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Provenance, paleogeographic and paleotectonic interpretations of Oligocene-Lower Miocene sandstones of the western-central Mediterranean region: A review

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ABSTRACT

The changing nature of detrital signatures in clastic wedges of the Circum-Mediterranean orogenic systems reflect the provenance relations from different source rocks of evolving geo-puzzle terranes, including ophiolite bearing, uplifted continental crust (both shallow to deep crust terranes), volcanic and sedimentary source rocks. We selected here sandstone suites directly occurring over the Mesomediterranean Micropaleoplate during the final stages of closure of the western-southern Tethyan realm. They are unconformably over the internal domains of the Circum-Mediterranean thrust belts, and include Oligocene-to-lower Miocene siliciclastic formations of the Betic Cordillera (As, Bosque, Río Pliego, El Niño, Ciudad Granada, Fuente-Espejos, Alozaina and Viñuela fms), Rif Chain (Fnideq and Sidi Abdeslam fms), and Calabrian terranes (Paludi, Pignolo and Stilo Capo d'Orlando fms). All these sandstone suites range from quartzolitic to quartzofeldspathic detrital modes reflecting close relations with their Paleozoic metasedimentary and plutonic source rocks and their related Mesozoic sedimentary covers. Marked differences have been recognized from western (Betic-Rif) to eastern (Calabria) portions in terms of detritic suites. Detrital suites of the Betic-Rif portions reflect a transition between a craton, transitional and recycled orogenic provenance type. Contrarily, detrital suites of the Calabria portions reflect their transition from transitional continental to basement uplift orogenic provenance reflecting deposition in wedge-top basins during final subduction of the MFB below the MM and the opening of the Mediterranean basin as a backarc.

1. Introduction

The Tethys oceanic realm was located between Gondwana (mainly, South America, Africa, India, Oceania and Antartica) and Laurasia (mainly, North America and Eurasia), until Cretaceous times, when the break-up of Gondwana begun (Gibbons et al., 2015; Matthews et al., 2016; Maffione et al 2017; Guerrera et al., 2021). It was composed by several oceanic branches and intermediate microplates and it started to closed in the Late Cretaceous (Maffione et al 2017). Part of the area occupied by the Tethys was replaced by the Mediterranean Basin since the Early Miocene (Amendola et al., 2016; Perri et al., 2017; Guerrera et al., 2021; Critelli et al., 2021) although Mesozoic oceanic lithosphere of the NeoTethys forms still the sea floor in the southern part of the Eastern Mediterranean (Vernant et al., 2014). The Alpine Circum-Mediterranean orogenic chains were constructed due to a rifting-drifting-oceanization Mesozoic phase followed by convergence, subduction, and collision during Cenozoic times of the Tethyan oceanic branches and involved margins of the surroundings plates and microplates (Malinverno and Ryan, 1986; Royden, 1993; Gueguen et al., 1998; Wortel and Spakman, 2000; Handy et al., 2010; Schettino and Turco, 2011; Chertova et al., 2014; Hosseinpour et al., 2016; Spakman et al., 2018; Martín-Martín et al., 2001, 2020a,b; Critelli et al., 2008; Caracciolo et al., 2011; Alcalá et al., 2013; Guerrera and Martín-Martín, 2014; Guerrera et al., 2012, 2015, 2021; Matano et al., 2020; Fornelli et al., 2022; Jafarzadeh et al., 2022). In the case of the western Mediterranean area (Fig. 1), Africa and Iberia-Europe were the main plates to the south and north, respectively (Doglioni, 1992; Guerrera et al., 2021). Between these, the Mesomediterranean (MM) and Adria-Apulia (AAM) microplates were located separating two main oceanic branches in late Cretaceous times (Fig. 1A): Magrebian-Lucanian-Ionian (MLB), to the south, and Nevado-Filabride-Liguride-Piemontese (NFLPB), to the north (Doglioni, 1992; Guerrera et al., 2021). Both basins connected to the

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west and, joined to the easternmost part of the Central Atlantic Ocean.

The closing of these oceanic Tethyan branches took place in two phases separated in time (Guerrera et al., 2021): The northern branch was closed by a southward subduction of the NFLPB oceanic branch below the MM during Paleogene (mainly Eocene) times in the so-called Eoalpine phase (Martín-Martín et al., 2020a,b; Guerrera et al., 2021). Contrarily, the southern branch and the western half of the northern branch, in the future Gibraltar Arc region to the SW of Iberia were closed by a northward subduction of the MLB below the MM during the late Oligocene-early Miocene in the Neoalpine phase (Martín-Martín et al., 2001, 2020a,b; Critelli et al., 2011, 2013,2017; Critelli, 2018; Malekzadeh et al., 2020). During the Eoalpine phase the Alps, Pyrenees and Iberian Range were constructed. In turn, during the Neoalpine phase the Betic, Maghrebian and Apennine chains were structured as a nascent orogenic belt usually known as AlKaPeCa (Bouillin et al., 1986; Guerrera et al., 1993; Martín-Martín et al., 2001, 2020a,b; Guerrera et al., 2021).

Nevertheless, for several authors (see discussion in Guerrera et al., 2021) the MM not existed but it was part of the eastern paleomargin of the Iberian Peninsula. These papers, usually start their models after the moment of closure of the northern Tethyan branch due to the Eoalpine phase. So that, this MM is attached as a “paleomargin” to Iberia. These papers usually do not address the previous (Mesozoic and lower part of the Paleogene) evolution and paleogeography.

In any case, the closing by subduction of the MLB was partially contemporaneous of the opening of the Mediterranean See as a back-arc basin related to this subduction from the Burdigalian (Guerrera et al., 2021).

Although this not yet demonstrated for its Nevado-Filabride part, the NFLPB and the MLB received thick sedimentary sequences during Cenozoic times. These sequences are now part of the Circum-Mediterranean belts in the most of the cases as metamorphic sequences. A main focus in this contribution were deposits related to accretionary orogenic systems just before and during the final stages of the orogenic evolution of these belts in late Oligocene-early Miocene times. These sedimentary successions constituted thick clastic wedges dominated by siliciclastic deposits interbedded with claciclastic and pelagic deposits. The sandstone composition of these clastic wedges provides critical information on source areas and on their coeval plate tectonic evolution within the circum-Mediterranean orogenic belt allowing defining intriguing relations from recycled orogenic areas, uplifted continental blocks and cratonic provenances, and also contribution from active magmatic arcs. Provenance interpretations are crucial to contribute to the paleogeographic and paleotectonic models since the distinctive sandstone petrofacies suites are related to specific provenance source areas (Ingersoll et al., 1984; Zuffa, 1980, 1985; Dickinson, 1985; Critelli and Ingersoll, 1995). The general significance here is that the application of provenance analysis can give detailed information to the complex tectonic history of the circum-Mediterranean orogens. This kind of studies on sediment dispersal systems can serve as a test of alternative tectonic scenarios useful for reconstruction to local, regional or global scale of others major orogens.

Cenozoic clastic strata are well represented in the Internal Domains/Zones of the central-western Mediterranean belts (Fig. 1B). This paper discusses detrital modes of Oligocene-lower Miocene sandstones derived from the MLB that are nowadays exposed in the Internal Domains/Zones of the western-central Mediterranean belt. Previously published and new fresh data from these units from the mentioned belts are presented.

2. Geological setting

Our study is focused on non-metamorphic Internal Units from the Betics, Rif and Calabria. These orogenic chains are composed by three main sets of units (Guerrera and Martín-Martín 2014; Guerrera et al., 2021) (Fig. 1B): (1) the Internal units derived from the MM with a pre-Alpine continental basement (Paleozoic or older crystalline rocks previously affected by the Hercinian orogeny) with Mesozoic-Cenozoic covers that were strongly deformed during the Neoalpine orogenic evolution, as they make part of thick-skinned thrust nappes and sometimes affected by Alpine metamorphism; (2) the Maghrebian-Lucanian Basin units (MLB) and consisted of latest Jurassic to Miocene clastic and pelagic deposits detached from their now subducted oceanic and/or transitional crust; and (3) the External units, belonging to the Iberia, Africa and Adria-Apulia Margins and made of parautochthonous pre-Alpine continental crust basements from which their sedimentary *meso*-Cenozoic covers were detached to form thin-skinned thrust systems that, especially on the Betic side, were also intensely affected by transpressional tectonics (Vera, 2004; Jabaly-Sánchez, 2019; Guerrera et al., 2021).

Sedimentary Oligocene-lower Miocene *syn*-tectonic clastic strata are well represented and preserved from metamorphism in the Maláguide Complex in the Betic Cordillera (S, Spain), the equivalent Ghomaride Complex in the Moroccan Rif, the Algerian Tellian Kabylide units, and the Calabria terranes with the upper units from the Sila and Serre-Aspromonte Massifs in the Southern Apennines.

2.1. Betic Cordillera (S Spain)

The Betic Cordillera is divided into the Internal and the External Zones in a classic way (Martín-Algarra, 1987; Vera, 2004). Between these, the Flysch Zone occurs, represented, in this sector, by the Campo de Gibraltar Complex. Neogene basins are unconformable onto these tectonic zones and appear locally associated with Miocene to Quaternary volcanism in the Almería-Murcia area and also in the Western Mediterranean (Alboran Sea and Valencia-Balearic Basin).

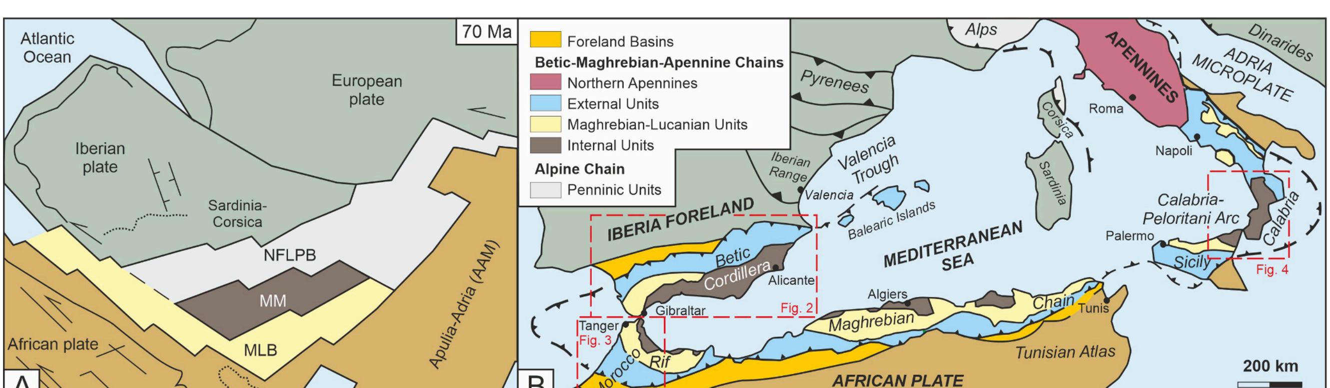

Fig. 1. A, Paleogeographic reconstruction of the central-western Mediterranean area showing the position of the Mesomediterranean Microplate. B, Geological sketch map of the Central-Western Mediterranean area. Modified from Doglioni (1992), Martín-Algarra (1987), Guerrera et al. (1993, 2005), Perrone et al. (2006), Critelli et al. (2008), Schettino and Turco (2011), Welford et al. (2012), Perri et al. (2013), Hosseinpour et al. (2016) and Guerrera et al. (2021).

The Internal Zone is subdivided in the Nevado-Filábride, Alpujárride and Maláguide complexes from bottom to top, which are structured in an antiformal thick-skinned nappe stack, plus detached cover nappes located in frontal position in the Interna-External Zone boundary and called in a generic way Frontal Units. These units derive from the MM, apart from the Nevado-Filábride Complex, which includes metamorphic ophiolitic suites derived from the NFLPM (Puga et al., 2017) and whose deepest units are now considered as an exhumed part of the Southern Iberian Paleomargin basement (Jabaloy-Sánchez et al., 2019). The Nevado-Filábride and Alpujárride complexes are totally composed of metamorphic rocks, while the Maláguide and the Frontal Units are mostly unaffected by the Alpine metamorphism (Vera, 2004; Jabaloy-Sánchez et al., 2019, and references therein). These units show basements mainly made of Devonian to Carboniferous terrigenous beds rich in graphite with carbonate and siliceous intercalated beds (Jabaloy-Sánchez et al., 2019) and Mesozoic covers with terrigenous and carbonate beds. Only the lower Alpujárride and mainly the Maláguide and the Frontal Units show Cenozoic sedimentary covers mainly characterized by siliciclastic successions.

The Intermediate Flysch Zone units are made of Cretaceous to Lower Miocene marine clastic successions deposited in the connecting area between the NFLPB and the MFB towards the Central Atlantic Ocean (Guerrera and Martín-Martín 2014; Guerrera et al., 1993, 2005, 2012). They now appear structured in thrust units and sandwiched between the Internal and the External units (Vera, 2004; Jabaloy-Sánchez et al., 2019, and references therein).

The External Zone is made of sedimentary Mesozoic and Cenozoic successions derived from the *meso*-Cenozoic Southern Iberian Paleomargin and is divided into Prebetic and Subbetic (Vera, 2004; Jabaloy-Sánchez et al., 2019, and references therein). The Prebetic is divided into an external (attached to the Iberian Foreland) and internal units derived from continental to shallow marine areas close to the Iberian continent. The Subbetic is constituted by more distal sedimentary successions dominated by Jurassic to Miocene pelagic sediments that appear systematically detached from a thick sole dominated by Triassic evaporites, and that are also divided in External, Median and Internal successions (Vera, 2004).

.Since Burdigalian times, the Neogene basins and volcanism appeared related to extension or strike-slip faulting associated to the Mediterranean back arc opening (Vera, 2004). The Guadalquivir Basin is the most important and acted as foreland basin of the modern Betic thrust belt (Vera, 2004).

2.2. Rif Cordillera (N Morocco)

The Rif Chain represents the southward continuation of the Betic Cordillera and it is also divided into Internal, Flysch and External Zones in a classic way (Chalouan et al., 2008; Michard et al., 2008), with postorogenic Neogene basins also well preserved.

Two main overthrusted units of the Internal Zone (Michard et al., 2008; Guerrera & Martín-Martín, 2014; Critelli et al., 2017; Martín-Martín et al., 2020a, 2020b, 2020c; among others) include the Sebtide (equivalent to the Alpujárride) in lower tectonic position, and the Ghomaride (equivalent to the Maláguide) in upper tectonic position. In the outer border of the Internal Zone, the Rifian Dorsal units, equivalent to the Betic Frontal Units appears also made of *meso*-Cenozoic cover nappes located in frontal position of the Internal Zone. The Sebtide Complex is exclusively made of metamorphic rocks, while the Ghomaride and the Frontal Units, are unaffected or slightly affected by the Alpine metamorphism. These units show crystalline basements and Mesozoic covers, but only the Ghomaride and the Frontal ("Dorsal") Units include Cenozoic deposits. All the units of the Rifian Internal Zones were derived from the westernmost part of the MM.

The Flysch Zone consists of thin-skinned tectonic units composed of siliciclastic Cretaceous-Miocene successions originally deposited on oceanic and/or continental crust of the MLB (Guerrera et al., 1993 2005; Durand Delga et al., 2000).

The External Zone is made of a set of tectonostratigraphic units derived from the Maghrebian (=North African) Paleomargin divided into Intrarif, Mesorif and Prerif units, respectively thrusting on each other from inner to outer sector of the chain. Their structural trend striking N—S close to the Gibraltar Strait and gradually rotate to W-E when moving to the S (Suter, 1980; Chalouan et al., 2008; Michard et al., 2008).

Neogene basins appear unclonformably installed onto the whole tectonic edifice, and are also related to the Mediterranean opening extension or strike-slip faulting. The most important is the foreland basin represented by the Gharb Basin, appearing in contact with the Moroccan Meseta from the Atlas system (Michard et al., 2008).

2.3. Southern Italy mountain belt

The Southern Italy mountain belt, includes the southern Apennines Chain and the Calabria terranes (Bonardi et al., 2009), and is also subdivided into the three set of units common to the above mentioned chains (Fig. 4): (1) The Internal units are represented by the Calabrian terranes (Amodio-Morelli et al., 1976; Scandone, 1982), including ophiolites (not excluded a partial origin from the NFLPB), crystalline basement rocks and Mesozoic sedimentary successions derived from the MM (Guerrera and Martín-Martín 2014; Guerrera et al., 2021); (2) The MLB units have ophiolitic, metasedimentary and sedimentary rocks; (3) The External units, which derived from the West Adria Paleomargin, are divided in (i) inner carbonate platform made of Mesozoic to Lower Miocene shallow marine beds, locally affected by Alpine metamorphism (Verbicaro and equivalent units); (ii) Campano-Lucanian Platform; (iii) Lagonegro Basin, made of Mesozoic to Upper Miocene pelagic deep-sea sediments; (iv) outer platform sequences (Monte Alpi Unit), which also include Miocene foreland strata; (v) Lucanian-Apulia lowland; and finally (vi) Apulian Swell, a practically unfolded external platform in the foreland area, made of Mesozoic to Quaternary carbonates (Critelli and Le Pera, 1995, 1998; Critelli et al., 2011, 2017, and references therein).

3. Studied sectors

Oligocene-Lower Miocene deposits of non-metamorphic units from the Internal Zones in the Maláguide, Ghomaride and Calabria complexes have been studied in detail in six sectors: Espuña, Almería and Málaga sectors (Betic Cordillera); Tetouan sector (Rif Chain) and the Northern and Southern sectors of Calabria (Fig. 5).

In each sector, the stratigraphy was previously defined in the literature (Bonardi et al., 2002, 2003; Perri et al., 2017; Critelli et al., 2021; Perri et al., 2022). The most complete Cenozoic succession is that of the Espuña area in the eastern Betic Cordillera (Perri et al., 2017) where several formations related by lateral or vertical gradual (in stratigraphic continuity) to sharp (unconformable to disconformable) facies changes are well documented, from bottom to top (Fig. 5): the lowermost As Fm (late Lower-early Upper Oligocene), the Upper Oligocene Bosque Fm, the Upper Oligocene-Aquitanian Río Pliego Fm, and the Burdigalian El Niño Fm. In the Almería and Málaga sectors of the Betic Cordillera, the succession is equivalent, but thinner and stratigraphically less complete (Fig. 5), with two main lithostratigraphic units (Martín-Algarra, 1987): the Ciudad Granada Group below (including several local formations equivalent to the Bosque and Río Pliego Fms of Sierra Espuña), and the Viñuela Group above (including also several local formations equivalent to the El Niño Fm of the Espuña area). In the case of the Tetouan sector from the Moroccan Rif (Fig. 5), the succession is also incomplete but also equivalent with the Upper Oligocene-Upper Aquitanian Fnideq Fm below and the Burdigalian Sidi Abdeslam Fm above. In the Calabrian Terranes, two sectors are discussed with incomplete successions: the Sila sector (Northern Calabria Terranes) and the Serre-Aspromonte-Peloritani sector (Southern Calabria Terranes). Several stratigraphic formations were defined (Fig. 5): in the northern Calabria sector, the

Paludi Fm (Zuffa and De Rosa, 1978; Critelli and Le Pera, 1995, 1998) ranges from the Late Oligocene to the earliest Miocene (Aquitanian), whereas in the southern Calabria sector appear the Upper Oligocene-Aquitanian Pignolo-Frazzanò Fm and the Burdigalian Stilo-Capo d'Orlando Fm (Bonardi et al., 2002, 2003). Although some authors mention the Lower Oligocene Palizzi Fm (Bouillin et al., 1985) in the Stilo Unit, in the studied successions in this work, the Lower Oligocene is also lacking (Bonardi et al., 2002, 2003).

3.1. Murcia sector (Eastern Betic Cordillera, S Spain)

In the Sierra Espuña area (Fig. 2) thick Lower Oligocene to Lower Miocene succession with several stratigraphic formations is well exposed (Figs. 5 and 6; Perri et al., 2017). The succession starts with 10 m of marls and sandy limestones with rounded quartz pebbles of the As Fm (late Lower-early Upper Oligocene) deposited in an internal marine platform. This is followed up, after an unconformity, by almost 1300 m of calcareous conglomerates, limestones, yellowish marls and calcarenites of the Bosque Fm (Upper Oligocene), which represents fan-delta deposits and their upward transition to an external marine platform. Upwards, the successions change by lateral-upward gradual passage to 300 m of reddish pelites, turbidite sandstones and slope channel polygenic conglomerates of the Río Pliego Fm (Upper Oligocene-Upper Aquitanian). After an unconformity, the succession ends with 20 m of greenish pelites with polygenic breccias, turbidite sandstones and silexite beds from the El Niño Fm (Burdigalian) deposited in a slope or deep basin.

3.2. Almería sector (Eastern Betic Cordillera, S Spain)

In this area (Fig. 2; Critelli et al., 2021), an incomplete and discontinuous Upper Oligocene to Lower Miocene succession from slope or deep basin is exposed (Figs. 5 and 6). The succession starts with 180 m of reddish pelites, turbidite sandstones and slope channel polygenic conglomerates from the Ciudad Granada Fm (Upper Oligocene-upper Aquitanian). After an unconformity, the succession ends with 90 m of greenish pelites with polygenic breccias, turbidite sandstones and silexite beds from the Fuente-Espejos Fm (Burdigalian).

3.3. Málaga sector (Central Betic Cordillera, S Spain)

This area (Fig. 2; Critelli et al., 2021) includes an incomplete, discontinuous and thin Upper Oligocene to Lower Miocene succession, deposited also in a slope or deep basin (Figs. 5 and 6). The succession starts with 25 m of reddish pelites, turbidite sandstones and slope channel polygenic conglomerates from the Alozaina Fm (Upper Oligocene-upper Aquitanian). After an unconformity, the succession ends with 35 m of greenish pelites with polygenic breccias, turbidite sandstones and silexite beds from the Viñuela Fm (Burdigalian).

3.4. Tetouan sector (Western Rif Cordillera, N Morocco)

This area (Fig. 3; Perri et al., 2022) includes thin Upper Oligocene to Lower Miocene succession (Figs. 5 and 6) that starts with 10 m of marls with sandy limestones with rounded quartz pebbles of the base of the Fnideq Fm (Oligocene), which belongs to a marine platform. This is followed in continuity by 40 m of reddish pelites, turbidite sandstones and slope channel polygenic conglomerates of the upper Fnideq Fm (Upper Oligocene-upper Aquitanian). After an unconformity, the succession ends with 60 m of greenish pelites with polygenic breccias, turbidite sandstones and silexite beds from the Sidi Abdeslam Fm (Burdigalian).

3.5. Sila sector (Northern Calabrian Terranes, S Italy)

The Sila sector belongs to the Northern Calabrian Terranes in S Italy (Fig. 4) and it was studied by Amodio Morelli et al. (1976), Messina et al. (1994), and Critelli and Le Pera (1995, 1998). In this area an incomplete and thin succession was deposited in marine external platform to slope realms (Figs. 5 and 6). The succession: it is made by the Paludi Fm (Upper Oligocene-upper Aquitanian), consisting in a few meters of clast-supported polygenic breccias (with phyllitic and quartzose clasts),

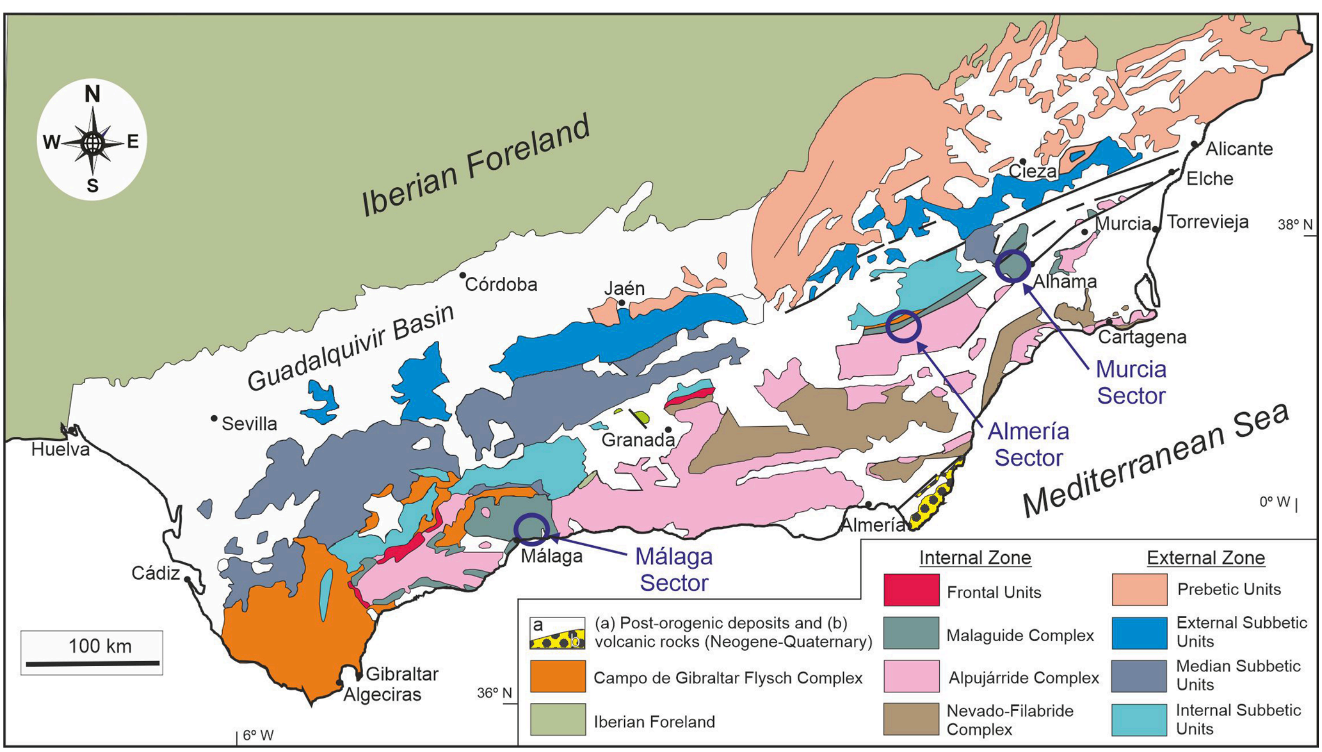

Fig. 2. Geological sketch map of the Betic Cordillera (S, Spain, modified from Martín-Algarra (1987) and Vera (2004).

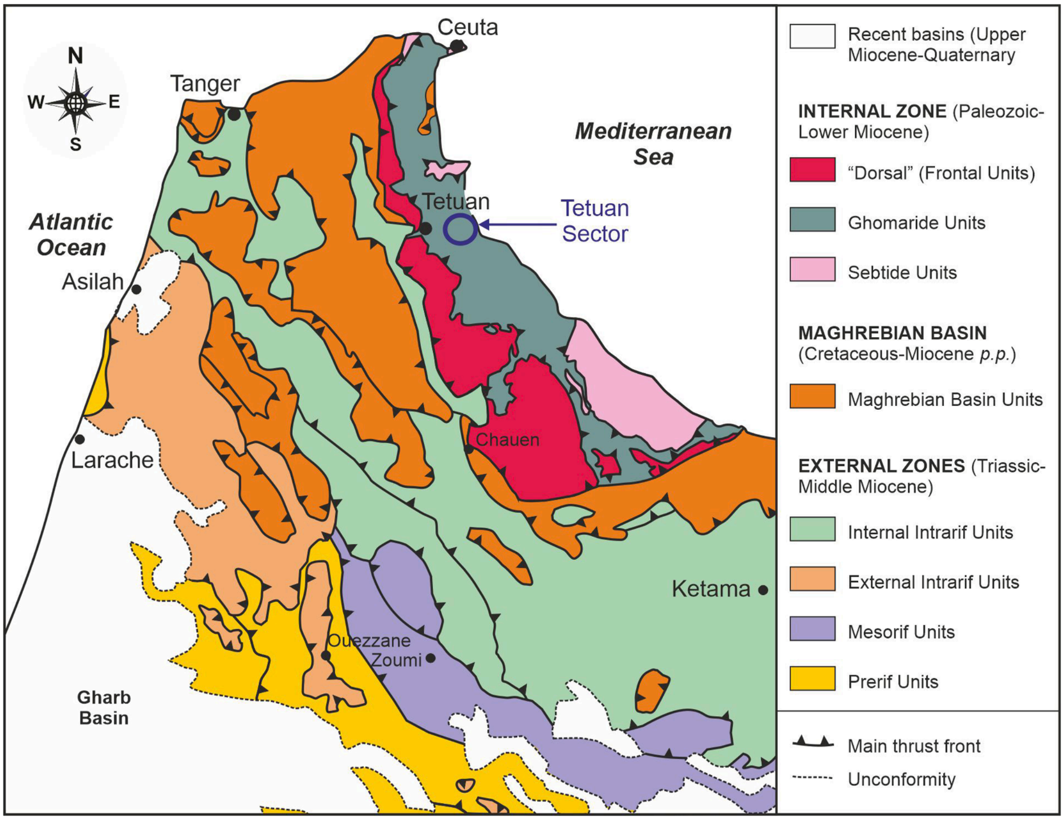

Fig. 3. Geological sketch map of the Rif Chain (N, Morocco, modified from Chalouan et al., (2008) and Michard et al. (2008).

followed by one hundred meters of polygenic conglomerates, passing upwards to 200 m of marls and silts with frequent intercalations of debris flows, mud flows, and olistoliths mostly made of Calpionella limestones (Maiolica facies: Bonardi et al., 2005), in the lower part. The succession ends with about 50 m of marls, pelites and sandstones (e.g. Zuffa and De Rosa, 1978). The formation rests unconformably on the Sila Unit basement almost everywhere and only in a few outcrops, it rests on the Mesozoic cover, with an angular unconformity. Nannoflora assemblages from the middle–upper part of the sequence point to an age not older than Aquitanian, but an Oligocene age of the lower portions cannot be excluded (e.g., Bonardi et al., 2005).

3.6. Serre-Aspromonte-Peloritani sector (Southern Calabrian Terranes, S Italy)

The Serre-Aspromonte-Peloritani sector belongs to the Southern Calabrian Terrane (Fig. 4) and was studied by Cavazza (1989), Cavazza et al. (1997), de Capoa et al. (1997) and Bonardi et al. (2002, 2003). In this area, an incomplete and thin Upper Oligocene-lower Miocene succession crops out and it is made of two formations of marine platform to slope realms (Figs. 5 and 6). In this work, the succession starts with 40 m of the Pignolo-Frazzanò Fm (Upper Oligocene-upper Aquitanian), made of calcareous conglomerates, calcarenites and limestones interbedded with marls, pelites and turbidite sandstones. After an unconformity, the succession ends with 80 m of the Stilo-Capo d'Orlando Fm (Burdigalian), with similar rocks to those exposed for the Sila sector.

Lower Oligocene continental to shallow marine deposits (Palizzi Fm.; Bouillin et al., 1985), outcropping only near Palizzi village, in the Aspromonte Massif, and Chattian-Aquitanian lepidocycline and Lithothamnium-rich calcarenites (Pignolo Fm.; Bonardi et al., 2003), present only in the Stilo area, disconformably rest on the Mesozoic carbonates. The Burdigalian Stilo-Capo d'Orlando Fm. (Bonardi et al., 1980; 2003; Tripodi et al., 2018), that seals the whole CPST nappe stack, rests with an angular unconformity on the Pignolo Fm. (Fig. 6).

The stratigraphic-structural pile, from the Stilo-Capo d'Orlando Fm. upwards, includes (i) a Cretaceous to Miocene " varicoloured clays" chaotic complex (Antisicilide Complex of Ogniben, 1973), whose interpretation (nappe vs olistostrome) is controversial, and which overlies the Stilo-Capo d'Orlando Fm, and, in a few places, even the basement; (ii) Serravallian-Tortonian slope and base-of-slope clastics, erosively overlying the " varicoloured clays" (Patterson et al., 1995) followed by a Messinian sequence made up of evaporites (limestones and gypsum, commonly eroded) and unconformably overlain by alluvial to fluvio-transitional clastics (Cavazza and De Celles, 1993); (iii) Lower Pliocene regularly alternating limestones and marls, rich in pelagic foraminifers and calcareous nannoplancton ("Trubi" facies), onlapping all the older units.

4. Sandstone detrital modes

Medium to coarse arenites are reported here as mean detrital modes of selected sandstone suites to decipher their provenance and tectonic and paleogeographic relations. Data set includes a review of previously published data from key areas of the central-western Mediterranean belt, including Betic Cordillera (S, Spain), Rif Chain (N, Morocco) and Calabrian Terranes (S, Italy) where the data set was obtained using comparable methodology to define overall compositional trends (e.g., Zuffa and De Rosa, 1978; Critelli, 1993, 1999, 2018; Critelli and Le Pera, 1994, 1995, 1998; Critelli et al., 2007, 2011,2013,2017,2021; Perri et al., 2017; Matano et al., 2020). Table 1 lists the mean detrital modes of the data subdivided according to the age and the sector of the central-western Mediterranean belts considered. The modal composition was determined by point-counting using the Gazzi-Dickinson method (Ingersoll et al., 1984; Zuffa, 1985, 1987). The framework grain types that are used for discussions of detrital modes are those of Dickinson (1970, 1985), Zuffa (1985, 1987), Critelli and Le Pera (1994), and

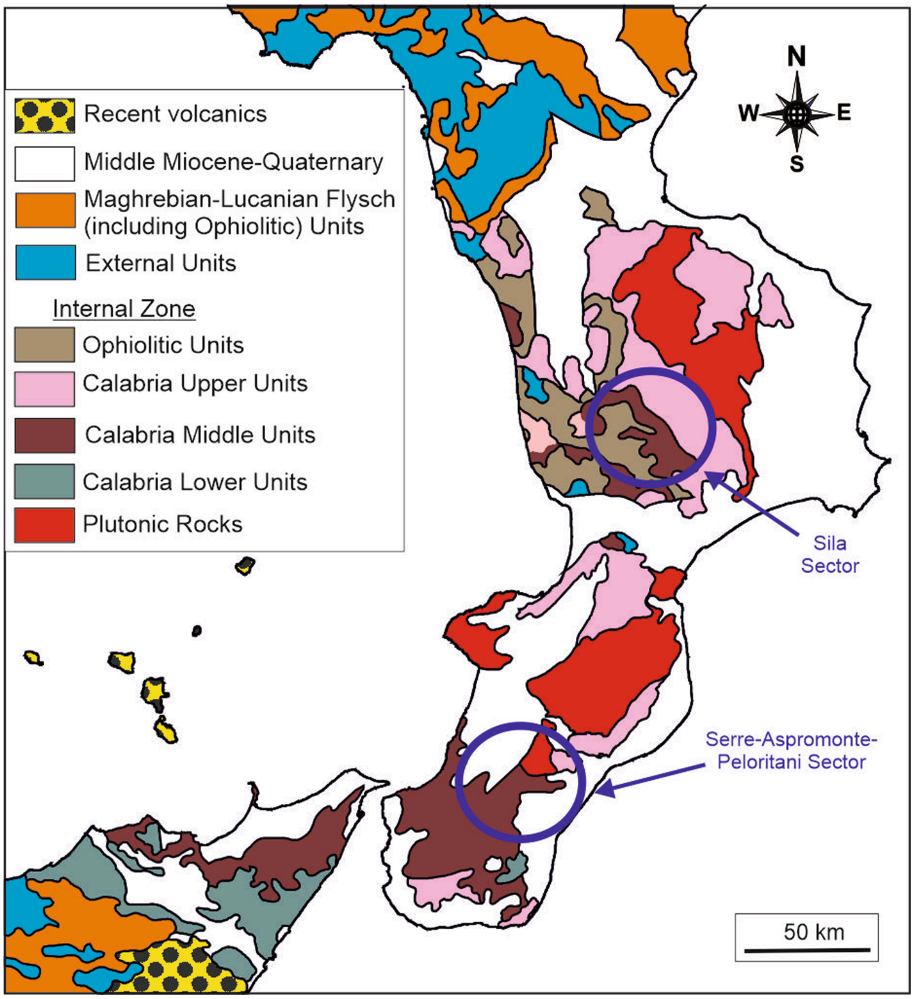

Fig. 4. Geological sketch map of the Calabria Terranes (S, Italy, modified from Critelli et al., 2008).

Critelli and Ingersoll (1995) and comprise:

a) Quartz grains, including monocrystalline quartz grains (Qm), and polycrystalline quartzose lithic fragments (Qp), and total quartzose grains (Qt = Qm + Qp);
b) Feldspar grains (F), including both plagioclase (P) and potassium feldspar (K);
c) Aphanitic lithic fragments (L), as the sum of volcanic and metavolcanic (Lv and Lvm), sedimentary (Ls) and metasedimentary (Lm; including Lsm as the sum of Ls + Lm). Ls includes here also carbonatelithic fragments (extrabasinal carbonate grains of Zuffa, 1980, 1985; Critelli et al., 2007), because of their importance and occurrence in detrital modes of Apenninic sandstones;
d) phaneritic + aphanitic rock/lithic fragments (R), recalculated by point-counting of specific assignment of aphanitic Lm, Lv and Ls lithic fragments plus quartz, feldspar, micas and dense minerals in polimineralic fragments, in which these minerals individually are larger than the lower limit of the sand range (0.0625 mm). During counting are summed as quartz (Qm) and feldspar (F) or micas and dense mineral grains (e.g., Ingersoll et al., 1984; Zuffa, 1985, 1987; Critelli and Le Pera, 1994; Critelli and Ingersoll, 1995; Caracciolo et al., 2011).

The results are in Fig. 7, in which the proportions of quartz grains, feldspar grains and aphanitic lithic fragments are recalculated to 100 %, and summary detrital modes are then reported as Qm%-F%-Lt%, for the diverse sections of the Circum-Mediterranean orogenic systems. The sandstone suites are within the orogenic provenance field of Dickinson (1985), even if regional petrofacies varies from quartzolithic to quartzofeldspathic from western portions (Betic and Rif) to eastern portions (Calabrian terranes).

4.1. Betic Cordillera

In the Murcia sector (Perri et al., 2017), sandstones of the As Fm (late Lower-early Upper Oligocene) are quartzarenite or sublitharenite (Qm92 F0 Lt8) with dominant quartz and signatures of sedimentary carbonate lithic fragments as well as intrabasinal carbonate fragments (Fig. 7A). The Bosque Fm (upper Oligocene) has a low siliciclastic content, which is predominantly of quartzose composition (Qm96 F0 Lt4, Fig. 7A) and ploting in the quartzarenite-subarkose-sublitharenite fields. Sandstones of the Río Pliego Fm (Upper Oligocene-upper Aquitanian) are quartzolithic (Qm26 F0 Lt74) with dominance of sedimentary clasts (mainly extrabasinal carbonate), and upwards increasing metamorphic lithic fragments (Fig. 7A) ploting in the sublitharenite-litharenite fields. The El Niño Fm (Burdigalian) has quartzolithic sandstone composition (Qm61 F0 Lt39) with dominance of sedimentary clasts (mainly carbonate), decreasing upwards metamorphic clast with respect to the former stratigraphic formation (Fig. 7A), and ploting in the litharenite field.

In the Almería sector (Critelli et al., 2021), the Ciudad Granada Fm (upper Oligocene-upper Aquitanian) has quartzolithic composition (Qm81 F8 Lt11) with dominance of sedimentary clasts (mainly carbonate), but in this case with a clear increase of metamorphic clasts

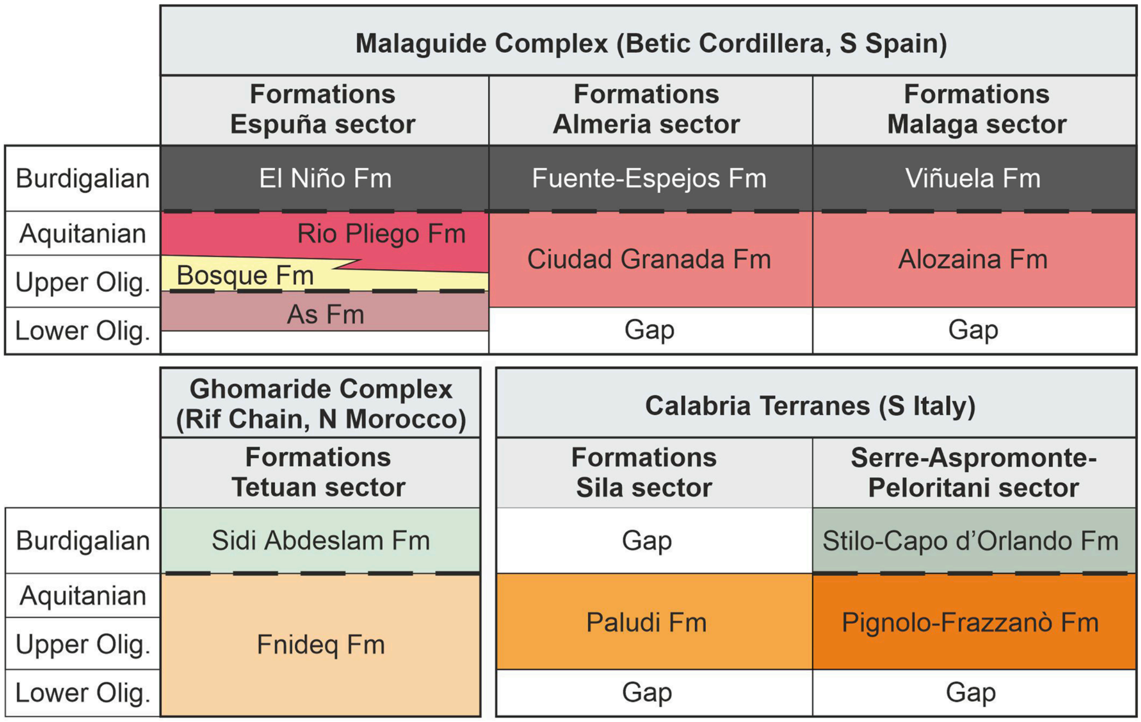

Fig. 5. Schematic table with the correlation of nomenclature from literature for the studied stratigraphic formations and groups in the Espuña, Almería and Málaga sectors from the Betic Cordillera (Perri et al., 2017; Critelli et al., 2021); Ghomaride of the Tetuan sector in the Rif Chain (Perri et al., 2022); and Sila and Serre-Aspromonte-Peloritani sectors in the Calabrian Terranes (Bonardi et al., 2002, 2003).

(Fig. 7B) and ploting in the feldespathic litharenite-litharenite fields. The Fuente-Espejos Fm (Burdigalian) has also a quartzolithic composition (Qm73 F7 Lt20) with dominance of sedimentary clasts (mainly carbonate) lower content of metamorphic clasts with respect to the underlying formation (Fig. 7B), and ploting in the litharenite field.

In the Málaga sector (Critelli et al., 2021), the Alozaina Fm (Upper Oligocene-upper Aquitanian) has a quartzolithic composition (Qm68 F11 Lt21) with dominance of sedimentary clasts (mainly carbonate), but in this case with clear increase of metamorphic clasts (Fig. 7C) and ploting in the feldespathic litharenite-litharenite fields. The Viñuela Fm (Burdigalian) has also a quartzolithic composition (Qm58 F4 Lt38) with dominance of sedimentary clasts (mainly carbonate), lower content of metamorphic clasts with respect to the underlying formation (Fig. 7C), and ploting in the litharenite field.

4.2. *Rif Chain*

In the Tetouan sector (Perri et al., 2022) the Fnideq Fm (Oligocene-upper Aquitanian) has a quartzolithic composition (Qm62 F2 Lt36) (Fig. 7D) with high proportion of quartz and with sedimentary lithics such as impure chert, the minor argillite and siltstone, and with plagioclase and mica being rare or absent. The Sidi Abdeslam Fm (Burdigalian) has quartzolithic composition with an abrupt increase of lithic content (Qm35 F2 Lt63) (Fig. 7D), being low-grade metamorphic lithic fragments and sedimentary lithics such as argillite and impure chert dominant components, with plagioclase only reliable in metamorphic grains, and presence of carbonatic grains (dolomite, spiritic, micritic, biomicritic grains) being present only at the base of the formation.

4.3. *Calabrian terranes*

In the Sila sector (Northern Calabrian terranes) the Upper Oligocene to Aquitanian *p.p.* Paludi Fm sandstones are quartzofeldspathic (Fig. 7E; Qm55 F36 Lt9; Zuffa and De Rosa, 1978) and reflects a local provenance from Paleozoic plutonic (mainly granodiorite) and metamorphic (phyllite to micaschist) source rocks, and Mesozoic sedimentary rocks (Longobucco Group; e.g., Zuffa 1980; Santantonio and Teale, 1987) of the Sila Unit.

In the Serre-Aspromonte-Peloritani sector (Southern Calabrian terranes) the sandstones of the Upper Oligocene to Aquitanian Pignolo-Frazzanò formations (Qm62 *F*23 Lt15) plot in the quartz-ofeldspatholithic field and the Burdigalian Stilo-Capo d'Orlando Formation (Qm45 F49 Lt6; Puglisi, 1987; Cavazza, 1989; Nigro and Puglisi, 1993; Critelli et al., 1995) also, both with a quartzofeldspathic composition.

5. Discussion

Petrological study allows obtain parameters of provenance and paleogeographi-paleotectonic value. The analysis testifies the changing nature of source-areas through time according to the studied sectors during progressive growth of the collisional belt and its unroofing sequence.

5.1. *Provenance implications*

5.1.1. *Betic Cordillera*

The counted siliciclastic sandstones plot mainly in a wide area at the QmLt side in the QmFLt diagram (Fig. 8), reflecting their transition between a craton, transitional and recycled orogenic provenance type. There are not cratons near the study area and the nearest craton is the West African Craton southwards of the Antiatlas. So, the source area probably is related to a transitional and recycled orogenic area from the Variscan belt. The Variscan and older basement of the Maláguide Complex mainly consists of a pre-Ordovician to Upper Carboniferous siliciclastic, siliceous and metasedimentary (slate, phyllite, carbonate and quartzite) succession including thin carbonate lenses, radiolarian chert beds and conglomerate bodies with some clasts of acid plutonic rocks and, less frequently, of basic vulcanites and plutonites (Jabaloy-

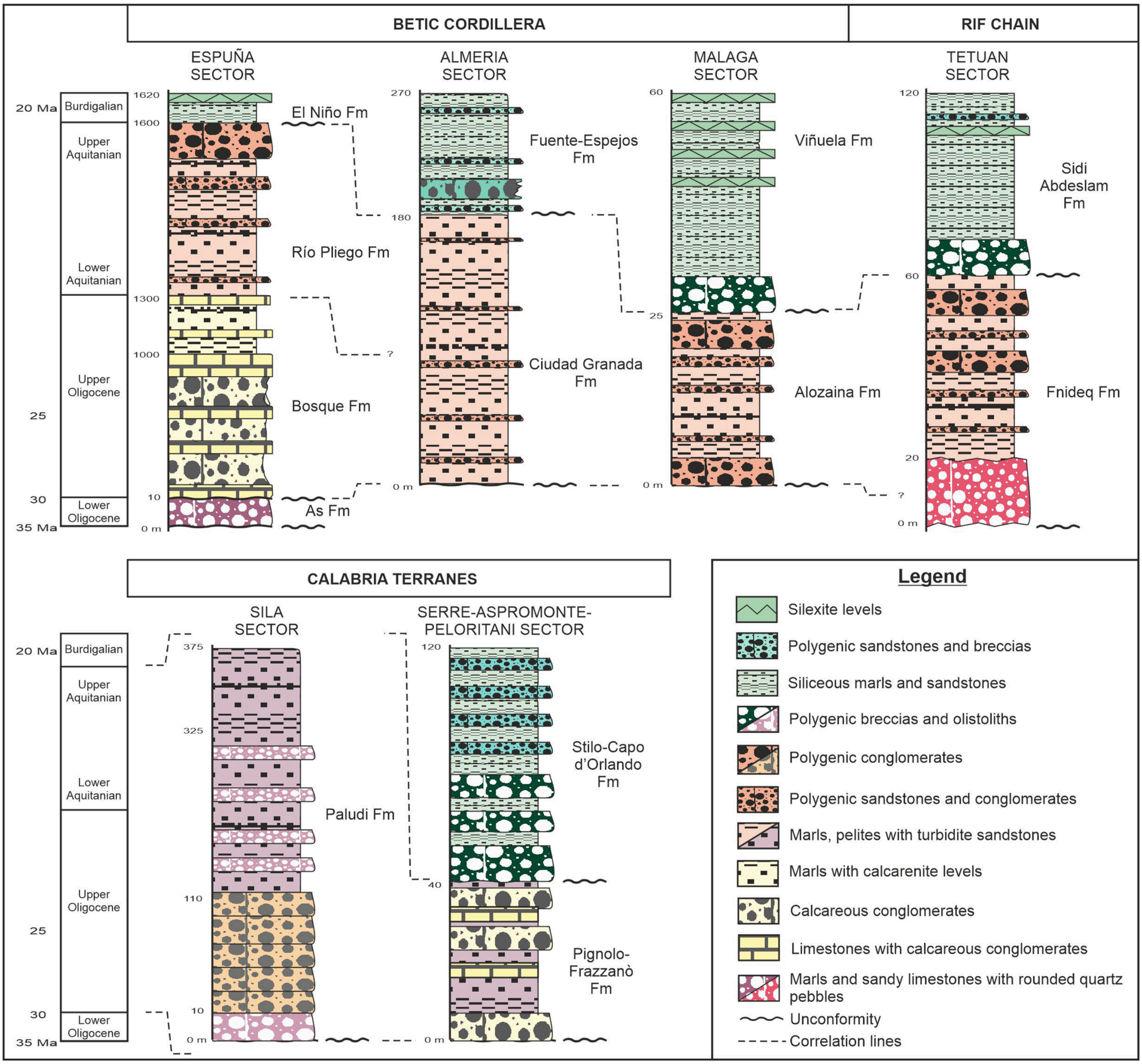

Fig. 6. Synthetic stratigraphic columns from the Espuña, Almería and Málaga sectors from the Betic Cordillera (Perri et al., 2017; Critelli et al., 2021); Ghomaride of the Tetuan sector in the Rif Chain (Perri et al., 2022); and Sila and Serre-Aspromonte-Peloritani sectors in the Calabrian Terranes (Bonardi et al., 2002, 2003).

Sánchez et al., 2019). This is overlain by an uppermost Triassic to Cretaceous carbonate succession comprising peritidal dolostones, ooidal and nodular limestones and thin-bedded mudrocks and cherty mudrocks. Related sedimentary successions also occur in other Alpine–Mediterranean Chains equivalent to the Maláguide Complex, such as the Moroccan Ghomarides, the Algerian Kabylides (Wildi, 1983), or the Italian Calabrian Terranes (Bonardi et al., 2001). The Mesozoic terrains are partially similar to those present in other Western Perimediterranean domains, such as the Subbetic Domain of the proper Betic Cordillera, the French Massif Central and the Italian Apennines.

The whole studied samples show lower rank metamorphic source terranes for the studied succession. The siliciclastic samples from the Oligocene As Fm highlight a high compositional maturity indicating a clear provenance from a craton interior area. Moreover, the presence of few phaneritic quartz-rich metamorphic lithic fragments might allow considering the residual influence of a high-medium grade metamorphic basement, more probably of extra Maláguide origin and may be identifiable with Calabro-Kabylide continental blocks (Martín-Algarra et al., 2000). In this formation, the redeposited macro foraminifers and extrabasinal carbonate lithic fragments, may represent the result of a first detrital supply eroded from the *meso*-Cenozoic cover of uplifted continental crust terranes.

The Bosque Fm is still marked by a continuous carbonate debris supply coming from early Cenozoic units of Maláguide Complex. The subordinate presence of shallow-marine platform lithic fragments including ooidal grainstones also indicates that the Mesozoic carbonates of the Maláguide cover were deeply eroded due to an active basement uplift. The sharp increase of siliciclastic component starting from the Upper Oligocene-upper Aquitanian Ciudad Granada Group (Alozaina, Ciudad Granada and Río Pliego fms) suggests abrupt changes in a source area dominated by Paleozoic to Triassic metamorphic and sedimentary terrigenous rocks. In detail, the upper Oligocene-upper Aquitanian formations belongs to quartzose and transitional recycled fields, while the Budigalian Viñuela Group (Viñuela, Fuente-Espejos and El Niño fms) is

Table 1
Recalculated modal point-count data of the studied sandstone suites (according to Dickinson, 1970; Ingersoll and Suczek, 1979; Critelli and Le Pera, 1994; Zuffa, 1980) for the studied sandstones. Q (quartz Qm + Qp), Qm (monocrystalline quartz), Qp (policrystalline quartz), F (feldspars), Lt (total lithic fragments L + Qp), L (aphanitic lithic fragments), NCE (non-carbonate extrabasinal grains), CI (carbonate), NCI (non-carbonate intrabasinal grains) CE (carbonate extrabasinal grains).

	Formation	%			%			%			References
		NCE	CI	CE	Qm	F	Lt + CE	Qt	F	L	
Espuña Sector	**El Niño**	62.4	0.0	37.6	61.0	0.0	39.0	60.0	0.0	40.0	Perri et al., 2017
	Río Pliego	83.6	3.9	12.5	26.0	0.0	74.0	61.9	0.0	38.1	
	Bosque	24.4	75.6	0.0	96.0	0.0	4.0	97.6	1.1	1.3	
	As	44.8	1.9	53.2	92.0	0.0	8.0	45.7	0.0	54.3	
Almería Sector	**Fuente-Espejos**	82.0	8.0	9.0	73.0	7.0	20.0	73.0	12.0	15.0	Critelli et al., 2021
	Ciudad Granada	85.0	6.0	9.0	81.0	8.0	11.0	78.0	9.0	13.0	
Málaga Sector	**Viñuela**	92.0	8.0	0.0	58.0	4.0	38.0	73.0	12.0	15.0	Critelli et al., 2021
	Alozaina	84.0	8.0	8.0	68.0	11.0	21.0	67.0	13.0	20.0	
Tetuán Sector	**Sidi Abdeslam**	96.0	0.0	4.0	35.0	2.0	63.0	41.0	2.0	56.0	Perri et al., 2022
	Fnideq	100.0	0.0	0.0	62.0	2.0	36.0	70.0	5.0	25.0	
Sila Sector	**Paludi**	75.0	6.0	19.0	55.0	36.0	9.0	57.0	36.0	7.0	Zuffa and De Rosa, 1978
Serre-Asprom.-Pelorit. Sector	**Stilo-Capo d'Orlando**	78.0	6.0	16.0	45.0	49.0	6.0	47.0	49.0	4.0	Cavazza, 1989; Puglisi, 1987
	Pignolo-Frazzanò	76.0	5.0	19.0	67.0	21.0	12.0	62.0	23.0	15.0	Puglisi et al., 2001

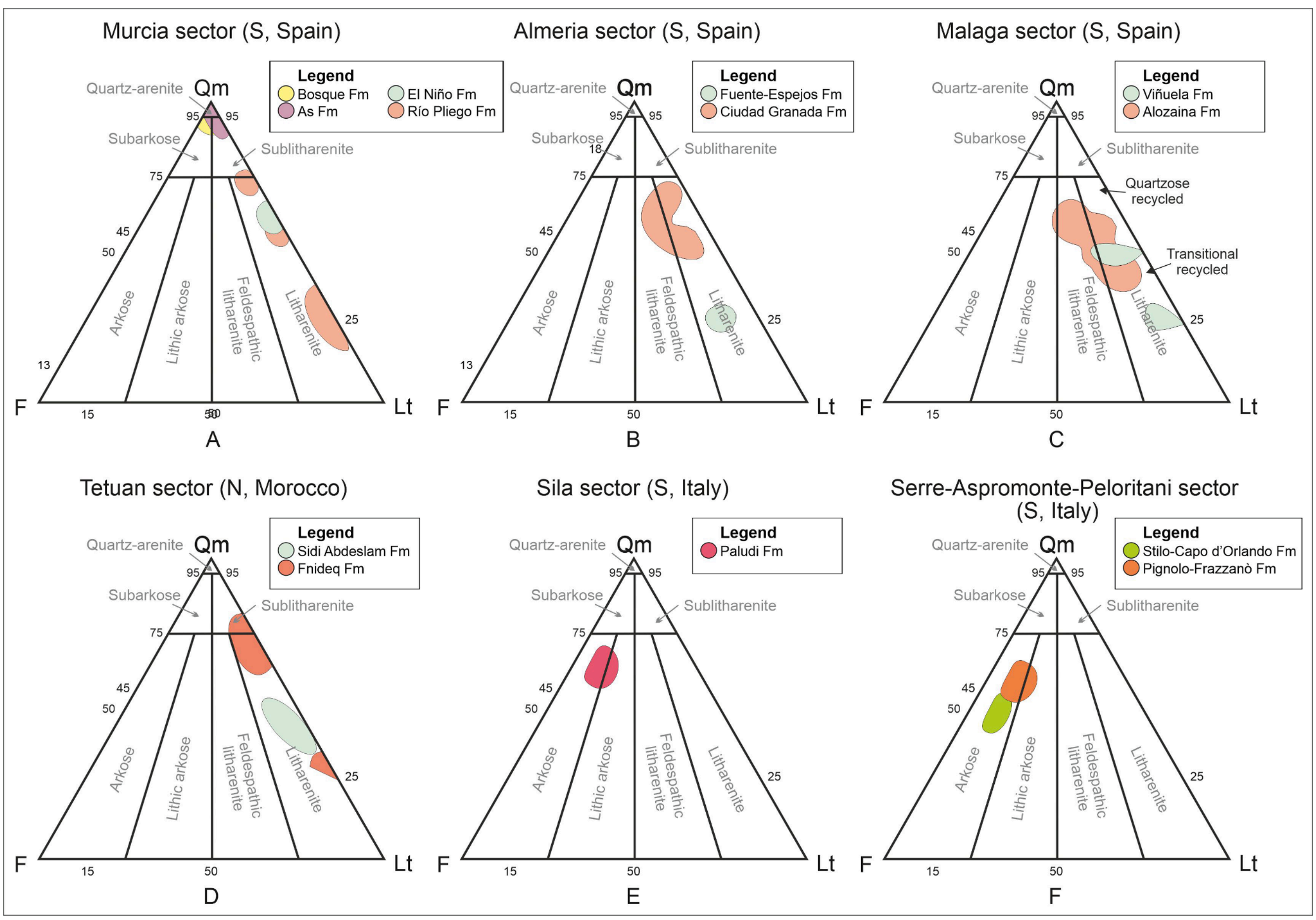

Fig. 7. QmFL diagrams with synthesis of detrital modes of the studied sectors: (Bonardi et al., 2002, 2003; Perri et al., 2017; Critelli et al., 2021; Perri et al., 2022): A, Espuña sector; B, Almería sector; C, Málaga sectorordillera; D, Ghomaride of the Tetuan sector; E, Sila sector; and F, Serre-Aspromonte-Peloritani sector. Qm (monocrystalline quartz), F (feldspars), Lt (total lithic fragments L + Qp), L (aphanitic lithic fragments), Qp (polycrystalline quartz).

entirely transitional recycled. It probably implies erosion of Variscan terranes (Ghomaride-Maláguide or similar) during the Oligocene-late Aquitanian, while during the Burdigalian a mainly mixed Variscan (Ghomaride-Maláguide) and Alpine (Setides-Alpujárrides) supply is intended due to tectonic unroofing (Lonergan and Platt, 1995). It is not excluded other source areas Kabylide-like according to Martín-Algarra et al. (2000).

5.1.2. *Rif Chain*

Petrological parameters and provenance analysis of the upper Oligocene-Burdigalian *syn*-orogenic strata of the Fnideq and Sidi Abdeslam fms also testify the changing nature of source-areas through time during progressive growth of the collisional belt and its unroofing sequence. The samples from this sector also mainly plot in a wide area at the QmLt side in the QmFLt diagram (Fig. 8) reflecting their transition between transitional and recycled orogenic provenance type.

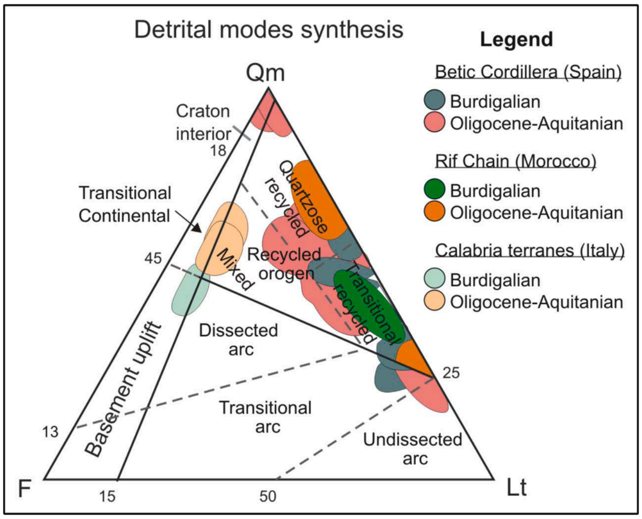

Fig. 8. QmFL diagram with synthesis of detrital modes from the whole considered sectors: Espuña, Almería and Málaga sectors from the Betic Cordillera; Ghomaride of the Tetuan sector in the Rif Chain; and Sila and Serre-Aspromonte-Peloritani sectors in the Calabrian Terranes.

Upper Oligocene to Burdigalian quartzolithic sandstones abruptly testify the progressive exhumation and erosion of the thrust belt involving Paleozoic metasedimentary rocks and their Mesozoic sedimentary cover. In detail, during the Late Oligocene-late Aquitanian, the source terranes seem to be the proper Ghomaride tectonostratigraphic unit (Mesozoic sedimentary cover and their Paleozoic low-grade metamorphic basement terranes), while, during the early Burdigalian, the lower units (i.e. deepest Ghomarides basements and locally Sebtides-Alpujárrides units and probably also other unknown units), source terranes seem to involve also sedimentary and metamorphic rocks.

5.1.3. Calabria terranes

Petrological parameters and provenance analysis of the Oligocene-Burdigalian strata of the Paludi, Pignolo-Frazzanò and Stilo-Capo d'Orlando fms also testify the changing nature of source-areas through time during progressive growth of the collisional belt and its unroofing sequence. Contrarily to the Betic and Rif sector, the samples from this sector mainly plot in an area near to the QmF side in the QmFLt diagram (Fig. 8) reflecting their transition between transitional continental and basement uplift orogenic provenance type with influence of a mixed recycled orogen and of a dissected arc. In detail, the Oligo-Aquitanian formations belong to the transitional continental-mixed recycled, while the Burdigalian formation show shifting to the basement uplift-dissected arc field.

5.2. Paleogeographic-paleotectonic implications

The deposition of the considered Oligocene-lower Miocene deposits was contemporaneous of the tectonic stacking of thrust units of the Internal Zones of the Betic-Rif-Calabria Circum-Mediterranean chains. Fig. 9 shows the evolutionary model for the central-western Mediterranean area (Amendola et al., 2016; Critelli, 2018; Critelli and Criniti, 2021; Guerrera et al., 2021) for the Cretaceous (Fig. 9A), Oligocene (Fig. 9B) and Burdigalian (Fig. 9C) times. Two sketch cross sections respectively for the Betic-Rif (Fig. 9 D) and Calabria (Fig. 9E) sectors at early Miocene times are also shown.

The petrographic analysis exposed before for the Betic and Rif Terranes reflect their local provenance from Paleozoic metasedimentary rocks and their *meso*-Cenozoic sedimentary cover. In detail, during the Oligocene-late Aquitanian, the source terranes seem to be the proper Maláguide-Ghomaride unit (Mesozoic sedimentary cover and their Paleozoic low-grade metamorphic basement terranes) (Fig. 9B) cotemporaneous to the shifting of the MM toward the west and the northwards stacking of thrust units within the MM. During the Burdigalian the lower units (i.e. Ghomarides-Maláguides basements and locally Sebtides-Alpujárrides units and probably also other unknown units), source terranes seem to involve also sedimentary and metamorphic rocks (Fig. 9C) contemporaneous of the subduction of the MLB below the MM and the opening of the Western Mediterranean Sea as a backarc basin. The tectonic setting was certainly complicated but these Oligocene-Lower Miocene formations were deposited unconformably over some crystalline basement and sedimentary cover units representing a piggy-back or wedge-top deposition on advancing Maláguide-Ghomaride thrust-belt (Martín-Algarra et al., 2000; Perri et al., 2017, 2022; Critelli et al., 2021) followed by backarc settings. The shifting of the supplies from quartzarenites, to lithic arenites and finally, litharenites the lithoclastic character in time implicates probably an unroofing from old terranes (during Oligocene and part of the Aquitanian) toward rejuvenated terranes with alpine metamorphic imprint (tectonic unroofing of the Alpine metamorphic units: Lonergan and Platt, 1995) in the Burdigalian.

The petrographic analysis exposed before for the Calabria Terranes reflect their local provenance from crystalline rocks of the Calabrian terranes. The tectonic setting of these basins is also complex; the sequences deposited unconformably over crystalline units could also represent a wedge-top deposition on advancing Calabrian thrust-belt (e.g. Weltje,1992; Critelli, 1993, 2018; Patacca et al., 1993; Wallis et al.,1993; Critelli and Le Pera, 1994, 1995, 1998; Tripodi et al., 2018). In this sector, the opening of the Tyrrhenian basin favoured a tectonic stacking toward the SE delayed with respect to the western sectors (Betic-Rif). The tectogenesis took place later during the Middle Miocene and, therefore, backarc basin opening took place later than in the western sectors. The fact of the direct erosion of a crystalline basement in the Calabria sector as revealed by this study implies a continental area with scarce or without sedimentary cover in the eastern part of the MM. The shifting of the supplies to increase the feldspathic character (arkose) implicates probably an unroofing toward plutonic rocks (granitic/orthogneissic) and rejuvenated terranes with the alpine metamorphic imprint.

6. Conclusions

- The clastic petrofacies study allowed to obtain parameters about the provenance and the paleogeographic-paleotectonic evolution of the Betic-Rif and Calabria sectors.
- The analysis performed in the Oligocene-Lower Miocene successions testifies the changing nature of source-areas through time, with marked differences in the studied sectors contemporaneous to the progressive growth of the collisional belt and the unroofing of source areas.
- In the western sector (Betic-Rif) the detrital suites are located in the QmLt side in the QmFLt diagram reflecting a transition between a craton, transitional and recycled orogenic provenance type. The whole studied samples show lower rank metamorphic source terranes for the studied succession.
- In detail, the Upper Oligocene-upper Aquitanian formations (Ciudad Granada Group: Alozaina, Ciudad Granada, Río Pliego and Fnideq fms) belongs to quartzose and transitional recycled provenance fields, while the Budigalian (Viñuela Group: Viñuela, Fuente-Espejos, El Niño and Sidi Abdeslam fms) is entirely transitional recycled.
- This evolution probably implies erosion of Variscan terranes (Ghomaride-Maláguide or similar) during the Oligocene-late Aquitanian, while during the Burdigalian a mainly mixed Variscan (Ghomaride-Maláguide) and Alpine metamorphic (Setides-Alpujárrides) supply is intended (not excluding other source areas from western sectors as the Kabylide-like.

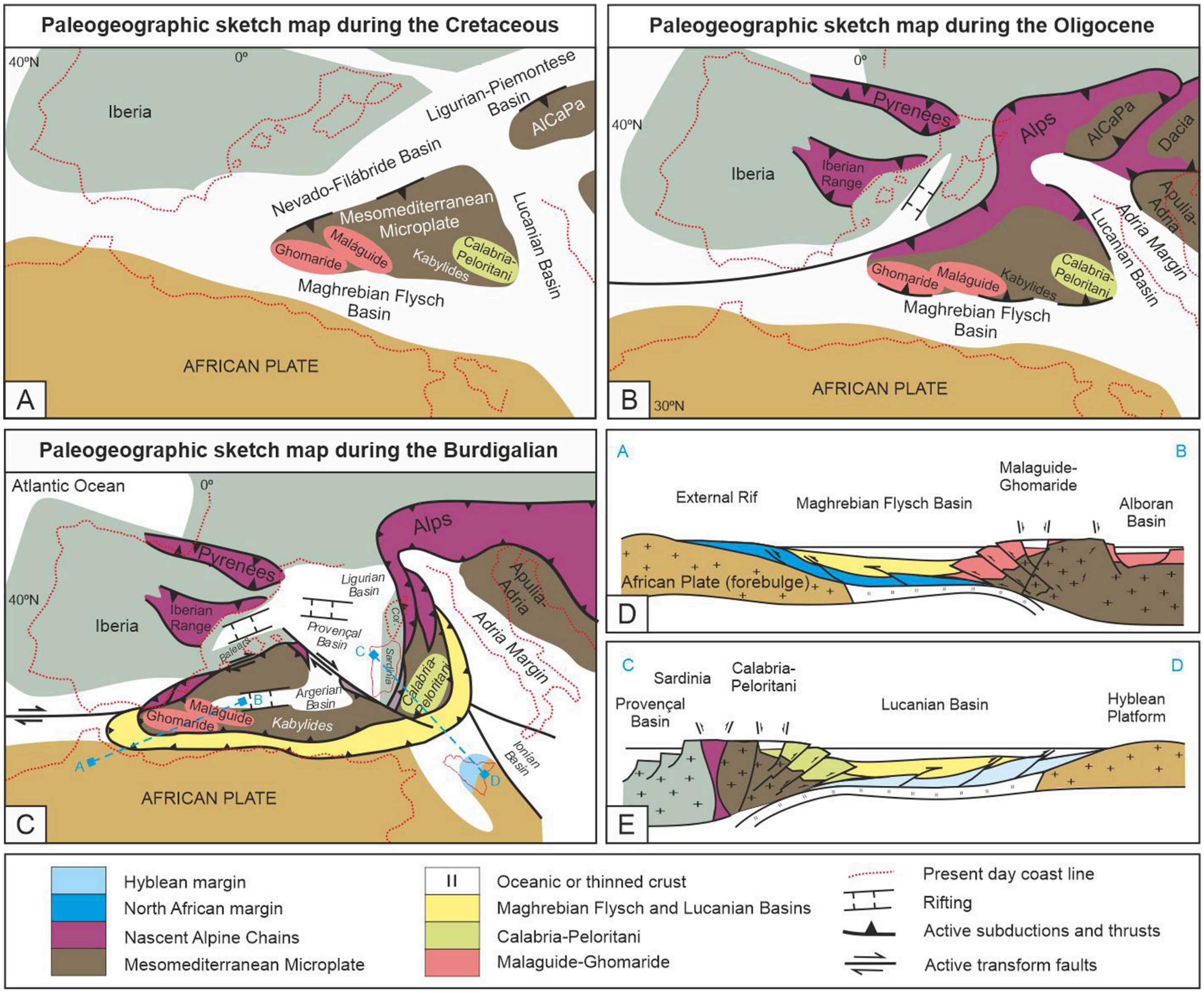

Fig. 9. Paleogeographic and paleotectonic evolutionary models for the Central-Western Mediterranean area during the Oligocene to Early Miocene. A) Cretaceous times sketch map (70 Ma); B) Oligocene times sketch map (25 Ma); C) Burdigalian times sketch map (20 Ma); D) paleogeographic sketch cross-sections of the Betic-Rif sector in the Burdigalian times (signaled in Fig. 9C). F) paleogeographic sketch cross-sections of the Calabria sector in the Burdigalian times (signaled in Fig. 9C).

- Contrarily to the Betic and Rif sector, the samples from the Calabria sector are mainly located in the QmF side in a QmFLt diagram reflecting their transition between transitional continental and basement uplift orogenic provenance type with influence of a mixed recycled orogen and of a dissected arc.
- In detail, the Oligo-Aquitanian formations (Paludi, Pignolo-Frazzanò fms) belong to the transitional continental-mixed recycled, while the Burdigalian Stilo-Capo d'Orlando formation show a shifting to basement uplift-dissected arc provenance fields.
- The deposition of the considered Oligocene-Lower Miocene formation was contemporaneous of the nappe stacking within the Internal Zones of the Circum-Mediterranean chains.
- For the Betic-Rif sectors the Oligocene-late Aquitanian, deposition was contemporaneous to the shifting of the MM toward the west and to the end of the northwards nappe stacking within the MM, and accounted in piggy-back or wedge top basins. During the Burdigalian sedimentation was contemporaneous of the subduction of the MLB below the MM and the opening of the Mediterranean basin as a backarc.
- The shifting of the supplies from quartzarenites, to lithic arenites and finally, litharenites the lithoclastic character in time implicates probably an unroofing from old terranes (during Oligocene and part of the Aquitanian) toward rejuvenated terranes with alpine metamorphic imprint in the Burdigalian.
- In the Calabria sector detrital suites reflect their local provenance from crystalline rocks. Deposition also took place on piggy-back or wedge-top basin over the advancing Calabrian thrust-belt toward the SE.
- In this sector, the opening of the Tyrrhenian basin was delayed with respect to western sectors (Betic-Rif) and, therefore, backarc basin opening was also delayed.
- The shifting of the supplies to increase the feldspathic character (arkose) implicates probably also an unroofing toward rejuvenated terranes with the alpine metamorphic imprint in the Calabria sector. This can reveal the great important of plutonic (granitic/orthogneissic) sources in this crustal segment, whereas such rocks in the Betic-Rif area should be much scarce.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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