LITHOSTRATIGRAPHY AND STRUCTURE OF THE TEMSAMANE UNIT (EASTERN EXTERNAL RIF, MOROCCO)

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Abstract: In the Eastern External Rif, the lithostratigraphic and structural analysis of the Temsamane massif, allowed us to define a complete lithological sequence from Palaeozoic to Albian. The Palaeozoic metamorphic rocks are overlain by Triassic volcanic rocks, calcitic and dolomitic marbles of Jurassic age, calc-schists and marble levels of Neocomian times, and brown schists and quartzites of Aptian-Albian age. These rocks underwent MP/LT metamorphism during and before the development of their main S-L fabric that includes a foliation (S_p) and a stretching lineation (L_p) associated to shearing criteria as S-C structures, asymmetric trails around porphyroblasts, etc., with a top-to-the-WSW sense of movement. The fabric is axial-planar of large SE-vergent recumbent folds. This main deformation stage was produced in a non-coaxial regime with WSW-directed transport and it involved both Palaeozoic basement and its Mesozoic sedimentary cover. We have differentiated three main units separated by brittle-ductile thrusts with a top-to-the-south sense of movement that cut the recumbent folds and have inverted the metamorphic order. Normal faults record the later thinning of the thrust pile. The first normal fault system is formed by low-angle normal faults that record extension parallel to the ductile lineation in the Temsamane Massif, and to the Rif Chain. This extension is similar to the WSW-ENE extension described in the Betics producing the exhumation of the Nevado-Filabride Complex during the Middle-Late Miocene. The younger system records N-S extension controlling the formation of the Kert Basin during the Messinian-Pliocene. The new distribution of the lithological units improves significantly the tectonic architecture of the massif and gives a more rational significance to the structures.

Key words: Lithostratigraphy, recumbent folds, thrusts, Rif Cordillera, normal faults

Resumen: El análisis de la litoestratigrafía y la estructura del Macizo de Temsamane en el Rif Externo Oriental, nos ha permitido definir una secuencia litológica completa desde el Paleozoico hasta el Albiense. Las rocas metamórficas paleozoicas están recubiertas por rocas volcánicas Triásicas, mármoles calcíticos y dolomíticos de edad Jurásico, calcoesquistos con niveles de mármoles de edad Neocomiense, y esquistos marrones y cuarcitas de edad Aptiense-Albiense. Estas rocas sufrieron un metamorfismo en condiciones de PI/BT antes y durante el desarrollo de la fábrica principal de la roca, que es una fábrica S-L que incluye una foliación (S_p) y una lineación de estiramiento (L_p) asociada a criterios de cizalla como estructuras S-C, sombras de presión asimétricas en torno a porfiroblastos, con un sentido de cizalla de techo hacia el OSO. La fábrica es plano axial de grandes pliegues recumbentes vergentes hacia el SE. Este plegamiento se produjo en un régimen de deformación no coaxial con un sentido del bloque de techo al OSO. Hemos diferenciado tres unidades principales separadas por cabalgamientos dúctil-frágiles con movimiento del bloque de techo hacia el sur que cortan a los pliegues recumbentes. Fallas normales tardías provocan el adelgazamiento de las unidades cabalgantes. El sistema de fallas normales más antiguo está formado por fallas normales de bajo ángulo que registran una extensión ENE-OSO paralela a la lineación dúctil en el Macizo de Temsamane. El sistema más reciente registra una extensión N-S que controló la formación de la Cuenca del Kert durante el Messiniense-Plioceno. La nueva distribución de las unidades litológicas y su estructura mejora significativamente la arquitectura tectónica del macizo y da un significado más regional a las estructuras del área.

Palabras clave: Litoestratigrafía, pliegues recumbentes, cabalgamientos, Rif, fallas normales

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The Rif belt (northern Morocco) (Fig. 1), with the Betics, defines an arc-shaped Alpine orogen. Both mountain belts have two common elements: a stack of mainly metamorphic units located towards the hinterland (Internal Zones or Alboran Domain, Balanyá and García-Dueñas, 1987), which overthrusts a stack of non-metamorphic Flysch units. The Flysch units, in turn, thrust over a series of mainly Mesozoic and Cenozoic rocks: the External Zones of the Betic or South-Iberian Domain and the External Zones of the Rif or Maghrebian Domain (Balanyá and García-Dueñas, 1987).

The Betic-Rif mountain belt is not a symmetric orogen and the External Zones of the Rif and the Betic are quite different in structure and evolution. The External Zones of the Betic are non-metamorphic and deformed always under brittle conditions with very low grade metamorphism reported only in a few outcrops. However, the external Zones of the Rif are characterised essentially by an olistostromic unit including rocks from the Palaeozoic and Mesozoic in a marly matrix of Tortonian age in the south (Fig. 1), and metamorphic Mesozoic units with penetrative deformations towards the north.

The Temsamane Massif is a mountain range with an ENE-WSW trend located in the eastern Rif (Fig. 1). It is formed essentially by Palaeozoic and Mesozoic rocks deformed and metamorphosed during the Alpine orogeny (Fig. 2). They show an intense ductile deformation developed under lower-greenschists metamorphic conditions (Frizon de Lamotte, 1985; Negro, 2005; Negro *et al.*, 2007). Its evolution is crucial to understand the evolution of the Rif, because in the eastern traverse the non-metamorphic units are practically absent in the belt, and the metamorphic rocks of the Temsamane Massif thrust directly over the rocks of the Medium Atlas foreland.

Here we present the result of a stratigraphic and structural study in the north Temsamane (Beni Said Massif). The previous interpretation of these rocks was based mainly in the attribution of several of the rocks of the sequence to the Middle Miocene (Frizon de Lamotte, 1985). However, the structures observed in the field (mainly recumbent folds), the ages indicated by fossils in the rocks attributed to the Miocene, and the structural data from the major mechanical contacts allow us to propose a new interpretation of the lithostratigraphy and the structure of the region.

Our main aims are to determine the lithostratigraphical sequence of the area, specially the relationship between the Palaeozoic and the Mesozoic rocks present in the region, and also, we want to establish the major structure of the region in order to determine its evolution.

Geological setting

The Rif forms the south-western termination of the Alpine peri-Mediterranean Chain. It constitutes part of the Gibraltar Arc, together with the Betics and Tell. This arcuate orogenic system has evolved since the Upper Cretaceous in the context of Africa-Eurasia NW-SE convergence (Dewey *et al.*, 1989). The chain is separated from the foreland (Moroccan Meseta and Middle Atlas) in the west and central areas by the foreland basin represented by the Gharb and Saïs basins (Fig. 1). In the eastern areas there is no foreland basin. The Rif is composed of two main tectonic domains the External and the Internal Rif (Fig. 1).

The Internal Rif

It is formed by the Alboran Domain, a polymetamorphic terrain formed by the Sebtide (called Alpujárride in the Betics) and Ghomaride (Maláguide in the Betics) complexes together with the Dorsal units (Balanyá and García-Dueñas, 1987). The Sebtide-Alpujarride includes several units with Permian-Triassic series that underwent HP/LT metamorphism (Tubía and Gil-Ibarguchi, 1991; Azañón *et al.*, 1997) during the Early Eocene (Platt *et al.*, 2005). The Ghomaride/Malaguide complex is mostly non-metamorphic (Chalouan, 1986), except at the base of the thrust pile where the Permian-Triassic sediments were metamorphosed under anchizone conditions (Nieto *et al.*, 1994; Lonergan and Platt, 1995). It also includes a Palaeozoic basement metamorphosed under lower greenschist conditions during the Variscan orogeny (Chalouan and Michard, 1990). The Dorsal units have a similar stratigraphy to the Mesozoic and Cenozoic cover of the Ghomaride/Maláguide complex, occupying a more external position. The Alboran Domain collided with the Maghrebian and South-Iberian passive margins during the Lower-Middle Miocene, after and during the subduction of the basement of the Flysch Through (*e.g.*, Zeck, 1996; Booth-Rea *et al.*, 2007) which was situated between both paleomargins.

The External Rif

It is overthrusted by the Internal Rif and it is interpreted as the North African passive margin of the Tethyan Ocean. The External Rif is characterised by evaporitic deposits of Triassic Germanic facies, by a Lower Jurassic carbonate sequence and by an Upper Jurassic detritic series. This paleomargin was a passive margin during most part of its evolution (Kuhnt and Obert, 1991) and it has undergone different stages of subsidence mainly during the Cretaceous, characterised by sequences with very important lateral thickness variations and with olistostromes (Lespinasse, 1975; Asebriy; 1984; Ciszak *et al.*, 1986; Asebriy *et al.*, 1987; Ciszak, 1987).

The main compressive deformation took place during the Early-Middle Miocene in the northern Rif and propagated to the south and southwest during the Late Miocene to the Quaternary (Morel, 1989; Ait Brahim, 1991). Also, during the Neogene there are active left-lateral NE-SW to E-W strike-lip faults and NW-SE to N-S right-lateral strike-slip faults. During the Messinian-Quaternary times, NNE-SSW to N-S normal faults also developed.

The rocks of the External Rif are grouped in the Subrif and the Prerif Zones (Fig.1). The Subrif represents the major part of the northern External Rif (Asebriy *et al.*, 1987); and includes the TangerKétama intrarif units, the Internal and the External Mesorif. It is characterised by a continuous

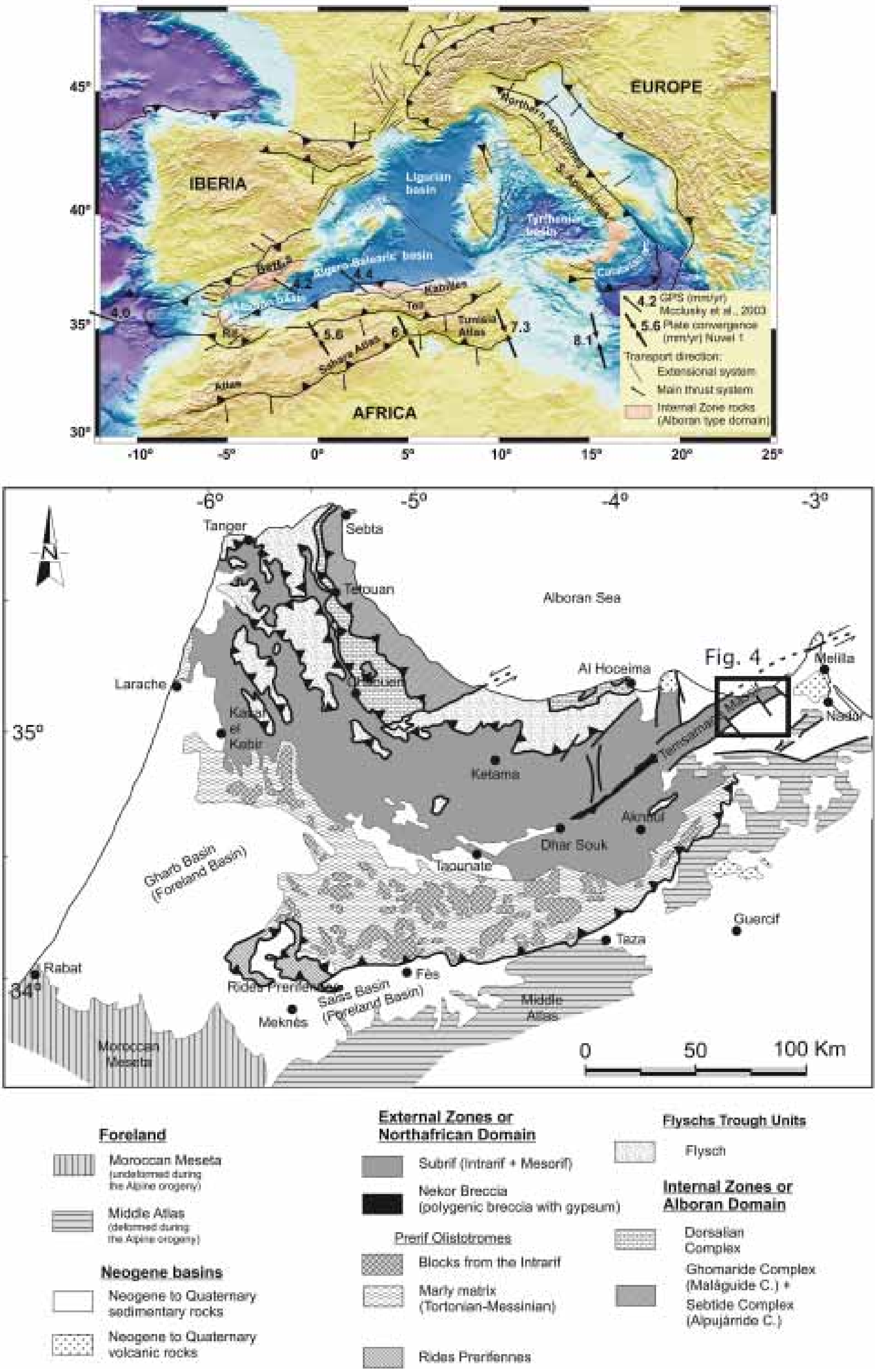

Figure 1.- A) Sketch of the Alpine mountain chains and basins in the western Mediterranean with the relative velocities between the European and the African plates. **B**) Geological map of the north of Morocco with the Rif Cordillera.

stratigraphical sequence from Early Jurassic to Cenozoic. The Tanger-Ketama Unit (Andrieux, 1971; Gübeli *et al.*, 1984) is formed in general by metapelites, quartzites and limestones metamorphosed under anchizone conditions during the Cretaceous rifting (Azdimousa *et al.*, 1998, 2003). These rocks are deformed by two deformation phases (Andrieux, 1971) producing two cleavages. The Upper Cretaceous cover is detached and is non metamorphic and less deformed than the older rocks (Leikine *et al.*, 1991). Towards the south, the Tanger-Ketama Unit has several antiforms with the core made by Jurassic limestones that form the substratum of the unit (Asebriy *et al.*, 1992). The unit was overthrusted in the Early Miocene by the Flysch units of Chouamate, Tisirène and Beni Idder. The whole Tanger-Ketama Unit thrust over the Prerif during the Burdigalian-Tortonian times and was later deformed by the NE-SW left-lateral and NW-SE right-lateral strike-slip faults.

The Subrif continues in the eastern Rif with the Temsamane units (Fig. 1). The Temsamane units are formed mainly by Cretaceous rocks as those of the Tanger-Ketama unit. These sequences deposited in the same paleogeographic basin, formed during Late Jurassic-Early Cretaceous (140 Ma) rifting that produced strong thinning of the continental crust (Michard *et al.*, 1992), including the exhumation of the Beni Malek serpentinites (eastern Rif). The Prerif is essentially a complex of olistostromes with blocks ranging from the Palaeozoic to the Cenozoic in a matrix formed mainly by Tortonian marls (Suter, 1980; Vidal, 1971; Leblanc, 1975-1979; Bourgois, 1977) (Fig. 1).

After the thrusting and metamorphism of the Subrif rocks and the Prerif development, between the Tortonian and the Plio-Quaternary basins such as Kert, Boudinar, Melilla, and Touanate formed. Basin development was associated to intense volcanism in the eastern Rif with rocks of the calc-alkaline and shoshonitic series followed by mostly Quaternary alkaline intraplate-type volcanism (*e.g.*, Hernandez, 1983; Duggen *et al.*, 2004, 2005).

The Temsamane Massif

The Temsamane units are part of the Subrif and are located in the eastern Rif, east of the Nekor Fault. The rocks in the massif have a roughly ENE-WSW trend (Choubert *et al.*, 1984). The Nekor Fault is a NE-SW trending left-lateral strike-slip fault, which separates anchizone to epizone rocks of the Tanger-Ketama unit in the northwest from the epizonal Temsamane Units to the southeast. The Nekor Fault cuts the ENE-WSW structures of the Temsamane

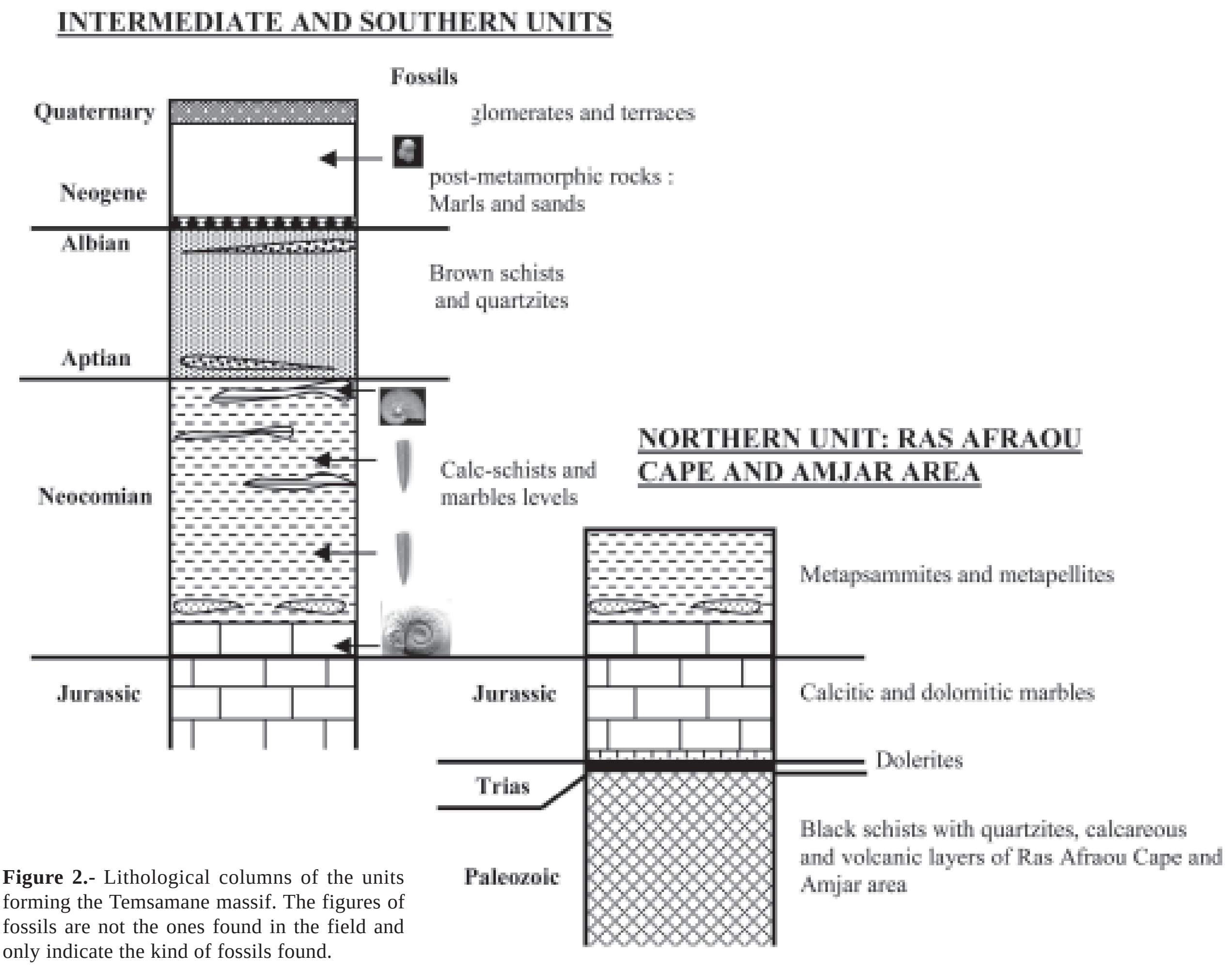

Figure 2.- Lithological columns of the units forming the Temsamane massif. The figures of fossils are not the ones found in the field and only indicate the kind of fossils found.

units and also cuts the E-W trend of the lithologies of the Tanger-Ketama Unit. Frizon de Lamotte (1985) has interpreted the Temsamane units as a pile of seven units with a stratigraphical sequence with a younging up polarity that were affected by south vergent folds with reverse or subvertical limbs of about 500 meters length. These units were structured in a wide left-lateral strike-slip shear zone due to intense non coaxial deformation with a top-to-the WSW sense of movement (Monié *et al.*, 1984; Frizon de Lamotte, 1985). This left-lateral strike-slip shear zone would have accommodated the convergence between Africa and Europe during the Miocene. The northern and upper unit corresponds to the Ras Afraou Unit (Frizon de Lamotte, 1985) with a Palaeozoic basement and a Mesozoic cover that several authors interpret as part of the Alboran Domain (Suter, 1980).

Frizon de Lamotte (1985) attributed several metamorphosed rocks of the southern units to the Middle Miocene in base to a sample with foraminifera from the Middle Serravallian. The fact that in the Kert Basin there are Messinian sedimentary rocks capping unconformably the Temsamane Massif implies that the age of deformation and metamorphism is pre-Messinian. The ^{40}Ar-^{39}Ar datations on micas by Monié *et al.* (1984), Negro (2005), and Negro *et al.* (2007) are scarce and range between 23 and 8 Ma. Recently, Negro (2005) and Negro *et al.* (2007) have studied the metamorphism of these rocks estimating conditions ranging between 350-400°C and 7-8 kbar in the northern rocks, while the southern rocks underwent lower temperatures and pressures. They propose an age between 28 and 23 Ma for the main metamorphic stage.

Lithostratigraphy

The stratigraphical sequence of the Temsamane units to the north (BeniSaïd Massif) begins with grey and black schists rich in graphite with quartzites that have a minimum thickness of 400 meters (Fig. 2). These rocks are attributed to the Palaeozoic due to their position in the sequence. The best outcrop is located in the Ras Afraou Cape and in the Amjar area (Fig. 2). In the Amjar area these Palaeozoic rocks include a lower member of grey and blue schists that contains flyschoid levels and an upper member with grey sericitic schists that contain quartzitic, calcareous and volcanic layers. There are basic volcanic rocks with black colours mainly in the Ras Afraou sector. These volcanic rocks can be sills intruded during a later volcanic stage. These rocks were attributed by Suter (1980) and Leblanc and Suter (1977) to the Palaeozoic of the Sebtide/ Alpujarride Complex due to the violet and red

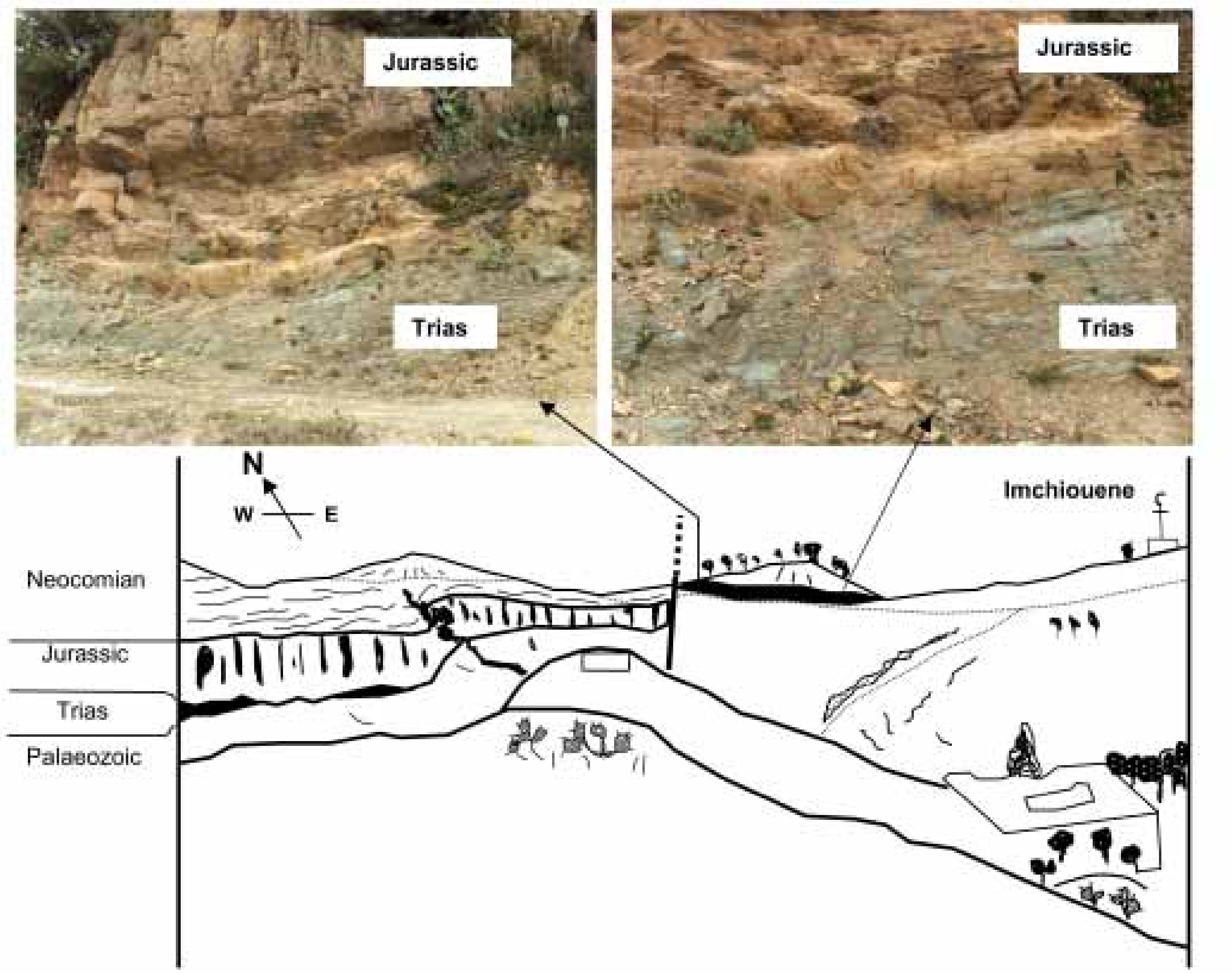

Figure 3.- Field outcrop of the Palaeozoic to Neocomian sequence, near the Imchiouene village.

alterations of the different mineralizations inside the rocks. However, there are similar rocks in the foreland: the Eastern Moroccan Meseta and Tell (Hoepffner, 1987), which is why we interpret here these rocks as the Palaeozoic basement of the Temsamane Mesozoic sequence. Furthermore, these dark schists locally show stratigraphical relationships with the overlying Mesozoic sequence.

Lenses of volcanic dolerites overlie the aforementioned Palaeozoic rocks by way of an angular unconformity. These volcanic rocks are thin (Figs. 2 and 3) with a maximum thickness of 10 meters. The dolerites have a microlithic texture, sometimes microgranular, rich in plagioclase. We attribute these volcanic rocks to the Triassic magmatism due to their similarity with the Triassic volcanism in the foreland of the Eastern Rif (Salvan, 1974; Hervouet, 1985). These dolerites are covered by 150 meters of calcitic and dolomitic marbles that have interlayered several levels of calc-phyllites. The calcitic marbles are black and massive and have a white patina. In several places, the basal surface of these carbonates lies directly on the Palaeozoic schist, without the appearance of any tectonic contact. Choubert *et al.* (1984) have attributed these carbonates to the Lower Jurassic; however, we attribute these rocks to the whole Jurassic times due to the fact that they are covered conformably by Lower Cretaceous rocks. Also, Frizon de Lamotte (1985) has found one ammonite attributed by Busnardo to the Early Cretaceous in the upper levels of these marbles.

The carbonate rocks are covered by metapelites and metapsammites with granoclassifications (arkoses) with thicknesses that vary between 0 and 10 meters (Fig. 2). They outcrop mainly in the Ras Afraou area and northwards of Jbel Bou Salah (Fig. 4). They can be interpreted as detritic deltaic deposits as those found in the Berriasian rocks of the foreland in the eastern Rif (Benest, 1985).

The sequence continues up-section with a thick series of calc-schists and marbles that are similar to those dated as Neocomian in the Tanger-Ketama Unit (Fig. 2). We have found three stretched belemnites that strongly support this attribution which agrees with the previous interpretations of the area (Frizon de Lamotte, 1985). In

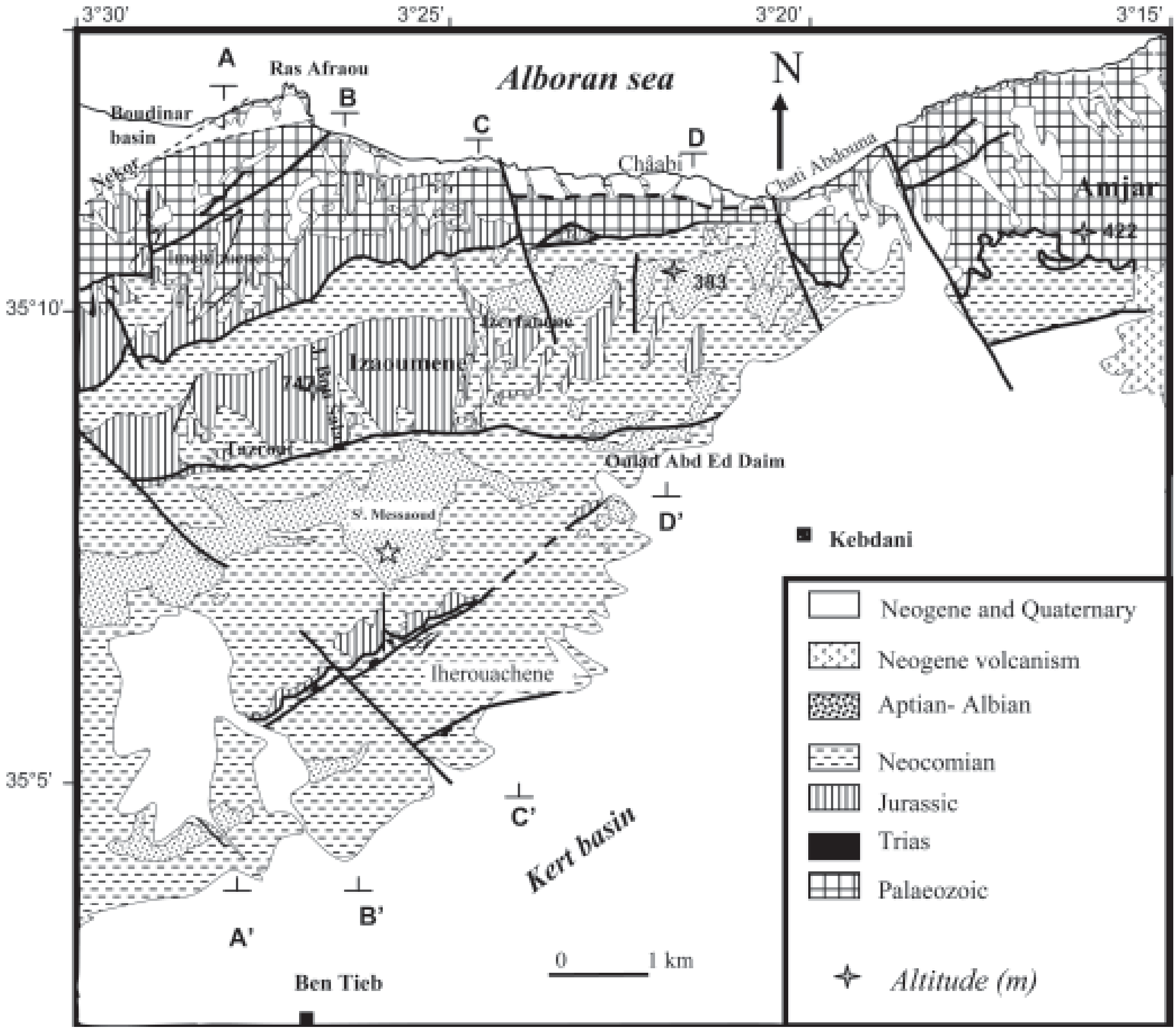

Figure 4.- Geological map of the Temsamane Massif with the location of the geological cross sections of figure 6.

the upper levels of this succession we have found a phylloceras sp (Fig. 5A). These upper levels are covered conformably by brown schists and quartzites attributed to the Aptian-Albian due to their position over the Neocomian rocks and also by their correlation with similar rocks dated in the Tanger-Ketama Unit.

In the southern part of the studied area there is also a thick succession of calc-shists and marbles that were previously attributed to the Lower-Middle Miocene by Choubert *et al.* (1984). We have found three belemnites within these rocks, allowing us to include these outcrops within the Neocomian rocks. Also, locally there are small bodies of serpentinites, near the thrust surfaces and below the Cretaceous rocks, with a small size and thickness of 1 or 2 meters.

The post-metamorphic rocks outcrop mainly in the borders of the massif (Fig. 4). They form the plain of the Oued Kert toward the southeast and east and fill the Boudinar Basin towards the west. The micropaleontological datation of the sedimentary filling of both basins: Kert Basin (Feinberg, 1986) and Boudinar Basin (Houzay, 1975; Barhoun and Wernli, 1999, Azdimousa *et al.*, 2006) indicate Late Miocene and Pliocene ages. The sedimentary filling begins with detritic rocks that were covered by marls. Towards the top of the sequence there are more lithological variations due to volcanic intercalations. The sedimentation ended with fluvio-marine and continental deposits. Plio-Quaternary sedimentation is mainly continental and characterised by the development of marine terraces near the coast.

Description of the structures and their P-T conditions

The most visible structure in the field is a planar-linear fabric composed by a cleavage defined by the preferential orientation of the sheet silicates in the metapelites (phengite, paragonite and chlorite). In thin sections, the cleavage is a schistosity (S_p) and in several microlithons, an older and crenulated foliation can be observed. This foliation is clearly visible when there is a cleavage fan near the hinge of a minor fold (Fig. 5F). The older foliation is a slaty cleavage defined by the preferential orientation of the sheets silicates. In most cases, the main foliation (S_p) has a phyllonitic character and obliterates the old cleavage. Minor ductile shear zones deform the main foliation and produce ductile S-C structures.

A clearly visible stretching lineation with an ENE-WSW trend (Fig. 5C) is observed on the surface of the main foliation (S_p). This stretching lineation has been studied by Frizon de Lamotte (1985) and is defined by stretched pebbles of conglomerates and clay minerals in the lower and less metamorphic units, and by micas and chlorites in the metapelites of the higher and more metamorphic units. In the marbles, the stretching lineation is defined by boudins of thin metapelitic levels and by strain shadows around pre-kynematic pyrite or calcite crystals (Fig. 5C). The kinematic criteria: ductile S-C, asymmetric strain shadows around porfiroblasts, and sheared veins filled with quartz and calcite (Fig. 5D) indicates a non coaxial deformation regime with a top-to-the WSW sense of movement (Frizon de Lamotte, 1985; Negro, 2005; Negro *et al.*, 2007) (Fig. 5D).

The S_p foliation is parallel to the axial plane of minor folds with curved hinges (sheath folds; Figs. 5E and 5F) and of minor and major folds with straight hinges parallel to the stretching lineation (a-type folds). The major a-type folds have ENE-WSW trending hinges and are vergent towards the ESE.

From north to south, we found four major folds within the upper more metamorphic unit (that groups the previous Ras Afraou and Talioune units of Frizon de Lamotte, 1985 and Negro, 2005). These folds are two anticlines cored by Palaeozoic rocks and to synclinals with Jurassic rocks in their nuclei (Figs. 5B and 6). In the Intermediate unit (which includes the ancient Ijer, Jbel Mahjar and Imzirene units from Frizon de Lamotte, 1985 and Negro, 2005) there is a major anticline with its nucleus formed by Neocomian metapelitic rocks. In the lower and less metamorphic unit (the previous Taferhsit unit from Frizon de Lamotte, 1985 and Negro, 2005) we have identified only a major syncline with its core defined by the Aptian–Albian metapelitic rocks (Fig. 6).

The ductile structures developed during this deformation phase: planar-linear fabric, ductile S-C, sheath folds and a-type folds are cut by a set of systematic joints. These systematic joints are usually normal to the main foliation S_p of the planar-linear fabric. However, two other sets of joints that are oblique to the lineation occur, although, in this case the stretching lineation is parallel to the bisector of the dihedral angle between these last sets of joints. All the sets are filled with calcite and quartz fibbers and these fibbers are sub-parallel to the stretching lineation. The calcite and quartz fibbers have a pattern indicating sintaxial growth within the vein and usually are deformed in the last increments of the non coaxial deformation. These deformations include the mechanical twinning of the calcite fibbers with at least two generations of twins that are superposed (Figs. 5G and 5H). The older twins are the previously described by broad and irregular twins and they are cut by a new set of twins that are thin and with planar and sharp borders. These brittle structures have been interpreted as the product of the brittle-ductile transition in the final stages of the non coaxial deformation produced by fluid overpressure within the metapelites (Frizon de Lamotte, 1985).

The P-T conditions of the structures developed during this main event of deformation has been studied by Negro (2005) and Negro *et al.* (2007) who found a reversed metamorphic gradient within the pile of units. Mineral associations with chloritoid, phengite and chlorite can be found only in the Palaeozoic dark schists

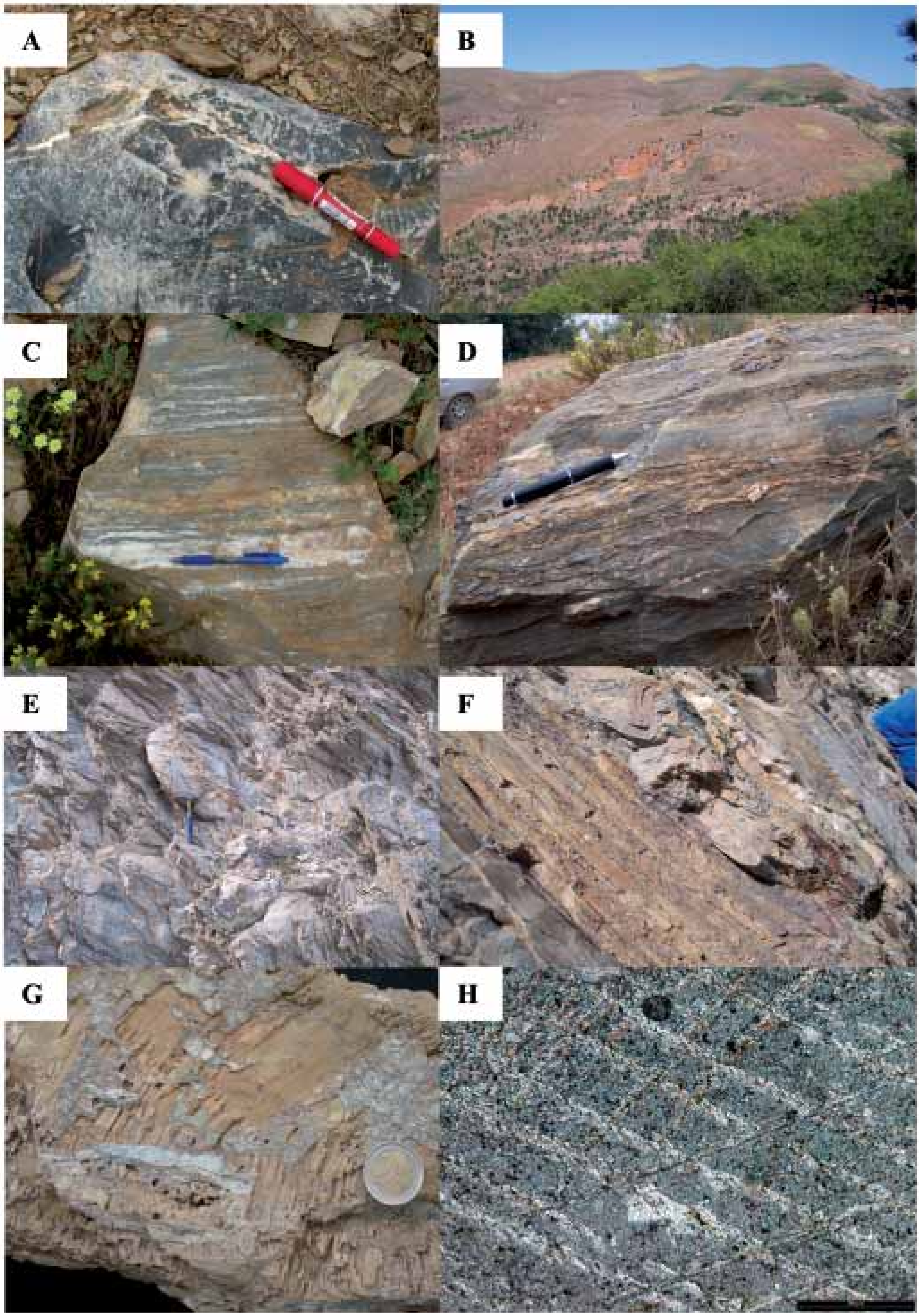

Figure 5.- A) Ammonites (phylloceras) in the marbles. **B)** The hinge of the recumbent anticlinal with core in the Jurassic marbles of the intermediate unit near the Jbel Bou Salah. **C)** Stretching lineation developed in the Jurassic marbles. **D)** Main schistosity developed in the Jurassic marbles, deformed quartz and calcite veins indicate the sense of shear. **E** and **F)** Minor sheath folds developed during the main deformation event, photography F shows a previous foliation folded around the hinges. **G)** Fibers of quartz and calcite developed within a vein cutting the main schistosity in the Neocomian pelites south of Sidi Messaoud Mountain in the lower unit. **H)** Microphotography of the twins developed within the calcite fibers of the previous veins.

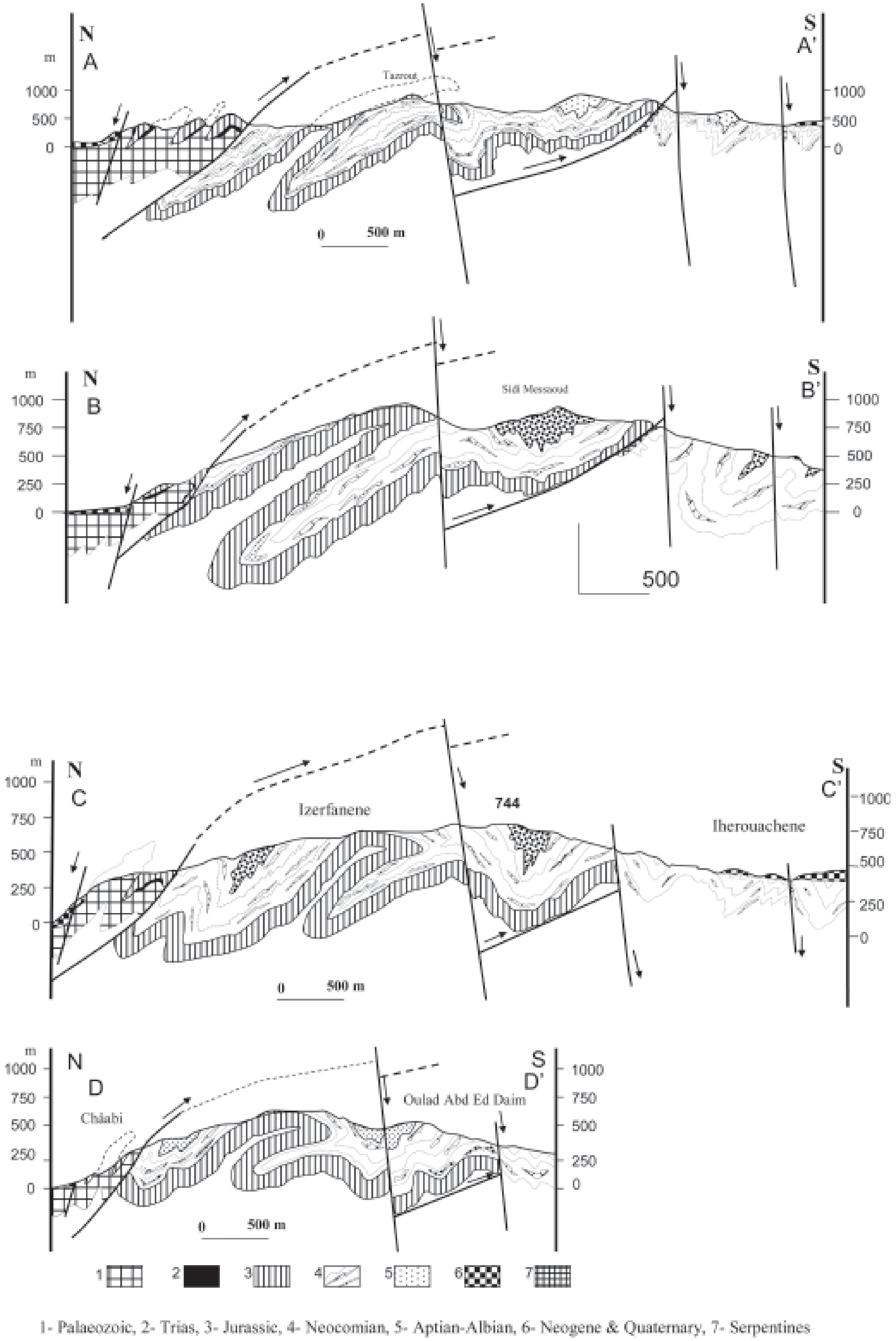

Figure 6.- Geological cross sections of the Temsamane Massif that illustrate the new proposal for the structure of the area. Location in figure 4.

at the top of the thrust pile (Ras Afraou Unit, of Negro, 2005). Negro (2005) estimated the conditions of the metamorphism of these rocks at 350 ± 30 ºC and 7-8 kbar. The metamorphic conditions seem to decrease towards the lower units as indicated by the microstructures developed within the sintaxial fibers of quartz and calcite that grow in joints within the Neocomian calcophyllites. The pre- to syn-kinematic calcite fibbers are strongly affected by broad and irregular twins (Figs. 5G and 5H) of type IV (Vernon, 1981) suggesting that the rocks have reached temperatures between 250 and 300ºC (Ferrill *et al.*, 2004). The conditions possibly have not surpassed 300ºC, as temperatures higher than 300ºC must produce dynamic recrystallization of calcite (Ferrill *et al.*, 2004).

Locally, a younger cleavage (S_c) developed associated with SE-vergent asymmetric folds. This younger cleavage (S_c) is usually a crenulation cleavage that can be penetrative in the hinge zones of the SE-vergent folds (Figs. 7A and 7B).

In the Temsamane region, we have identified two major thrust surfaces that separate three major units (Figs. 4 and 6). These thrusts are oblique to the lithological contact and to the recumbent folds and cut the normal limbs of these folds (Fig. 6). The fault rock is a carbonate gouge with a thickness that can reach 4 meters and that is formed by angular clasts of the metapelites, calcophyllites and marbles surrounded by an orange to brown carbonate matrix. The lineament of the major axis of the clasts indicates a stretching lineation with a N-S trend and the cut-off of the normal limbs of the folds indicate sense of transport towards the south.

These structures are deformed by very open folds with ENE-WSW to E-W trending axes and subvertical axial surfaces. These folds are: the synform in the central part of the studied area cored by dark metapelites of the Aptian-Albian times and an antiform located northward.

All the aforementioned structures are cut by normal and strike-slip faults. The older set of faults are low-angle normal faults with N160ºE strike and dips that range between 25º towards the west to subhorizontal (Figs. 7E to 7H). The best outcrops of these faults are located in the new coastal road. There are also several high-angle normal faults with dips near 60º toward the west that usually sole in the low angle faults. This fault system records an ENE-WSW brittle extension. Another system of faults is represented by ENE-WSW high-angle normal faults mainly directed towards the SE that bound the north-western margin of the Kert Basin (Fig. 7C).

Discussion

The litho-stratigraphical data, the fossils and the lack of most of the mechanical contacts previously distinguished allow us to propose new lithological sequences within the Temsamane massif (Azdimousa, 1991) and also to define new tectonic units. The new lithological units range from the Palaeozoic to the Early Cretaceous in the northern unit, and from the Jurassic to the Aptian-Albian times in the intermediate and southern units. The three belemnites found in the southern unit, in outcrops previously attributed to the Miocene (Frizon de Lamotte, 1985), shows that most part of these outcrops must be ascribed to Mesozoic times. The identification of the age of these outcrops is very important because the attribution of these rocks to the Early Miocene was one of the most important arguments to date the metamorphism in the Temsamane rocks as Middle Miocene (Frizon de Lamotte, 1985). However, new ^{40}Ar-^{39}Ar from Negro (2005) suggest an age for the main metamorphic episode around 20-23 Ma. The lithological sequence is similar to those sequences described in the Tanger-Ketama unit (Asebriy, 1984), allowing the correlation between the different rock units.

Another characteristic is the presence of bodies of serpentinites at the base of the sequences in the intermediate and southern units, fact that is similar to the outcrops of the bodies of the Beni Malek peridotites and serpentinites at the base of the Tanger-Ketama unit (Michard *et al.*, 1992; El Azzab *et al.*, 1997). These serpentinite bodies suggest a stage of continental rifting and thinning of the crust that produced the exhumation of the mantle directly in the sea bottom (Michard *et al.*, 1992; El Azzab *et al.*, 1997), allowing then the erosion of these rocks. The continental basement of the sequences is preserved in the Palaeozoic rocks of the northern unit. Fission track age studies on zircon and apatites (Azdimousa *et al.*, 2003) indicate an Early Cretaceous age (130 Ma) for this rifting stage in the Tanger-Ketama, agreeing with previous data from Monié *et al.* (1984) that have dated the neoformation of micas of this age in the Temsamane units.

The structures described in this work do not support the interpretation of the Temsamane Massif as a succession of thin splays (Frizon de Lamotte, 1985), but as three main units separated by brittle-ductile thrusts with a top-to-the-south sense of movement (Fig. 6). The internal structure of these units corresponds to great recumbent folds with a vergence towards the SE. These folds were formed during the main stage of deformation that also generated the planar-linear fabric and was syn-metamorphic. The conditions estimated by Negro (2005) and Negro *et al.* (2007) range around 350-400ºC and 8 kbar in the northern unit and seem to decrease towards the south and the lower units. This main deformation stage seems to correspond to left-lateral transpression, as we can identify a compression producing the main recumbent folds and also a non-coaxial regime with an ENE-WSW transport trend and a sense of movement of the hanging-wall towards the WSW (Frizon de Lamotte, 1985). Local overpressure produced by fluids can explain the brittle-ductile

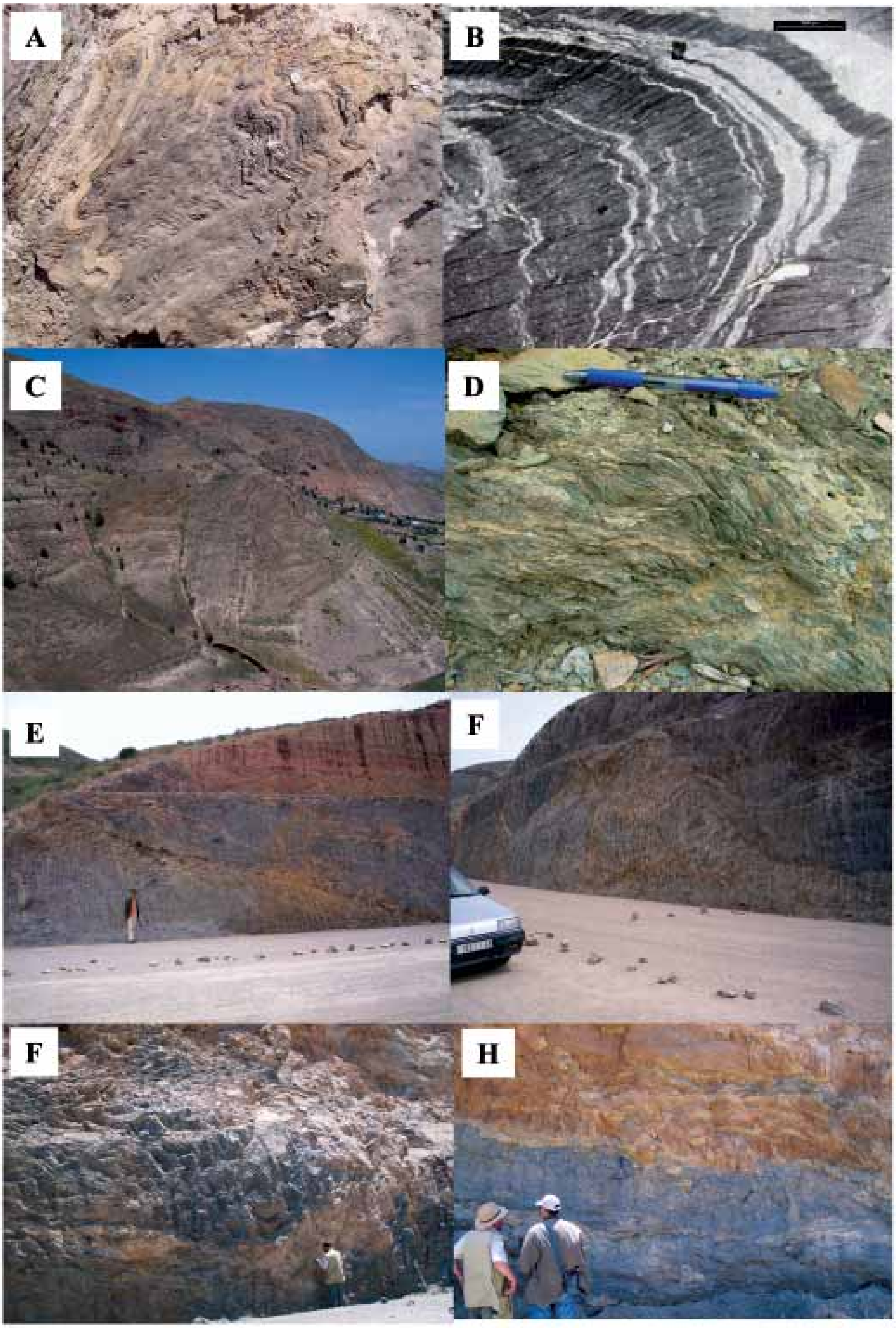

Figure 7.- A) Crenulation cleavage folding the main schistosity in the Neocomian pelites south of Sidi Messaoud Mountain in the lower unit. **B)** Microphotography of the crenulation cleavage. **C)** High angle normal fault cutting the Jurassic marbles and the Neocomian pelites south of Sidi Messaoud. **D)** S-C brittle structures developed in Triassic dolerites metamorphosed under lower greenschist facies conditions in the northern and uppermost unit. **E** and **F)** field outcrop of low-angle normal faults accommodating the late WSW-ENE extensions. **G** and **H)** Fault gouges developed within these low-angle normal faults.

transition recorded in several rocks by the formation of joints and later ductile deformation of the same structures (Frizon de Lamotte, 1985).

The formation of the main thrusts and the superposition of the units towards the south seem to correspond to the last steps of the compressional stage. The age of the exhumation of these rocks is not well constrained due to the lack of datations, but in the upper Tanger-Ketama unit fission track estimates in apatites indicate an age of exhumation ranging between 19 and 13 Ma (Early Burdigalian-Early Serravallian) (Azdimousa *et al.*, 2003).

Normal faults record the later thinning of the pile of units (Fig. 7). The first set of low-angle normal faults records extension parallel to the ductile lineation in the Temsamane Massif and to the Rif Chain orientation. This is similar to the WSW-ENE extension described in the Betics producing the exhumation of the Nevado-Filabride Complex during the Middle-Late Miocene (*e.g.*, Johnson *et al.*, 1997). The younger system records a N-S extension controlling the formation of the Kert Basin during the Late Miocene.

Conclusions

The geological study in Temsamane massif makes it possible to show its lithostratigraphic and tectonic characteristics. We have distinguished a complete lithological sequence from Palaeozoic to Albian. The Palaeozoic metamorphic rocks are overlain by Triassic volcanic rocks, calcitic and dolomitic marbles of Jurassic age, calc-schists and marbles levels of Neocomian times, and brown schists and quartzites of Aptian-Albian ages. The Temsamane units, including the Palaeozoic schists of the Ras Afraou unit represent the sedimentary cover and basement of the Mesozoic Maghrebian paleomargin, which was inverted during the Lower Miocene forming a thrust stack metamorphosed under MP/LT conditions. Early syn-metamorphic deformation was characterised by the development of large recumbent folds and an associated ENE-WSW-oriented planar-linear fabric (S_p). Later out-of-sequence ductile-brittle thrusting and associated asymmetric folds inverted the metamorphic order producing the present thrust stack observed in the Temsamane massif. Brittle exhumation initiated with SW-directed low-angle normal faults and an associated listric fan and continued during the Messinian with the development of high-angle SE-directed normal faults that produced the Kert basin to the south of the massif.

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