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La Galite Archipelago (Tunisia, North Africa): Stratigraphic and petrographic revision and insights for geodynamic evolution of the Maghrebian Chain

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ABSTRACT

The location of the La Galite Archipelago on the Internal/External Zones of the Maghrebian Chain holds strong interest for the reconstruction of the geodynamic evolution of the Mesomediterranean Microplate-Africa Plate Boundary Zone.

New stratigraphic and petrographic data on sedimentary successions intruded upon by plutonic rocks enabled a better definition of the palaeogeographic and palaeotectonic evolutionary model of the area during the early-middle Miocene.

The lower Miocene sedimentary units (*La Galite Flysch* and *Numidian-like Flysch*) belong to the Mauritanian (internal) and Massylian (external) sub-Domains of the Maghrebian Chain, respectively. These deposits are related to a typical syn-orogenic deposition in the Maghrebian Flysch Basin Domain, successively backthrusted above the internal units. The backthrusting age is post-Burdigalian (probably Langhian-Serravallian) and the compressional phase represents the last stage in the building of the accretionary wedge of the Maghrebian orogen. These flysch units may be co-relatable to the similar well-known formations along the Maghrebian and Betic Chains.

The emplacement of potassic peraluminous magmatism, caused local metamorphism in the Late Serravallian-Early Tortonian (14–10 Ma), after the last compressional phase (backthrusting), during an extensional tectonic event. This extensional phase is probably due to the opening of a slab break-off in the deep subduction system.

La Galite Archipelago represents a portion of the Maghrebian Flysch Basin tectonically emplaced above the southern margin of the "Mesomediterranean Microplate" which separated the Piemontese-Ligurian Ocean from a southern oceanic branch of the Tethys (i.e. the Maghrebian Flysch Basin).

The possible presence of an imbricate thrust system between La Galite Archipelago and northern Tunisia may be useful to exclude the petroleum exploration from the deformed sectors of the offshore area considered.

1. Introduction

La Galite Archipelago (Fig. 1), due to its position between Sardinia and Tunisia, is considered of great interest in the geological and tectonic reconstruction on Internal/External Zones of the Maghrebian Chain of the central Mediterranean region. The archipelago is located 45 km off the Cap Serrat and 60 km north of the town of Tabarka (northern Tunisia shore) in the Sardinia-Tunisia Channel (central Mediterranean Sea). It consists of six isles aligned SW to NE: La Fauchelle and Galiton, the main La Galite Island and the three "des Chiens" islets. La Galite Island is 5 km long and 2–3 km wide, with a total surface area of 8 kmq.

1.1. Background and aim

Large outcrops of intrusive granitoids (granodiorite, microgranite and granitic aplite) characterize the geology of the archipelago

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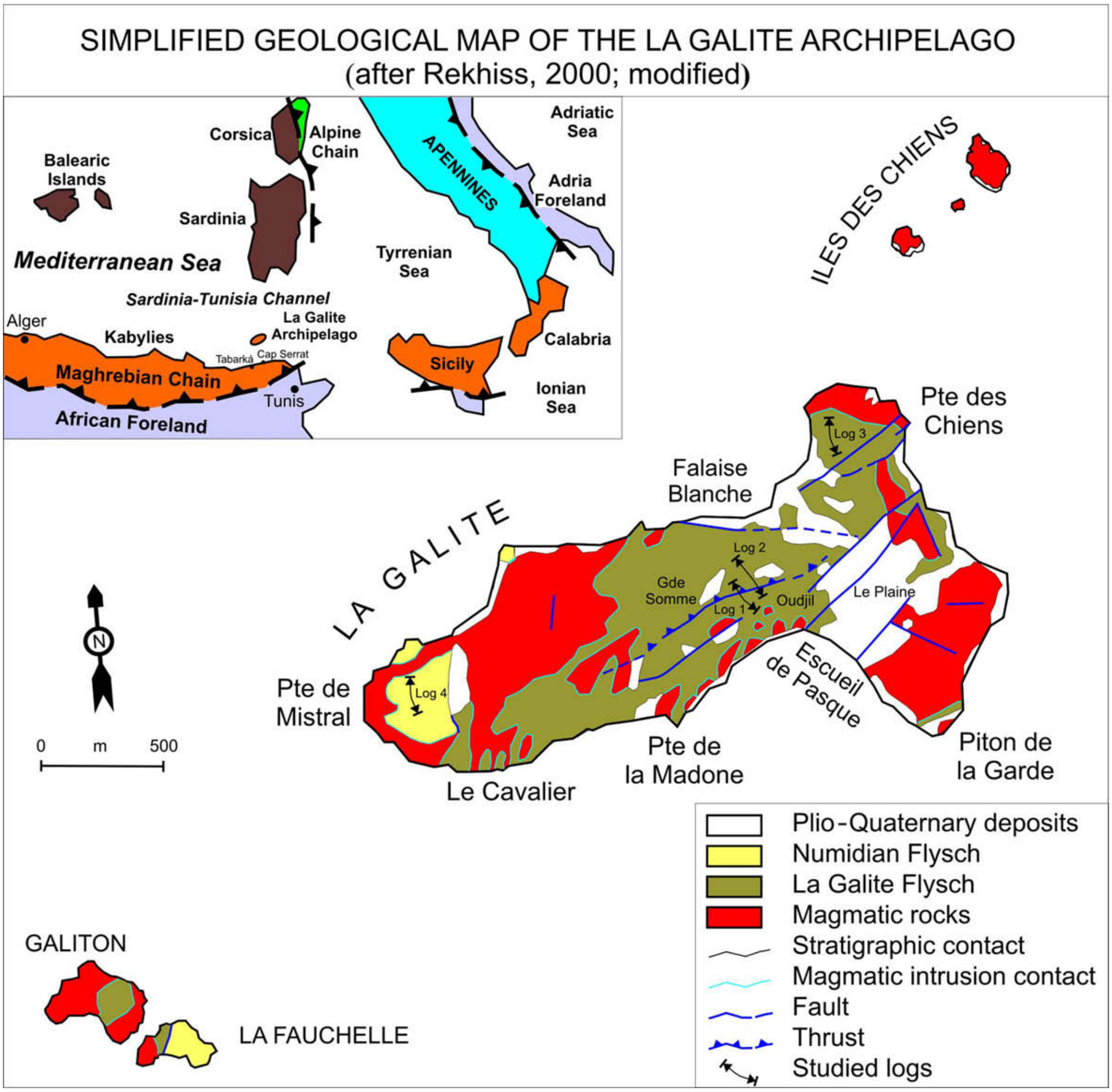

Fig. 1. Simplified geological map of the La Galite Archipelago with the location of the stratigraphic sections measured (after Rekhiss, 2000; modified).

(Fig. 1). They cut through a sedimentary succession that appears slightly metamorphosed along the contact with the magmatic intrusions. Intrusive magmatic granitoids have previously been studied by Bellon (1976), Rekhiss (1984, 1985, 1988, 2002), Rekhiss et al. (1993), Laridhi Ouazaa (1994), Laridhi-Ouazaa (2000) and Talbi et al. (2005). The sedimentary rocks have been described by Solignac (1927), Durand Delga (1956a,b) and Yaïch (1997).

The intrusive bodies were emplaced along the ‘‘La Galite fault'': a major NE–SW trending structure (Talbi et al., 2005, *cum bibl.*). The intrusive tectonic setting and rock association closely resemble to the Lesser Kabylie granitic intrusions in north-eastern Algeria, consisting of undeformed K-rich peraluminous granitoids (Rekhiss et al., 1993; Rekhiss, 2002).

Durand Delga (1956a) pointed out numerous (decimetric to metric) gneiss and pegmatite xenoliths scattered within the intrusives. Chelly (1989), Laridhi Ouazaa (1994) and Rekhiss (2002) reported the presence of micaschists, as well as metasedimentary and garnet-bearing gneiss as the main xenolith lithologies.

The sedimentary succession, firstly described by Durand Delga (1956a), consists of 500-m-thick late Oligocene siliciclastic, micaceous, feldspathic, and calcareous deposits named ‘‘Flysch de La Galite''. Petrographically distinct Numidian-like sandstones have been recognized to be contemporaneous to the *La Galite Flysch* (Durand Delga, 1956a) and corresponding to the *Numidian Flysch* of the Kroumirie mountains (northern Tunisia; Rouvier, 1977). Yaïch (1997) emphasized the difficulty of correlating the sedimentary succession cropping out on La Galite Island both to the ‘‘Oligo-Miocène Kabyle'' and to the ‘‘Flysch grésomicacé'' *Auct.* because lithofacies are only vaguely comparable to those of the ‘‘flysch gréso-micacés mixtes'' (*sensu* Didon and Hoyez, 1978). However, the succession could represent the lateral equivalent of the ‘‘Oligo-Miocène Kabyle''. According to Rekhiss (2002) the Oligo-Miocene succession outcropping over 2/3 of the main island corresponds to the ‘‘Flysch gréso-micacé'', made up of mainly arkosic and micaceous sandstones. This succession is tectonically overlain by the *Numidian Flysch* formed primarily by quartzarenites.

Based on marine geophysical investigations (Compagnoni et al., 1989; Tricart et al., 1994; Mascle et al., 2004), La Galite Archipelago has been included in the Calabro-Peloritano-Kabylo Domain of the Sardinia-Tunisia Channel.

In the context of the geological evolution of the Tellian Chain (Rouvier, 1977; Vila, 1980; Wildi, 1983; Hoyez, 1989; Burollet, 1991; Delteil et al., 1991) and particularly the Tunisia-Sardinia Channel (Auzende, 1970; Auzende et al., 1974; Compagnoni et al., 1989; Tricart et al., 1991, 1993, 1994; Bouillin et al., 1998; Mascle et al., 2004), La Galite Archipelago is commonly interpreted as a part of the Internal Zone of the Maghrebian orogenic belt, palaeogeographically representing the European Margin of the Tethys.

Here, we present the results of a detailed study combining stratigraphic and petrographic analyses of the flysch succession and associated intrusives together with a stratigraphic revision of the whole succession of La Galite Island. In particular, the biostratigraphic results allowed to define the timing of the closure of the Maghrebian Basin and beginning of building of the Maghrebian Chain. Moreover, based on new data and interpretations, a regional tectonic evolutionary model and, at a wider scale, a comprehensive geodynamic evolution of the African/European plate boundary in the central Mediterranean region during the Miocene is proposed.

1.2. Geological and structural setting

La Galite Archipelago (Figs. 1 and 2) represents a window over a portion of the Maghrebian Chain and particularly important because of the outcropping of units of the Internal Domain which are submerged in the Tunisia-Sardinia Channel and laterally outcropping in the Algerian Tell and Calabria-Peloritani Arc.

The sedimentary succession outcropping in the archipelago is not complete and cut by a magmatic intrusion. The presence of a crystalline basement in depth can be hypothesised on the basis of marine geophysical data (Compagnoni et al., 1989; Tricart et al., 1994; Bouillin et al., 1998; Mascle et al., 2004) and of the study of the xenolith population. Gneissic and pegmatitic xenoliths suggest a basement composition similar to that of the Internal Domain of the Kabylies, as pointed out by Durand Delga (1956a), who furthermore observed that the absence of a Mesozoic-Eocene succession may also suggest that the lower Miocene sediments directly overlie the gneissic metamorphic basement.

The La Galite Archipelago therefore represents a key sector to unravel the geodynamic evolution of this portion of the Mediterranean region. At the scale of the central Mediterranean area, the structure of the Sardinia-Tunisia Channel results from crustal thickening followed by thinning, related, respectively, to shortening (formation of the Maghrebian Chain) and to rifting which, together with the successive phase of thermal subsidence, caused the opening of the Tyrrhenian basin between Africa and Europe (Mascle et al., 2004).

The sedimentary succession of La Galite Archipelago is affected by a marked folding and thrusting similar to those recognized across the northern Tunisia offshore (Tricart et al., 1994). New field observations, presented in this paper, enable the recognition of variable trending (from E–W to SE–NW) folds and thrusts with a general S to SW vergence, in agreement with Rekhiss (2002). A NE–SW to E–W trending thrust fault appears in the Oudjill area (Fig. 1), this structure representing the most remarkable compressive feature on La Galite Island.

The sedimentary succession has been locally slightly metamorphosed at the contact area with the magmatic intrusions. This is observable, for instance, in the Numidian-like quartzarenites outcropping east of Pointe de Mistral (Log 4; Fig. 2) and somewhere at the base of *La Galite Flysch* succession.

1.- Southern side of La Galite Island

2: La Fauchelle and Galiton islands

3: Log 1 located to the West from Oudjil

4: Log 2 located to the NW from Oudjil

5: Log 3 located to the W from Pte des Chiens

6: Tectonic contact in Log 2 affecting pelites and sandstones from La Galite Flysch

7: Pelites and sandstones from La Galite Flysch in Log 1

8: Volcanic rocks and metamorphosed Numidian-like sediments

9: Metamorphosed Numidian-like sediments

Fig. 2. Photos showing several sites from the La Galite Archipelago, reconstructed and measured logs, as well as the sedimentary and volcanic rocks, logistic requirements and the international research team.

The lower Miocene siliciclastic turbidites outcropping mainly on La Galite Island, are represented by *La Galite Flysch* (Durand Delga, 1956a) and *Numidian-like Flysch* deposits. *La Galite Flysch* consists of differently stratified petrofacies represented by: (a) blackish-grey pelites; (b) greyish marls; (c) texturally and compositionally immature micaceous arenites and less frequently (d) fine-grained calcareous arenites. Several slumps which are often laterally co-relatable are recognizable in the succession.

The *Numidian-like Flysch* is represented by brownish pelites and typical super-mature quartzarenites often affected by the abovementioned metamorphism which deeply alters the macroscopic features.

In agreement with previous authors the relationships between *La Galite Flysch* and *Numidian-like Flysch* are not clearly definable on the basis of field observations.

Magmatic rocks are represented by massive microgranular granodioritic sub-intrusives with millimetric to centimetric plagioclase, pyroxene, and biotite fenocrysts. Overall, the entire succession is characterized by small grain size and abundant glassy matrix. Greyish to brownish in colour, the main granodioritic intrusions are cut by several decimetric to meter-wide leucocratic dikes, randomly oriented, represented mainly by late microgranular granites and aplites. All outcrops are characterized by the presence of abundant centimetric to decimetric xenoliths belonging to sedimentary, metamorphic, and magmatic protoliths. These appear locally deformed, consistently with the intrusive magmatic foliation. Intrusive rocks are locally disseminated by numerous millimetric to centimetric pink-violet garnet and cordierite xenocrysts. The entire succession presents a clear sub-vertical flux-controlled foliation consistent with the main cooling-joint system.

2. Stratigraphic results

2.1. Lithostratigraphy

The distribution of the sedimentary deposits outcropping at La Galite Archipelago hardly allows the reconstruction of the whole stratigraphic succession along a single profile. Moreover, the poor amount and continuity of outcrops and the intense local folding and faulting hampers detailed stratigraphic reconstructions. Consequently, to reconstruct a composite log of the sedimentary deposits in La Galite Island, we carried out a stratigraphic analysis of four partial sections, three of which were found to be laterally correlated (Fig. 3). Three logs run across the *La Galite Flysch* (Log 1, Log 2 and Log 3) and one across the *Numidian-like Flysch* (Log 4). Log 1 and Log 2 are located in the Oudjill area, in the southern and central side of the island (Fig. 2), representing the lower-middle portion of the Early Burdigalian *La Galite Flysch.* Log 3, which represents the middle-upper portion of the formation, is located close to the northern beach of the island (Fig. 2). Log 4 is located on the western crest of the island overhanging the Pointe de Mistral (Fig. 1); it represents a small, mainly quartzarenitic interval (about 45 m thick) of a *Numidian-like Flysch*, probably Aquitanian-Early Burdigalian in age.

The successions measured are characterized by the following lithofacies (Fig. 3):

2.1.1. Log 1 (Oudjil west)

The base of the sedimentary succession is cut by intrusive granodiorite 30–40 m thick. From bottom to top, the succession starts with a 10-m-thick brownish to greyish pelites intercalated with decimetric turbiditic sandstone beds. Above, the succession continues with about 20 m of brownish to greyish marls and pelites enclosing slumped turbiditic sandstone bodies. The 12-m-thick overlying beds are made up of brownish to greyish marls with intercalated decimetric turbiditic sandstones. It is followed by a 2-m-thick turbiditic sandstone bed, 3 m of brownish to greyish pelites intercalated with decimetric turbiditic sandstones beds, overlain by a 15-m-thick brownish to greyish marls and pelites intercalated with some decimetric turbiditic sandstone beds. Above, a tectonic contact (the south-verging main thrust fault) separates the described succession from an overlying highly deformed interval consisting of brownish to greyish fragmented marls and sandstones up to 25 m thick. This deformation zone presents several mainly reverse shear planes affecting a pre-existing succession also containing some slump levels, successively re-deformed by tectonics.

The whole succession at the footwall seems to be arranged into three parasequences, indicating a regressive trend marked by an upwardly increasing grain size and thickness of turbidite beds. The regressive trend and the occurrence of slumps at the top of the lowermost parasequence could indicate greater tectonic activity.

2.1.2. Log 2 (Oudjil east)

From bottom to top, the 135-m-thick succession is composed of 15 m of brownish to greyish marls interbedded with decimetric turbiditic sandstones. The succession overlying this interval is separated by the main thrust fault, which represents the lateral extension of the structure visible in Log 1 (Fig. 1). The associated 35-m-thick deformed interval represents a shear zone showing the same features described in Log 1. Above, the succession continues with brownish to greyish pelites with interbedded decimetric turbiditic sandstones and some thin beds of calcareous arenites. Two regressive parasequences resulting by the presence of upwardly coarsening and thickening turbidite beds can be recognized at the footwall of the thrust fault.

2.1.3. Log 3 (Pte des Chiens)

The 35-m-thick succession, which can be correlated with the lower part of Log 1, is represented by brownish to greyish pelite and marl layers with interbedded thin to medium grained turbiditic sandstone beds. This interval shows a regressive organization with upwardly more abundant and coarser turbidite beds.

Different stratigraphic intervals recognized in Logs 1, 2 and 3, have been laterally correlated and the entire succession (170 m) has been reconstructed in a synthetic stratigraphic column (Fig. 3) as representative of the *La Galite Flysch* succession outcropping in the main island.

The parasequences recognized within La Galite Flysch are characterized by regressive trends. Considering the deep depositional environment, this seems to suggest sea-level fluctuations probably related to tectonics with an increase of the tectonic activity (as also could be indicated by slumps) in the upper part of each parasequence. However, this interpretation is widely hypothetical, as it is not possible to reconstruct complete or more detailed stratigraphic sections.

2.1.4. Log 4 (Pte de Mistral)

This consists of alternating brownish pelites nearly 45-m-thick locally grading to greenish (schist-like materials) together with typical quartzarenitic beds of the *Numidian-like Flysch*. The lowermost portion of the succession, mainly quartzarenitic, is slightly metamorphosed by the presence of the magmatic intrusion generating a metamorphic aureole less than 10 m thick. The contact, some metres thick, is clearly visible in different sectors at the base of the succession. Brownish pelites are more frequent in the upper part. The Aquitanian-Early Burdigalian age has been attributed on the basis of regional data (Guerrera et al., 1992, *and references therein*) and recent new biostratigraphical analyses from the Cap

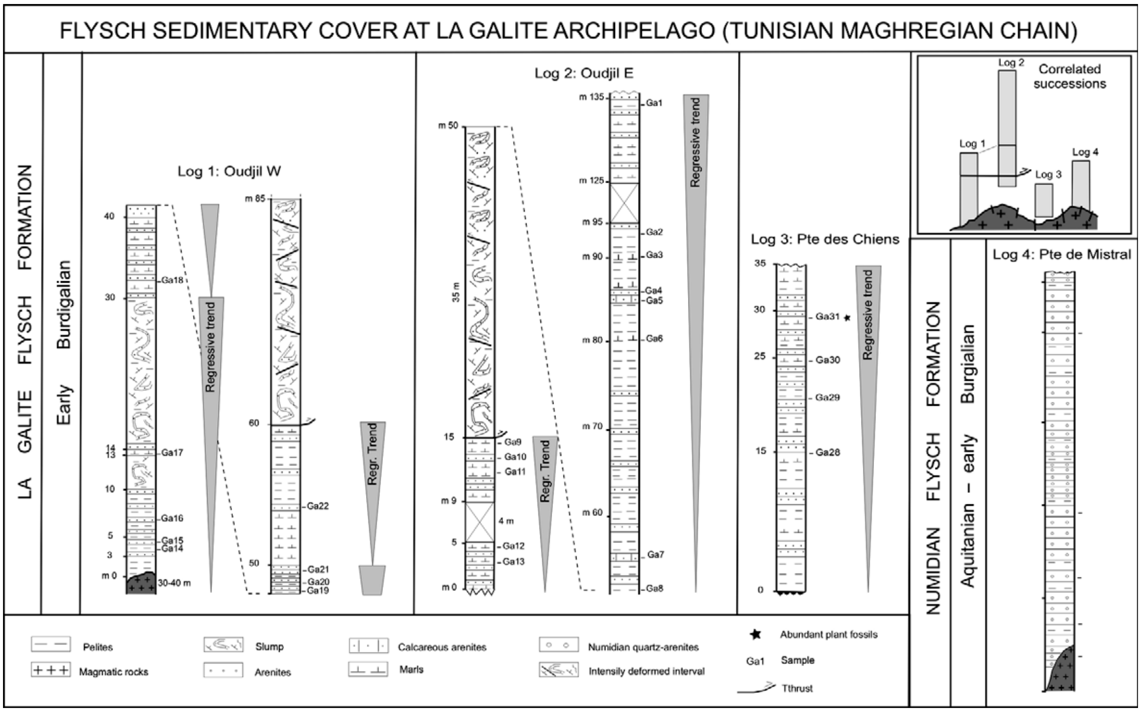

Fig. 3. Lithostratigraphy of the sedimentary succession at La Galite Archipelago. Logs 1, 2 and 3 and the locations of samples are shown.

Serrat logging (Tunisian coast) (Serrano 2008, personal communication).

2.2. Chronostratigraphy

The chronostratigraphy of the *La Galite Flysch* succession has been established by the biostratigraphic study of calcareous nannoflora as well as of planktonic foraminifera. Samples have been processed according to de Capoa et al. (2003). Our main goal was to date the La Galite Flysch accurately in order to obtain new data for the reconstruction of a general framework concerning the Maghrebian Basin evolution.

Fourteen samples were studied to characterize the nannofossil content: four samples from Log 1, nine samples from Log 2, and two samples from Log 3. The results provide an accurate date for the outcropping part of the *La Galite Flysch* basal succession. The calcareous nannoplankton, particularly the presence of *Helicosphaera mediterranea* (Fig. 4(1 and 2)) collected from the basal interval of Log 1 (sample Ga16), supports an age not older than Early Burdigalian (NN2 of Martini, 1971 = MNN2b of Fornaciari and Rio, 1996) for the base of the *La Galite Flysch*. This age is confirmed by the presence of *Tetralithoides symeonidesii* (Fig. 4(9–12)) collected from the basal levels of Log 3 (Ga28). Most of the samples from Log 2 (Ga13, Ga11, Ga9 and Ga8) also furnished a reworked Upper Eocene nannofossil assemblage, indicating an age of not older than Bartonian.

Similar samples are usually devoid of foraminifers. Only some samples provided very scarce and poorly preserved microfauna, composed of non-identifiable radiolarians and foraminifers. One sample from the upper part of Log 2 (Ga 13) provides a planktonic foraminiferal assemblage in which the following species have been identified: *Globoquadrina dehiscens* (Chapman, Parr and Collins) (Fig. 4, 13), *Globigerina venezuelana* Hedberg, *Globigerina woodi* Jenkins, *Globigerinella obesa* (Bolli), *Neogloboquadrina siakensis* (Le Roy) and *Globorotalia peripheroronda* Blow and Banner (Fig. 4, 14). This assemblage is restricted to the Late Aquitanian-Burdigalian.

On the base of the data discussed, we infer the outcropping *La Galite Flysch* succession to be Burdigalian in age.

3. Petrographic results

3.1. Petrography of magmatic rocks

The La Galite Archipelago represents the roof of a large batholith of high-K cordierite/garnet-bearing granitoids intruding onto the *La Galite Flysch* and developing a metamorphic aureole (Rekhiss, 1985; Laridhi Ouazaa, 1994). A pervasive, sub-vertical, decimetre-wide, planar cooling-joint system affects the main outcrops, attesting to a flux-controlled intrusion of the plutons in a cold-shallow hypoabyssal environment. Accordingly, all sampled rocks have a significant, glassy to fine-grained mesostasis (5–30%).

The granitoids from La Galite intrusive sequence can be characterized on the basis of the mafic-phases distribution: garnet, cordierite, orthopyroxene, clinopyroxene, amphibole, and biotite. Ilmenite is systematically present while muscovite is absent.

Petrographically, the main intrusive types are represented by: (a) a two-pyroxene granodiorite (outcropping in the western La Galite (Fig. 1) and Galiton Island); (b) a single cpx-granodiorite (outcropping at the Piton de la Garde and at the Pointe des Chiens); (c) granite and monzonitic microgranite existing both as large primary bodies (eastern La Galite and Chiens islets) and as late intrusives (forming dikes and pluri-metric bodies cutting the main granodiorite at the Piton de la Garde, Galiton and Fauchelle); and (d) aplitic dikes cutting through the entire magmatic sequence (Rekhiss, 1985; Laridhi Ouazaa, 1994). Biotite, amphibole, and garnet are variably resorbed due to the progressive Al enrichment of the different parageneses. A strong coronitic reaction involving garnet and crystallizing quartz and cordierite affect all the rocks with the progressive stabilization of cordierite. Data on mineral composition are reported and discussed in Laridhi Ouazaa (1994); in the present paper, only bulk rock data will be discussed, giving constraints on the major tectono-magmatic relationships.

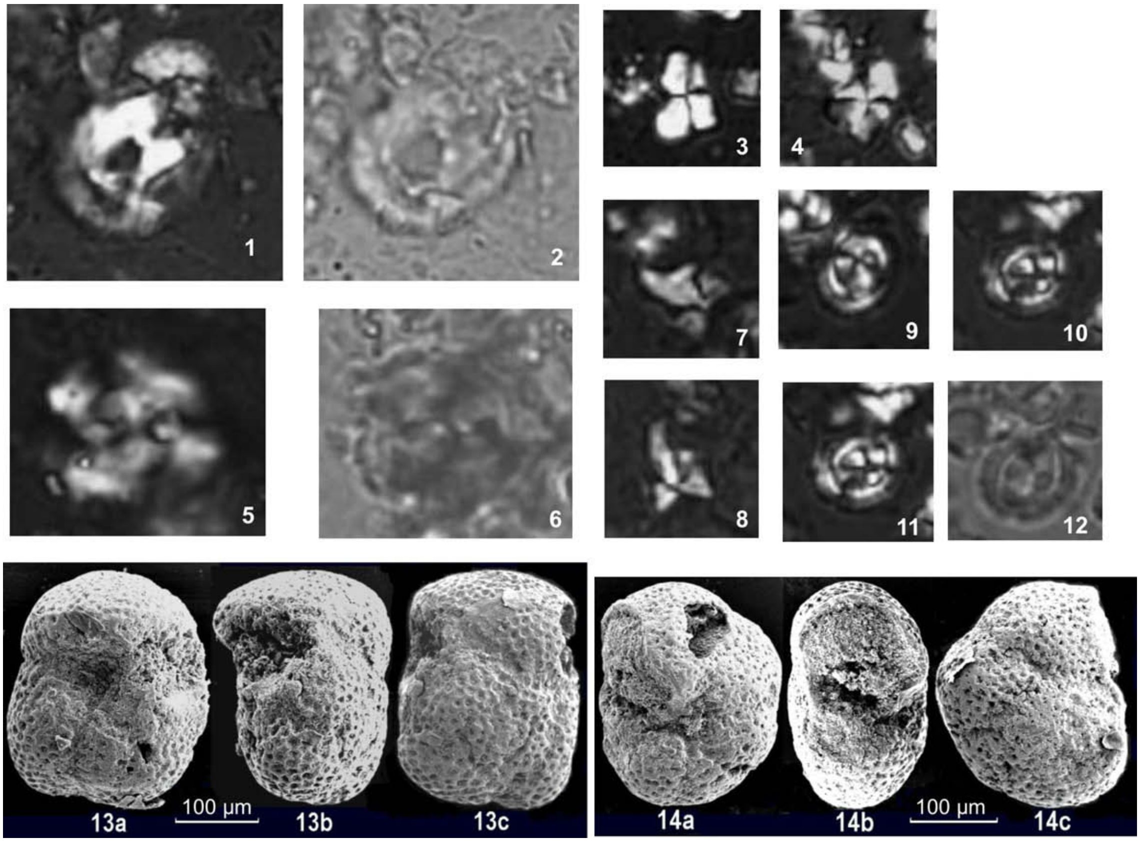

Fig. 4. Calcareous nannofossils microphotographs (all × 2500): (1 and 2) *Helicosphaera mediterranea* (sample Ga16); (3 and 4) *Sphenolithus disbelemnos* (sample Ga16); (5 and 6) *Reticulofenestra bisecta* (sample Ga20); (7 and 8) *Sphenolithus ciperoensis* (sample Ga18); (9–12) *Tetralithoides symeonidesii* (sample Ga28). Planktonic foraminifera (for magnification, see scale bar); (13a–c) *Globoquadrina dehiscens* (sample Ga13); (14a–c) *Globorotalia peripheroronda* (sample Ga13).

A large xenolith and xenocryst population characterizes the whole sequence. The first are represented by sedimentary, metamorphic and magmatic rocks. Sedimentary xenoliths belong mainly to the *La Galite Flysch* succession. They have undergone variable *P–T* metamorphic conditions until partial melting. Magmatic xenoliths are micro-granites to granodiorite and tonalite with variable amounts of biotite, feldspars and oxides. An important class of metamorphic xenoliths is represented by paragneiss-bearing quartz, feldspar, and biotite, possibly representative of the metamorphic basement underlying the *La Galite Flysch* (Laridhi Ouazaa, 1994). Metamorphic phases are represented by garnet, cordierite, sillimanite ± spinel, indicating metamorphism reaching the granulite facies (Chelly, 1989). Xenocrysts are represented by mm-cordierite and garnet grains scattered in the groundmass. These can be recognized by their habit, zoning, reactional structures, and the presence of abundant sillimanitic and sphene inclusions. Cordierite appears either as resorbed or as euhedral magmatic grains, suggesting an evolution from Al-undersaturation to saturation. Garnet appears as disseminated xenocryst or surrounding the gneissic xenoliths, implying a reactive genesis between the parent magma and the metamorphic aluminous country rocks (Fig. 5).

3.2. Whole rock/xenolith composition

Compositionally, La Galite intrusives are potassic and high-K (K_2O/Na_2O: 0.53–2.62) strongly peraluminous rocks (A/CNK: 1.3–1.9) (Table 1). This character is typical of the tertiary magmatism in the North African province (Fourcade et al., 2001). Based on major- and trace-element systematics, Laridhi Ouazaa (1994) recognized a general fractionation trend driving the La Galite magmatic sequence. Major oxides depict a biotite + pyroxene + amphibole + plagioclase + ilmenite fractionation trend. An appreciable K_2O decrease in the late aplitic events marks the fractionation of K-feldspar at this stage. The major-element composition (Table 1, Fig. 6A) clearly shows the fractional crystallization trend leading to the evolved aplitic late composition. Our data

Fig. 5. Reactive garnet growing on a migmatitic metapelite xenolith (Piton de la Garde). The growing of reactive aluminous garnet attests to the progressive Al saturation of a meta-aluminous magma by assimilation of Al-rich metapelitic rocks. The digestion of such lithologies enriches the magma with cordierite and garnet xenocrysts (Laridhi Ouazaa 1994; Fourcade et al., 2001).

Table 1
Bulk rock major-element composition of La Galite granitoids. Gd = granodiorites; G = granites; A = aplites; X = magmatic granitoid xenoliths; F = flysch. Data are from this work (a) and Laridhi Ouazaa, 1994 (b).

	Gd-a GT3-02	*Gd-b* GA10	*Gd-a* PM3-02	*Gd-b* GA3	*Gd-b* GT2	*G-b* GT5	*G-b* GT4	*G-b* GA15	*G-b* GA2	*G-b* CH1	*G-b* CH3	*G-b* GA8	*G-b* CH2
SiO_2	60.10	60.81	62.03	62.86	64.78	62.65	65.07	65.55	66.07	65.95	65.11	66.11	66.3
TiO_2	0.63	0.72	0.67	0.7	0.61	0.61	0.61	0.58	0.57	0.52	0.55	0.56	0.54
Al_2O_3	15.84	16.33	15.98	16.52	15.51	17.91	16.26	18.83	15.81	15.64	15.92	15.73	15.42
Fe_2O_3	5.99	0.84	–	1.01	1.28	1.25	1.39	1.14	0.77	1.05	1.07	1.14	1.02
FeO	–	4.96	5.57	4.57	3.7	3.56	2.81	3.25	3.66	2.85	3.26	3.04	3.15
MnO	0.12	0.10	0.10	0.09	0.1	0.06	0.06	0.05	0.06	0.06	0.07	0.06	0.07
MgO	4.44	3.92	3.39	2.71	2.01	1.47	1.98	1.95	1.88	1.83	1.99	2.02	2.13
CaO	6.88	5.31	5.23	4.51	4.16	3.78	5.00	2.36	2.96	2.98	3.02	2.57	2.92
Na_2O	2.63	2.95	3.32	3.07	3.27	3.9	3.8	3.53	3.2	3.02	3.03	2.82	3.01
K_2O	2.37	2.85	2.78	2.83	3.39	3.46	2.00	3.87	3.64	4.08	3.92	4.49	3.75
P_2O_5	0.12	0.15	0.16	0.2	0.12	0.1	0.13	0.17	0.17	0.17	0.19	0.19	0.2
H_2O	0.09	1.56	0.19	0.43	0.82	0.9	1.01	1.51	1.61	2.62	2.7	2.01	1.74
H_2O^-	0.64		0.49										
Total	99.86	100.5	99.92	99.50	99.75	99.65	100.1	102.8	100.4	100.8	100.8	100.7	100.3
	A-b FA1e	*A-b* GT3	*A-b* GT1	*A-a* GT4-02	*X-a* GAL3-02	*X-a* GAL5-02	*X-b* GA2-1	*X-b* GA2-4	*X-b* GA2-8	*X-b* GA10b	*X-b* CH1d	*F-a* GA5	
SiO_2	75.53	75.31	76.98	78.03	60.77	61.65	49.14	42.86	62.1	57.58	44.28	67.39	
TiO_2	0.03	0.23	0.05	0.04	0.62	1.08	0.91	1.73	0.99	0.91	2.04		
Al_2O_3	13.07	12.62	12.7	12.36	16.85	15.17	17.1	32.98	15.98	18.97	33.2	12.32	
Fe_2O_3	0.47	0.3	0	–	5.18	5.95	9.32	8.05	1.32	1.66	7.09	3.63	
FeO	0.37	1.82	0.36	0.25					5.22	5.61			
MnO	0.01	0.02	0.06	0.00	0.08	0.11			0.06	0.29			
MgO	0.6	0.33	0.18	0.16	2.79	2.43	4.81	2.49	3.56	3.95	1.07	0.45	
CaO	0.57	0.95	0.43	0.30	3.93	2.86	16.38	4.07	3.74	2.27	0.58	4.17	
Na_2O	2.84	3.43	2.31	3.16	3.16	4.04	1.82	0.92	3.04	2.27	1.71	3.23	
K_2O	4.94	4.4	6.06	5.15	2.60	1.92	0.47	3.73	1.46	2.78	5.7	1.42	
P_2O_5	0.01	0.1		0.03	0.15	0.25							
H_2O	1.97	0.77	0.72	0.11	0.19	0.16		3.20	2.87	3.85	2.41		
H_2O^-				0.47	3.71	3.44						5.90	
Total	100.4	100.3	99.85	100.1	100.0	99.06	99.95	100.0	100.3	100.1	98.08	98.51	

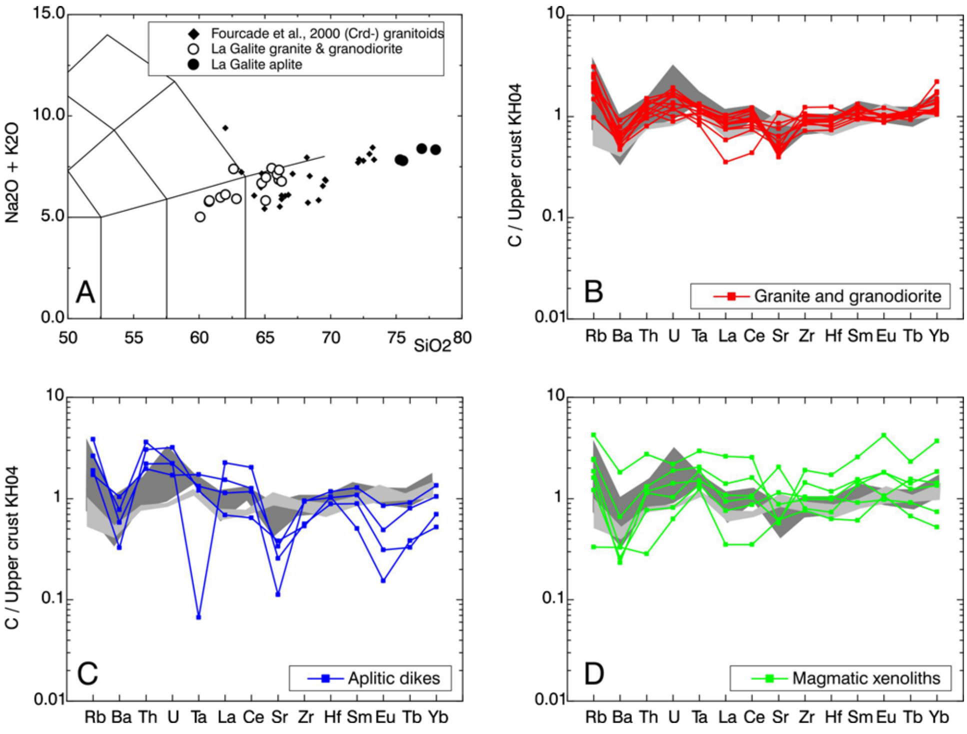

Fig. 6. Major- and trace-element systematics in the La Galite rocks (Tables 1 and 2). Inset A: Total Alkali–Silica plot: open circles granodiorite and granite, black solid circles: aplites, small solid diamonds: cordierite and garnet bearing granitoides from Fourcade et al. (2001). Insets B–D: extended trace-element pattern of granite and granodiorite (red lines) aplitic dikes (blue lines) and xenoliths (green lines), respectively. Flysch composition (light-grey field) and granitoides from Fourcade et al. (2001) (dark-grey field) are reported for comparison. Trace-element compositions normalized to the upper-crust composition after Kemp and Hawkesworth (2004) (KH04) are plotted in order of decreasing incompatibility from left to right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are in good accordance with the composition of garnet- and cordierite- bearing granitoids studied by Fourcade et al. (2001).

The compositional superposition of the intrusive suite and the host flysch for both major and trace elements (Table 2, Fig. 6B) suggests a large incorporation of *La Galite Flysch* lithologies by assimilation or mingling of an anatectic magma with deep mantle-derived component, as also suggested by Fourcade et al. (2001). Notable differences in trace-element systematics derive from fractionation of ilmenite (Ta-negative anomaly) and the accumulations of plagioclase (Sr anomaly). The composition of the aplitic dikes (Fig. 6C) reflects the evolution during fractional crystallization owing to enrichment in the most incompatible elements and depletion in the most compatible ones. One of the samples of the xenolith suite possibly represents a composition of an early differentiated aplitic dike (HREE depletion) incorporated in late intrusions.

Table 2
Bulk rock trace-element composition of La Galite granitoids. Gd = granodiorites; G = granites; A = aplites; X = magmatic granitoid xenoliths; F = flysch. Data are from this work (a) and Laridhi Ouazaa, 1994 (b).

	Gd-a	*Gd-b*	*Gd-a*	*Gd-b*	*Gd-b*	*G-b*	*G-b*	*G-b*	*G-b*	*G-b*	*G-b*	*G-b*	
	GT3-02	GA10	PM3-02	GA3	GT2	GT5	GT4	GA2	CH1	CH3	GA8	CH2	
Rb	121.8	154.0	142.5	149.0	162.0	173.0	80.0	170.0	214.0	197.0	253.0	197.0	
Sr	345.8	160.0	204.2	242.0	157.0	178.0	274.0	201.0	144.0	137.0	127.0	144.0	
Cs		5.8		5.4	8.2	10.9	3.3	4.9	8.3	6.4	8.2	6.5	
Ba	398	321	295	332	412	439	357	577	349	396	495	348	
Sc		18.3		16.2	14	12.8	13.3	11	10.8	10.6	11.2	11.2	
Co		20.2		15.4	11.3	9.6	8.5	9.6	10.3	10.5	10.6	11.1	
Ni		38		31	15	13	14	24	16	18	16	20	
Zr	169.7	139.0	161.3	206.0	238.0	193.0	199.0	172.0	172.0	179.0	180.0	168.0	
Hf	4.2	3.9	4.4	5.3	6.6	5.3	5.3	5.1	4.7	4.8	5.0	4.7	
Th	10.1	8.4	11.8	10.7	11.0	11.6	13.0	13.6	14.3	14.8	15.0	15.8	
Ta	0.74	0.82	0.87	1	1.06	0.99	0.97	1.1	1.11	1.11	1.2	1.16	
U	3.24	3.2	4.44	3.7	4.3	2.4	2.7	4.7	3.6	4.4	3.2	4.7	
Nb	8.6		9.6										
La	10.9	18.2	23.1	25.9	26.7	31	25.7	23.4	29.5	28.1	31.9	31.9	
Ce	27.5	46.6	49.4	56.7	59.3	58	58.8	52.6	72.2	67.6	73	76.7	
Pb	12.47		53.99										
Pr	3.96		5.98										
Nd	18.03		22.51										
Sm	4.63	4.4	5.03	5.1	4.7	4.5	4.4	5.1	5.6	5.8	6	6.2	
Eu	0.90	1	0.87	1.21	0.97	0.98	0.88	1.04	1	1.02	0.96	0.94	
Gd	4.20		4.64										
Tb	0.71	0.72	0.76	0.72	0.71	0.65	0.71	0.73	0.79	0.77	0.82	0.81	
Dy	4.22		4.53										
Ho	0.88		0.90										
Er	2.42		2.41										
Tm	0.33		0.34										
Yb	2.29	4.4	2.28	2.4	3.5	2.5	3.4	2.2	2.8	2.1	3	2.3	
Y	26.88		25.82										
Lu	0.34		0.33										
	A-b	*A-b*	*A-b*	*A-a*	*X-a*	*X-a*	*X-b*	*X-b*	*X-b*	*X-b*	*X-b*	*F-b*	*F-b*
	FA1e	GT3	GT1	GT4-02	GAL3-02	GAL5-02	GA2-1	GA2-8	GA10b	CH1d	GA5	GA5a	GA4a
Rb	141.0	316.0	216.0	154.7	151.9	131.9	27.3	99.0	201.0	348.0	63.9	75.6	40.1
Sr	108.0	36.0	82.0	121.7	197.9	192.6	654.0	366.0	280.0	183.0	311.0	268.0	411.0
Cs	10.1	12	2.8				2.8	5.1	20.5	11.1	2.6	4	1.46
Ba	652	363	486	205	208	146	206	164	416	1138	244	291	915
Sc	4	4.4	0.56				16.8	17.6	13.8	24.2	9.5	12.4	8.1
Co	0.86	2.7	0.3				32.6	22.7	35.5	33.4	10.3	14.2	6.6
Ni	3	2.7	2.4				130	33	159	92	62	83	51
Zr	181.0	183.0	108.0	103.2	146.9	277.3	153.0	200	189	369	147	162	143
Hf	6.2	5.4	4.7	5.5	3.3	6.2	3.9	5.4	5.2	9.1	4.3	3.9	3.3
Th	20.7	23.2	38.0	32.1	3.0	11.9	12.3	8.1	13.8	28.7	7.9	7.8	5.8
Ta	1.56	1.19	0.06	1.08	1.11	1.68	1.36	1.24	1.85	2.65	0.95	1.11	0.65
U	4.6	6	6	8.63	1.69	2.78	3.80	2.2	5.1	5.9	2.1	2.1	1.63
Nb				3.3	13.9	21.1							
La	47.3	35.1	70	21.3	10.9	28.9	33.4	23.4	43.6	81	21.4	18.2	19.6
Ce	79.5	74	128	40.7	22.2	64.1	67.3	54.8	101	160	42.8	40.2	42.9
Pb				10.15	18.32	23.04							
Pr				4.18	2.76	7.83							
Nd				13.62	10.93	30.98					4.8	18.8	
Sm	6	5.1	4.2	2.37	2.85	7.24	6.40	4.3	7.1	12.1	3.7	4.3	3.8
Eu	0.85	0.49	0.31	0.15	1.06	1.05	1.82	0.97	1.81	4.2	0.9	1.05	1.26
Gd				1.75	2.70	6.58							
Tb	0.64	0.56	0.23	0.27	0.47	1.09	0.87	0.64	0.99	1.62	0.49	0.66	0.72
Dy				1.52	2.71	6.38							
Ho				0.29	0.52	1.23							
Er				0.92	1.32	3.22							
Tm				0.14	0.17	0.45							
Yb	2.7	2.1	1.4	1.05	1.04	2.86	2.70	1.48	3.7	7.4	1.46	1.98	2.7
Y				10.09	16.99	37.23							
Lu				0.18	0.15	0.44							

The composition of the magmatic xenoliths (granitoids) presents variable trace-element enrichments and depletions with respect to both the intrusives and host flysch. The sub-parallel trending of trace-element patterns suggest that they underwent variable degrees of partial melting/assimilation (Fig. 6D). The observed scatter of the trace element in the xenoliths derives from the increasing of the residual character of the rock due to the preferential melting of the most fusible phases (quartz and feldspar) that are at the same time the least enriched in incompatibles (Bea et al., 1994; Laridhi Ouazaa, 1994).

3.3. Preliminary petrographic characterization of the sedimentary rocks

The scant amount of unweathered rocks and discontinuous outcrops in the La Galite Archipelago hinders a systematic sampling, thus hampering the identification of possible thin variations of the some lithofacies. However, the sampling achieved seems sufficient for a preliminary characterization of the main lithofacies of the sedimentary successions. In addition, a comparison with similar petrofacies already studied in adjacent sectors of the Maghrebian Chain can contribute to a better identification of the sedimentary rocks recognized.

The macroscopic and microscopic petrographic analyses of 11 arenitic samples collected from the *La Galite Flysch* and *Numidian-like Flysch* allow recognition of three different petrofacies, corroborating the field observations. Two of these represent the main lithofacies which characterize *La Galite Flysch* and one the *Numidian-like Flysch*. Analytic results of the modal analysis are shown in Table 3.

3.3.1. Petrofacies 1 (samples Ga4, Ga15, Ga21, Ga22, Log 1, La Galite Flysch)

The rock is heterogeneous and shows various angular-shaped elements, cemented by a fine-grained mesostasis. Elements consist of quartz (13.6–14.2%), feldspar (8.3–9.3%), chloritized biotite (5.4–5.9%), carbonates (calcite and dolomite, 2.8–3.4%), and various clasts or microfragments of rocks (microdolerite, granitoids, metaquartzites, etc., 11.3–12.2%) as well as bioclastic fragments (foraminifers, radiolarians and sponge spicules, etc., 2.9–3.7%). Cement is abundant (52.1–53.6%) with a mixed argillaceous-calcareous composition including some accessory minerals (garnet, hematite, zircon, epidote, sphene, etc., 0.4–0.6%. Such a petrographic composition (Fig. 7a–d) is typical of an immature litharenite transported over a short distance and originating from a source close to the sedimentary basin. On the other hand, the petrographic composition indicates that the clastic materials have been sourced from crystalline terrains (magmatic and metamorphic). Accordingly, this Petrofacies 1 could be described as immature litharenitic sandstone.

3.3.2. Petrofacies 2 (samples G5, Ga7, Ga10, Log 2, La Galite Flysch)

The rock here displays a structure of very fine grains (size < 0.1 to 0.5 mm) varying in nature and cemented by an argillaceous/calcareous cement (60.6–61.3%). The grains consist of: a high proportion of angular-shaped quartz crystals (29.8–30.8%), enriched in solid (mainly apatite) and fluid inclusions; some sericitized and deformed plagioclase crystals (0.7–0.9%); rare phyllites (chloritized and muscovitised biotite, 3.4–3.6%) often deformed; very rare carbonates (calcite and dolomite, 0.8–0.9%); rare bioclasts (forams, 2.1–2.6%); and accessory minerals (opaque and zircon, 1.1–1.3%). The rock is locally crossed by some diaclases filled with calcite and iron oxide. These petrographic characteristics (Fig. 7e and f) indicate that Petrofacies 2 is very similar to Petrofacies 1 and consists of highly immature fine-grained litharenite sandstones, cemented by argillaceous/calcareous cement. Also Petrofacies 2 could be described as immature litharenitic sandstone.

On the basis of this preliminary petrographic study, Petrofacies 1 and 2 can be considered as belonging to the well-known immature turbiditic arenite family, which is very common in the Mauritanian Domain of the Maghrebian Flysch Basin (e.g., Chiocchini et al., 1980; Guerrera, 1981/82; Guerrera et al., 1989; de Capoa et al., 2000, 2002; Zaghloul et al., 2002). In this context the immature arenites of the *La Galite Flysch* can be related to the syn-orogenic flysch sedimentation of the internal Maghrebian Flysch Basin (*sensu* Guerrera et al., 1993, 2005). However, for a more precise comparison, further studies are necessary to verify the dolomite:calcite ratio and the nature of clay minerals. The deformation recorded by the plagioclase polysynthetic gemination and phyllites as well as the other features described above (e.g., the siliciclastic supply) suggest a tectonic activity of the depositional environment and of the source area.

3.3.3. Petrofacies 3 (samples Ga24, Ga25, Ga26, Ga27, Log 4, Numidian-like Flysch)

The rock, with slightly oriented granoblastic texture, consists of 96.8-97.6% of well-sorted quartz grains (average size 0.3 mm). A detailed observation reveals that these quartz grains are limpid and include some solid (zircon and biotite) and fluid (monophasic and biphasic) inclusions. In polarized light, these grains display an undulating extinction and evidence of recrystallization, thus indicating that the rock has been affected by severe deformation and heating. This is well confirmed by the presence of sericitized feldspars (0.4–0.6%), chloritized biotite (1.7–1.9%), and muscovite as well as of some other rare opaque (0.2–0.7%) and epidote. All these petrographic characteristics (Fig. 7g and h) indicate that the lithofacies consists of supermature quartzarenites affected by heating and deformation (contact metamorphism) related to the emplacement of the magmatic rocks.

Without considering the effects of the thermal metamorphism but taking into account the general geological framework, we conclude that these quartzarenites closely resemble those of the *Numidian Flysch*, well known in northern Tunisia and along the Betic, Maghrebian and Southern Apennine Chains, which represent (for nearly all researchers) the typical sedimentation of the external sector (Massylian Domain) of the Maghrebian Flysch Basin

Table 3
Volume modal analyses determined on 1,000 point x thin section.

Samples	Petrofacies 1 (*immature litharenite*)				Petrofacies 2 (*highly immature fine litharenite*)			Petrofacies 3 (*quartzarenite*)			
	Ga4	Ga15	Ga21	Ga22	Ga5	Ga7	Ga10	Ga24	Ga25	Ga26	Ga27
Quartz	13.6	13.7	14.2	13.8	29.8	30.4	30.8	97.5	96.8	97.6	97.2
Feldspar (K–Fs and plagioclase)	8.9	9.3	8.3	8.7	0.9	0.7	0.8	0.4	0.6	0.4	0.6
Phyllites (biotite, muscovite, chlorite)	5.6	5.4	5.9	5.7	3.4	3.5	3.6	1.8	1.9	1.8	1.7
Carbonate (calcite, dolomite)	2.9	3.4	3.1	2.8	0.9	0.8	0.8	–	–	–	–
Clastes	11.6	12.1	12.2	11.3	–	–	–	–	–	–	–
Bioclastes	3.4	3.6	2.9	3.7	2.6	2.5	2.1	–	–	–	–
Opaque and accessory phases	0.4	0.4	0.6	0.5	1.1	1.2	1.3	0.3	0.7	0.2	0.5
Cement	53.6	52.1	52.8	53.5	61.3	60.9	60.6	–	–	–	–
Total	100	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

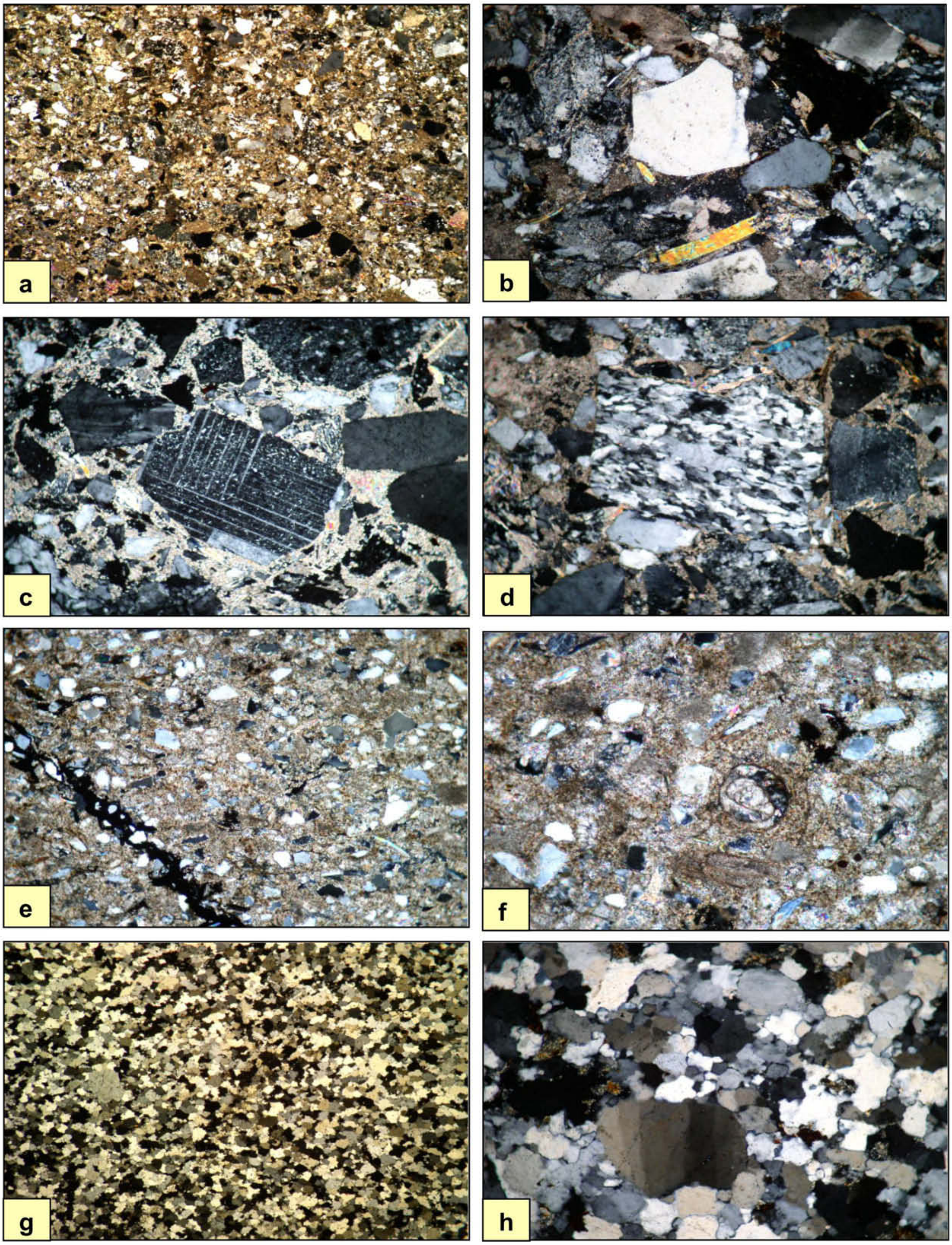

Fig. 7. Litharenite and Quartzarenite characters. *Petrofacies 1, immature litharenite*: (a) Binocular observation showing the total texture of the rock (LP – L = 1.2 mm); (b) Micrography showing heterogeneous nature and the angular shape of the detrital elements of the rock (LP – L = 0.85 mm); (c) Quartz and plagioclase fragments cemented by a fine-grained mesostase (LP – L = 0.85 mm); (d) Fragment of recrystallized quartzite and angular detrital elements (LP – L = 1.7 mm). *Petrofacies 2, highly immature, fine litharenite*: (e) Heterogeneous composition with angular feldspar and quartz grains cemented by a carbonated mesostase (LP – L = 1.7 mm); (f) Coexistence of detrital elements and bioclastes (Foraminifera) cemented by a microsparitic mesostase (LP – L = 0.43 mm). *Petrofacies 3, quartzarenite*: (g) Binocular observation showing granoblastic texture (LP – L = 2.2 mm); (h) Quartz crystals recrystallized and showing an undulating extinction (LP – L = 1.7 mm). (LN: natural light; LP: polarized light; L: width of micrography).

(Guerrera et al., 1992, 1993; *and references therein*). Further focused analyses are necessary to confirm the real correspondence between the Numidian quartzarenites and those (Petrofacies 3) recorded in La Galite Archipelago.

4. Discussion

4.1. Geotectonic context and sedimentation

La Galite Archipelago has been considered to be located above a crystalline basement belonging to the Calabro-Peloritano-Kabylo Internal Zone (Tricart et al., 1993, 1994; Bouillin et al., 1998; Rekhiss, 2002) corresponding to AlkaPeCa (Bouillin, 1986; Bouillin et al., 1986) and considered the southern margin of the European Plate (Tricart et al., 1994; Bouillin et al., 1998; Rekhiss, 2002). Our data support the presence of basement units deeply below the sedimentary cover; however, we suggest a different palaeogeographic reconstruction. We attribute the basement to the Internal Domain of the Maghrebian Chain belonging to an intermediate plate located between the Africa and European plates ("Mesomediterranean Microplate", *sensu* Guerrera et al., 1993, 2005, 2007).

Previous interpretations concerning the sedimentary successions of La Galite Archipelago (Tricart et al., 1994; Rekhiss, 2002) consider these deposits equivalent to the upper Burdigalian Stilo-Capo d'Orlando Formation, which represents the thrust top cover of the Internal Zones of the Maghrebian Chain (Bonardi et al., 2003 and *references therein*).

Our new results, concerning the early Burdigalian age of La Galite Flysch and the preliminary petrographic features of this formation, do not agree with previous interpretations and we attribute this sedimentary unit to a deposition occurring in the Maghrebian Flysch Basin (*sensu* Guerrera et al., 1993, 2005) despite its present location above the Internal Zones of the Maghrebian Chain. In particular, *La Galite Flysch* represents the syn-orogenic deposition related to the internal Mauritanian sub-Domain of the Maghrebian Flysch Basin. Meanwhile, the *Numidian-like Flysch* is deposited above the external Massylian sub-Domain of the same basin.

The present position of the *La Galite Flysch* over the Internal Zones may have resulted from a backthrusting of part of the Maghrebian Flysch Basin deposits during the last stage of the chain building, due to a wedge shape of the Internal Zone (Fig. 8). Such geometry is also visible in other sectors of the Maghrebian and Betic Cordillera orogens (Guerrera et al., 1993; de Capoa et al., 2004). The south-vergent thrust fault recognized at La Galite Island is interpreted as a secondary backthrust plane probably associated to the main backthrust, which is located in depth at the base of the sedimentary cover and therefore never coming to the surface. As an alternative, the south-vergent thrust could be explained also as a structure related to a more recent tectonic deformation.

A similar structural setting is recognizable in the Betic-Rifian Arc (central-western portion of the chain, Malaga Province) where the late Oligocene to early Burdigalian basinal flysch successions (Algeciras and/or Bolonia Fms) override, by backthrusting, the Internal Zone of the chain in the so-called Colmenar-Periana Complex (Martín-Algarra, 1987).

The presence of a former sedimentary cover unconformably overlying the Internal Zones (i.e. the Stilo-Capo d'Orlando Fm of the Calabria-Peloritani Arc equivalent) and underlying *La Galite Flysch* is still an open question, for which possible interpretations are: (1) the Stilo-Capo d'Orlando-like sediments are present in depth and buried; (2) the palaeogeographic setting was unfavourable for the sedimentation, the area being isolated from the main clastic supply; (3) the Stilo-Capo d'Orlando-like sediments were

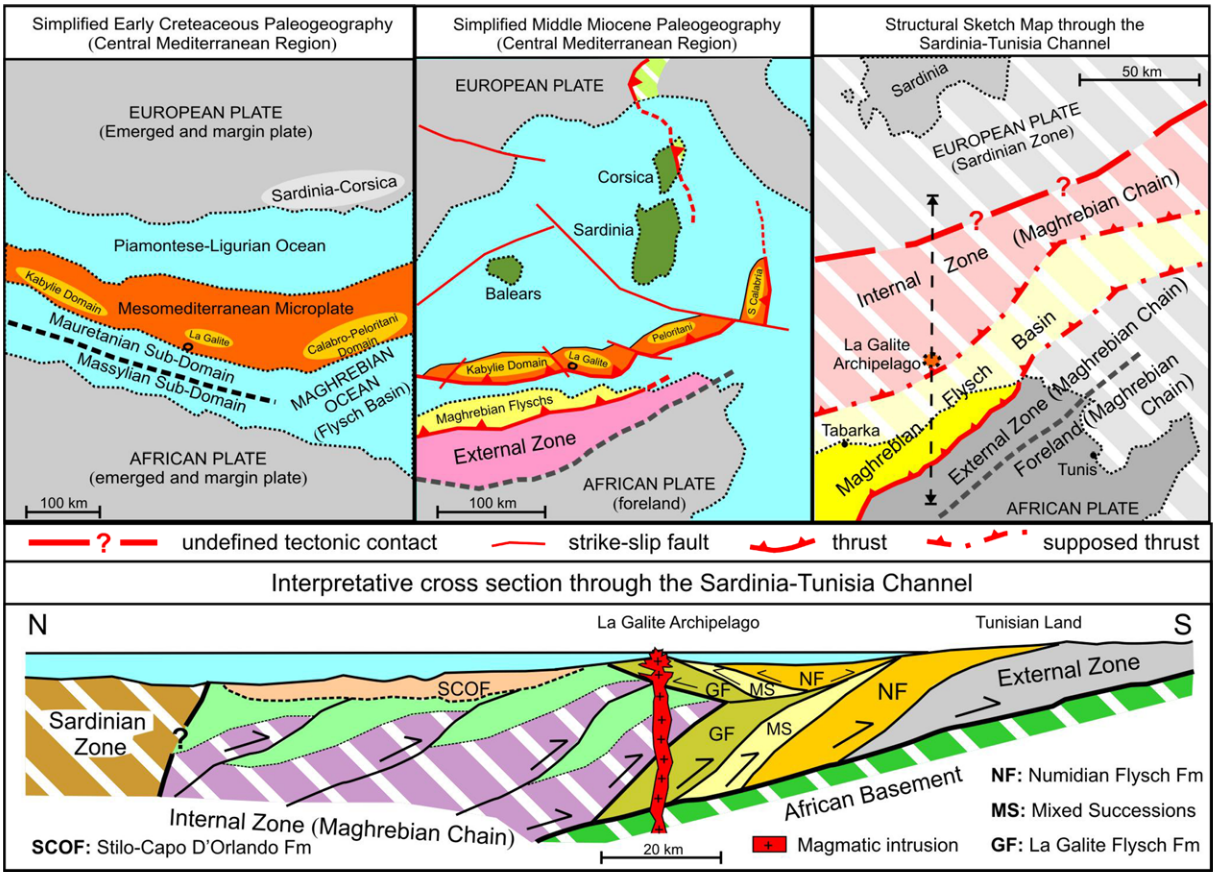

Fig. 8. Early Cretaceous and the Middle Miocene palaeogeography and geodynamic evolution of the central-western Mediterranean region. A present-day structural map is also sketched. An interpretative cross section through the Sardinia-Tunisia Channel (indicated by double arrows in the structural sketch) showing the relationships between domains and nappes of the Maghrebian Chain is proposed.

deposited but they may have been partially or totally cancelled both by the successive magmatic intrusion as well as by erosion. Given that a thick Stilo-Capo d'Orlando-like sedimentary cover has been pointed out in seismic profiles immediately north of the La Galite Archipelago (Tricart et al., 1994), it is possible that this formation continued beneath La Galite Archipelago. Such a hypothesis is reinforced by the composition of the xenolith population within the magmatic intrusion (Durand Delga, 1956a; Rekhiss, 1988, 2002; present paper). If confirmed, the presence of the Stilo-Capo d'Orlando Formation over the metamorphic internal units is expected to correlate with similar lateral deposits in the western part of the Maghrebian Chain like the "Oligo-Miocène Kabyle" in the Algerian Tell and the Viñuela-Sidi Abdeslam Group in the Betic-Rifian Arc (Guerrera et al., 1993). Therefore, we propose that *La Galite Flysch* represents a new internal succession to be added to the different formations correlated along the entire Maghrebian orogenic belt (Guerrera et al., 1989, 2005), resulting from the deposition in the internal sector (i.e. the Mauritanian sub-Domain) of the Maghrebian Flysch Basin. The age distribution of the outcropping units determined and discussed in the present paper fit well with the deposition in the internal flysch-basin domain.

As mentioned above, the *Numidian-like Flysch* cropping out at La Galite Island corresponds to a part of the intermediate "Numidian Interval" of the External Numidian Sequence (*sensu* Guerrera et al., 1992), considered Aquitanian-Early Burdigalian in age and deposited in the external part (Massylian sub-Domain) of the Maghrebian Flysch Basin. In agreement with previous works, it seems impossible to ascertain definitively the relationships between the *La Galite Flysch* and the *Numidian-like Flysch* on the basis of the field observations. Structural features and regional similarities lead us to consider the contact between *La Galite Flysch* and *Numidian-like Flysch* as tectonic. It is not possible, however, to exclude the presence of some stratigraphic intervals corresponding to the "Mixed Successions" (*sensu* Guerrera et al., 1986; Carmisciano et al., 1989) as some observations from Durand Delga (1956a) suggest.

4.2. On the source and genesis of magmas

Trace-element systematics and Nd–Sr–Pb isotopes (Juteau et al.,1986) are consistent with a dominant metasedimentary crustal source; the outcropping plutons being cogenetically linked by a primary fractional crystallization-assimilation process (Laridhi Ouazaa, 1994). However, several mineralogical evidences (cordierite resorption, reactive garnet, quartz-feldspar xenolith depletion) suggest that peraluminous magmas probably derive from a meta-aluminous parent melt. Its evolution is driven by metapelite assimilation responsible of the Al-enrichment until the precipitation of magmatic cordierite, as suggested by Fourcade et al. (2001) for the coeval Kabylian suites. Both major- and trace-element systematics show a clear superposition of the La Galite magmas with the cordierite-bearing granitoids from the Lesser Kabylie (Fig. 6; Fourcade et al., 2001) suggesting not only the coeval emplacement but also a striking similarity in the source and evolutionary characters. The lack of both mantle-derived as well as andesitic magmas suggests that the crustal metapelitic melting/assimilation is the main magmatic contribution. The limited compositional variability shown by the whole suite suggests a deep homogenization of magmatic pulses prior to the emplacement in the crust. The metamorphic basement does not outcrop in the La Galite region; however, paragneiss xenoliths hosted in the cordierite-bearing granitoids from Lesser Kabylie Massif (northern Algeria) show a strict mineralogical and compositional correspondence with the xenolith population hosted by the La Galite magmas. Those xenoliths have been interpreted as being representative of regionally metamorphosed metapelites in the biotite, andalusite, garnet (±muscovite) facies. The metamorphic peak of the protolite has been attributed to the M1/D1 event by Mahdjoub et al. (1997) and dated to the Hercynian by Peucat et al. (1996). The progressive depletion in KFs and Qtz and enrichment in residual phases agrees with the xenoliths being representative of country rocks fluxed by ascending magmas and progressively assimilated. The mechanism of magma generation is then represented by a possible bulk anatexis of Hercynian-like lithologies underneath La Galite Flysch due to thermal re-equilibration immediately after the backthrust event. The contemporaneous opening of a tectonic window in the deep subduction system (Fourcade et al., 2001) may be the mechanism responsible for the generation of deep primary magmas (detected only in the Lesser Kabylie domain) together with a strong thermal anomaly responsible for the anatexis of La Galite Flysch succession.

4.3. Structural relationships and age constraints

The contact between the magmatic plutons and the flysch sequence is characterized by the presence of a metamorphic aureole ten to a hundred meters thick made of cornubianite, mica-schist, and quartzite with local domains of tourmaline-bearing quartzite. The intrusion occurred in a shallow, cold environment as attested to by the large amount of glassy to fine-grained mesostasis (up to 30%) and the developing of the cooling-joint system.

The granodioritic intrusion of Pointe de Mistral, along the western and south-western cliffs of the island, helps to reveal the timing of the intrusion. Intrusives crosscut the frontal back-thrust fold in the flysch country rocks at Le Cavalier cliff (Fig. 1). Model rock ages have been estimated by Bellon (1976), based on K–Ar systematics, giving an age range of 14.2 ± 0.5 Ma in the Pointe de Mistral biotite-bearing granite to 10.0 ± 1 Ma for the biotite- and chlorite-bearing microgranite dikes of the Piton de la Garde.

Microgranodiorites from Piton de la Garde and Pointe des Chiens date, respectively, to 14.1 ± 0.6 and 13.7 ± 0.7 Ma. According to the estimated ages, the intrusion of the La Galite plutons span from the Serravallian to the Tortonian. The granodioritic intrusion of Pointe de Mistral (being the older one and cutting the back-thrust frontal fold gives an age constraint to the onset of magmatism with respect to deformation, suggesting the granodioritic intrusion to have been emplaced after the backthrusting of the *La Galite Flysch* at 14.2 Ma.

5. Concluding remarks

The present study provides a better resolution of the sedimentary and magmatic succession cropping out at La Galite Archipelago. Based on new stratigraphic and petrographic data of both sedimentary and magmatic rocks, as well as taking into account the evolution of the Maghrebian Chain, we suggest a comprehensive geodynamic evolution of the La Galite region and hence the boundary between the African Plate and Mesomediterranean Microplate.

The early Burdigalian (*La Galite Flysch*) and latest Aquitanian-earliest Burdigalian (*Numidian-like Flysch*) sedimentary units belong to the Mauritanian and Massylian sub-Domains (the internal and external portion of the Maghrebian Flysch Basin, respectively), located palaeogeographically in an external position with respect to the Internal Zones (Calabro-Peloritani-Kabylian basement) of the chain.

Sedimentary bodies belonging to the Maghrebian Flysch Basin, represented by *La Galite Flysch* and *Numidian-like Flysch*, were tectonically transported over the internal units. The age of this backthrusting is post-Burdigalian (Langhian-Serravallian as recorded in Sicily; de Capoa et al., 2004). This compressional phase represents the last stage in the building of the accretionary wedge of the Maghrebian orogen.

A buried thrust top sedimentary cover, similar to the Stilo-Capo d'Orlando Fm of Sicily (Bonardi et al., 2003), may be present in La Galite area above the metamorphic basement units (Maghrebian Internal Zones), probably deformed in the early Aquitanian as already recorded in Sicily (de Capoa et al., 1997).

An extensional tectonic event, successive to the backthrusting and which, occurred during the Late Serravallian-Early Tortonian, resulted in the emplacement of the magmatic granodioritic intrusion into the sedimentary succession (*La Galite Flysch* and *Numidian-like Flysch)*, causing local contact metamorphism.

This tectonic extensional phase occurred when, in Sicily (Terravecchia Fm, Belayouni et al., 2006) and Tunisia (study in progress), post-orogenic middle-late Tortonian deposits unconformably sedimented above the structured Maghrebian Chain.

According to our hypothesis, as depicted in the cross section of Fig. 8, La Galite Archipelago represents a portion of the Maghrebian Flysch Basin tectonically emplaced above the southern margin of the "Mesomediterranean Microplate" (*sensu* Guerrera et al., 2005, 2007). This microplate separated since the early Cretaceous the Piemontese-Ligurian Ocean from the southern oceanic branch of the Tethys represented by the Maghrebian Flysch Basin.

We suggest the presence between La Galite Archipelago and northern Tunisia of an imbricate thrust system constituted in its internal sector, corresponding to the internal sector of the Maghrebian Flysch Basin, by the deposits of *La Galite Flysch* and in the external part by the Numidian Flysch units (Fig. 8). Instead, previous interpretations (e.g., Tricart et al., 1994) considered the occurrence only of Numidian deposits. Considering data from other sectors of the Maghrebian Chain (Sicily and Rif), we estimate the age of the south-vergent thrusting in this submerged area as Burdigalian-Langhian.

Our reconstruction is well constrained by regional data concerning clearly defined palaeogeographic and palaeotectonic events at the scale of the central-western Mediterranean area (Africa/Europe boundary).

The onset of magmatism involving La Galite Archipelago at 14–10 Ma, is due presumably to the opening of a slab break-off in the deep subduction system. Evidence for an extensional phase suggests such phenomenon correlated with the progressive slab tear from the centre to the borders of the magmatic line. Melting of the metamorphic and sedimentary cover, induced by a low amount of deep melts and a strong thermal anomaly, generated the high-Al intrusives by progressive assimilation of shallow sedimentary units.

The results of the present study may also be useful for the petroleum exploration on the northern Tunisia onshore and offshore. In fact, if our reconstruction considering the Maghrebian Flysch Basin located between La Galite Archipelago and the Tunisian onshore is correct, oil is probably not present in the strongly deformed internal deposits of the Maghrebian Flysch Basin. It may be possible to find oil in the external Numidian deposits (Massylian sub-Domain) of the same basin; the latter characterize the Tunisian onshore and a belt offshore, close to the coastline.

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