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Tectonic evolution of the Sicilian Maghrebian Chain inferred from stratigraphic and petrographic evidences of Lower Cretaceous and Oligocene flysch

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Abstract: The occurrence of a Lower Cretaceous flysch group, cropping out from the Gibraltar Arc to the Balkans with a very similar structural setting and sedimentary provenance always linked to the dismantling of internal areas, suggests the existence of only one sedimentary basin (Alpine Tethys s.s.), subdivided into many other minor oceanic areas. The Maghrebian Basin, mainly developed on thinned continental crust, was probably located in the westernmost sector of the Alpine Tethys. Cretaceous re-organization of the plates triggered one (or more) tectonic phases, well recorded in almost all the sectors of the Alpine Tethys. However, the Maghrebian Basin seems to have been deformed by Late- or post-Cretaceous tectonics, connected with a "meso-Alpine" phase (pre-Oligocene), already hypothesized since the beginning of the nineties. Field geological evidence and recent biostratigraphic data also support this important meso-Alpine tectonic phase in the Sicilian segment of the Maghrebian Chain, indicated by the deformations of a Lower Cretaceous flysch sealed by Lower Oligocene turbidite deposits. This tectonic development is emphasized here because it was probably connected with the onset of rifting in the southern paleomargin of the European plate, the detaching of the so-called AlKaPeCa block (Auct.; i.e. Alboran + Kabylian + Calabria and Peloritani terranes) and its fragmentation into several microplates. The subsequent early Oligocene drifting of these microplates led to the progressive closure of the Maghrebian Basin and the opening of new back-arc oceanic basins, strongly controlled by extensional processes, in the western Mediterranean (i.e. Gulf of Lion, Valencia Trough, Provençal Basin and Alboran Sea).

Key words: Alpine Tethys, Sicilian Maghrebian Chain, sedimentary petrography, meso-Alpine tectonics, western Mediterranean, Cretaceous-to-Oligocene paleogeography, plate tectonic context.

State of the art and objectives

Strong geological affinities between the Betic-Maghrebian Chain, an east-west-trending belt extended between the Gibraltar and Calabria-Peloritani Arcs, and the whole central Alpine Chains (Apennines, Alps, Carpathians, Balkans, Dinarides and Hellenides) have long been emphasized on the basis of the continuity of the sedimentary basin and of a common sedimentary evolution in almost all cases (Biju-Duval et al. 1977; Dercourt et al 1986).

This basin (Alpine Tethys, Auct.) is connected with the Upper Triassic–Lower Jurassic break-up of the Pangaea (Abbate et al. 1994), formed on a transcurrent boundary between the African and European plates (Durand-Delga & Fontboté 1980; Bouillin et al. 1986). Alpine Tethys is usually subdivided into different sectors, differently named along all the Alpine Chains of Western and Central Europe (i.e. Maghrebian and Ligurian Tethys, Magura Ocean and Ceahlău-Severin Ocean, from the west to the east, respectively; Fig. 1).

Recently, the Maghrebian and Ligurian Basins have been joined to represent a common sedimentary basin named the Ligurian-Maghrebian Basin, *sensu* Chalouan et al. 2008, extending from the Gibraltar Arc to the western Alps and showing the character of a true oceanic basin in its eastern wider part, whereas it was floored mainly by thinned continental crust in its narrower part. The Maghrebian sector, in fact, seems to have experienced only a partial oceanization, indicated by the occurrence of Middle to Upper Jurassic slices of basic rocks, scattered in the Rifian Chain (Morocco) and in Sicily (Durand-Delga et al. 2000).

Nevertheless, all the above-mentioned oceanic areas have been affected by middle-late Cretaceous tectonic events (Schmid et al. 2008 and references therein), which have not been recorded in the evolutionary geological history of the Maghrebian Chain or, if recognized, they have often been neglected and/or not sufficiently emphasized (Puglisi 2009).

In fact, due to the Cretaceous re-organization of the plates, this late Cretaceous-early Tertiary convergence-related evolution is widely recognized in all the central-eastern Tethys-related Mesozoic oceans (Dal Piaz 1993; Săndulescu et al. 1995; Oszczypko 1999, 2006; Stampfli 2000; Schmid et al. 2004). These tectonics, for example, were manifested in the outer Carpathian area by the deepening of the Magura Ocean and by emergence of intrabasinal source areas (Oszczypko 2006; Oszczypko et al. 2012), but it is recognized only locally within the sedimentary successions of the Maghrebian Basin (Puglisi 2009 and references therein).

Thus, the objective of this paper is to check the main steps of the sedimentary-tectonic evolution of the Maghrebian Chain and to evaluate the possibility of comparing them with those of the Central European Alpine chains, on the basis of the existence of a similar tectonic evolutionary scheme.

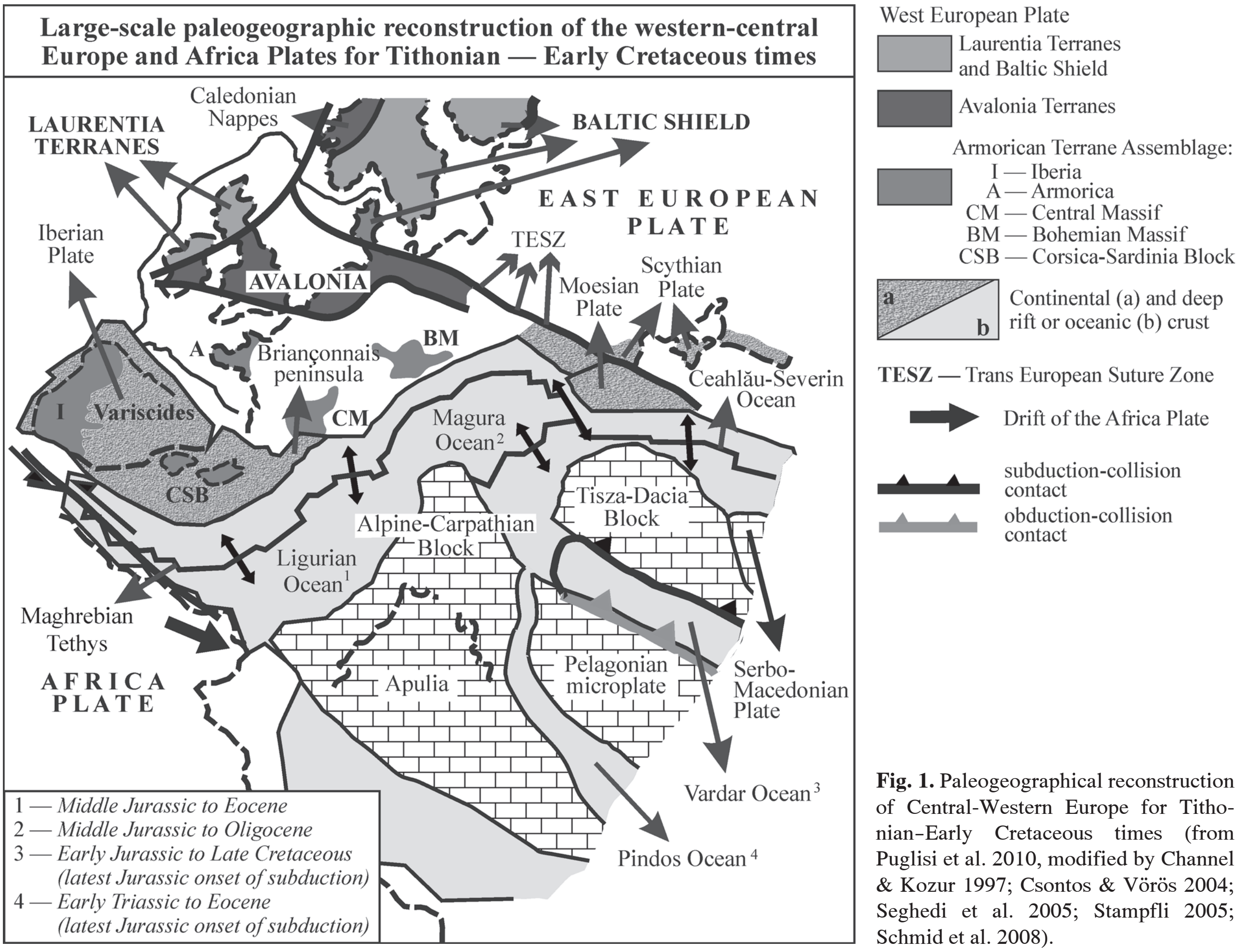


Fig. 1. Paleogeographical reconstruction of Central-Western Europe for Tithonian–Early Cretaceous times (from Puglisi et al. 2010, modified by Channel & Kozur 1997; Csontos & Vörös 2004; Seghedi et al. 2005; Stampfli 2005; Schmid et al. 2008).

Geological framework of the Maghrebian Chain

Three main structural domains can be recognized in all the sectors of the Maghrebian Chain:

1. Internal Domain, cropping out in the Betic-Rifian Chain Internal Zones (henceforth BRIZ, according to Serrano et al. 2007), in the Kabylian sector as well as in the Calabria-Peloritani Arc, formed by a nappe complex, made up of Variscan-derived Paleozoic terranes, high-grade metamorphic and mantle rocks (Kornprobst 1974; Chalouan et al. 2008) with remnants of their original Mesozoic-Cenozoic sedimentary cover. The sedimentary succession of these internal sectors (the so-called "Dorsale Calcaire", *sensu* Fallot 1937) is almost the same along all the western peri-Mediterranean chains, between the Gibraltar and Calabria-Peloritani Arcs. The Rifian "Dorsale Calcaire" is often marked by a pronounced discontinuity because its Mesozoic portion (Triassic–Liassic Verrucano-like redbeds evolving to Lower Jurassic platform carbonates; Perrone et al. 2006; Critelli et al. 2008; Zaghloul et al. 2009; Perri et al. 2011, 2013), related to the Tethyan rifting, usually lacks post-Toarcian to Upper Cretaceous deposits (Chalouan et al. 2008) and, locally, it is topped by Eocene detrital Nummulitic limestones (Nold et al. 1981; El Kadiri et al. 2006), representing a depositional sequence post-dating an early Alpine compressive event (Maate 1996; Martin-Algarra et al. 2000). Unconformable Oligocene turbidite deposits locally characterize the top of the succession (Olivier 1979; Durand-Delga & Fontboté 1980; Wildi 1983; Zaghloul et al. 2005; Puglisi 2008);

2. Flysch[1] Domain, which consists of a complex structural edifice made up of several tectonic units, derived from the deformation of the 'Flysch Basin' successions (Durand-Delga 1972). The siliciclastic flysch units have classically been grouped into two main stratigraphic successions, according to their position within the sedimentary basin (Bouillin et al. 1970; Raoult 1974; Barbera et al. 2006, 2011): **(a)** the internal 'Maurétanien' flysch, located close to the northern margin of the 'Flysch Trough', fed by the Internal Domain and represented by Cretaceous-Eocene Variegated Clays grading upward to Lower Oligocene marly-calcareous-arenaceous turbidites, tectonically overlain by Lower Cretaceous flysch (Jebel Tisirène, Guerrouch and Monte Soro Flysch in Morocco, Algeria and Sicily, respectively), the latter, in turn, overthrust by the Hercynian crystalline units of the Internal Domain and **(b)** the Cretaceous 'Massylien' flysch, located close to the southern paleomargin of the Flysch Trough, fed from the African craton and evolving into the well-known Oligocene-Miocene Numidian Flysch;

[1]The term "flysch" is used here with a different meaning according to the traditional geological names regionally adopted in the different Countries. It does not always imply any specific sedimentological and/or geotectonic significance.

3. External Domain, mainly formed by parautochthonous to autochthonous Triassic-Tertiary sedimentary successions originating from the African paleomargin, and by the African forelands.

Flysch and Internal Domains will be treated in the next chapters and the discussion will focus on the most peculiar petrographic and stratigraphic characters of their sedimentary successions, useful for a better understanding of the tectonic evolution of the Maghrebian Chain.

Flysch Domain: Lower Cretaceous and Lower Oligocene flysch

Lower Cretaceous flysch

Turbidite deposits belonging to the Flysch Domain (Early Cretaceous to Early Miocene) form a tectonic edifice, widespread along the whole Betic-Maghrebian Chain, whose sedimentary history and tectonic evolution have long been debated by many authors.

The main problems, still under discussion, regard the stratigraphic context of the Lower Cretaceous flysch, nearly always incomplete because they lack a sedimentary substratum, and the timing of their deformation. In Algeria (Raoult et al. 1982) and in Sicily (Puglisi 1981), in fact, these Lower Cretaceous flysch can be distinguished in several tectonic units piled up to form a complex structural edifice unconformably covered by Lower Oligocene turbidite deposits.

Puglisi (2009) compared these successions with other Lower Cretaceous flysch from different sectors of the Central and Western European Alpine Chains (northern Apennines and Alps, Dinarides, Hellenides, Carpathians and Balkans) on the basis of strong similarities concerning **(a)** the tectonic position, always marking the contact between the internal and external areas, **(b)** the stratigraphic evolution, from calcareous turbidites grading upward to arenaceous turbidites, and **(c)** the sedimentary provenance, always linked to internal areas made up by Hercynian crystalline sources and, locally, by ophiolitic complexes (e.g. Boeothian Flysch from external Hellenides; Puglisi et al. 2010).

The comparison of the Maghrebian Lower Cretaceous flysch with other coeval deposits in the Carpathians was tentatively supposed only with the successions of the External Dacides (Auct.), whose basin (Ceahlău-Severin Ocean, Fig. 1) seems to be coeval to the westernmost Magura and Ligurian-Maghrebian oceans (Oszczypko 1992, 1999; Chalouan et al. 2008). The External Dacides group three main units (Black Flysch, Ceahlău and Bobu Nappes; Săndulescu 2009) in the Eastern Carpathians and the Severin (=Ceahlău) Nappe in the Southern Carpathians, representing complex rift systems from Early Jurassic to middle- or Late-Cretaceous (age of their deformations; Săndulescu 1984, 2009; Bădescu 1998). Each of these units consists of Jurassic within-plate volcanics underlying Tithonian–Valanginian and Barremian–Aptian flysch deposits. The most internal unit (Black Flysch Nappe) is widely metamorphosed whereas the other ones show very thick successions, the most important of which is the Sinaia Formation (Ceahlău Nappe). This formation has already been compared with the Maghrebian Lower Cretaceous flysch (Puglisi 2009).

In contrast, these Lower Cretaceous flysch in the Maghrebian Chain very rarely show remnants of their Jurassic substratum. This, in fact, is scarcely represented by rare outcrops of Middle to Upper Jurassic limestones and radiolarites in Algeria (Raoult 1974; Raoult et al. 1982), by rare ophiolite-like olistoliths in the Rifian Chain (Besson 1984) and by only one outcrop of Kimmeridgian–Tithonian coarse-grained turbidites evolving into Tithonian–Valanginian radiolarites in Sicily (the Contrada Lanzeri Formation, Bouillin et al. 1995).

Sandstones of the Betic-Maghrebian Lower Cretaceous flysch (Los Nogales, Jebel Tisirène, Guerrouch and Monte Soro Flysch from Spain, Morocco, Algeria and Sicily, respectively) usually show high maturity, absence of K-feldspars and sporadic occurrence of plagioclases and epimetamorphic rock fragments. These compositions have been ascribed to the "plagioclase subarkose" clan (*sensu* Folk 1974) by Puglisi (1981, 1987) and their heavy mineral assemblages (mainly from the Betic Cordillera and Sicilian Maghrebian Chain) show high maturity with abundance of ultrastable minerals, such as zircon, tourmaline and rutile, and low amounts of chloritoid, staurolite and picotite (Puglisi 1987). Chloritoid and staurolite testify to an internal provenance from low- and middle-rank metamorphic sources (i.e. from the European paleomargin; Puglisi 1981, 2009, 2010; Barbera et al. 2006, 2011), whereas picotite is usually connected to ophiolitic rocks (Cassola et al. 1990), even if ophiolitic-like detrital supply has never been recorded within the sandstones of the Maghrebian Lower Cretaceous flysch.

The Maghrebian Basin, in fact, seems to have been mainly developed on thinned continental crust with very little evidence of an only partial oceanization, testified by the occurrence of outcrops of Middle to Upper Jurassic slices of basic rocks with an E-MORB affinity (Durand-Delga et al. 2000). Other sectors of the Alpine Tethys, instead, achieved real oceanic conditions, testified by abundant ophiolitic slices, olistoliths or slide-blocks, included within the Cretaceous deposits of the Ligurian Ocean (Critelli 1993, 1999; Rampone & Piccardo 2000) and by detrital ophiolite-like clasts, locally present within the sandstones of some Lower Cretaceous flysch. The Boeothian Flysch, a Lower Cretaceous turbidite deposit from the Pindos Ocean (south-central branch of Tethys, Fig. 1), which marks the boundary between the External/Internal zones in central-southern Greece, represents the best example of a detrital supply derived from the dismantling of ophiolite sources (Puglisi et al. 2010). Ophiolite nappes, in fact, were formed on the Pelagonian microcontinent by means of obduction processes occurring in the western margin of the Vardar Ocean (eo-Hellenic orogenic phase, Auct.). These westerly directed compressions affected these areas before the deposition of the Boeothian Flysch in the adjacent Pindos Ocean (Puglisi et al. 2010 and references therein — Fig. 1).

In conclusion, the structural settings and clastic provenances of all the Lower Cretaceous flysch are very similar along the whole Alpine chain, from the Gibraltar Arc to the Balkans. The provenance, in particular, is always linked to the dismantling of internal areas, and locally considerable differences in the detrital modes can be explained with the diverse lithologies of the terranes which served as sediment sources.

Thus, all this evidence emphasize a significant paleogeographic continuity, from west to east, between all the oceanic areas of the Alpine Tethys and the Maghrebian Basin, the last supposed to have been located in the westernmost sector (Bouillin et al. 1988; Puglisi 2009, 2010 — Fig. 1).

Lower Oligocene flysch

An important Cretaceous re-organization of the plates affected almost all the different sectors of the Alpine Tethys. This tectonic development led to the closure of the following oceanic spaces: **(i)** South Penninic Ocean, with the consequent opening of the Valais Ocean, active until the Middle Eocene (Schmid et al. 2008), **(ii)** Vardar Ocean with the obduction of its oceanic crust onto the Pelagonian microplate (Puglisi et al. 2010), **(iii)** Ceahlău-Severin Ocean, coeval with the South Penninic Ocean (Csontos & Vörös 2004) and located at the north of the Tisza and Dacia blocks and **(iv)** the so-called "Nish-Troyan flysch trough", located between the Moesian microplate to the north and the Serbo-Macedonian massif to the south (Zagorchev 2001).

Thus, only the Maghrebian Basin escaped these Cretaceous events. This area, in fact, seems to have been deformed during slightly successive times, as testified in Algeria by a "Late Lutetian phase" (Raoult 1975; Vila 1980) and, in the Sicilian Maghrebian Chain, by evidence of meso-Alpine[2] compressive tectonic events, hypothesized on the base of the following data at the beginning of the nineties (Cassola et al. 1992; Puglisi 1992):

• The Lower Cretaceous flysch (i.e. Monte Soro Flysch), already deformed in several tectonic units (Puglisi 1981), is sealed by a Lower Oligocene flysch deposit (Cassola et al. 1990, 1992; Gigliuto & Puglisi 2002 — Fig. 2, **'a'** square), known as the Reitano Flysch. The whole succession (Reitano Flysch together with the underlying Lower Cretaceous Monte Soro Flysch, already deformed), overthrust the more external units, here represented by the Sicilide Units and by the tectonically underlying Numidian Flysch (Fig. 2 — Puglisi 1992; Cassola et al. 1992, 1995). On the basis of similar geological settings and petrographic characters, Reitano Flysch has also been considered as an equivalent succession of the Beni Ider and Algeciras Flysch in the Betic Cordillera and Rifian Chain, respectively, as well as of the '*Marno-greso-micacé*' Flysch in the Algeria sector (Puglisi & Carmisciano 1992; Puglisi et al. 2001). Unluckily, the age of the Betic and Rifian flysch seems to be slightly younger than that of the Reitano Flysch (Zaghloul et al. 2002) and, consequently, this comparison is, at the present, only speculative and hypothetical because it needs further investigations;

• Lower Oligocene volcano-arenitic sediments characterize several deposits in southern Apennines and in the Sicilian Maghrebian Chain: these are the Tusa Tuffites (southern Apennines and Sicily; Critelli 1999; Critelli et al. 2011; Perri et al. 2012) and the above-mentioned Reitano Flysch (only in Sicily), both of them dated to the early Oligocene (Baruffini et al. 2002; Torricelli & Knezaurek 2010). Volcanic clasts of Tusa Tuffites show a sub-alkaline character (calc-alkaline, in particular; Ogniben 1964; Ardito et al. 1985 — see Fig. 3), probably linked to a subductive-collisional magmatism. These successions have been correlated with other Rupelian volcanogenic deposits of the western Alps and northern Apennines (i.e. Taveyannaz Sandstones, Aveto-Petrignacola and Ranzano Formations, respectively) by many authors (D'Atri & Tateo 1994; Baruffini et al. 2002) on the basis of a similar provenance, connected to the erosion of the same Early Oligocene volcanic arc event that occurred in the Alps/Apennines orogenic system.

Reitano Flysch, instead, shows two distinct volcanic grain populations: a paleovolcanic one, Late Permian in age and calc-alkaline in character (Fig. 3), probably linked to a late Hercynian magmatism, and a neovolcanic one, penecontemporaneous to the sedimentation, with an alkaline (potassic) character (Balogh et al. 2001). This latter volcanic component, in particular, recently dated to 33 Ma by Torricelli & Knezaurek (2010), can be compared with other Lower Oligocene volcanogenic deposits from the northern Apennines (D'Atri & Tateo 1994) and connected to volcanic events very close to the sedimentary basins and associated with extensional processes (Balogh et al. 2001);

• The Lower Cretaceous flysch only sporadically shows a very thin Tertiary cover, probably as a result of an incipient underthrusting below the internal Hercynian crystalline units of the southern sector of the Calabria-Peloritani Arc (Peloritani Mts, Sicily — Fig. 2), as suggested by Cassola et al. (1990). Durand-Delga et al. (1999) dated the upper part of the Jebel Tisirène Flysch in the Rifian Chain to the middle Albian and they interpreted the lack of a Tertiary cover as the result of a sudden interruption of the detrital supply, probably related to eustatic phenomena tectonically linked to the incipient connection between the central and southern Atlantic. Also in the Sicilian Maghrebian Chain, the sedimentary cover of the Lower Cretaceous flysch is almost always absent. Locally, very few outcrops of thin and discontinuous upper Cretaceous-to-Paleocene successions are present and doubtfully interpreted as a possible sedimentary cover (Cassola et al. 1990; Puglisi 1992, 1998);

• Finally, the above mentioned Hercynian crystalline units of the Betic-Maghrebian Chain, tectonically overlying the Lower Cretaceous flysch, belong to the so-called AlKaPeCa block (*sensu* Bouillin et al. 1986), which includes the Alboran, Kabylides and Peloritani + Calabria terranes, originally located in the southern Iberian paleomargin, according to many authors (Biju-Duval et al. 1977; Stampfli et al. 1998; Sanz de Galdeano et al. 2001; Rosenbaum et al. 2002; Mauffret et al. 2004; Schettino & Turco 2006; Perrone et al. 2006; Critelli et al. 2008; Perri et al. 2013).

Internal Domains: Lower Oligocene flysch

Remnants of Internal Domains form the present Calabria-Peloritani Arc, Kabylian and BRIZ (Betic-Rifian Internal Zones) massifs, mainly made up by Hercynian crystalline units unconformable overlain by Tertiary turbiditic deposits. The base of these successions ranges in age from Early Oligocene in the Calabria-Peloritani Arc to the Oligocene-Miocene boundary toward the westernmost Mediterranean sectors (BRIZ).

[2]Meso-Alpine tectonic phase, dated to the Late Ctretaceous–Late Eocene time span (*sensu* Doglioni & Bosellini 1987).

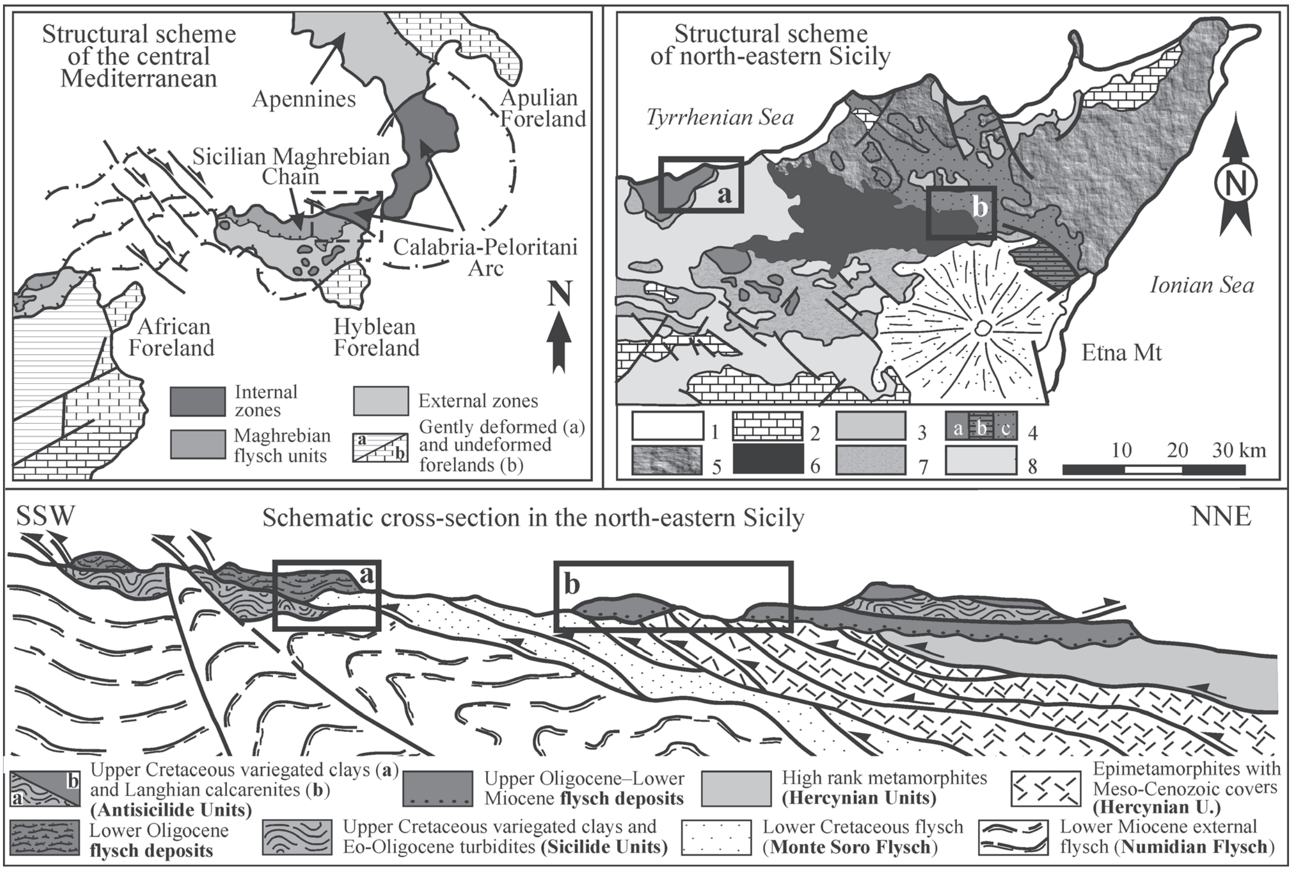


Fig. 2. Schematic geological structure of the Sicilian Maghrebian Chain (top left) and its Internal Domains in north-eastern Sicily (Calabria-Peloritani Arc, top right and bottom), showing the structural position of the Lower Cretaceous Flysch. Keys for the structural scheme of north-eastern Sicily: **1** — Pliocene-Quaternary deposits, **2** — post-orogenic successions (late Miocene–lower Pliocene), **3** — Upper Cretaceous Variegated Clays and Langhian calcarenites (Antisicilide Units), **4** — Lower Oligocene (a,b) and Upper Oligocene–Lower Miocene (c) flysch deposits, **5** — Hercynian crystalline units with remnants of Mesozoic-Cenozoic sedimentary covers, **6** — Lower Cretaceous Monte Soro Flysch, **7** — Upper Cretaceous Variegated Clays and Eocene–Oligocene turbidites (Sicilide Units), **8** — external units. **a** and **b** squares indicate the stratigraphic contacts between the Oligocene turbidite successions and the underlying Early Cretaceous-to-Eocene deposits already deformed.

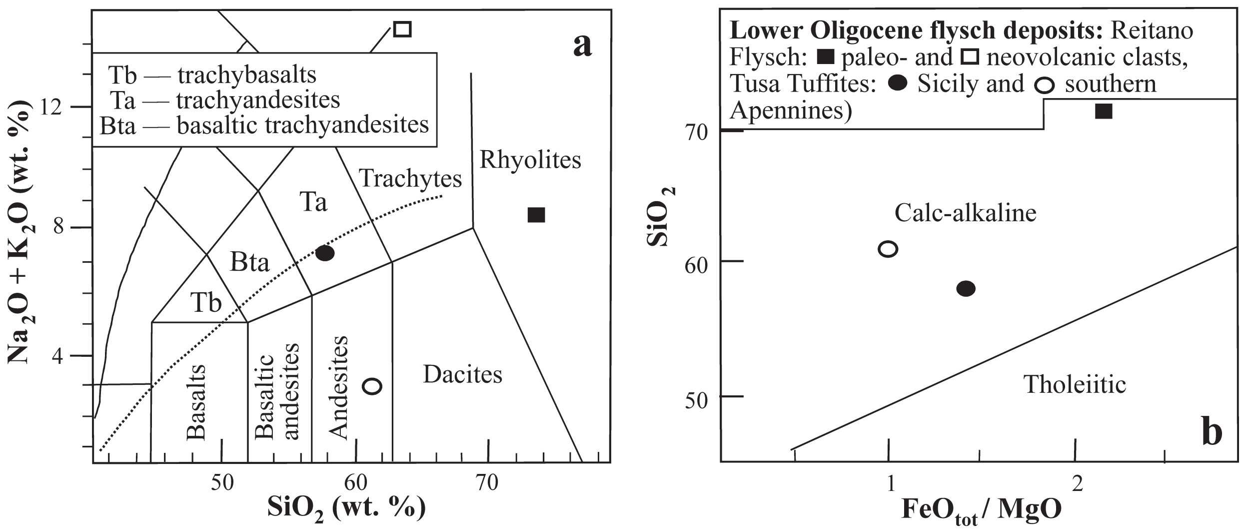


Fig. 3. a — TAS diagram (after Le Maitre 1989, with the Irvine & Baragar's curve 1971) showing the average groundmass composition of the volcanic grains within the Reitano Flysch sandstones, **b** — SiO_2 vs. FeO_{tot}/MgO diagram discriminating the calc-alkaline and tholeiitic products (after Balogh et al. 2001).

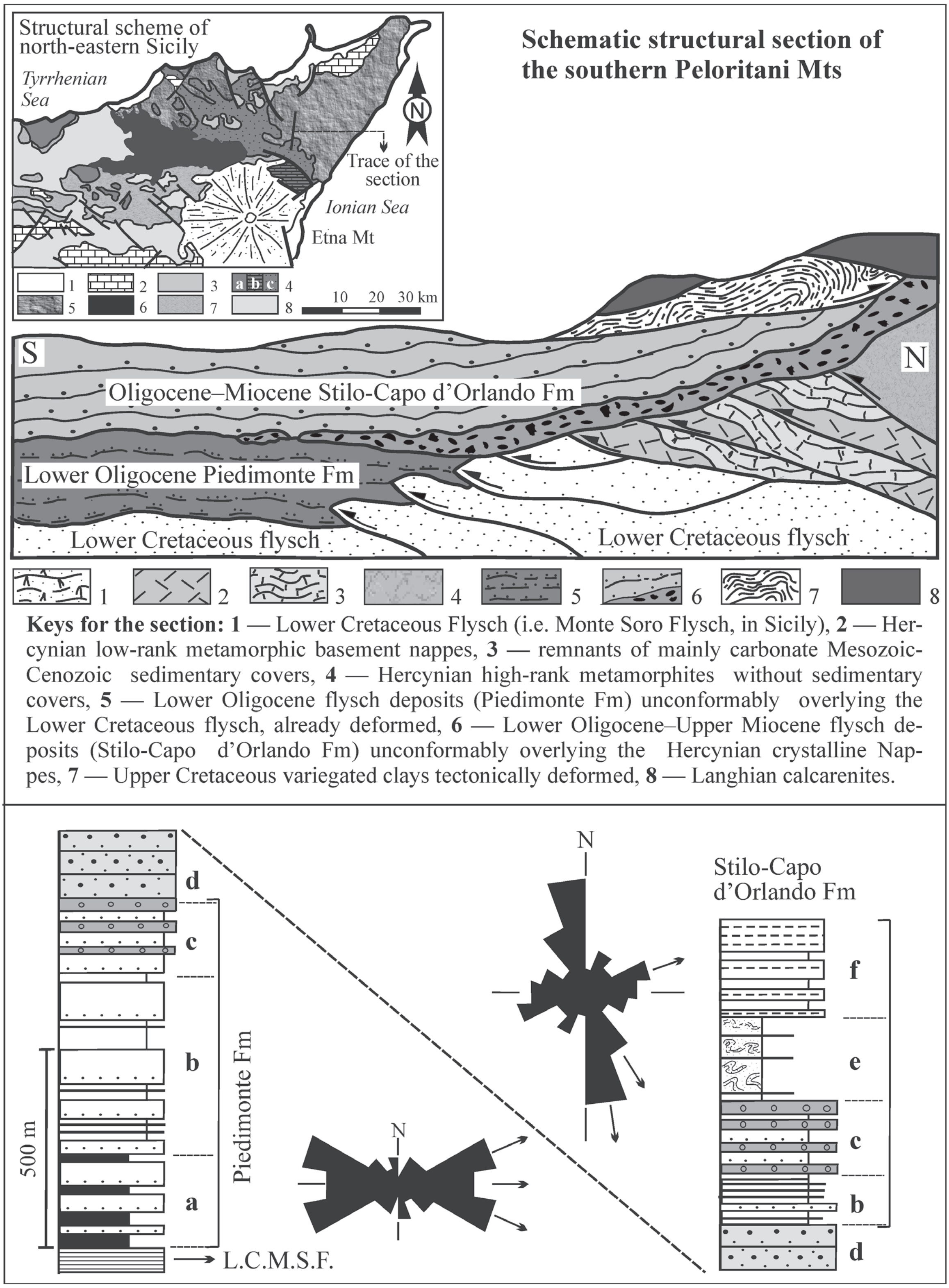


Fig. 4. Schematic structural section across north-eastern Sicily (see Figure 2 for the keys of the structural scheme) with, at the bottom, the columnar sections of the turbidite succession cropping out in the southern Peloritani Mts (i.e. Piedimonte + Stilo-Capo d'Orlando Fms) and the paleocurrent distribution. **L.C.M.S.F** — Lower Cretaceous Monte Soro Flysch, **a** — pelitic-arenaceous lithofacies, **b** — thin- or medium-bedded graded sandstones with thin pelitic beds, **c** — very coarse-grained sandstones, frequently in multiple amalgamated beds, with conglomerates, **d** — disorganized conglomerates, **e** — chaotic interval with frequent slumps, **f** — thick-bedded graded and laminated sandstones, frequently amalgamated and organized in coarsening- and thickening-upward cycles. In the paleocurrent diagrams, the arrows show the most frequent paleocurrent orientations based on flute cast measures.

In the southern sector of the Calabria-Peloritani Arc (Peloritani Mts, Sicily) a continuous turbidite succession, up to 1500 m thick (Puglisi 1998 — Fig. 2, 'b' square) seals the contacts between all the Hercynian crystalline units and their tectonic substrate, here represented by the Lower Cretaceous Monte Soro Flysch (Cassola et al. 1990; Puglisi 1992, 1998). This succession is dated to the Early Oligocene at the bottom (Piedimonte Formation, Cassola et al. 1991) and to the Late Oligocene–Early Miocene at the top (Stilo-Capo d'Orlando Formation, Auct.), thus suggesting that the southern sector of the Calabria-Peloritani Arc already overthrust the Lower Cretaceous Monte Soro Flysch necessarily before the Early Oligocene.

The Piedimonte Formation, in particular, shows a well marked coarsening- and thickening-upward trend with pelitic and pelitic-arenaceous lithofacies at the bottom, grading upward to arenaceous-conglomeratic lithofacies and channelled conglomerate bodies, which mark a gradual transition to the overlying Stilo-Capo d'Orlando Formation (Puglisi 1998 — Fig. 4).

Furthermore, the Piedimonte Formation unconformably rests on different stratigraphic levels of the Lower Cretaceous Monte Soro Flysch with its mainly pelitic basal horizons, which do not show any deformation (Fig. 5) thus confirming the stratigraphic (and not tectonic) nature of the Piedimonte Formation/Monte Soro Flysch contact (Puglisi 1998).

A very similar tectonic scenario characterizes the Kabylian sector of Algeria. A late-Lutetian tectonic phase, in fact, seems to have been responsible for an early deformation of the Internal Domains and their overthrusting above the Lower Cretaceous flysch (Raoult 1975; Vila 1980; Wildi 1983). Late Eocene-to-early Miocene terrigenous deposits, known in French geological literature as 'Nummulitique II' and 'Oligo-Miocène Kabyle' (at the bottom and top, respectively), suture all these tectonic contacts.

Finally, also in the BRIZ, the innermost domains (Malaguide/Ghomaride realms, in Spain and Morocco, respectively) underwent the main Alpine deformation during the Eocene–Late Oligocene (Kornprobst 1974; Chalouan & Michard 2004; Chalouan et al. 2006). Thus, their overthrust on the underlying Alpujarride/Sebtide Units (Spain and Morocco, respectively) is antecedent to the deposition of the Oligocene–Miocene deposits belonging to the so-called 'Ciudad Granada-Fnideq Formation Cycle', which seals all the tectonic contacts between the above-mentioned internal tectonic units (Feinberg et al. 1990; Maate et al. 1995; Serrano et al. 2006, 2007).

Furthermore, as the provenance of all these Tertiary sandstone suites is linked to the dismantling of the above mentioned AlKaPeCa block, it is important to underline a clear bimodality of provenance recently recorded between coeval and equivalent turbidite successions of the BRIZ and Calabria-Peloritani Arc (Fig. 6 — Puglisi 2008 and references therein). In fact, litharenite compositions mainly derived from carbonate covers and, partially, from epimetamorphic sources characterize the BRIZ sandstones suites, whereas arkosic compositions, connected to granitic and/or gneissic sources, are typical of the Calabria-Peloritani Arc turbidite sandstone suites. These different compositions strongly point out significant paleogeographical implications linked to the structural context of the AlKaPeCa block which was probably partially subdivided into several microplates already before the deposition of the above mentioned Oligocene deposits (Puglisi 2008). Thus, it is possible to hypothesize that the beginning of fragmentation of the

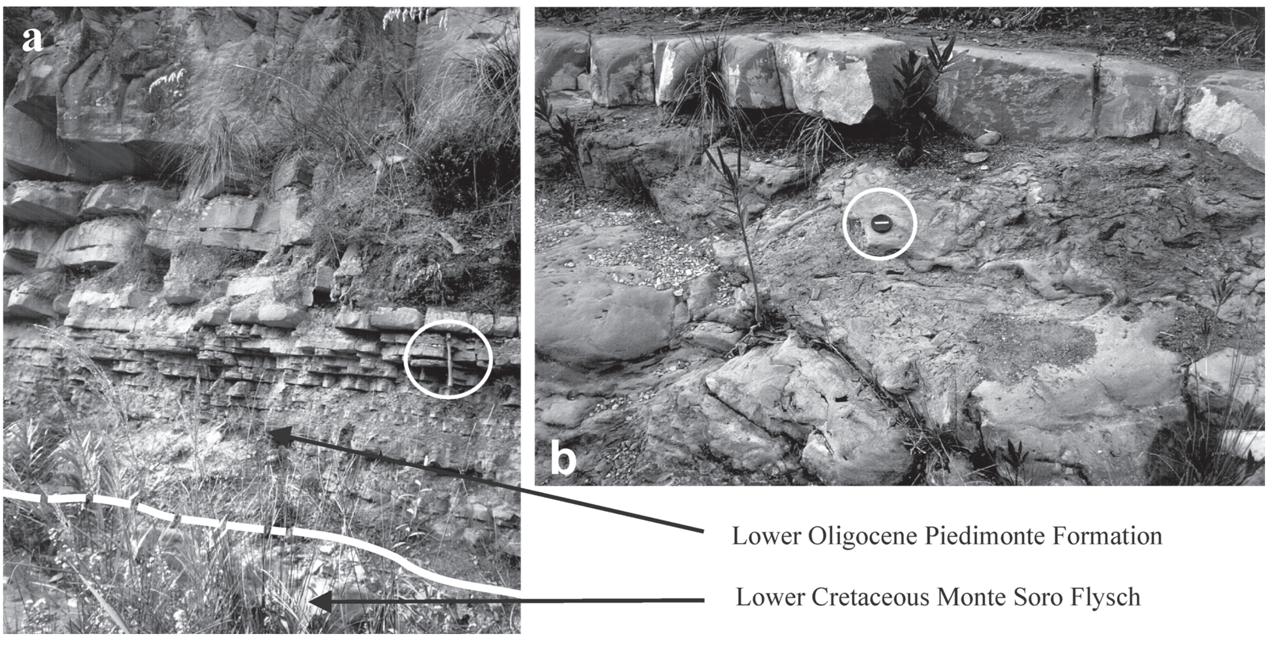
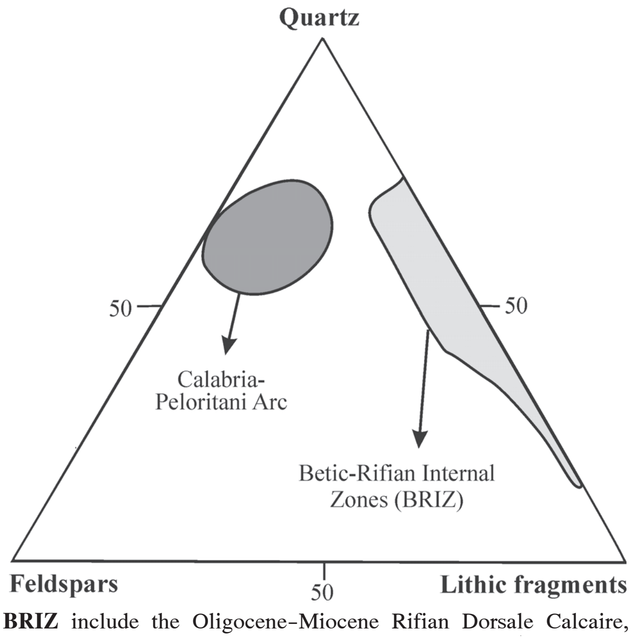


Fig. 5. a — Basal pelitic and pelitic-arenaceous lithofacies of the Piedimonte Formation unconformably overlying the Lower Cretaceous Monte Soro Flysch (southern Peloritani Mts, Zambataro Valley, NE of Piedimonte Etneo village), **b** — coarse-grained medium-bedded sandstones with abundant coal fragments in the uppermost horizons of the Piedimonte Formation.

AlKaPeCa block, the drifting of the different microplates and their partial accretion onto the different sectors of the African margin started during Late Eocene–Early Oligocene times, before the deposition of the above-mentioned Tertiary turbidite deposits.

In the southern sector of the Calabria-Peloritani Arc this hypothesis seems to be supported by the occurrence of an important Middle Oligocene tectonic phase (Rupelian/Chattian boundary). This tectonic event is responsible **(a)** for the deposition of thick conglomerate channelled bodies (about 500 m in thickness), marking the boundary between the Lower Oligocene Piedimonte Formation and the Upper Oligocene–Lower Miocene Stilo-Capo d'Orlando Formation (Fig. 4), and **(b)** for the different sedimentological and petrographic characters recorded within both these sedimentary successions (Puglisi 1998, 2008). Finally, the variations of the paleocurrent directions between the above mentioned successions (Fig. 4) also indicate a drastic change in sedimentary supply, probably as a result of a tectonic event.

This tectonic phase could easily correspond to the 28.6 Ma extensional phase recently recorded by Heymes et al. (2008, 2010) in the Aspromonte Massif, very close to the Peloritani Mountains, both belonging to the same internal zones (Calabria-Peloritani Arc).



BRIZ include the Oligocene–Miocene Rifian Dorsale Calcaire, Fnideq and Sidi Abdesslam Fms and the Betic El Niño and Rio Pliego Formations (Guerrera et al. 1997; Puglisi et al. 2001; Zaghloul et al. 2003; Gigliuto 2005; Puglisi & Gigliuto 2006).
Calabria-Peloritani Arc includes the Lower Oligocene Frazzanò Flysch and Piedimonte Formation and the Oligocene–Miocene Stilo-Capo d'Orlando Formation (Carmisciano & Puglisi 1978, 1982; Carmisciano et al. 1981; Cassola et al. 1991; Nigro & Puglisi 1993; Puglisi 1998).

Fig. 6. Quartz-Feldspar-Lithic Fragments ternary plot showing a clear bimodality of provenance between the Lower Oligocene-to-Upper Oligocene/Lower Miocene sandstone suites from the Betic-Rifian Internal Zones and Calabria-Peloritani Arc (modified after Puglisi 2008).

Discussion

The existence of a Lower Cretaceous flysch family with similar geological-structural setting and internal clastic provenance along all the Western and Central European Alpine chains for more than 7,000 km, from the Gibraltar Arc to the Balkans (Puglisi 2009), strongly supports the hypothesis of paleogeographical continuity between the different oceanic areas of the Alpine Tethys during Late Jurassic and Early Cretaceous times. The Maghrebian Basin, in particular, could have been located in the westernmost sector of the Alpine Tethys (Fig. 1).

Due to the Cretaceous re-organization of the plates, almost all the successions of the easternmost and central basins (Severin-Ceahlău Ocean in the Carpathians, 'Nish-Troyan flysch trough' in the Balkans, Vardar and Pindos Oceans in the Dinarides and Hellenides and Ligurian Ocean in the western-central Alps and northern Apennines) experienced Middle-to-Late Cretaceous tectonic developments, responsible for the deformation of the Lower Cretaceous flysch and their Triassic-Jurassic ophiolitic and sedimentary substratum (Puglisi 2009 and references therein).

In contrast, the Maghrebian Basin seems to have escaped these Cretaceous tectonics and its deformation seems to start in successive times. The Maghrebian Lower Cretaceous flysch, in fact, in Algeria as well as in Sicily (Raoult 1975; Puglisi 1981, 1992, 2009; Raoult et al. 1982) is piled up to form a complicated structural edifice with many tectonic units, formed only by Lower Cretaceous flysch without Tertiary sedimentary cover and tectonically underlying the Hercynian crystalline units (Kabylian Units and Calabria-Peloritani Arc in Algeria and Sicily, respectively). The absence of Tertiary cover was interpreted as the result of an early underthrusting of the Lower Cretaceous flysch beneath the internal Hercynian crystalline units (Cassola et al. 1990, 1991; Puglisi 1992) or, otherwise, this has also been related to post-Albian eustatic phenomena affecting the continental shelves, responsible for a sudden interruption of the detrital supply (Durand-Delga et al. 1999).

Thus, the first compressive events can be related to a meso-Alpine stage, as long hypothesized in Algeria (Raoult 1975; Vila 1980) and in the Sicilian Maghrebian Chain at the beginning of the nineties (Puglisi 1992; Cassola et al. 1992), where these deformations of the Lower Cretaceous flysch are sealed by Lower Oligocene turbidite deposits (Cassola et al. 1991; Cassola et al. 1992; Puglisi 1992).

Unfortunately this evidence is often neglected in many recent geological studies carried out in the Sicilian Maghrebian Chain, where the Early Oligocene age of several turbidite deposits has been strongly debated. Nevertheless, recent biostratigraphic data (Torricelli & Knezaurek 2010) confirm the Early Oligocene age of these Maghrebian turbidite deposits. An Alpine metamorphic overprint, recognized within the Hercynian crystalline units of the Calabria-Peloritani Arc (Pezzino et al. 2008) also seems to strengthen the previous hypothesis of meso-Alpine tectonic events (Puglisi 2008 and references therein).

Finally, the different composition and sedimentary provenance of coeval and equivalent sandstone suites from the BRIZ and Calabria-Peloritani Arc suggests that both their source areas belonged to different sectors of the AlKaPeCa block. An incipient fragmentation of the AlKaPeCa block, in fact, is here suggested to hypothesize a paleogeographical scenario with different microplates, already widely separated during the Late Eocene-Early Oligocene, in order to justify different supplies in different sedimentary basins.

Concluding remarks

This paper emphasizes a geological history of the Maghrebian Basin very similar to that of the other sectors of the Alpine Tethys, but with different times of deformation.

The deformation history of the Maghrebian Basin, in fact, seems to have started in early meso-Alpine times, connected with the northward subduction of the African plate beneath the European one (Heymes et al. 2010 and references therein), as the result of the progressive closure of the Alpine Tethys, diachronous toward its westernmost sectors (Puglisi 2010).

Successively, due to the slow convergence between Africa and Europe, rapid extensional processes, mainly governed by subduction rollback (Lonergan & White 1997; Jolivet & Faccenna 2000; Mauffret et al. 2004), started on the overriding plate in the back-arc position (Rosenbaum et al. 2002), partially coeval with these meso-Alpine compressive tectonic events. Successive increasing of these extensional tectonics triggered the break-up of the AlKaPeCa block and the formation of new oceanic spaces (Gulf of Lion, Valencia Trough, Provençal Basin). At the same time, new microplates formed and started to drift as long as subduction rollback took place (Rosenbaum et al. 2002).

The age of the beginning of fragmentation of the AlKaPeCa block and the formation of these new basins is still under discussion. Figure 7 shows some possible paleogeographical reconstructions of the Western Mediterranean, where the beginning of the extension process is mainly dated to the Eocene-Oligocene boundary or to the Early Oligocene.

Jolivet & Faccenna (2000) suggested that the inception of extension in the Provence area is dated to ~35 Ma. This early

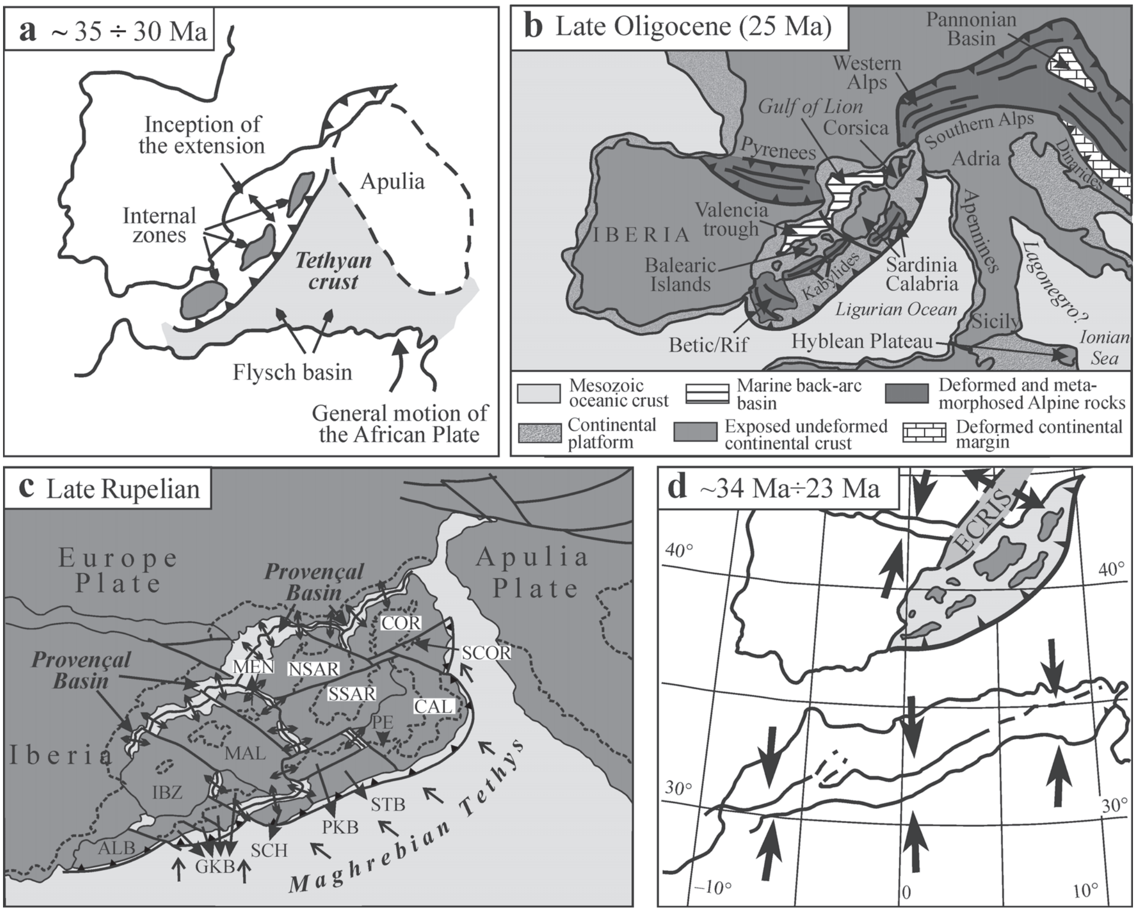


Fig. 7. Fragmentation of the southern European paleomargin, with consequent formation of the AlKaPeCa-derived microplates, occurred in: **a** — Early Oligocene times (modified from Lonergan & White 1997 and Jolivet & Faccenna 2000), **b** — Late Oligocene times (Rosenbaum et al. 2002), **c** — Late Rupelian times (Schettino & Turco 2006, modified by Chalouan et al. 2008) or, finally, **d** — during the Eocene-Oligocene evolution of the ECRIS (European Cenozoic Rifted System, sensu Dèzes et al. 2004; after Frizon de Lamotte et al. 2009). **Keys of (c):** solid lines with arrows = extension centers, straight solid lines = strike-slip faults, curved black lines with teeth = subduction zones, arrows = direction of motion relative to Europe Plate. **Western Mediterranean Microplates:** COR, SCOR = Corsica and South-Corsica; MEN, MAL = Menorca and Mallorca; NSAR, SSAR = northern and southern Sardinia; IBZ = Ibiza; CAL, PE = Calabria and Peloritani; GKB, PKB = great and small Kabylian; SCH, STB, ALB = Sardinia Channel, south Tyrrhenian and Alboran Blocks.

extension process is interpreted as the continuation of a system of grabens which affected Central Europe during the Eocene (Brun et al. 1992). The rifting of the Provençal Basin, in particular, started at 30 Ma (Jolivet & Faccenna 2000).

Rosenbaum et al. (2002) also dated the onset of the extension in the western Mediterranean to 32–30 Ma because the Gulf of Lion and the Valencia Through were already formed during Chattian times. The Valencia Trough, in fact, seems to have been definitively formed in a short time span, during Late Rupelian times (31.1 to 28.0 Ma; Schettino & Turco 2006), slightly before the opening of other oceanic spaces, such as the Provençal Basin and the west Alboran Sea (Rosenbaum et al. 2002).

Dèzes et al. (2004) also related the Rupelian-Chattian formation of the Gulf of Lion and Valencia Through to the southward propagation of the graben systems of the southern part of the ECRIS (European Cenozoic Rift System), whose evolution was responsible for the opening of the Provençal Basin. In contrast, Mauffret et al. (2004) consider the formation of the Valencia Trough coeval to the Provençal rifting or slightly younger, both of them dated to the Oligocene-Miocene boundary (~23 Ma).

Not very different ages have also been proposed by Carminati et al. (2012a,b and references therein), who stated that the rifting in the Provençal basin started during latest Eocene–Early Oligocene (34–28 Ma) and ended in the middle Aquitanian (21 Ma).

Handy et al. (2010) also suggest that the AlKaPeCa Block, interpreted as an independent microplate located between the European and African plates, was already widely subdivided into two sectors in the Priabonian (35 Ma).

Finally, concerning the Sicilian Maghrebian Chain, two concluding remarks can be emphasized. The Peloritani tectonic edifice, the southern portion of the Peloritani-Calabria microplate, **(1)** overthrust the Lower Cretaceous Monte Soro Flysch before the unconformable deposition of the Lower Oligocene- Lower Miocene turbidite succession (Piedimonte and Stilo-Capo d'Orlando Formations) and **(2)** this microplate was, probably, already separated from the other sectors of the AlKaPeCa block, thus suggesting that the onset of fragmentation of this block can be dated to the early Oligocene and/or Eocene-Oligocene boundary, and not to more recent times.

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