Letters*, *311*(1-2), 112–123. https:// doi.org/10.1016/j.epsl.2011.09.003

Sani, F., del Ventisette, C., Montanari, D., Bendkik, A., & Chenakeb, M. (2007). Structural evolution of the Rides Prerifaines (Morocco): Structural and seismic interpretation and analogue modelling experiments. *International Journal of Earth Sciences*, *96*(4), 685–706. https://doi.org/10.1007/s00531-006-0118-2

Şengör, A. M. C., & Natal'in, B. A. (2001). Rifts of the world. In R. E. Ernst, & K. L. Buchan (Eds.), *Mantle plumes: Their identification through time*, *Special Paper* (Vol. 352, pp. 389–482). Boulder, Colorado: Geological Society of America. https://doi.org/10.1130/0-8137-2352-3.389

Soto, J. I., Flinch, J., & Tari, G. (2017). *Permo-Triassic salt provinces of Europe, North Africa and the Central Atlantic: Tectonics and hydrocarbon potential* (pp. 243–261). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809417-4.00038-0

Suter, G. (1964a). Carte géologique du Rif, région du Moyen Ouerrha, feuille de Tafrannt de l'Ouerrha-Moulay BouChtaa au 1/50.000. Notes et Mémoires du Service géologique du Maroc, 165.

Suter, G. (1964b). Carte géologique du Rif, feuille de Taounate-Aïn Aicha au 1/50.000. Notes Mémoire du Service géologique du Maroc, 166.

Suter, G. (1965). La région du Moyen Ouen-ha (Rif, Maroc). Etude préliminaire sur la stratigraphie et la tectonique. Notes Mém. Serv. Géol. Maroc, 183, 7-17.

Suter, G. (1980a). Carte geologique de la chaine rifaine a 1/500 000. Notes et Mdm. Serv. geol. Maroc, n ° 245a.

Suter, G. (1980b). Carte structurale de la chaine rifaine h 1/500000. Notes et Mdm. Serv. geol. Maroc, n ° 245b.

Tari, G., Brown, D., Jabour, H., Hafid, M., Louden, K., & Zizi, M. (2012). The conjugate margins of Morocco and Nova Scotia. In D. G. Roberts, & A. W. Bally (Eds.), *Regional geology and tectonics: Phanerozoic passive margins, cratonic basins and global tectonic maps* (pp. 285–323). Amsterdam: Elsevier.

Tari, G., Novotny, B., Jabour, H., & Hafid, M. (2017). Salt tectonics along the Atlantic margin of NW Africa (Morocco and Mauritania). In J. I. Soto, J. F. Flinch, & G. Tari (Eds.), *Permo-Triassic salt provinces of Europe, North Africa and the Central Atlantic: Tectonics and hydrocarbon potential* (pp. 243–261). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809417-4.00016-1

Tugend, J., Manatschal, G., & Kusznir, N. (2015). Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics and timing of the Iberian-European plate boundary. *Geology*, *43*(1), 15–18. https://doi.org/10.1130/G36072.1

Verati, C., Rapaille, C., Féraud, G., Marzoli, A., Marzoli, H., Bertrand, H., & Youbi, N. (2007). Ar-Ar ages and duration of the Central Atlantic magmatic province volcanism in Morocco and Portugal and its relation to the Triassic-Jurassic boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *244*(1-4), 308–325. https://doi.org/10.1016/j.palaeo.2006.06.033

Vergés, J., & Sàbat, F. (1999). Constraints on the Neogene Mediterranean kinematic evolution along a 1000 km transect from Iberia to Africa. *Geological Society, London, Special Publications*, *156*(1), 63–80. https://doi.org/10.1144/GSL.SP.1999.156.01.05

Vidal, J. C. (1977). Structure actuelle et évolution depuis le Miocène de la chaîne rifaine partie sud de l'Arc de Gibraltar. *Bulletin de la Société géologique de France*, *19*(7), 789–796.

Vidal, J. C. (1979). Carte géologique du Rif, feuille de Beni Frassene au 1/500.000. Notes et Mémoires du Service géologique du Maroc, 283.

Vidal, J. C. (1983). Carte géologique du Rif, feuille de Dhar Souk au 1/50.000. Notes et Mémoire du Service géologique du Maroc, 298.

Vitale, S., Zaghloul, M. N., El Ouaragli, B., Tramparulo, F. D. A., & Ciarcia, S. (2015). Polyphase deformation of the Dorsale Calcaire Complex and the Maghrebian Flysch Basin Units in the Jebha area (Central Rif, Morocco): New insights into the Miocene tectonic evolution of the Central Rif belt. *Journal of Geodynamics*, *90*, 14–31. https://doi.org/10.1016/j.jog.2015.07.002

Vitale, S., Zaghloul, M. N., Tramparulo, F. D. A., & El Ouaragli, B. (2014). Deformation characterization of a regional thrust zone in the northern Rif (Chefchaouen, Morocco). *Journal of Geodynamics*, *77*, 22–38. https://doi.org/10.1016/j.jog.2013.09.006

Vitale, S., Zaghloul, M. N., Tramparulo, F. D. A., El Ouaragli, B., & Ciarcia, S. (2014). From Jurassic extension to Miocene shortening: An example of polyphasic deformation in the External Dorsale Calcaire Unit (Chefchaouen, Morocco). *Tectonophysics*, *633*, 63–76. https:// doi.org/10.1016/j.tecto.2014.06.028

Wildi, W. (1981). Le Ferrysch: Cône de sédimentation détritique en eau profonde à la bordure nord-ouest de l'Afrique au Jurasique moyen à supérieur (Rif externe, Maroc). *Eclogae Geologiae Helvetiae*, *74*, 481–527.

Wildi, W. (1983). La chaîne tello-rifaine (Algérie, Maroc, Tunisie): Structure, stratigraphie et évolution du Trias au Miocène. *Revue de Géologie Dynamique et de Géographie Physique*, *24*, 201–297.

Zaghloul, M. N., Di Staso, A., de Capoa, P., & Perrone, V. (2007). Occurrence of upper Burdigalian silexite beds within the Beni Ider Flysch Fm. in the Ksar-es-Seghir area (Maghrebian Flysch Basin, Northern Rif, Morocco): Stratigraphic correlations and geodynamic implications. *Bollettino della Società Geologica Italiana*, *126*, 223–239.

Ziegler, P. A. (1992). Plate tectonics, plate moving mechanisms and rifting. In: P.A. Ziegler (Editor), Geodynamics of Rifting Volume III. Thematic Discussions. *Tectonophysics*, *215*(1-2), 9–34. https://doi.org/10.1016/0040-1951(92)90072-E

Ziegler, P. A., & Cloetingh, S. (2004). Dynamic processes controlling evolution of rifted basins. *Earth-Science Reviews*, *64*, 1–50. https://doi.org/10.1016/S0012-8252(03)00041-2

Zizi, M. (2002). Triassic-Jurassic extensional systems and their Neogene reactivation in Northern Morocco: the Rides Prerifaines and Guercif Basin. In *Notes et Mémoires du Service Géologique* (Vol. 416, pp. 1–138).