Tectonophysics 710–711 (2017) 249–265

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Thick-skinned tectonics closing the Rifian Corridor

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ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form 7 July 2016
Accepted 23 September 2016
Available online 24 September 2016

Keywords:
Late stage orogenic deformation
Slab retreat
Thick-skinned tectonics
Gibraltar arc
Rifian Corridor

ABSTRACT

Tectonic processes in the Gibraltar region are associated with Africa-Iberia convergence and the formation of the Betic-Rif orogenic system. The Late Miocene shortening recorded in the Rif orogen resulted in gradual shallowing and eventual closure of the Rifian Corridor, a narrow marine gateway connecting the Atlantic Ocean with the Mediterranean Sea. This closure is associated with paleoenvironmental changes that ultimately led to the Mediterranean Messinian Salinity Crisis. Here we present a structural analysis based on a combination of field kinematic data and interpretation of reflection seismic lines acquired for petroleum exploration to understand the deformational phases associated with the closure of the Rifian Corridor. We show the succession of three Late Miocene to present day events, an initial thin-skinned nappe thrusting, followed by regional subsidence and continued by thick-skinned contraction. The transition from in sequence thin-skinned tectonics during subduction to thick-skinned contraction during continental collision resulted in significant acceleration of tectonic uplift and associated exhumation. This is related to a change in the regional deformation linked to plate convergence, but possibly also coupled with deep lithospheric or dynamic topography processes. Such a mechanism is also common for other Mediterranean orogens during late stages of slab retreat, where accelerated tectonics resulted in rapid sedimentation and associated basins evolution. We conclude that the thick-skinned contraction in the Rif orogeny initiated in the late Tortonian, has created a cumulative uplift in the order of 1 km, and provided high enough uplift rates to close the Rifian Corridor.

1. Introduction

The final stage of orogenic collision is a period when the buoyancy of the continental lower plate involved in subduction changes the coeval evolution of back-arc and forearc basins in mountain chains affected by slab retreat (e.g., Baes et al., 2011; Duretz and Gerya, 2013). This process results in inversion of extensional back-arc basins associated with widespread out-of-sequence deformation, rapid uplift and sedimentation in the fore-arc domain and its foredeep (Bertotti et al., 2001; Doglioni et al., 2007; Roure, 2008; Ziegler et al., 1995). Such processes are rather common in the Mediterranean or SE Asia domains, where the formation of highly curved orogens is associated with rapid slab retreat (e.g., Faccenna et al., 2004; Matenco et al., 2010; Spakman and Hall, 2010). In the Carpathian, Apennines or Banda arc orogenic areas, the gradual subduction accretion of lower plate material culminated during continental collision, when the arrival of buoyant non-stretched continental crust at the subduction zone created marked inversions, out-of-sequence thrusting and accelerated orogenic exhumation (e.g., Hall, 2013; Horváth et al., 2015; Matenco et al., 2010; Pubellier and Morley, 2014). Particularly interesting is the transition from in sequence thin-skinned accretion, characteristic of the slab-retreat period, to the out-of-sequence, commonly thick-skinned contraction that is associated with the late stages of continental collision, when the proximal part of the lower plate passive continental margin enters the subduction zone (Bocin et al., 2009; Picotti and Pazzaglia, 2008; Sokoutis et al., 2005; Willingshofer et al., 2013). This results in a significant acceleration to almost one order of magnitude higher of the tectonic uplift and associated exhumation in the orogen that may be associated with comparable subsidence in its fore-wedge or retro-wedge foredeep if the slab is still attached, or with rapid rebound of the entire system after slab detachment (Bertotti et al., 2006; Matenco et al., 2015; Merten et al., 2010).

In this context, the Betic-Rif orogenic system was associated with the rapid retreat of the Gibraltar slab and it ultimately led to the collision with the Iberian and African foreland during their continuous slow convergence, which was associated with partial inversion in the Alboran back-arc and renewed/enhanced exhumation in the orogen (e.g.,

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http://dx.doi.org/10.1016/j.tecto.2016.09.028
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Frizon de Lamotte et al., 1991; Lonergan and White, 1997; Platt et al., 2006; Vergés and Fernàndez, 2012 and references therein). Tectonic forcing in the Gibraltar arc was driven by two competing and partly coeval processes: the westward drift of the Alboran Plate, that was associated with the Gibraltar slab-retreat and created W- to SW-ward transport kinematics in the Rif, and the roughly N-S continuous convergence between Africa and Iberia (e.g., Frizon de Lamotte et al., 1991; Jolivet et al., 2006; Morel, 1989). The mechanism of out-of-sequence contraction and enhanced exhumation that is commonly observed in similar Mediterranean orogens is rather unclear in the external part of the Rif Mountains (Fig. 1), although such processes have been observed in their lateral prolongation along the African margin (e.g., Roure et al., 2012). Such a process is relevant in the context of the Mediterranean Sea evolution that became gradually isolated from the Atlantic Ocean during the Late Miocene, when the Mediterranean salinity rose and caused the Messinian Salinity Crisis (MSC), one of the most dramatic environmental changes of the last ten million years (e.g., Roveri et al., 2014). The Rifian Corridor (Fig. 1) through Northern Morocco was a major marine connection just before the MSC isolation of the Mediterranean (e.g. Krijgsman et al., 1999; Flecker et al., 2015). The upper crustal structural control of its closure at the time of Rif collision is still not quantified, although a number of processes have been discussed, such as dynamic topographic uplift (Duggen et al., 2003), isostatic response to desiccation and salt deposition (Govers, 2009), crustal-scale thrusting (Weijermars, 1988) or localized volcanism driving regional uplift (the Morocco Hot Line of Frizon de Lamotte et al., 2009, Fig. 1). In this area, significant uplift driving the onset of the Messinian Salinity Crisis is suggested by the late Messinian uplift of the Taza-Guercif Basin that is located in this Morocco Hot Line near the junction between the Rif foredeep and the Middle Atlas (Fig. 1, Krijgsman et al., 1999). These large-scale processes are rather difficult to constrain at Miocene-Pliocene stratigraphic resolution and may not necessarily explain by themselves the closure of the corridor, in particular because of the large-wavelength of the asthenospheric upraise beneath the Atlas Mountains and the Rifian Corridor (e.g., Babault et al., 2008; Fullea et al., 2007), a significant acceleration of localized uplift is required to overcome the erosional deepening due to bottom currents in the seaway (Garcia-Castellanos and Villaseñor, 2011).

We analyse the structural evolution of the external part of the Rif orogen and its foreland in order to derive the upper crustal effects of the collisional mechanics and associated vertical movements during the closure of the Rifian Corridor. We use a combination of field kinematic observations and interpretation of seismic lines to derive the succession of deformation and study its effects during sediment deposition. Four key study areas have been selected (Fig. 2), the transition from orogenic nappes to the Saiss foredeep and the interrupting Prerif Ridges, the transition from the orogenic nappes to the Gharb basin onshore and offshore Morocco, the Late Miocene basins overlying the external nappe (i.e. Had Kourt Basin) and the more internal Mesorif nappes (i.e. the Taounate Basin). These areas were connected in a larger scale interpretation considering other existing kinematic, stratigraphic and seismic interpretation studies in the external part of the Rif (e.g., Chalouan et al., 2008; Esteban, 1991; Flinch, 1993; Le Roy et al., 2014; Michard et al., 2008; Plaziat et al., 2008; Roldán et al., 2014; Sani et al., 2007; Wernli, 1988). Ultimately a novel, three-step evolutionary model is proposed for the Late Miocene to present day external Rif, with key implications on the evolution of the Rifian Corridor.

2. The evolution of the Rif orogen and the sedimentation in its foreland

The Gibraltar arc is part of the highly curved system of Mediterranean orogens that includes the Calabrian arc, the Alps-Apennines transition and the Carpathians. It formed during Africa – Iberia convergence and is associated with a westward, rapid retreat of the Gibraltar slab (Lonergan and White, 1997; Vergés and Fernàndez, 2012; Platt et al., 2013; van Hinsbergen et al., 2014). The Rif orogen (Fig. 1) is the southern branch of this arc. It consists of an internal zone affected by the Miocene extension of the Alboran Domain, and an external fold and thrust belt composed of Flysch units, Intrarif, Mesorif and Prerif nappes (Fig. 1). The overall contractional deformation in the Rif started in the Late Eocene - Oligocene, continued throughout the Miocene and ultimately led to the frontal Prerif nappes emplacement over the African foreland during the late Tortonian (e.g., Chalouan et al., 2008; Michard et al., 2006 and references therein). Contractional deformation continued as observed by the deformation of recent Quaternary sediments (e.g., Bargach et al., 2004), and is still active at present, as indicated by GPS data (Koulali et al., 2011).

The Flysch units comprise turbidites thought to originate from the sedimentary infill of the Ligurian – Maghrebian Ocean that was located between the Iberian and African margins (Chalouan et al., 2008; Michard et al., 2008). The Intrarif and Mesorif units include Mesozoic-Paleogene turbidites and shallow-water deposits derived from the North African margin (e.g., Crespo-Blanc and Frizon de Lamotte, 2006; Negro et al., 2007). The Mesorif unit to the west of the Nekor fault (Fig. 1) consists of imbricated Mesozoic platform carbonates up to the

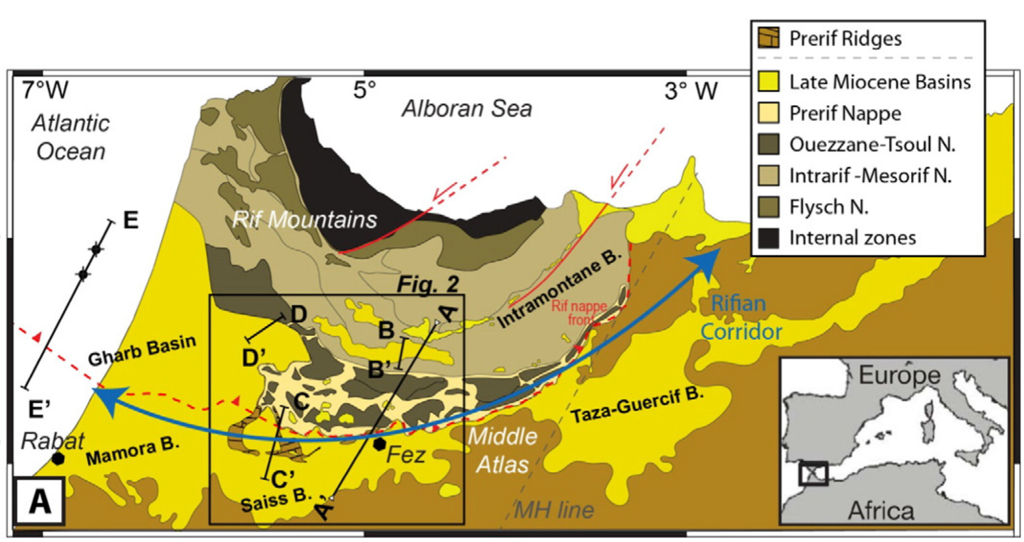

Fig. 1. Tectonic map of the Rif orogenic system, the nappe structure and its foreland (Chalouan et al., 2008; Michard et al., 2006). MH line is the Morocco hot line of volcanism (Frizon de Lamotte et al., 2009). A-A′, B-B′, C-C′, D-D′ are interpreted seismic sections and cross-sections in Figs. 4 and 7. The inset is the location of the figure in Western Mediterranean area.

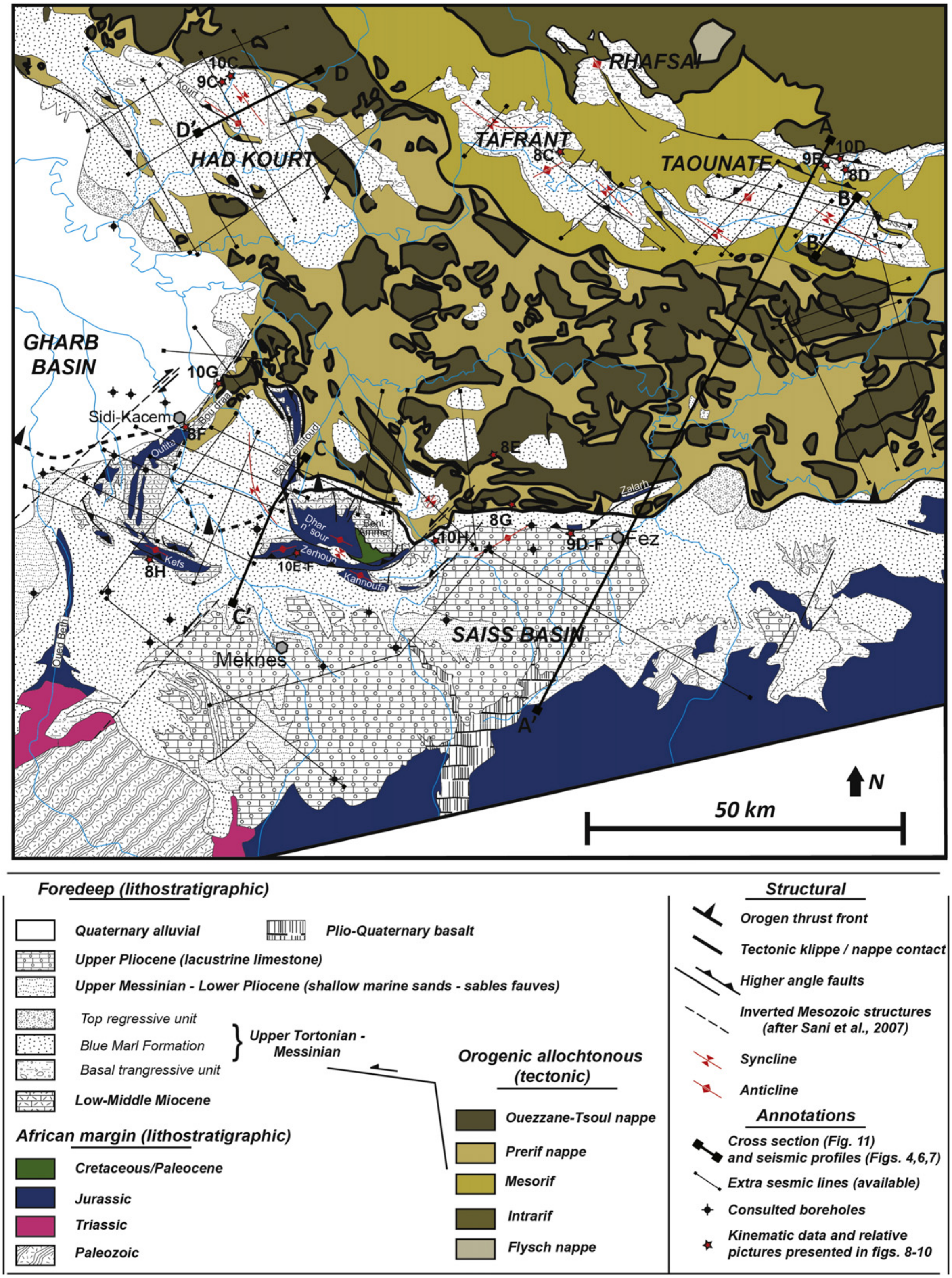

Fig. 2. Tectonic map of the Rif nappe stack and geological map of their foreland in the study area with the location of field kinematic data, seismic lines, correlation wells and geological cross sections (modified from Sani et al., 2007; Suter, 1980 and the local 1:100.000 and 1:50.000 geological maps). A-A′, B-B′, C-C′, D-D′ are interpreted seismic sections and cross-sections in Figs. 4 and 7.

Early Jurassic, followed by Middle to Late Jurassic and Cretaceous deep water siliciclastic facies, which are thrusted over para-autochthonous Lower-Middle Miocene siliciclastic rocks in wedge-top basins (Chalouan et al., 2008). Thickness changes observed in the Mesorif Jurassic suggest syn-kinematic deposition possibly related at high depth to normal faults affecting the African margin (Andrieux, 1971; Wildi, 1983).

The upper Ouezzane-Tsoul Nappe (Fig. 3) is considered to be a far-travelled thrust-sheet from the northern Intrarif that was thrusted over the Prerif domain to the south (Chalouan et al., 2008; Zaghloul et

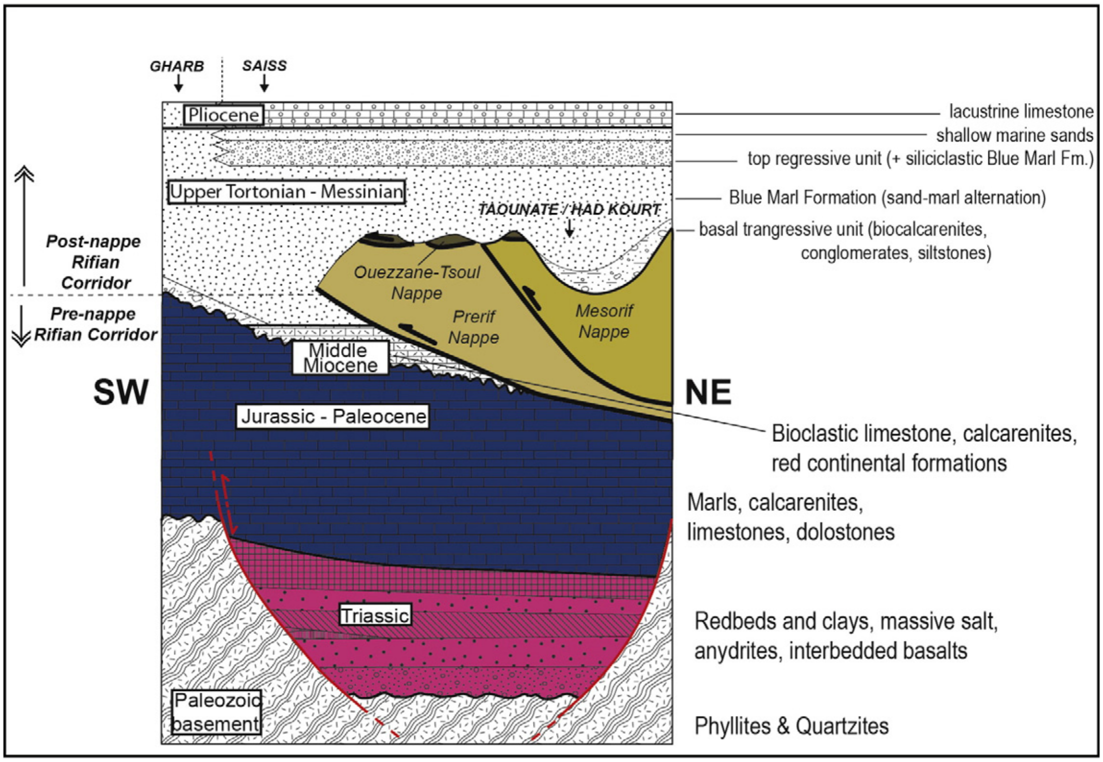

Fig. 3. Stratigraphic column and tectonogram illustrating the relationship between litho-stratigraphy and tectonic in the foreland of the Rif orogen (compiled from Sani et al., 2007 and the results of the present study).

al., 2005). Similar southward displacements of Intrarif units are observed also in the Mesorif domain (e.g., the Aknoul and Habt nappes in Chalouan et al., 2008) and they generally represent the detached upper part of the Intrarif stratigraphy. The overall deposition of this unit started with the Jurassic syn-rift sedimentation and continued with a post-rift series characterised by Upper Jurassic - Berriasian carbonates and clastics and pelagic limestones passing upwards in Cretaceous quartz-rich turbidites and hemipelagic marls (Andrieux, 1971; Wildi, 1981). In our southern studied areas, the Ouezzane-Tsoul Nappe is characterised by thicker Cenomanian deposits, a higher proportion of carbonates, and frequent diapiric intrusions of Triassic clay-gypsum complexes (Lespinasse, 1975). The overlying Tertiary contains Eocene marly limestones, which possibly acted as a decollement level, and olistostromes are locally recorded in the Oligocene (Ben Yaïch, 1991). The overlying Lower-Middle Miocene contains sand-marls alternations with similarities with the coeval para-allochton of the Mesorif north of the Taounate Basin (Chalouan et al., 2008).

The frontal Prerif Nappe (the *Nappe Prérifaine* of Levy and Tilloy, 1962) consists of a chaotic tectono-sedimentary complex of blocks of different lithologies (evaporites, basalts, carbonates, sandstones) and ages (Triassic, Cretaceous, Paleogene and Neogene up to Middle Miocene), which are mixed within Cretaceous to Middle Miocene marls (e.g., Feinberg, 1986; Leblanc, 1979). Previously regarded as a mixture of gravity slides and olistostromes (e.g.; Wildi, 1983), the overall unit is likely the external part of the accretionary wedge resulting from westward migration of the Alboran upper plate (Flinch, 1993). A clear distinction between the more competent Ouezzane-Tsoul klippens thrusted above the shaly chaotic Prerif Nappe is not possible anymore when the nappes are buried beneath the post-orogenic sediments in the Gharb Basin (Figs. 1 and 2), and therefore in this area these nappes are commonly referred to as 'the Prerif (or Prerifaine) Nappe' onshore and offshore (e.g., Flinch, 1993).

The African margin dips gently below the Rif orogen and broadly consists of a Paleozoic metamorphic basement overlain by Mesozoic-Paleocene carbonates-shales and Paleocene marly limestones (Wildi, 1983). Differences in Mesozoic thickness observed in the area of the Prerif Ridges (Figs. 1 and 2, the *Rides Prerifaines* of Daguin, 1927) are controlled by NNE-SSW oriented normal faults (Zizi, 1996, 2002). The reactivation of these normal faults from the Late Miocene onwards resulted in the unusual topography of the ridges, which were interpreted as ramp-anticlines with variable orientation, from WNW-SSE to W-E and WSW-ENE that connect with lateral ramps oriented NNE-SSW (Fig. 2) (Fig. 2, Sani et al., 2007). Deep drilling of the Prerif Nappe across the western and eastern Rif foreland basin indicates a middle-late Tortonian age for the latest nappe emplacement, which was broadly synchronous across the Betic-Rif segments of the orogen and then capped by post-8 Ma sediments (Dayja et al., 2005; Feinberg, 1986; Hilgen et al., 2000; Krijgsman et al., 1999; Wernli, 1988).

2.1. Miocene sedimentary evolution of the Rifian Corridor

The frontal Rif Nappe thrust (Fig. 1) separates the foredeep sediments in two parts, a pre- and post- nappe emplacement sedimentary sequence (Fig. 3). An unconformity and depositional hiatus separates the Mesozoic - Paleocene from the overlying pre-nappe sequence. This includes Middle Miocene shallow marine, clastic carbonates and clay-conglomerate intercalations, likely continental (Faugères, 1978), which are locally overlain by lower Tortonian white marls that witness the progressive deepening of the foredeep. The post-nappe sequence contains the Blue Marl Formation and, locally in the Saiss and Taza-Guercif basins (Fig. 1), the transition to overlying lacustrine deposits (e.g., Krijgsman et al., 1999), while the Pliocene deposits are marine in the Gharb Basin (Wernli, 1988). Outside the area of the Prerif Ridges the Middle Miocene foredeep sequence is absent and the post-nappe sediments are unconformably and gradually transgressive either over the Paleozoic – Mesozoic of the African margin to the south or the older Cretaceous – Lower Miocene sediments deformed in the external nappes to the north (Fig. 2). The overall post-nappe sequence reaches up to 2–3 km in the Gharb Basin onshore and offshore, 1200 m in the Saiss Basin, ~2000 m in the Taounate and other intramontane basins and ~1500 m at Taza-Guercif (Wernli, 1988). Furthermore, many remnant exposures of highly eroded Blue Marl Formation reaching a couple of hundred meters in thickness are found above the external Rif nappes (Figs. 1 and 2).

In more detail, the upper Tortonian - Messinian Blue Marl Formation starts with a basal unit of coarse terrigenous and bioclastic deposits with thicknesses from few meters in the Mamora Basin (e.g., Hilgen et al., 2000) up to a hundred metres in the wedge top deposition of Taounate and other intramontane basins (Fig. 3; e.g., Wernli, 1988). In Had Kourt area (Fig. 2) the basal unit consists of ~30 m thick upper Tortonian biocalcarenites that are absent from the basin margins. They outcrop only at J. Kourt ridge (Fig. 2) by out-of-sequence tectonics and are overlain by ~50 m thick silty sands, which onlap the Ouezzane-Tsoul nappe to the north. This demonstrates a transgressive event post-dating nappe emplacement (Esteban, 1991). These basal units are overlain by the typical Blue Marl Formation deposits that consist of few hundred metres of fossil-rich, grey-blue marls, with episodic turbiditic or more terrigenous intercalations. The Blue Marl Formation is getting gradually coarser upwards. The upper Tortonian deposition has been interpreted as a transgressive sequence, followed by a high stand system tract, while the Messinian, where present, is thought to be regressive and attests to a phase of infill with increased siliciclastic input in the basin (Esteban, 1991). While Tortonian sediments are extensively observed in the Rifian Corridor basins, Messinian deposition is scarcely documented east of the Gharb Basin (Esteban, 1991), or observed in detailed studies only with 200 kyr after the Tortonian/Messinian boundary (e.g., Barhoun and Bachiri Taoufiq, 2008; Dayja et al., 2005; Krijgsman et al., 1999).

In the Saiss Basin, the last marine environment is recorded by the overlying coastal-marine sands (i.e. *sables fauves* of Wernli, 1988) that pre-dates the Plio-Quaternary continental deposition of extensive oncolitic, fresh-water limestones (Taltasse, 1953). The reported age for the sable fauves is early Pliocene and, although this age was established in the Gharb on the reference planktonic foraminifer *G. crassaformis*, in the Saiss this was mainly based on the occurrence of *G. margaritae* (Wernli, 1988). More recent biostratigraphic and astronomically tuned records (e.g., Sierro et al., 1993; Krijgsman et al., 2004) suggested that this species appeared gradually throughout the middle - late Messinian in Atlantic environments. Furthermore, the presence of one other species (*G. miotumida*) found recently near the gradual transition from the Blue Marl Formation to the sables fauves indicates also a Messinian age. These improvements suggest that the shallowing of the basin took place already during the Messinian. The lack of Messinian sediments at Oued Beth and the occurrence of lacustrine deposits only in the Saiss Basin (Fig. 2) possibly documents tectonic-induced uplift that isolated this basin from the Gharb (Esteban, 1991). This took place in response to the Late Miocene-Early Pliocene activity of a NE-SW oriented bathymetrical high between the Saiss and the Gharb basin, probably due to an uplift along the Sidi Fili Fault (Fig. 2). In the Taza-Guercif Basin, the last marine deposits are middle Messinian, have a paleobathimetry in the order of 100 m and are unconformably overlain by continental deposits (Krijgsman et al., 1999). In the more internal Had Kourt, Taounate and other intramontane basins, the upper regressive part of the Blue Marl Formation is generally missing, the lower, open marine part being truncated and unconformably overlain by Quaternary conglomerates (Wernli, 1988; Barhoun, 2000). The upper part of the Pliocene sequence varies laterally from continental lacustrine and alluvial in the eastern Saiss basin to marine sediments in the western Gharb (Wernli, 1988).

3. Methodology

We combined regional seismic interpretation with outcrop observations to detect phases of deformation in the Rif foreland. Deformation structures, such as faults and folds, and their kinematic direction of transport were recorded in the field and paleostress was subsequently determined (Angelier, 1989; Angelier, 1994). The sense of shear on faults and shear joints was derived from common kinematic indicators such as Riedel shears, drag folds or slickensides. The relative timing of deformation was defined based on cross-cutting and stratigraphic relationships, combined whenever possible with the seismic interpretation. We have separated tectonic phases based on the type of deformation and higher-order tectonic events based on consistency of kinematics with stratigraphic time. The evolution of the external Rif was then analysed by interpreting an onshore and offshore regional network of industrial seismic reflection profiles. We focused on the Upper Miocene–Pliocene basins overlying the external nappes and the frontal foredeep. The seismic network calibrated by exploration wells (courtesy of ONHYM and Repsol) has allowed lateral correlations and converting the two-way travel time information of seismic lines in depth. The depth conversion is less available offshore, where only two exploration wells were available for our area of interpretation (Fig. 1). The overall seismic and wells database available was also described elsewhere (see Le Roy et al., 2014; Roldán et al., 2014; Samaka et al., 1997; Sani et al., 2007; Zizi, 1996, 2002 and references therein for further details). Differently from these studies, we have focussed our interpretation to discriminate the latest Miocene - Quaternary geometries and associated syn-kinematic facies. The key study areas are the Gharb offshore, the Prerif and Ouezzane-Tsoul nappes, the Prerif Ridges and their foredeep flanks, the Had Kourt and Taounate basins, including Tafrant and Rhafsai prolongations or small neighbouring sub-basins (Fig. 2). We have selected four representative interpreted seismic lines for the studied areas (Figs. 4–6), where the seismo-stratigraphic interpretation identified seismic facies units and seismic facies associations bounded by unconformities.

4. Interpretation of seismic reflection profiles in the external part of the Rif orogen

A NNE-SSW oriented seismic profile illustrates the structure of the Prerif Ridges and overlying Prerif Nappe (Fig. 4). Similar with previous interpretations (Roldán et al., 2014; Sani et al., 2007), these Prerif Ridges (J. Zerhoun and J. Bou Kennfoud, Fig. 4) are uplifted along near-surface high-angle thrusts and appear to re-activate inherited Jurassic normal faults rooted at high depth in the pre-Miocene sequence. Although the inversion is total, the inherited normal faults can still be detected by thickness and facial changes across these faults (Zizi, 1996, 2002). We did not observe any significant diapirism of the Upper Triassic salt in our interpretation, which was likely limited beneath the thick carbonate sequence. However, salt diapirism could have occurred along the main faults and below the pop-up structures. The uplifted anticlines separate the frontal Prerif Nappe contact and its foredeep in three intervening areas where multiple seismic units are clearly visible. The U1 seismic unit was deposited during the low-angle thrusting of the Prerif Nappe, the latter being differentiated by its characteristic transparent and chaotic reflectors. This sequence can be subdivided into three seismic subunits based on reflectors terminations at unconformities, seismic facies and surface correlations. The first syn-kinematic U1.1 sub-unit was deposited unconformably beneath the Prerif Nappe and in wedge top basins. The overlying syn-kinematic sub-unit, U1.2, is deposited unconformable over the earlier sub-unit and the Prerif Nappe and marks the moment during deformation when the frontal emplacement was already achieved. Seismic sub-unit U1.3 is still syn-kinematic by filling the accommodation space created earlier by thrusting in the frontal part of the nappe. The U1 sub-units correspond to the basal coarser facies of the Blue Marl Formation and outcrop along the flanks of the Prerif Ridges as marine sediments that are late Tortonian in age (Fig. 4). High amplitude parallel reflectors define the first post-kinematic seismic unit U2, which fills the space created by the earlier thrusting and locally reaches up to 500 m in thickness. It is onlapping on the Zerhoun ridge and extends transgressively SSE- and NNW-wards. It illustrates rapid and regional subsidence that enlarged the foredeep

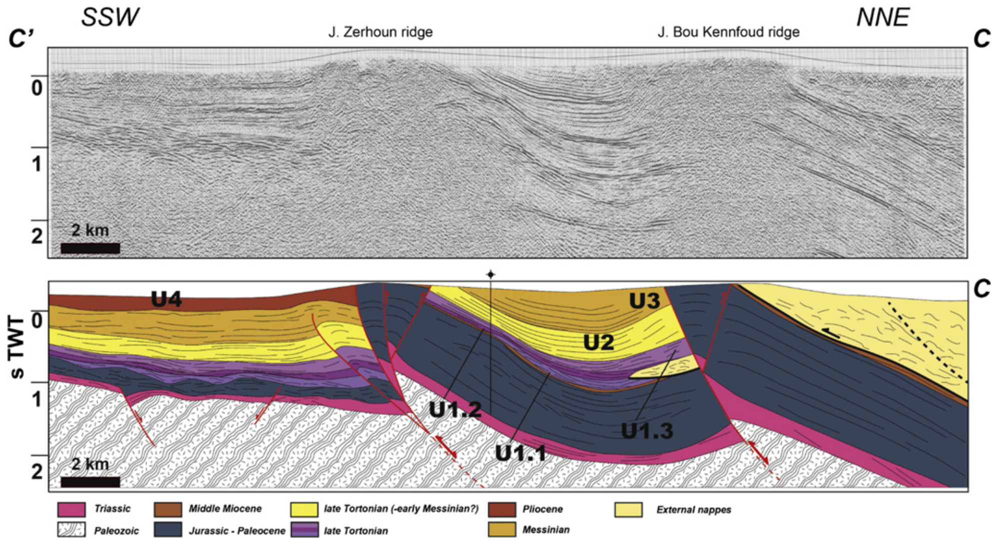

Fig. 4. Non-interpreted and interpreted seismic line C-C′ crossing over the Prerif ridges and overlying Prerif Nappe in the frontal part of the Rif orogen. U1–4 are seismic facies units corresponding to the evolution of the basin. Location of the seismic lines is displayed in Figs. 1 and 2. For further description see the text.

with deposition overlying the frontal Prerif Nappe. The overlying seismic unit, U3, shows a clear syn-kinematic character controlled by the activation of steeper, high-angle thrusts that controlled the uplift of the ridges with vertical offsets reaching 1–2 km and truncate the Prerif Nappe and its earlier foredeep (Fig. 4). The correlation with the surface strata shows that the deposition of U3 started during the Messinian and possibly continued throughout the Pliocene (see Section 2.1) with a forced regressive character that resulted in continental deposition (Esteban, 1991; Wernli, 1988). The overlying Pliocene-Quaternary sediments (seismic unit U4) cap the sequence in a foreland position.

A NE-SW oriented representative profile (Fig. 5) has been selected in the frontal part of the Rif orogen in the offshore Gharb Basin. The profile is passing through two recently perforated wells with available biostratigraphic data, which gives the opportunity to date the units more confidently. The Prerif Nappe is characterised by transparent and discontinuous to chaotic seismic facies (Fig. 5), as observed in other studies before (e.g., Iribarren et al., 2007; Le Roy et al., 2014; Zitellini et al., 2009). The base of the Prerif Nappe and the detailed structure at higher depth is less obvious due to lack of seismic acoustic contrast. In this area, the interpretation is based on the few confident seismic reflectors (high amplitude, low frequency pre-Miocene strata or basement), but most importantly on the surface to depth prolongation of the associated deformation on sedimentation. In other words, due to the low resolution of the seismic below the nappe complex we have intended model-driven interpretation. The low-angle thrusting observed over the African foreland is in line with earlier interpretations (e.g., Iribarren et al., 2007; Le Roy et al., 2014; Zitellini et al., 2009). Similarly to the onshore, the Prerif Nappe is covered by uppermost Miocene to Quaternary sediments that display multiple seismic facies units (U1-U4). The U1 seismic unit was deposited during the low-angle thrusting

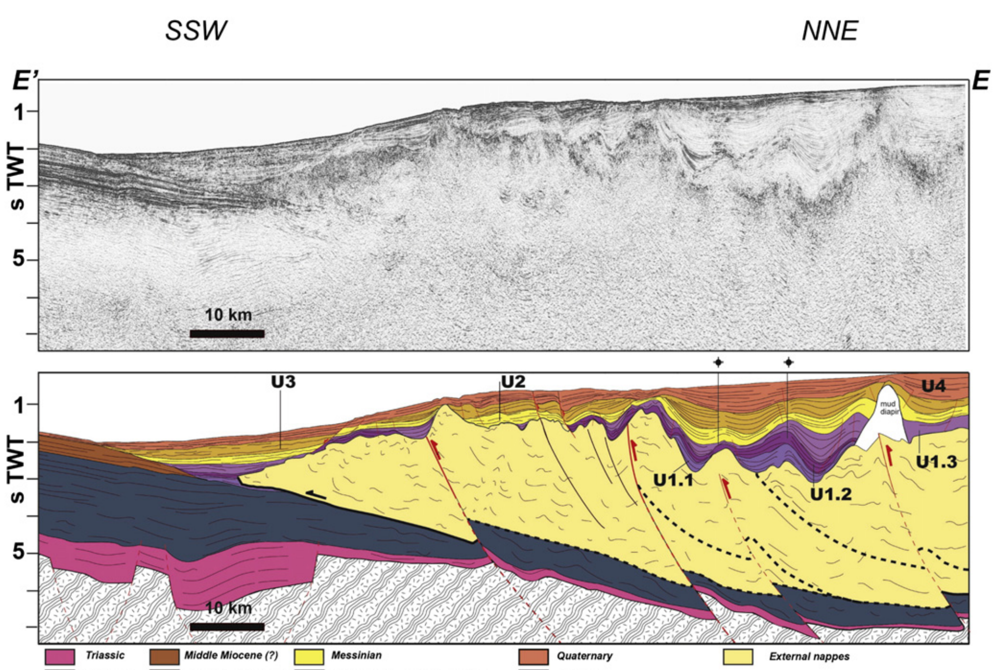

Fig. 5. Non-interpreted and interpreted seismic line E-E′ crossing the Rif nappe and its foreland in the offshore Morocco. U1–4 are seismic facies units corresponding to the evolution of the basin. Location of the seismic lines is displayed in Figs. 1. For further description see the text.

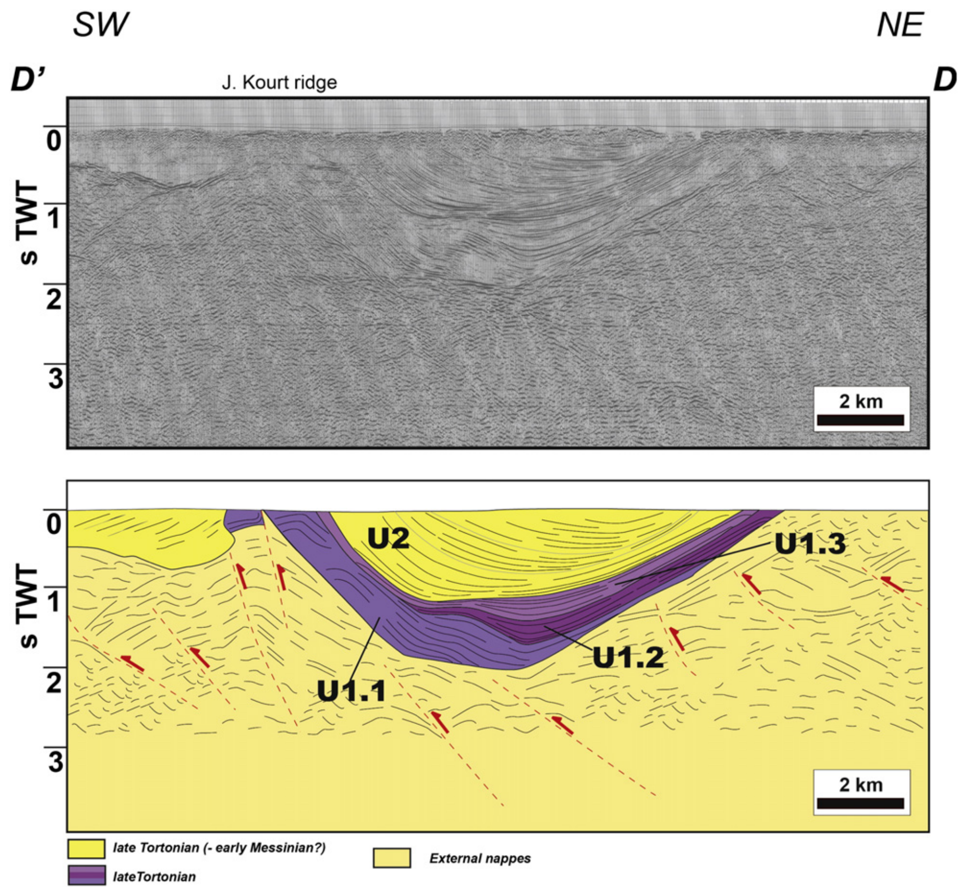

Fig. 6. Non-interpreted and interpreted seismic line D-D′ crossing over the Had Kourt Basin. Location of the seismic lines is displayed in Figs. 1 and 2. U1–2 are seismic facies units corresponding to the evolution of the basin. For further description see the text.

of the Prerif Nappe and correlates with the upper Tortonian sediments deposited in often overlying thrust sheet top basins and, less obvious, beneath the frontal part of this nappe (Fig. 5). This sequence can also here be subdivided into three seismic sub-units based on reflectors terminations at unconformities and seismic facies. The first upper Tortonian, syn-kinematic U1.1 sub-unit was deposited unconformably over the Prerif Nappe in the wedge-top basins and can likely be correlated with the similar narrow seismic facies unit beneath the frontal part of the nappe. The overlying syn-kinematic sub-unit, U1.2, is deposited on top of an unconformity and marks the northwards out-of-sequence migration of thrusting. Seismic sub-unit U1.3 is early Messinian in age, still syn-kinematic in wedge-top basins and fills the accommodation space created earlier by thrusting and tilting in the frontal part of the nappe. High amplitude, low frequency reflectors onlap gradually the previous units and define the first post-kinematic seismic unit U2. This unit fills the space created earlier in the wedge-top basins and is also affected by extensional normal faults, which are better observed on perpendicular cross-sections due to their orientation. Similarly with the onshore, it shows some regional enlargement of the foredeep and the wedge-top basins. The overlying seismic unit U3 has a syn-kinematic character and must be controlled by the activation of steeper, higher-angle faults with vertical offsets in the order of 1 km. The exact position at depth of these faults is speculative and only inferred. However we note that such structures are required to explain the lateral variation in thickness of the sedimentary units U3 and the deformation in the chaotic external nappes. Additionally, mud diapirs are often related to the high angle thrusts as seen on the profile. A close relationship between fluid escape and tectonic structures has been established and in the Betic–Rif orogen the mud volcanoes are suggested to be controlled by structures resulting from a NW compressional regime (Medialdea et al., 2009). Lastly, the overlying Quaternary sediments (seismic unit U4) fill the space created by earlier thrusting and drape earlier structures.

A NE-SW oriented profile has been selected in the frontal part of the Rif orogen in the Had Kourt Basin (Fig. 6). The external Rif nappes make the lower part of the profile by the chaotic seismic facies underlying the wedge-top basin. This basin contains Upper Miocene sediments that display multiple seismic facies units (U1–U2)·Similarly with the section offshore, the U1 seismic unit was deposited during the low-angle thrusting of the Prerif Nappe and can be subdivided into three seismic sub-units based on reflectors terminations at unconformities, seismic facies and surface correlations. A) first syn-kinematic U1.1 sub-unit is observed by an initial progradation from the SW flank of the basin that gradually passes upwards to syn-kinematic wedges; b) the overlying sub-unit U1.2 shows clear syn-kinematic deposition and is overlain by c) the seismic sub-unit U1.3, which was deposited when the local sub-basin was filled. In the field, unit 1.1 likely corresponds to the basal biocalcarenites of the sequence outcropping at J. Kourt ridge (Fig. 2). In the seismic line, the seismic unit U2 was deposited over an unconformity and shows clear syn-kinematic patterns that indicate a gradual deepening of the SE part of the Had Kourt Basin. Interestingly, this is the only basin where the post-nappe subsidence is associated with such clear syn-kinematic deposition. The entire package formed by units 1 and 2 were subsequently tilted along the two flanks of the syncline, the reflectors correlating with similar dipping strata outcropping at the surface. Such geometry can be achieved only by a renewed phase of contraction after the deposition of the U2 unit.

In the more internal part of the Rif orogen a number of seismic lines cross the intramontane basins situated above the Mesorif unit, i.e. the Taounate basin and its prolongations in small neighbouring sub-basins. One representative NE-SW oriented seismic line crossing the Taounate sub-basin shows the Upper Miocene sediments of the intramontane basin overlying the earlier deformed sediments of the Mesorif (Fig. 7). The correlation of the seismic facies in the latter is rather difficult due to the often discontinuous facies and, therefore, its interpretation should be considered speculative. In contrast, the overlying sediments show a good continuity of reflectors grouped in clear seismic facies units and, therefore, the interpretation has a good degree of confidence. At their base, a clear group of seismic facies units have a syn-kinematic character that was coeval with an earlier moment of tiling along the synform flanks. Similar with the earlier explained seismic interpretation this U1 seismic unit can be divided in three sub-units based on reflector terminations and separation of unconformities. It crops out along the plunging strike of the Taounate Basin where it is exposed by subsequent high-angle thrusting, its age being late Tortonian. The first syn-kinematic sub-units U1.1 and U1.2 were deposited unconformably over the Mesorif domain in this wedge top basin. They are overlain by U1.3 which wedges out in an opposite direction (south) and fills the accommodation space created by the earlier contraction. High amplitude, low frequency, parallel reflectors define the post-kinematic seismic unit U2 that reaches more thank 1 km in thicknesses. The correlation to outcrops shows deep water upper Tortonian marine sediments (Barhoun, 2000). Interesting is that this entire seismic unit is tilted along the two flanks of the syncline, the reflectors correlating with similar high-angle dipping strata outcropping at the surface. Such geometry can only be achieved by a renewed phase of contraction towards the end or after the deposition of U2. Our interpretation contrasts with previous inferences, which ascribed the synkinematic deposition to the formation of half-grabens during extensional collapse (Samaka et al., 1997). Such normal faults are not observed by our field kinematic data in places where unit U1 is exposed along the profile or laterally along the strike of the structure. Furthermore, this unit is affected by contractional structures (see below), while the parallel and high-amplitude reflectors of U2 unit suggest that shortening was followed by regional subsidence.

5. Field kinematic observations

The seismic interpretation was combined with field kinematic observations in outcrops (e.g. brittle faults with sense of movement or fold geometries) in the selected key areas. A significant amount of data is already available in the frontal part of the external nappes, its foredeep and over the Prerif Ridges, which are described in details in other publications (Aït Brahim et al., 2002; Aït Brahim and Chotin, 1989; Bargach et al., 2004; Faugères, 1978; Morel, 1989; Roldán et al., 2014; Sani et al., 2007; among others). These data do not make a clear distinction of any events of regional subsidence separating the rather continuous contractional episodes of the external Rif. Starting from these data, we have performed a field kinematic analysis in selected places of the Prerif and Ouezzane-Tsoul nappes, Prerif Ridges and their foredeep flanks, and along the Had Kourt, Taounate and other intramontane sub-basins. We note that our intent was to start from an existing database and find key elements for a temporal discrimination in combination with the interpretation of seismic lines.

The first deformation event is characterised by numerous low-angle thrusts and folds and strike-slip faults, observed in the field in the basal sedimentary units of the various post-Paleogene basins, at the contact between Prerif and Ouezzane-Tsoul nappe, as well as in the hanging-wall of the Prerif Ridges (Figs. 2 and 8). The thrusts indicate an overall

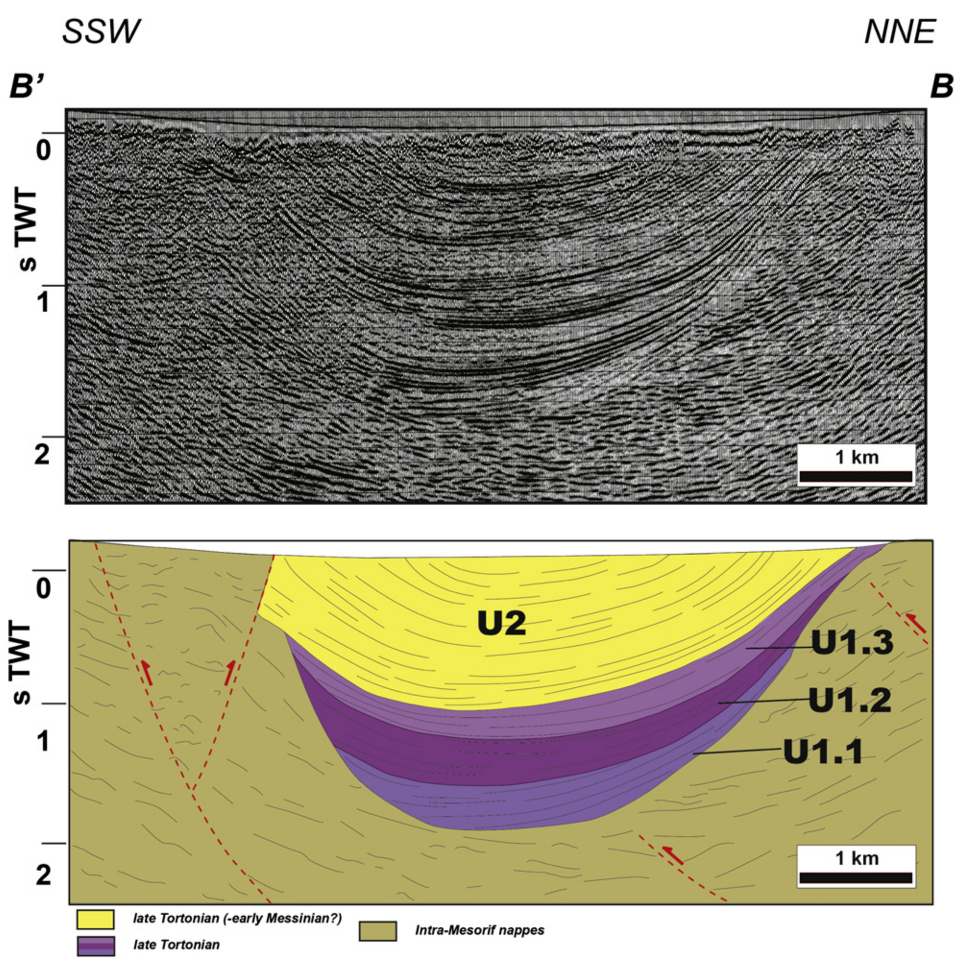

Fig. 7. Non-interpreted and interpreted seismic line B-B′ crossing the Taounate Basin and the adjacent part of the Mesorif nappes. U1.1, U1.2, U1.3 and U2 are seismic facies units corresponding to the evolution of the basin. Location of the seismic lines is displayed in Figs. 1 and 2. For further description see the text.

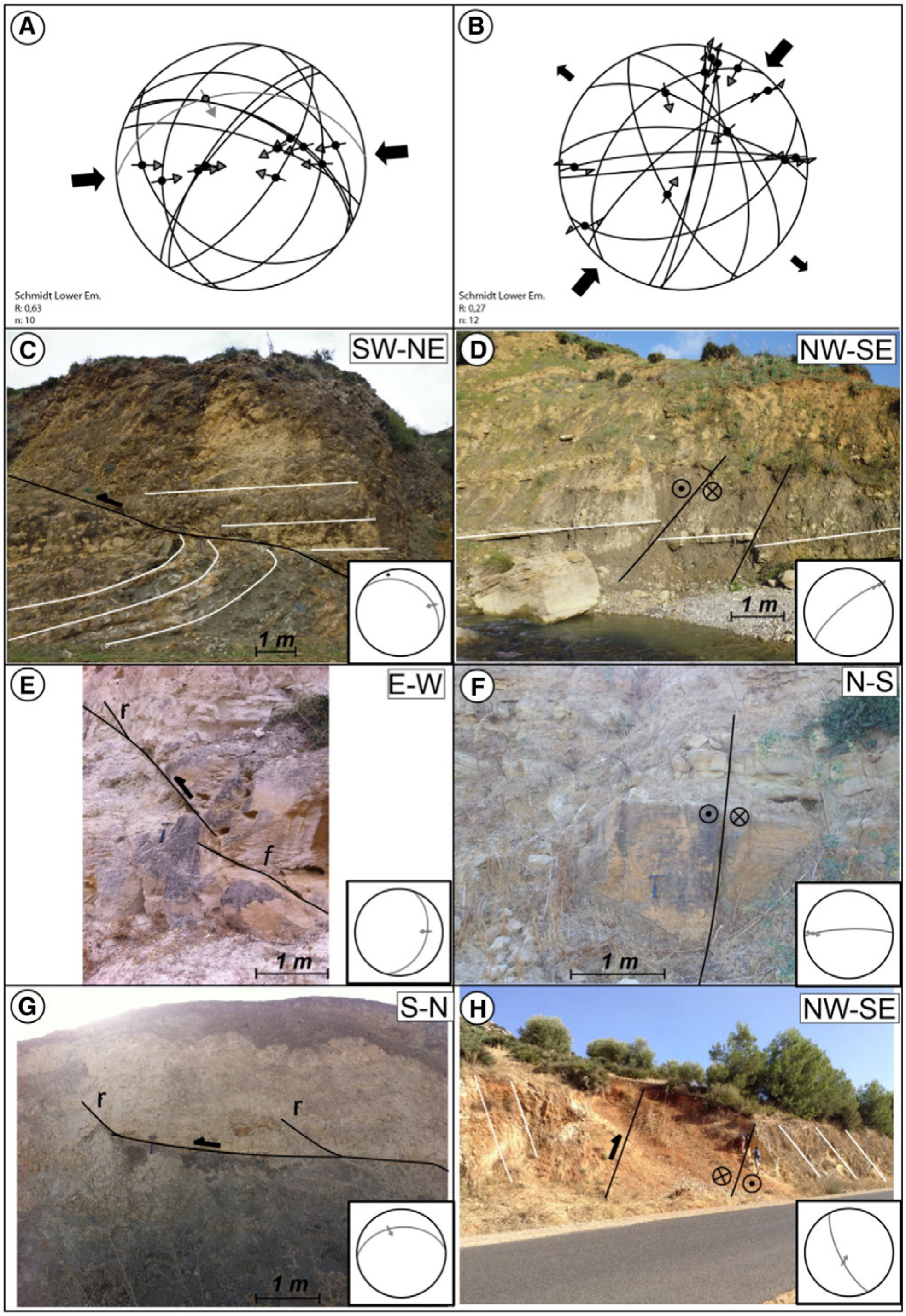

Fig. 8. Field kinematic data for the first late Tortonian contractional phase of deformation. Locations of outcrops in Fig. 2. a) cumulative stereoplot showing thrusts documenting (E)NE-(W)SW contraction; b) associated strike slip faults (dextral and sinistral) documenting NE-SW oriented compression and NW-SE oriented tension; c) field example showing low angle thrusting associated with footwall drag-folding in Upper Tortonian detritic limestones; d) High angle transpressive sinistral strike-slip faults in Upper Tortonian alternation of marls, conglomerates and detritic limestones; e) Thrusting in the lower Miocene sediments of the Ouezzane-Tsoul nappe; f) Sinistral strike slip fault in the Middle Miocene foredeep; g) major low-angle nappe contact between the Ouezzane-Tsoul and Prerif nappe; h) dextral transpressive shear zone located in the J. Kefs ridge that separates the Jurassic of the ridge from Middle Miocene clastic sediments.

ENE-WSW rotating to NE-SW direction of contraction (Fig. 8a, b) and are associated with compatible NW-SE oriented folds. A significant amount of transpressive E-W oriented sinistral and NNE-SSW to N-S oriented dextral strike slip faults are associated with this deformation event with a compatible (E)NE-(W)SW direction of compression. These structures affect sediments as young as the upper Tortonian. This kinematics reflects the low-angle emplacement of the Prerif and Ouezzane-Tsoul nappes, the remnants of the latter being preserved as erosional klippen in a higher structural position (Fig. 2). In the field this deformation can be observed as low angle thrusting associated with footwall drag-folds that affect mainly the lower part of the upper Tortonian sequence, such as in the Tafrant Basin (Fig. 8c), or cross cutting the lower Miocene sediments of the Ouezzane-Tsoul nappe (e.g., Fig. 8e). A significant number of strike-slip faults can be observed either affecting the upper Tortonian alternation of marls, conglomerates and detritic limestones, such as in the Taounate Basin (Fig. 8d), the Middle

Miocene foredeep (Fig. 8f), or often affecting the uplifted areas near the frontal thrust of the Prerif Nappe, such as in the J. Kefs ridge (Fig. 8h). The basal contact of the Ouezzane-Tsoul nappe overlying the Prerif Nappe has locally a different kinematic showing top-SSE thrusting (Fig. 8g). Our data are insufficient to explain such differences, but this can be related to either an earlier phase of deformation in respect to the frontal Prerif Nappe emplacement, or to local strain partitioning.

The second deformation event observed in the field structures is an extensional event observed by reduced offsets along outcrop-scale normal faults. These structures affect sediments as young as the Messinian. In order to discriminate between the Mesozoic normal faults associated with the opening of the Rif domain and the Neogene ones, our analysis has considered only such structures that truncate the Miocene sediments (Fig. 9). The low-offset normal faults formed coeval with the deposition of the uppermost Tortonian - Messinian deep to shallow water deposition in the foredeep, which is well observed in the exposures along the flanks of the Prerif Ridges. These faults show no preferential direction and do not appear to be accompanied by the formation of larger scale regional structures. They are rather coeval with an overall event of subsidence affecting the external nappes and the foredeep than a coherent extensional kinematic event. In the field, these faults can be observed often as shear planes with associated Riedel shears truncating the basal upper Tortonian conglomerates, such as in the Taounate

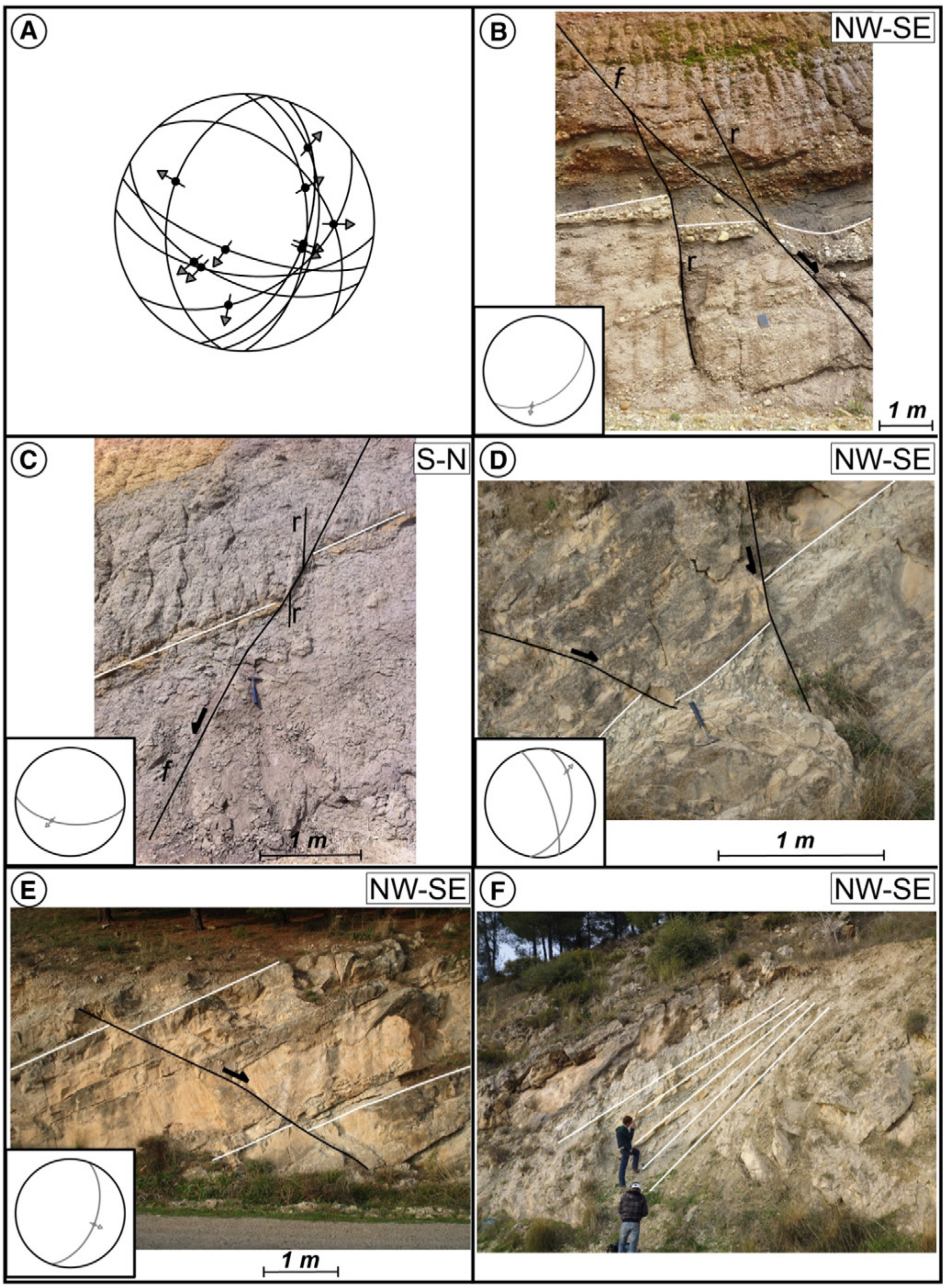

Fig. 9. Field kinematic data for the second latest Tortonian – earliest Messinian subsidence phase associated with normal faulting. Location of outcrops in Fig. 2. a) cumulative stereoplot of normal faults that indicate no preferential direction of extension; b) normal fault and associated Riedel shear truncating the basal Upper Tortonian conglomerates of the northern Taounate Basin; c) similar normal fault and associated Riedel shear truncating the Upper Tortonian siltstones of the northern Had Kourt Basin; d) conjugated normal faults in the Upper Tortonian clastic mudstones located in the northern part of the Saiss basin. The normal fault was subsequently tilted during the subsequent uplift of the a smaller Prerif ridge exposing Jurassic limestones of the African platform; e) tilted normal faults and f) the associated syn-kinematic wedge in the Uppermost Tortonian clastic limestones in the northern part of the Saiss Basin.

Basin (Fig. 9b) or in the upper Tortonian siltstones of the Had Kourt Basin (Fig. 9c). Interesting is that conjugated normal faults found in upper Tortonian clastic mudstones in the N-Saiss were subsequently tilted by another phase of deformation, likely during the uplift of the Prerif Ridges (Fig. 9d). At this location, clear syn-kinematic deposition demonstrates an upper Tortonian age of extension (Fig. 9e, f).

The third deformation event was associated with the formation of high-angle reverse and strike slip faults. Numerous structures were observed to be associated with this deformation event in the field. The kinematics (Fig. 10a) indicates top-S to top-SSW thrusting accompanied by a large number of transpressional faults. Sinistral faults strike N-S to NNE-SSW, while dextral faults are oriented WNW-ESE, showing a

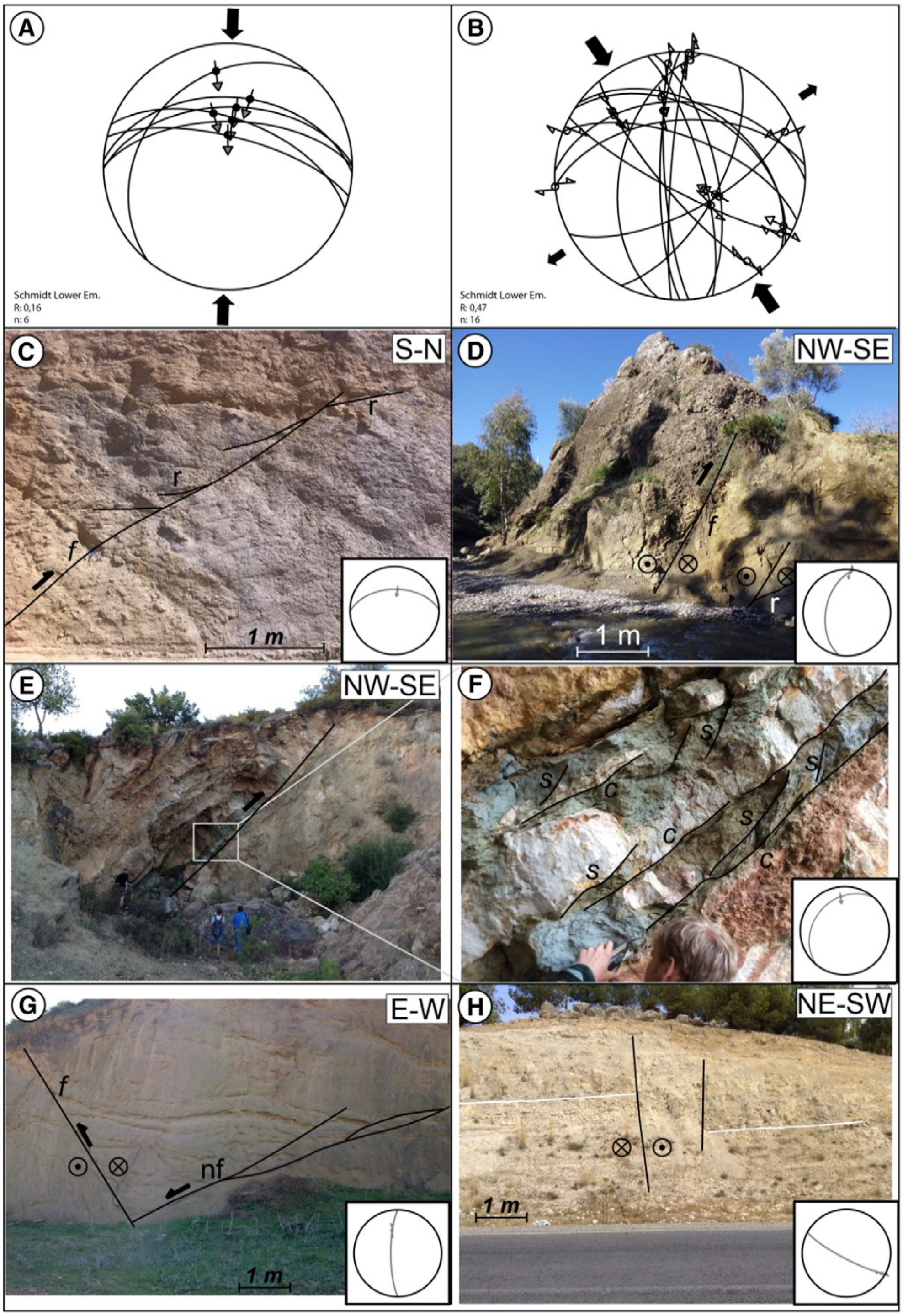

Fig. 10. Field kinematic data for the third post-Tortonian contractional phase of deformation. Locations of outcrops in Fig. 2. a) cumulative stereoplot showing high-angle thrusts documenting N-S oriented contraction; b) associated strike slip faults (dextral and sinistral) documenting NNW-SSE oriented compression and WSW-ENE oriented tension; c) thrust fault and associated Riedel shears truncating the Upper Tortonian siltstones of the northern Had Kourt Basin; d) High angle transpressive sinistral strike-slip faults in Upper Tortonian sediments of the northern Taounate basin. The fault thrusts basal conglomerates over much younger marine marls; e) Large scale high-angle reverse fault with a significant component of sinistral strike slip in the core of the Zerhoun Ridge in Jurassic platform limestones of the African margin; f) Detail of the high angle thrust in Fig. 10e showing a shear zone with S-C brittle shear bands formed in cataclastic material; g) High-angle sinistral transpressive strike-slip fault cross-cutting an earlier normal fault in Messinian sandstones on the northern prolongation of the Bou Draa Ridge; h) dextral transpressive fault in Pliocene continental deposits in the eastern part of the Prerif Ridges.

compatible NNW-SSE direction of compression. These structures appear to be controlled by the reactivation of pre-existing Mesozoic normal faults that affected the underlying African basement and cover, in agreement with previous studies (Sani et al., 2007; Zizi, 1996, 2002). In the field often thrust faults and associated Riedel shears truncate the upper Tortonian, such as in the Had Kourt Basin (10c). Large scale high-angle reverse fault with a significant components of strike slip were observed in the core of the Prerif Ridges, such as in the core of the Zerhoun Ridge (Fig. 10e, f). The more strike-slip type of faults is generally high-angle transpressive to sub-vertical and affect upper Tortonian sediments. In the Taounate basin for example they show large offsets (Fig. 10d). Clear cross-cutting relationships were observed in the field with previous events, such as cross-cutting earlier normal faults in Messinian sandstones (Fig. 10f). These types of structures affect sediments as young as the Pliocene, such as observed in the Saiss basins (Fig. 10h).

6. Combining the seismo-stratigraphic and kinematic interpretation

The higher resolution seismo-stratigraphic and structural interpretations show that the external Rif was affected by three successive stages of tectonic deformation and associated vertical movements. These stages are visible in the present-day geometry (Figs. 4–7) and reconstructed kinematics (Figs. 8–10). All direct lines of evidence show that the original nappe stack (Ouezzane-Tsoul and Prerif nappes) was subsequently covered by upper Tortonian – lower Messinian sediments associated with a second stage of subsidence and minor normal faulting. The nappe stack and the overlying sediments were subsequently dissected in a third event by a thick-skinned contractional phase whose expression in the near surface kinematics is high-angle thrusts and transpressional structures. Our analysis correlated with existing wells and outcrop data infer that the syn-kinematic unit U1 is late Tortonian and the onset of U2 subsidence is latest Tortonian. The onset of U3 renewed contraction took place during the early Messinian, as inferred from shallowing and isolation trends in the Gharb onshore, Saiss and Taza-Guercif basins (e.g., Esteban, 1991; Flinch, 1993; Krijgsman et al., 1999). High resolution biostratigraphic data in the offshore part of the Gharb basin suggests a time delay of tectonic episodes, where the synkinematic units U1 is late Tortonian and partly lower Messinian in age, the U2 subsidence is Messinian and the renewed contraction activating high-angle faults during U3 seems to start around the latest Messinian and continued throughout the Pliocene (Fig. 5). If these preliminary data are confirmed, this would suggest a gradual migration of the genetic mechanism along the orogenic strike in a W-ward direction.

The initial late Tortonian thin-skinned low-angle thrusting is the most marked event during the evolution of the Rif orogen (Figs. 11a, b and 12a, phase 1). The best near-surface expression of low-angle character of the thrusting of the Ouezzane-Tsoul nappe are its klippens that can be connected up to 70 km along a basal decollement (Fig. 11a), in agreement with other previous interpretations (Chalouan et al., 2008; Platt et al., 2013). In more details, field observations show that this decollement is locally folded and much steeper dipping, the nappe being deformed and eroded by subsequent deformation and uplift (Fig. 11a). It is often also affected at both outcrop and regional scale by shale diapirism and gravitational sliding. The transport direction varies significantly being slightly blurred by the additional numerous transpressional structures, but their kinematics is also compatible: thrusting indicates a change from top-W to top-S, with the change in regional strike from N-S to E-W along the connecting arc towards the Betics that is in agreement with the inferred late stage kinematics at the scale of the entire Rif orogen (Fig. 1, Frizon de Lamotte et al., 1991; Platt et al., 2013). The syn-kinematic sedimentation of units 1 overlying the external nappe and the thrusting geometry suggest that the overall orogenic uplift was in the order of hundreds of meters, certainly <1 km and decreased towards the foredeep. This is in agreement with thermochronology studies, which suggest relatively little Late Miocene exhumation in the internal Rif, possibly counteracted by the coeval extension of the overall Alboran domain (Romagny et al., 2014). In addition, the superposed geometries of U1.1, U1.2, U1.3 at Taounate and Had Kourt suggest that the intramontane basins are wedge-top basins that were active during the nappe emplacement. Here, normal faults potentially controlling regional basin extension were not observed neither at outcrop or seismic scale, which contrasts with previous interpretations (Samaka et al., 1997). In the offshore, the continuation of wedge-top syn-kinematic deposition U1.2 and U1.3 took place by out-of-sequence thrusting, as the low-angle frontal emplacement of the Prerif Nappe stopped in the late Tortonian (see also Iribarren et al., 2007). This is exemplified by undeformed sediments onlapping the frontal nappe thrust (Fig. 5).

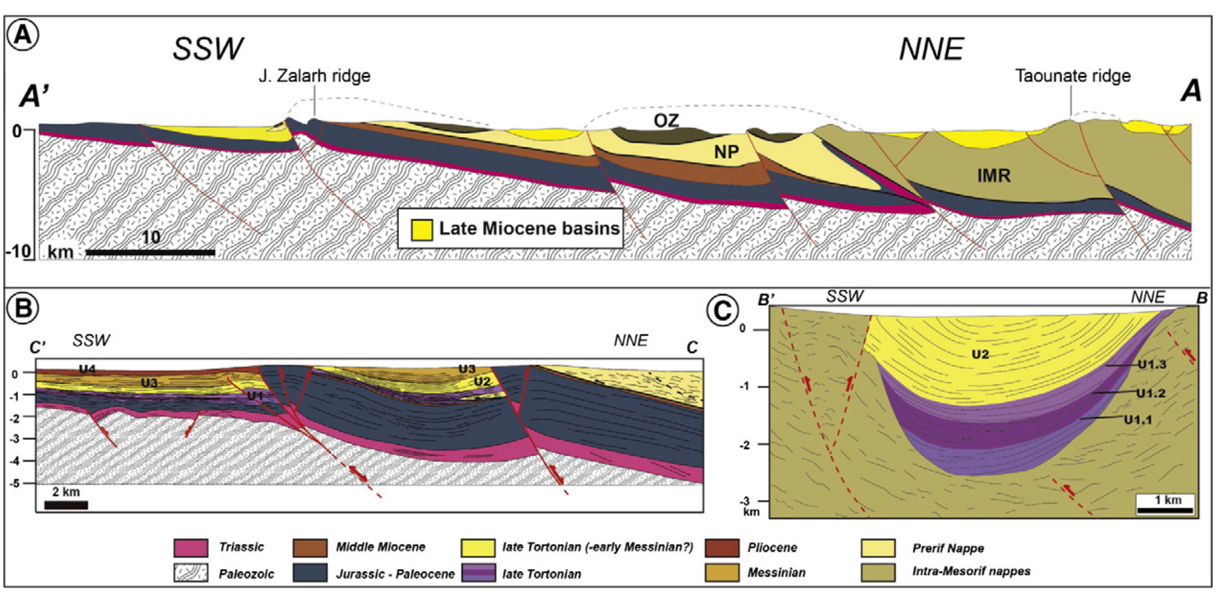

Fig. 11. (a) Simplified regional cross-section spanning from the Mesorif to the African margin, illustrating the relationship between postnappe basins and the Rif external zones. The crustal structure was modified from Chalouan et al., 2008. NP = Prerif Nappe; OZ = Ouezzane-Tsoul nappe; IMR = Intra and Meso Rif domains. (b; c) Depth converted line drawing of the industrial seismic lines C and B, Figs. 4 and 7, respectively. Depth conversion was done by using average interval velocities derived from well logs. Basement-rooted reverse faults cross-cut the African margin and the Rif nappe system, causing the excess of vertical movement observed in the Rifian Corridor. Locations are displayed in Fig. 2.

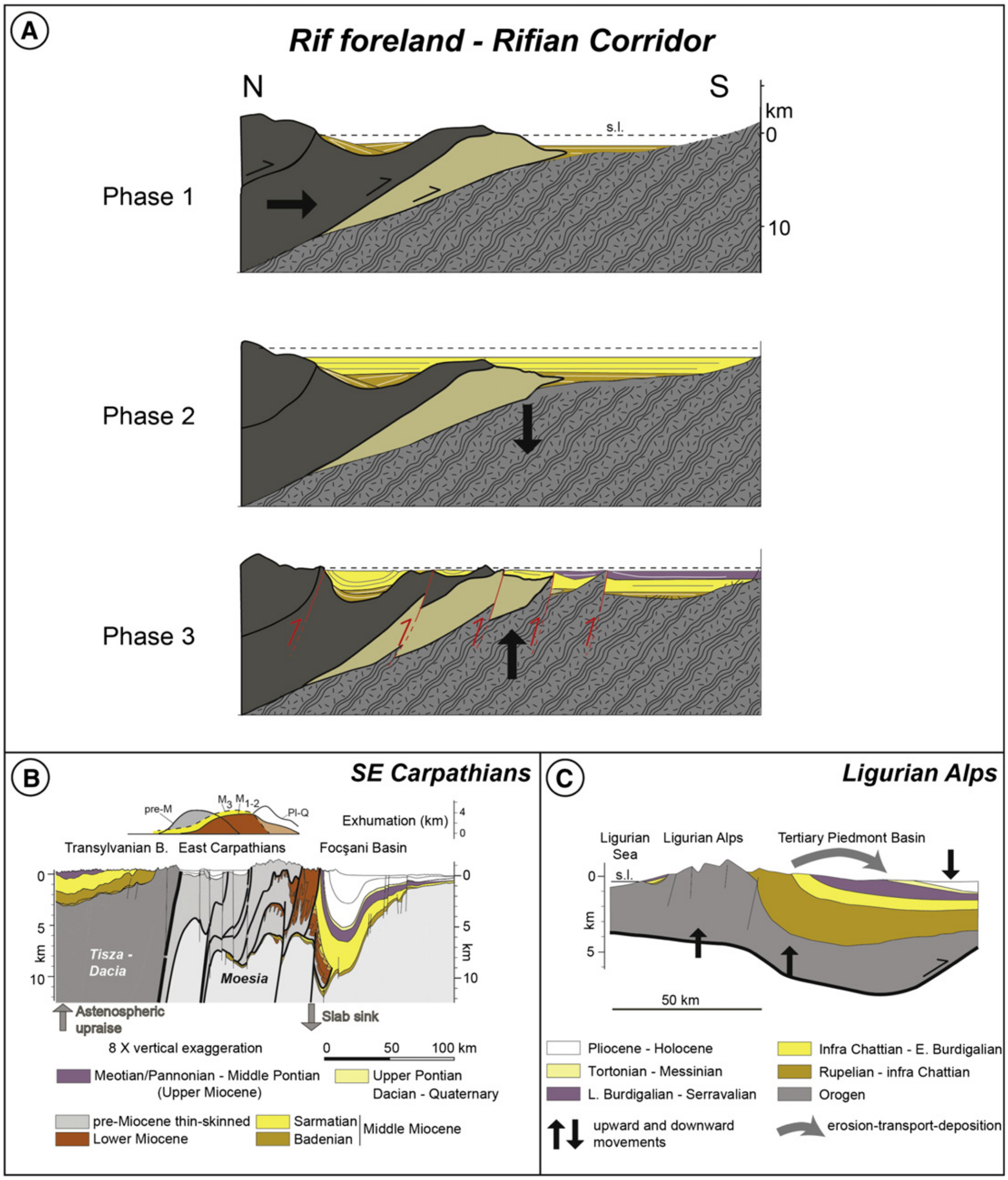

Fig. 12. a) Cartoon model illustrating the three-step tectonic evolution of the Rifian Corridor during the Late Miocene. Black arrows indicate the driving vertical movements. Dashed line depicts the estimated sea level of the Rifian Corridor and shows how its depth is affected by tectonic mechanisms; b) comparison with a cross-section in a similar geodynamic evolution resulting in a three steps thin-skinned, subsidence and thick-skinned sequence of deformation in the SE Carpathians (modified after Matenco et al., 2015). pre-M = pre-Miocene; M1 = Early Miocene; M2 = Middle Miocene; M3 = Late Miocene; Pl = Pliocene; Q = Quaternary. Note that in the SE Carpathians the Vrancea slab is still attached and continues to drive the subsidence of the foredeep. c) comparison with the sketch of a similar geodynamic evolution in the Po Plain at the transition with the Ligurian Alps (modified after Bertotti et al., 2006). Note that the grey fill are the orogenic nappes.

The subsequent Late Miocene covering of the entire external orogenic part by marine sediments, observed in the remaining wedge-top basins and correlated with coeval deposition in the foredeep, requires a second phase of latest Tortonian tectonic subsidence, which can also be Messinian in the offshore (Fig. 12a, phase 2). The sedimentary geometry in these basins displays high-angle erosional truncations (Fig. 11b, c) and shows that the basinal extent was far larger than today, most likely connecting the foreland with the internal intramontane basins overlying the Intrarif nappes to the north (Figs. 11a and 12a).

The last phase of thick-skinned tectonics and transpressive deformation (Fig. 12a, phase 3) is a renewed continuation of the regional contraction. The change from ENE-WSW to N-S oriented contraction in thrust kinematics marks the thin- to thick-skinned transition in the Rif foreland. It started during the Messinian and was characterised by the activation of numerous high-angle thrusts observed in our analysis and previous studies (Bargach et al., 2004; Roldán et al., 2014; Sani et al., 2007). Kinematic analysis indicates N-S to NNW-SSE contraction along structures with variable strike due to reactivation of inherited normal faults in the underlying African foreland. The high-angle thrusts are associated with narrow syn-kinematic wedges in their vicinity and tectonic uplift in the order of ~1 km, as indicated by the offsets of thrusts or other transpressional structures (Fig. 11b). This phase of deformation was associated with regional uplift distributed over the entire external Rif and its foredeep. It exhumed all internal basins and created a forced regression in the foredeep, which was ultimately uplifted to continental conditions in the present day onshore during Messinian times (see also Esteban, 1991; Krijgsman et al., 1999).

7. Geodynamic implications

Our study shows that the collision in the Rif segment of the Gibraltar arc is not different from the mechanics of other orogenic arcs dominated by slab retreat situated in the Mediterranean (Carpathians, Apennines and their transition to the Alps, Fig. 12b, c) or SE Asia. The introduction of the African non-stretched buoyant continental crust in the Rif subduction system during the last stages of collision has induced a transition from thin-to thick-skinned deformation, associated with more transpressional structures. In other Mediterranean orogens the accelerated upper crustal out of sequence deformation is always associated with dynamic topography and deep lithospheric processes. A similar three stages evolution with a transition from thin-skinned to external orogenic subsidence followed by thick-skinned deformation has been documented in the external SE Carpathians and their Focsani foreland (Leever et al., 2006, Fig. 12b). Here, thermochronological studies have demonstrated increased exhumation rates from ~0.4 to ~1.6 mm/yr during the collisional transition from thin- to thick skinned tectonics (e.g., Merten et al., 2010) associated with rapid subsidence of the foredeep Focsani Basin, resulting in its unusual tilted foredeep geometry (Fig. 12b, Matenco et al., 2015). This deformation and exhumation was intimately related with deep mantle processes related to the still attached Vrancea slab and its hinterland asthenospheric upraise (e.g., Ismail-Zadeh et al., 2012). The last orogenic movements recorded at the transition between the Ligurian Alps and the Apennines recorded a transition from nappe emplacement to out-of sequence deformation that involved deep structures cross-cutting the earlier orogenic geometry (Fig. 12c, Bertotti et al., 2006; Picotti and Pazzaglia, 2008). This was temporally and spatially related with the evolution of the Calabrian slab along the Apeninnes and its hinterland asthenospheric upraise (Faccenna et al., 2014).

Is such coupling between deep Earth and upper crustal processes taking place in the Rif orogen? Certainly so, although not all details are yet clear. Geodynamic and kinematic studies have inferred uplift accompanied by volcanism in the easternmost Rif at the time of the Messinian Salinity Crisis (Booth-Rea et al., 2012; Duggen et al., 2008). This was coeval with significant crustal thinning east of the Nekor Fault, where the crust may reach only 22–30 km thicknesses in a region of elevated topography (Mancilla et al., 2012). The Taza-Guercif Basin, where significant early Messinian uplift has been recorded (Krijgsman et al., 1999) is situated above the magmatic Morocco Hot Line (Frizon de Lamotte et al., 2009). These are likely the expression of asthenospheric upraise beneath the Atlas Mountains and Eastern Rif, whose wavelength is in the order of 200–300 km (e.g., Babault et al., 2008; Fullea et al., 2007). Interestingly, the foredeep recorded continuous marine sedimentation during and after the initial thin skinned tectonic event. This indicates that although the Rifian Corridor was substantially narrowed towards the end of Tortonian to the areas of the present day foredeep and wedge top zones such as the Taounate Basin, it was not yet closed (Fig. 12a), allowing water exchange between the Atlantic and Mediterranean. The examples of the other Carpathians or Apeninnes orogens where similar regional asthenospheric anomalies are observed indicates that a significant acceleration of localized uplift is required to overcome the erosional deepening due to bottom currents (Leever et al., 2011). Therefore, these deep mantle processes must be assisted by significant localized uplift by upper crustal shortening to overcome the erosion in the corridor during a late stage contraction. This shortening is likely to be still active because its NNW-SSE direction is compatible with the movement directions derived by GPS data (Koulali et al., 2011).

The thin- to thick-skinned transition observed in the Rif external zones indicates that significant deformation took place in the external part of the orogen after nappe emplacement. The inverted Mesozoic faults truncating the African lower plate trend NE-SW to NNE-SSW, which is similar to the direction our first, Late Miocene shortening phase (Fig. 8), in agreement with previous studies (Aït Brahim et al., 2002; Morel, 1989; Sani et al., 2007). The geodynamic mechanism for this first Late Miocene tectonic phase (Fig. 12a) was the westward migrating Alboran Block, which imposed south-westward kinematics in the external part of the Rif (Frizon de Lamotte et al., 1991). Such deformation could not have reactivated the Mesozoic grabens in the study area because the direction of deformation was roughly parallel with their strike. By the time the external Rif/Gibraltar accretionary wedge was emplaced at ~8 Ma (e.g., Iribarren et al., 2007), the thin-skinned tectonics stopped or possibly continued only with minor out-of-sequence thrusting. This suggests that the accelerated uplift observed in the Rif external zone occurred when the Alboran plate was already locked between the two continental margins. This uplift was therefore the result of the continuous Africa-Iberia convergence in a N-S direction, which was prone to reactivate the Mesozoic grabens. Hence, we propose that the onset of thick-skinned tectonics that closed the Rifian Corridor in the areas west of the Nekor fault post-dated the slab-retreat and associated asthenospheric upwelling, and was likely caused by the combination of: (a) the locking of the subduction zone by the non-stretched African crust and (b) regional ongoing Africa-Iberia contraction post-dating the main westward kinematics of the Alboran plate.

Our interpretation is in agreement with the previously suggested regional role of the onset of N-S compression in the westernmost Mediterranean in driving the MSC, which post-dated the Gibraltar slab retreat and the nappe emplacement of the Betic - Rif system (Jolivet et al., 2006). However, late stage successions of subsidence and enhanced uplift migrating in time along the orogenic strike is often used as an argument for mantle mechanics such as slab-detachment (Wortel and Spakman, 2000) or STEP structures (subduction-transform edge propagators, Govers and Wortel, 2005). Obviously, further dating, exhumation studies, paleobathymetric reconstructions and a good correlation with such deep mantle processes are required to detect variations in amplitudes and the evolution of this enhanced uplift phase across the Rifian Corridor.

8. Closure of the Rifian Corridor

The recognition of three successive tectonic phases affecting the Rifian Corridor has major implications for the water and salt exchange between Atlantic Ocean and Mediterranean Sea (Simon and Meijer, 2015; De la Vara et al., 2015). As a consequence of Late Miocene gateway restriction, the Mediterranean evolved into a hypersaline basin during the MSC (Roveri et al., 2014), but the exact role of the Rifian Corridor in this context is still poorly understood (Flecker et al., 2015). The initial phase of thin-skinned nappe thrusting in the Rif domain culminated during the late Tortonian (~8 Ma) and already significantly influenced the water exchange with the Mediterranean. Here, many basins experienced a major change in sedimentation regime and depositional environment around the same age (e.g. Hüsing et al., 2009; Köhler et al., 2010) and some Spanish basins show evidence of evaporite formation during their so-called Tortonian Salinity Crisis (Krijgsman et al., 2000; Garcés et al., 2001; Corbí et al., 2012; García-Veigas et al., 2013). The transition from thin- to thick-skinned contraction occurred across the Tortonian-Messinian boundary in the Rif domain brought along high uplift rates that closed the gateway. Similar increases of uplift rates have previously been reported from the stratigraphic successions of the Taza-Guercif Basin (Krijgsman et al., 1999; Krijgsman and Langereis, 2000). Paleobathymetry estimates from foraminifera suggested that late Tortonian marls and turbidites were deposited at a depth of ~500 m, while earliest Messinian marls accumulated at a depth of <100 m, resulting in uplift rates of ~5 mm/yr at the interval straddling the Tortonian/Messinian boundary.

High uplift rates are crucial to close such seaways. A recent model study (Garcia-Castellanos and Villaseñor, 2011) shows that moderate uplift of the Gibraltar arc can restrict the Atlantic-Mediterranean gateways but cannot close them completely. Erosion of bottom currents counteracts for the bathymetry loss, and episodes of refill of the

Mediterranean due to seaway deepening harmonically follow episodes of drawdown after seaway uplift. Only after overcoming a threshold in uplift rate values at the sill, the gateway would emerge and isolate the Mediterranean. Values of uplift rates so low to be counteracted by erosion were sustained by means of large wavelength uplift due to lithospheric slab tear or roll-back (Garcia-Castellanos and Villaseñor, 2011). Such a scenario can indeed explain inflow of Atlantic seawater during the first stage of the MSC, where gypsum evaporated in marginal basins and the evaporative drawdown was minor. It is still unclear how the geodynamic mechanism that sustained such constant equilibrium suddenly changed to increasing uplift rates, causing the closure of the gateways. We show here that the thin- to thick-skinned tectonics transition provides a mechanism to explain the upsurge of uplift rates that finally overcomes seaway bottom erosion and closes the marine connection. The activation of high-angle faults rooted in the basement caused much higher vertical movement than the previously active nappe-detachment thrusts. And as inferred from previous studies (e.g., Chalouan et al., 2008; Sani et al., 2000, 2007; Zizi, 1996, 2002), the Mesozoic grabens are pervasive in the Moroccan margin. With only minor amount of shortening, Africa-Iberia convergence and contemporary deep-seated vertical movements could have created faster uplift.

We dated the initiation of thick-skinned tectonics as latest Tortonian to earliest Messinian in age. This is based on the presence of lower Messinian, shallow marine deposits exclusive to the Saiss Basin, the widespread absence of Messinian sediments in the intramontane and scattered satellite basins above the nappes (Barhoun, 2000 and results of the present study). Furthermore, the youngest, coastal, marine sediments in the Taza-Guercif basin belong to a reversed magnetic chron which minimum age is ~6.8 Ma (Krijgsman et al., 1999; Krijgsman and Langereis, 2000). An early Messinian age for the termination of the Rifian Corridor is also in agreement with biostratigraphic results from the Melilla basin that indicate a closure age of 6.84–6.58 Ma (Van Assen et al., 2006) and geochemical data from the entire gateway suggesting a closure age of 6.64–6.44 Ma (Ivanovic et al., 2013). We therefore conclude that the Rifian Corridor closed in the early Messinian, significantly before the MSC and that its closure can thus not be seen as the trigger for gypsum (start at 5.97 Ma) or halite (peak event at 5.5 Ma) formation in the Mediterranean. In contrast, however, it may have caused severe restriction in the overall Atlantic connectivity and probably links to the impoverished faunal conditions of the deep Mediterranean Basin that occurred in the early Messinian (Kouwenhoven et al., 2003, 2006).

In conclusion, our data strengthen the hypothesis that the Rifian Corridor was closed well before the onset of the MSC and that is was thus not the latest marine gateway in the Gibraltar domain, as suggested in earlier reconstructions (Martín et al., 2001, 2014). Another seaway must have persisted until at least 5.5 Ma to supply the inflow of seawater necessary to accumulate the huge volumes of halite at the peak stage of the MSC (e.g., Krijgsman and Meijer, 2008). Candidates for this latest marine connection are the Guadix Strait (Hüsing et al., 2010, 2012), the Guadalhorce Corridor in the western Betics (Martín et al., 2001) and ultimately the Gibraltar Straits.

9. Conclusions

Thick-skinned structures truncating the earlier emplaced Rif nappe and its foreland uplifted the Rif basins during a post-Tortonian shortening phase. This orogenic process was intimately associated with a deep asthenospheric upraise and possibly other slab -migration driven processes. Nonetheless, the main driver of thick-skinned tectonics in late orogenic stage was the relative strengthening of Africa-Iberia convergence after the Gibraltar slab-retreat ceased, at a time when the subduction zone was locked by African continental crust. The transition from thin- to thick skinned tectonics is a common mechanism during the final stages of orogenic collision when the foreland is coupled due to locking of the subduction zone (e.g., Ziegler et al., 1998) and is often observed in Mediterranean or SE Asia orogens. In all these cases, the thick-skinned event is controlled by the continuation of the regional contraction associated with deep lithosphere mechanics, rather than by solely the inherited subduction zone. The change from thin- to thick-skinned deformation has exhumed the Rifian Corridor, closed the Moroccan connection between the Atlantic Ocean and Mediterranean Sea during Messinian times and eventually led to the Messinian Salinity Crisis. Pinpointing the sedimentary wedges associated with the process of closure may be a new way forward to date more precisely gateway restrictions, such as the one that caused the Mediterranean isolation.

Acknowledgements

ONHYM and Repsol are thanked for providing the seismic data and for the technical support. This research has been conducted in the framework of the MEDGATE project and funded by EU Marie Curie Actions, 7th Framework Programme FP7/2007-2013/under REA Grant Agreement No. 290201. D. Frizon de Lamotte and an anonymous reviewer are gratefully acknowledged for their comments that have improved significantly the manuscript.

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