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Review Article

Cenozoic detrital suites from the Internal Betic-Rif Cordilleras (S Spain and N Morocco): implications for paleogeography and paleotectonics

Manuel Martín-Martín [a,*], Francesco Perri [b], Salvatore Critelli [c]

[a] Departamento de Ciencias de la Tierra y Medio Ambiente, University of Alicante, Alicante, Spain
[b] Dipartimento di Biologia, Ecologia e Scienze della Terra, Università della Calabria, 87036 Arcavacata di Rende, CS, Italy
[c] Dipartimento di Ingegneria dell'Ambiente, Università della Calabria, 87036 Arcavacata di Rende, CS, Italy

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ABSTRACT

A synthesis of Cenozoic detrital suites from the Internal Betic-Rif Cordilleras is discussed in relations with major paleotectonic phases during growth of orogenic belts. The discussion has been focused on the Malaguide and Ghomaride complexes that have a Cenozoic sedimentary detritic cover. The heterogeneous petrographic composition of coarse detrital rocks, and the mineralogy and geochemistry of mudrocks indicate a multiple source area consisting in metamorphic, and recycled siliciclastic and carbonate source rocks, with a minor supply of mafic rocks during the early Miocene. The siliciclastic coarse detrital suites plot mainly in a wide area at the Qm-Lt side in a Qm-F-Lt diagram reflecting their transition between a craton, quartzose recycled, quartzose transitional orogenic, and finally lithic transitional orogenic provenance type. The Paleocene-Eocene successions seem to be affected by higher weathering effects than the Oligo-Miocene ones. Significant recycling and reworking processes should take place during the Paleocene-Eocene and the Oligo-Miocene before the final deposition. The source areas were characterized by non-steady-state weathering conditions reflecting a progressive cooling contemporaneous to the typical evolution of source areas where active tectonism allows erosion within weathering profiles developed on source rocks. A sharp increase of siliciclastic content together with the changes in sorting-recycling-weathering suggests abrupt changes in the source area starting from Oligocene. This fact allows subdividing the succession into the lower (Paleocene-Eocene) and the upper (Oligocene-Early Miocene) cycles. Lower cycle was contemporaneous to the Eo-Alpine tectonic phase, which was reflected in the Malaguide and Ghomaride domains by basement folding and deep tectonics with fault-propagation folds, accomplished by minor rising or reliefs and deepening of subsidence areas. Contrarily, the upper cycle took place during the Neo-Alpine phase, when in the Malaguide and Ghomaride domains, thrustings should become superficial contemporaneous to subduction and stacking of tectonic units. This led to a strong increasing of rising areas reflected in the sedimentation by the occurrence of coarse terrigenous deposits in wedge-top basins. The early Miocene also shows the influence of volcanism in the Mediterranean region, and/or the erosion of magmatic-metamorphic rocks derived from deep tectonic levels affected in the Eo-Alpine phase or belonging to the Hercynian bedrock. This evolution fits well with recent paleogeographic-geodynamic models for the western-central Mediterranean.

1. Introduction

The Alpine circum-Mediterranean orogenic belts were constructed due to a cycle of extension (rifting-drifting-oceanization) during the late Paleozoic-to-Mesozoic, and compression (convergence-subduction-collision) during Cenozoic in the Tethyan domain, and involved plates and microplates derived from the Pangea break-up in this area (Critelli, 1993, 2018; Critelli et al., 2008; Alcalá et al., 2013; Guerrera and Martín-Martín, 2014; Guerrera et al., 2013, 2015, 2021; Martín-Martín et al., 2001, 2020a, 2020b, 2022, 2023; Matano et al., 2020; Belayouni et al., 2023; Criniti, 2023). The Tethys Ocean was located between Africa and Eurasia mainly during the Mesozoic (Guerrera et al., 2021). It was composed by several oceanic branches and intermediate microplates and it was closed during Cretaceous-Cenozoic times being replaced by the Mediterranean Ocean since the late Lower Miocene (Critelli, 1993, 2018; Perri et al., 2017; Critelli et al., 2021). In the case

* Corresponding author.
E-mail address: manuel.martin@ua.es (M. Martín-Martín).

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of the western Tethys (Fig. 1A), Africa and Iberia-Europe were the main plates to the south and north, respectively (Doglioni, 1992; Guerrera et al., 2021). Two groups of models explain the Alpine evolution of this region. One group consider a microplate separated by two oceanic branches; the second group do not consider a microplate but a domain continuation of the Iberian Massif. In the case of the first group of models, between Africa and Iberia, the Mesomediterranean Microplate (*MM*) was located separated by the Maghrebian Flysch Basin (*MFB*), to the south, and Nevado-Filábride Ocean, to the north (Doglioni, 1992) (Fig. 1A). Contrarily, the group of models not considering the intermediate microplate proposed the *AlKaPeCa* (acronym of Alboran-Kabylide-Peloritani-Calabria) domain attached to the Iberia Massif until the Algerian Sea opening during Oligocene-early Miocene times. In this case, only the *MFB* existed in the westernmost Tethys. Towards central Tethyan areas both groups of models propose the existence of two Tethyan oceanic branches separating other microplates as Adria and Apulia (Liguride-Piemontese, to the north, Lucanian-Ionian, to the south). Whatever the model considered, the closing of these oceanic Tethyan branches took place in two phases separated in time (Critelli, 2018; Martín-Martín et al., 2020a, 2020b; Guerrera et al., 2021): The northern branch was closed by a southward subduction during Cretaceous-Paleogene times in the so-called Eo-alpine phase (Martín-Martín et al., 2001, 2020a, 2020b; Guerrera et al., 2021; Critelli and Martin-Martin, 2022). Contrarily, the southern Tethyan branch was closed by a northward subduction of the Maghrebian Flysch-Lucanian-Ionian below the *MM* or *AlkaPeCa* during the late Oligocene-early Miocene in the Neo-alpine phase (Martín-Martín et al., 2001, 2020a, 2020b; Guerrera et al., 2021). During the Eo-alpine phase the Alps, Pyrenees and Iberian Range were constructed (Guerrera et al., 2021). In turn, during the Neo-alpine phase the Betic, Maghrebian and Apennine chains were developed (Martín-Martín et al., 2001, 2020a, 2020b; Guerrera et al., 2021). This was followed of the opening of the different basins of the Mediterranean Ocean as back-arc basins related to the Neo-alpine subduction mainly from early Miocene times on (Guerrera et al., 2021).

Tethyan oceanic areas and also the margins of the plates and microplates 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. The goal of this research was the study of the deposits related to accretionary orogenic systems just cotemporaneous to the structuring in folds and thrust nappes during the Cenozoic. These sedimentary strata were clastic with interbedding of pelagic and carbonate beds. The detrital supply of these strata gives information from sources areas 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 areas. Provenance interpretations are essential to reconstruction and testing of paleogeographic and paleotectonic models since the distinctive detrital petrofacies suites are related to specific provenance source areas. In the case of mudrocks, the geochemical analyses allow determining the source areas composition, as well as, paleoweathering, paleotectonic, sorting, reworking and recycling processes. In the source are, is possible identifying sedimentary, metamorphic or magmatic (felsic vs. mafic) source areas. For that purpose, Cr/V vs. Y/Ni plots, and V-Ni-La*4 ternary diagram were used. Moreover, these analyses also allow proposing the sorting, reworking and recycling during erosion, transport and sedimentation meanwhile Al–Ti–Zr ternary diagram. Finaly, the paleoweathering and paleotectonic process (warm vs. cold, and/or wet vs. dry periods) can be analyzed by the use of A-CN-K and A-N-K plots. The general significance here is that the application of petrographic, mineralogical and geochemical provenance analysis can give light 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. Sedimentary Cenozoic strata are well represented in the Internal Tectonic Units of the Mediterranean belts (Fig. 1B). This paper discusses the petrography, mineralogy and geochemistry of Cenozoic rocks (sandstones and mudrocks) derived from the southern margin of the *MM* that are nowadays exposed in the Internal Units of the Betic Cordillera and Rif Chain of the western Mediterranean belts. A synthesis of previously published partial data from these units from the mentioned belts is presented.

2. Geological setting

The Betic and Rif orogenic chains are composed by three main sets of units (Guerrera and Martín-Martín, 2014) (Fig. 1B): (1) the Internal Units derived from the *MM* (or *AlKaPeCa* according the models) with a pre-Alpine continental basement (Paleozoic or older crystalline rocks previously affected by the Hercinian orogeny) with carbonate-pelagic-clastic Mesozoic-Cenozoic covers strongly deformed, part of thrust nappes and frequently affected by Alpine metamorphism; (2) the Maghrebian Flysch Basin Units (*MFB*) formed by clastic and pelagic deposits on oceanic and/or transitional crust; and (3) the External Units, belonging to the Iberia and Africa Margins and made of a pre-Alpine continental crust, followed by sedimentary carbonate-pelagic-clastic Mesozoic-Cenozoic covers also deformed and part of thrust nappes. Equivalent to these units can be found in the Algerian Tellian Kabylide units and in the Calabria-Peloritani Terranes in Sicily and the Southern Apennines. Our studies on the Cenozoic strata are focused on non-metamorphic Internal Units from the Betic Cordillera (S, Spain) and

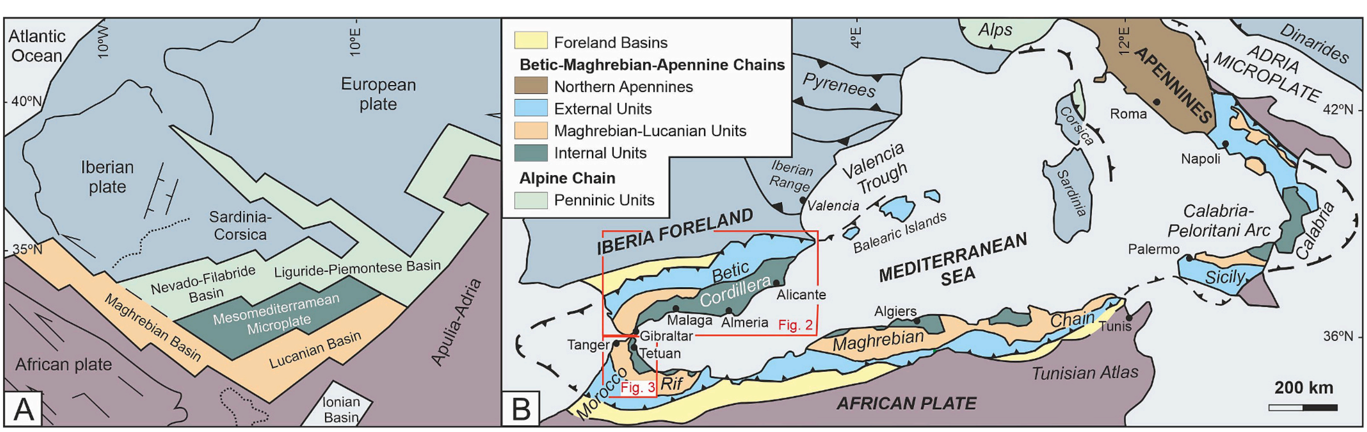

Fig. 1. A, Paleogeographic reconstruction of the central-western Mediterranean area showing the position of the Mesomediterranean Microplate (Doglioni, 1992). B, Geological sketch map of the Central-Western Mediterranean area with location of studied sectors in Figs. 1 and 2. Modified from Martín-Algarra (1987), Guerrera et al. (1993, 2005), Perrone et al. (2006), Critelli et al. (2008), Perri et al. (2013) and Guerrera et al. (2021).

Rif Chain (N, Morocco). Sedimentary Cenozoic deposits are well represented and preserved from metamorphism in the Malaguide Complex in the Betic Cordillera and the equivalent Ghomaride Complex in the Rif Chain, being these deposits the aim of this research. Since we support the existence of the Mesomediterranean Microplate (*MM*) separated by two oceanic branches in the westernmost Tethys (sensu Doglioni, 1992; Gerrera et al., 2021), our results will be presented considering this paleogeographic-geodynamic model.

2.1. Betic Cordillera (S Spain)

The Betic Cordillera is divided in a classic way into the Internal and the External Zones (Martín-Algarra, 1987; Vera, 2004). These are separated by the intermediate *MFB* units represented by the Campo de Gibraltar Complex. Unconformable over these ensembles the Neogene basins can be found. The framework is completed with the Neogene volcanism in the Almería area and below the Mediterranean Sea. The Internal Zone is, in turn, divided from bottom to top in the Nevado-Filábride, Alpujárride and Malaguide complexes structured in an anticlinal stack and derived from the *MM* and surrounded oceanic areas (Martín-Algarra, 1987). The Internal Zone is also composed by the so-called Frontal Units made of Alpujarride-Malaguide cover nappes located in frontal position in the Internal-External Zone boundary. The Nevado-Filábride and Alpujarride complexes are mainly metamorphic, while the Malaguide and the Frontal Units, are not metamorphic or slightly affected in the basements. The Malaguide units show a crystalline basement and a Mesozoic-Cenozoic cover. The Frontal Units show a very reduced or absent crystalline basement and mainly a Mesozoic-Cenozoic cover. Only a few Alpujarride and mainly the Malaguide and the Frontal Units show Cenozoic sedimentary covers mainly characterized by siliciclastic successions. The Intermediate *MFB* Units are made of Cretaceous to Lower Miocene marine clastic successions deposited in the Maghrebian Flysch Basin (Martín-Algarra, 1987; Vera, 2004; Guerrera and Martín-Martín, 2014; Guerrera et al., 1993, 2005, 2015, 2021) appearing now structured in thrust units and sandwiched between the Internal and External units. The External Zone is divided in the tectono-paleogeographic Prebetic (attached to the Iberian Foreland) and Subbetic units (Martín-Algarra, 1987; Vera, 2004). Prebetic is divided into internal and external (a meridional Prebetic is also mentioned as transition to the Subbetic in the eastern part of the chain), while the Subbetic is divided into internal, medium and external. Other more complex divisions associated to regions are also mentioned in literature for Prebetic and Subbetic (Vera, 2004). These units usually thrust from S to N to the next externalmost unit. Prebetic and Subbetic are made of sedimentary Mesozoic and Cenozoic successions. The Neogene basins and volcanism appear related to extension or strike-slip faulting from Burdigalian times on and associated to the back-arc aperture of the Mediterranean Ocean (Vera, 2004). A special case is the Guadalquivir Basin that acted as foreland basin of the Betic system (Vera, 2004).

2.2. Rif Chain (N Morocco)

This orogenic chain represents the southward continuation of the Betic Cordillera by mean of the Gibraltar Strait and it is also divided in a classic way into the Internal and the External Zones (Martín-Martín et al., 2022, 2023) with the Intermediate Flysch Units (Chalouan et al., 2008; Michard et al., 2008). In a similar way to the Betic Cordillera, Neogene basins are located over these units. The Internal Zone is made of two main overimposed units (Guerrera and Martín-Martín, 2014; Critelli et al., 2017; Martín-Martín et al., 2020a, 2020b, 2020c; among others): Sebtide (equivalent to the Betic Alpujárride) and Ghomaride (equivalent to the Betic Malaguide). The Rif Internal Zone is also composed by the Frontal Units also made of Sebtide-Ghomaride cover nappes located in frontal position in the Internal-External Zone boundary. The Sebtide Complex is mainly metamorphic, while the Ghomaride and the Frontal Units, are not metamorphic or slightly affected in the basements. These units show crystalline basements and Mesozoic covers. Only a upper Sebtide and mainly the Ghomaride and the Frontal Units show Cenozoic sedimentary covers. The Intermediate Flysch Zone consists of Cretaceous-Miocene tectonic units mainly characterized by siliciclastic successions deposited on oceanic and/or continental thinned crust of the *MFB* located between *MM* and African Margin (Guerrera et al., 1993, 2005; Durand Delga et al., 2000). The External Zone is made of a set of thrust units (oriented describing and arc from the S to the W) and divided into the Intrarif, Mesorif and Prerif from internal to external position in the mountain chain (Suter, 1980; Chalouan et al., 2008; Michard et al., 2008). Overimposed to the whole structure the Neogene basins appear related to extension or strike-slip faulting due to the Mediterranean opening. The most important is the Gharb Basin that acted as foreland basin and in contact with the Moroccan Meseta and the Middle Atlas as Foreland of the Rif system (Michard et al., 2008).

3. Studied sectors

The study of Cenozoic deposits of non-metamorphic units from the Internal Zones in the Malaguide (Betic Cordillera) and Ghomaride-Internal Frontal Units (Rif Chain) complexes were published in several papers in the last years (Perri et al., 2017; Critelli et al., 2021; Perri et al., 2022). In concrete, five sectors were studied: three along the Betic Cordillera (Espuña, Almería and Málaga sectors) and two along the Rif Chain (Tetouan and Martil sectors). In each sector stratigraphic formations were defined in literature (Fig. 4). The most complete Cenozoic succession can be found in Sierra Espuña in the Murcia area (Perri et al., 2017) where a complete Paleocene-Lower Miocene succession is represented by several stratigraphic formations related by lateral or upward stratigraphic passages (Mula, Espuña, Valdelaparra, Malvariche, Canovas, As, Bosque, Rio Pliego and El Niño fms). This sector must be considered the reference sector for the Cenozoic Succession of the Malaguide-Ghomaride complexes. In the Almería (Xiquena, Ciudad Granada and Fuente-Espejos fms) and Málaga (Paleocene, Eocene, Alozaina and Viñuela fms) sectors from Betic Cordillera the successions are more incomplete and discontinuous. In the case of the Moroccan Rif, the succession is also incomplete and discontinuous and outcropping in two different sectors: Tetouan (Paleocene and Eocene fms) and Martil (Fnideq and Sidi Abdeslam fms). A synthetic nomenclature is adopted in this research made of four stratigraphic groups which take into consideration all the stratigraphic formations (Fig. 4): Mula (Paleocene), Espuña (Eocene-Lower Oligocene), Ciudad Granada (Upper Oligocene-Aquitanian) and Viñuela (Burdigalian). In all the sector and cases an important increase in the detrital supply is noticed from Oligocene times on (Perri et al., 2017; Critelli et al., 2021; Perri et al., 2022).

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

The Murcia sector belongs to the Malaguide Complex from the Sierra Espuña area in S Spain (Fig. 2) and it was studied by Perri et al. (2017). In this area, it crops out a complete and thick Paleocene to Lower Miocene succession (considered as a reference) consisting in nine stratigraphic fms (Figs. 4 and 5). The succession starts with the Paleocene Mula Fm made of 30 m of grayish pelites, limestones and calcarenites representing the marine platform. It is followed after an unconformity by the Espuña and Valdelaparra fms representing the marine internal platform and made of 75 m of nummulite-alveolina limestone (with a quartzose basal level of a few meters) and marshy marls with lignite beds, respectively. Upwards, the succession follows with the Malvariche and Cánovas fms representing the marine external platform and made of 485 m of nummulite-rich calcarenites and sandy reddish marls. It follows with 10 m of marls with sandy limestones with rounded quartz pebbles from the As Fm (Lower Oligocene) belonging to an internal marine platform. This is followed after an unconformity by almost 1300 m of calcareous conglomerates, limestones, yellowish marls and calcarenites from the Bosque Fm (Upper Oligocene) representing a

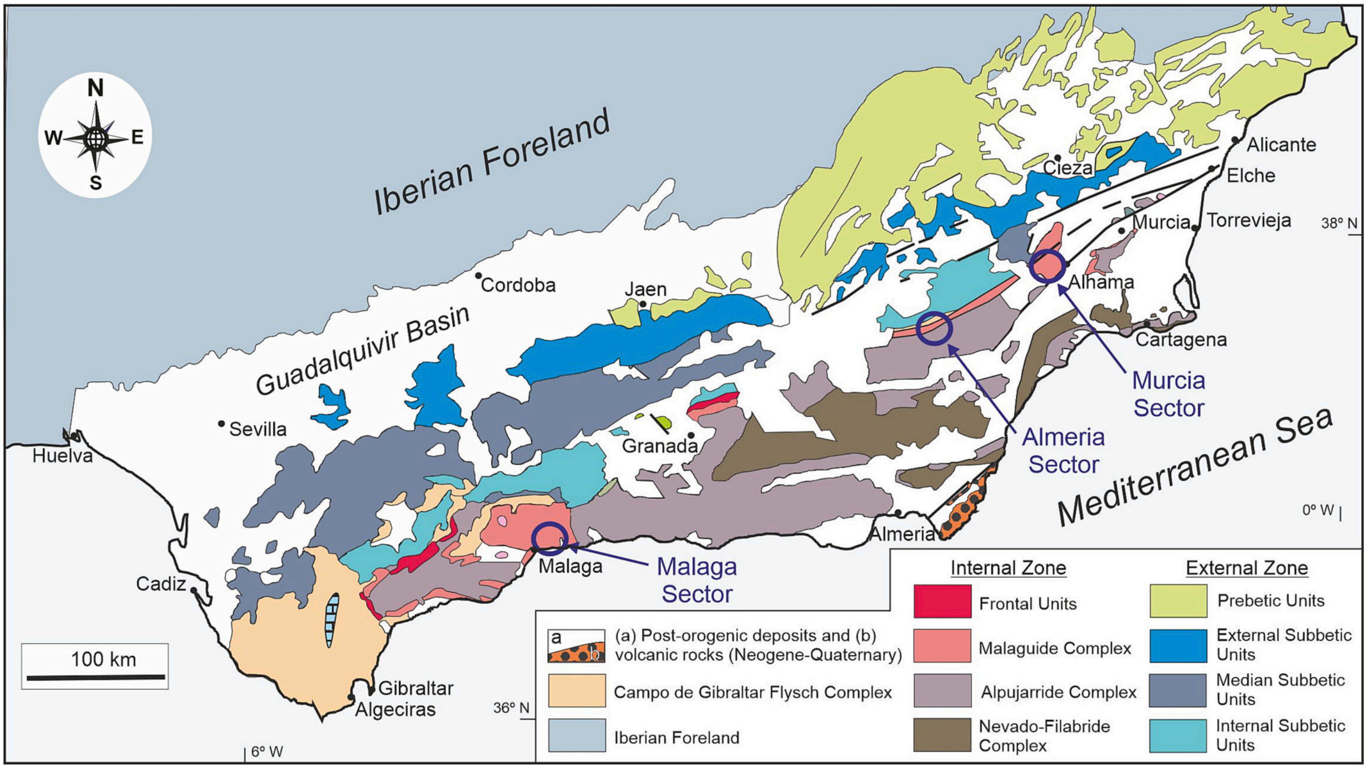

Fig. 2. Geological sketch map of the Betic Cordillera (S, Spain, modified from Martín-Algarra (1987) and Vera (2004) with location of the studied sectors.

delta and the 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 from the Río Pliego Fm (Upper Oligocene-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)

The Almeria sector belongs to the Malaguide Complex from the Velez-Rubio area in S Spain (Fig. 2) and it was studied by Critelli et al. (2021). In this area an incomplete and discontinuous Eocene to Lower Miocene succession crops-out representing the shallow marine realms evolving upward to slope or deep basin (Figs. 4 and 5). The succession starts with Xiquena Fm made of 60 m of nummulite-alveolina limestones with a quartzose basal level of a few meters and followed by 90 m of nummulite- and algae-rich calcarenites with intercalations of pinkish sandy marls. After an unconformity, it follows the Ciudad Granada Fm (Upper Oligocene-Aquitanian) made of 180 m of reddish pelites, turbidite sandstones and slope channel polygenic conglomerates. After a new unconformity the succession ends with the Fuente-Espejos Fm (Burdigalian) made of 90 m of greenish pelites with polygenic breccias, turbidite sandstones and silexite beds from.

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

The Málaga sector belongs to the Malaguide Complex from the Málaga city area in S Spain (Fig. 2) and it was studied by Critelli et al. (2021). In this area, it crops out also an incomplete, discontinuous and very deformed Paleocene to Lower Miocene succession, arranged into a transgressive sequence representing the shallow marine or transitional realms passing upward to slope or deep basin (Figs. 4 and 5). The succession begins with the Paleocene Fm made of 30 m of reddish continental beds, and grayish pelites, limestones and conglomerates representing the shallow marine platform. It is followed after an unconformity by the Eocene Fm representing the marine internal platform and made of 30 m of nummulite-alveolina limestone (with a quartzose basal level of a few meters) with marshy marls intercalations (locally with black levels) in the upper part. It follows the Alozaina Fm (Upper Oligocene-Aquitanian) made of 25 m of turbidite sandstones and slope channel polygenic conglomerates with reddish pelites from. 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)

The Tetouan sector belongs to the Internal Frontal Units (with Ghomaride bearing) from the Internal Rif Zone in N Morocco (Fig. 3) and it was studied by Perri et al. (2022). In this area, it crops-outs a discontinuous Paleocene-Eocene succession with two shallow marine stratigraphic formations (Figs. 4 and 5). The succession starts with the Paleocene Fm made of 10 m of grayish pelites and calcarenites representing a shallow marine platform. It is followed after an unconformity by the Eocene Fm representing the marine platform and made of 30 m of alveolina-rich limestone (with a quartzose basal level of a few meters) followed by another 30 m of nummulite- and algae-rich calcarenites with intercalations of pinkish-yellowish sandy marls.

3.5. Martil sector (Western Rif Cordillera, N Morocco)

The Martil sector belongs to the Ghomaride Complex in N Morocco (Fig. 3) and it was also studied by Perri et al. (2022). In this area a complete but thin Oligo-Lower Miocene succession with two marine stratigraphic formations crops-out (Figs. 5 and 6). The succession begins with 10 m of marls with sandy limestones with rounded quartz pebbles from the base of the Fnideq Fm (Oligocene) followed in continuity by 40 m of reddish pelites, turbidite sandstones and slope channel polygenic conglomerates from the upper Fnideq Fm (Upper Oligocene-

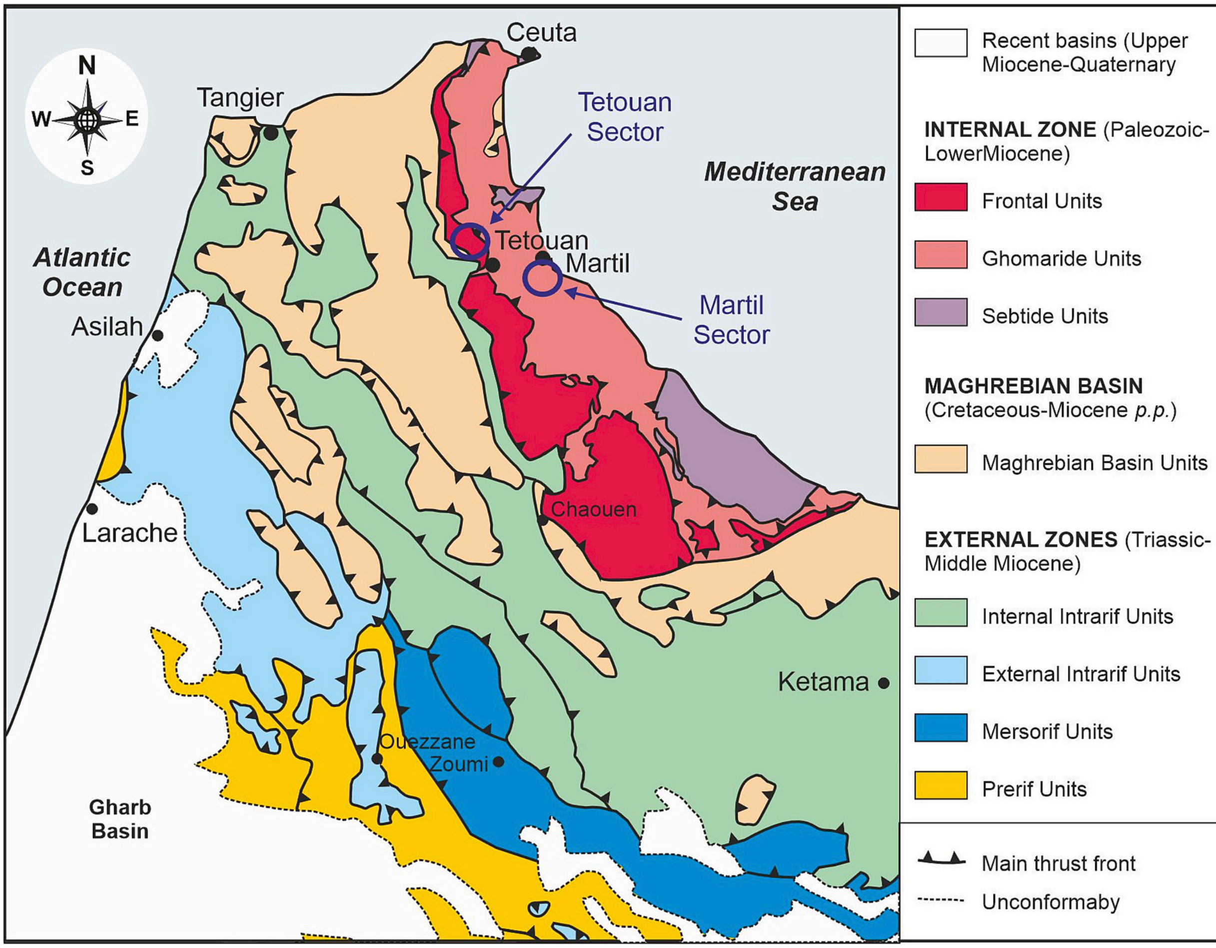

Fig. 3. Geological sketch map of the Rif Chain (N, Morocco, modified from Chalouan et al. (2008) and Michard et al. (2008) with location of the studied sectors.

Malaguide Complex (Betic Cordillera, S Spain)			Ghomaride Complex (Rif Chain, N Morocco)		Malaguide-Ghomaride Complexes
Stratigraphic Formations Espuña sector	Stratigraphic Formations Almeria sector	Stratigraphic Formations Malaga sector	Stratigraphic Formations Tetouan sector	Stratigraphic Formations Martil sector	Synthetic adopted nomenclature
El Niño Fm	Fuente-Espejos Fm	Viñuela Fm		Sidi Abdeslam Fm	Viñuela Group
Rio Pliego Fm	Ciudad Granada Fm	Alozaina Fm		Fnideq Fm	Ciudad Granada Group
Bosque Fm					
As Fm	Gap	Gap			Espuña Group
Canovas Fm					
Malvariche Fm	Xiquena Fm		Eocene Fm		
Valdelapara Fm		Eocene Fm			
Espuña Fm					
Mula Fm	Gap	Paleocene Fm	Paleocene Fm		Mula Group

Fig. 4. 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); and Tetuán and Martil sectors fom the Rif (Perri et al., 2022).

Aquitanian). The succession finishes after an unconformity with the Sidi Abdeslam Fm (Burdigalian) made of 60 m of polygenic breccias, turbidite sandstones and greenish pelites and silexite beds.

4. Detrital modes composition

The composition of 15 samples of sandstones, calcarenites and microconglomerates are presented here as mean detrital modes. Data set includes a review of previously published data from key areas of the western Mediterranean belt, including Betic Cordillera (S, Spain) and the Rif Chain (N, Morocco) where data were analyzed with comparable methodology to define overall compositional trends. Table 1 lists the mean detrital modes of the data subdivided according to the age and the sector. 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

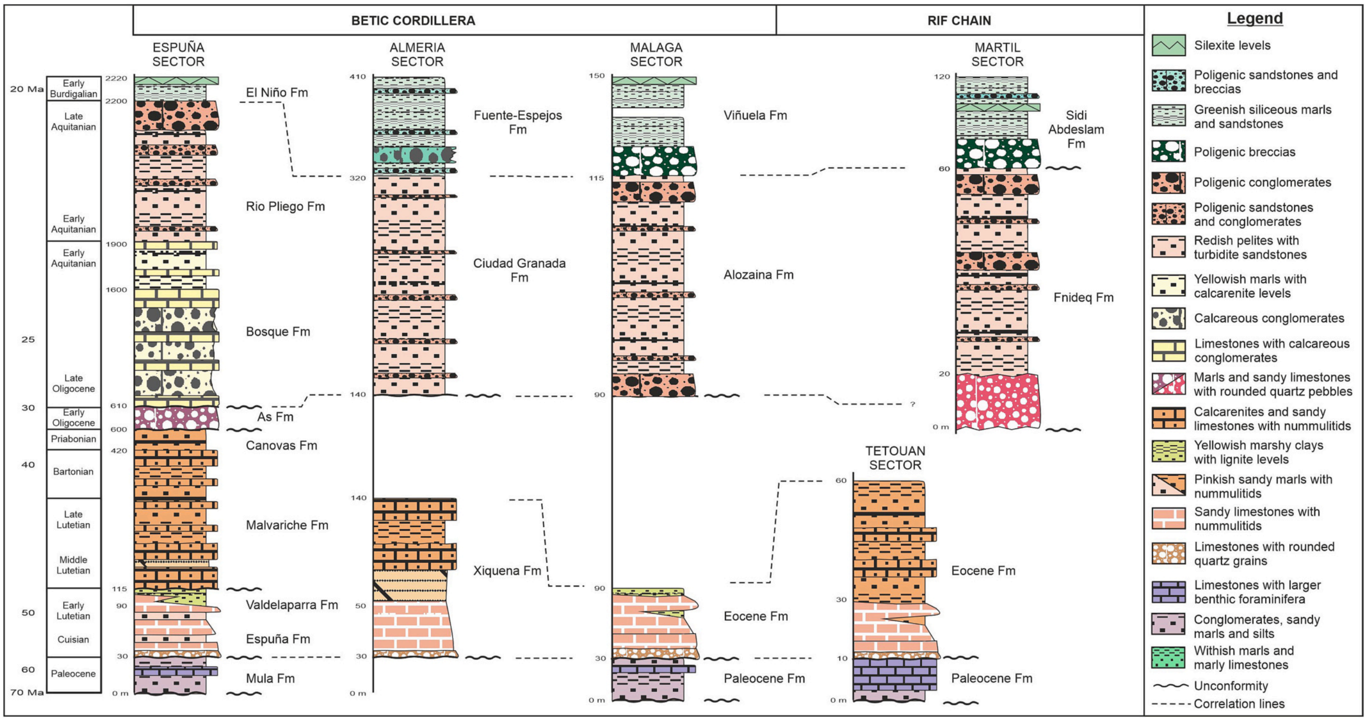

Fig. 5. Synthetic stratigraphic columns from the Espuña, Almería and Málaga sectors from the Betic Cordillera (Perri et al., 2017; Critelli et al., 2021); Tetuán and Martil sectors fom the Rif Chain (Perri et al., 2022).

modes are those of Dickinson (1970, 1985), Zuffa (1985, 1987), Critelli and Le Pera (1994), and Critelli and Ingersoll (1995), Critelli et al. (2022) 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 carbonate lithic 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), that during counting are summed as quartz (Qm) and feldspar (F) or micas or dense mineral grains (e.g., Ingersoll et al., 1984; Zuffa, 1985, 1987; Critelli and Le Pera, 1994; Critelli and Ingersoll, 1995; Critelli and Criniti, 2021).

The results are represented in the diagrams from Fig. 6 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%. In all sectors most of the samples are represented in the Qm-Lt part of the diagram and these belong to the quartarenite, sublitharenite and litharenite fields. In the case of the Almería, Málaga and Tetouan sector a few Eocene to Oligo-Aquitanian samples are represented in the subarkose-feldespathic litharenite fields.

4.1. Betic Cordillera

In the Internal Betic Cordillera only the Malaguide Complex has preserved sedimentary suites from Paleocene to Lower Miocene detrital suites. This tectonic complex was studied in three sectors of the cordillera with 11 samples: Murcia (eastern), Almería (eastern) and Málaga (central) (Perri et al., 2017; Critelli et al., 2021). In the Murcia sector (5 samples), the Paleogene succession (Table 1; Fig. 6A) (Perri et al., 2017) evolves from quartzarenites (Qm96 F0 Lt4) (Eocene) with poor in litic content, to quartzarenites (Qm92 F0 Lt8) (Lower Oligocene) with dominance of sedimentary clasts with carbonatic content (Fig. 6A), to calcarenites with a low detritic content but with quartzose composition (Qm96 F0 Lt4) (Upper Oligocene) (Fig. 6A). During the uppermost Oligocene-to-Burdigalian sandstones evolve to quartzolithic: (Qm26 F0 Lt74) (Upper Oligocene-Aquitanian) with dominance of sedimentary clasts (NCE), but in this case with a clear increase of metamorphic clasts (Fig. 6A); and (Qm61 F0 Lt39) (Burdigalian) with dominance of sedimentary clasts (NCE) and an abrupt decrease of metamorphic clasts with respect to the former stratigraphic formation (Fig. 6A). The sandstones from the Almería sector (3 samples) are more monotonous with always a quartzolithic composition (Table 1; Fig. 6B) (Critelli et al., 2021): (Qm66 F7 Lt27) (Eocene) with a dominance of the detritic content (NCE); (Qm81 F8 Lt11) (Upper Oligocene-Aquitanian) with dominance of sedimentary clasts (NCE), but in this case with a clear increase of metamorphic clasts (Fig. 6B); (Qm73 F7 Lt20) (Burdigalian) with dominance of sedimentary clasts (NCE) and a progressive decrease of metamorphic clasts with respect to the former stratigraphic formation (Fig. 6B). The sandstones from the Málaga sector (3 samples) also show a monotonous quartzolithic composition (Table 1; Fig. 6C) (Critelli et al., 2021): (Qm62 F8 Lt29) (Paleocene-Eocene) with low detrital content and dominance of CI; (Qm68 F11 Lt21) (Upper Oligocene-Aquitanian) with dominance of sedimentary clasts (NCE), but in this case with a clear increase of metamorphic clasts (Fig. 6C); (Qm58 F4 Lt38) (Burdigalian) with dominance of sedimentary clasts (NCE) and a reduction of metamorphic clasts with respect to the former stratigraphic formation (Fig. 6C).

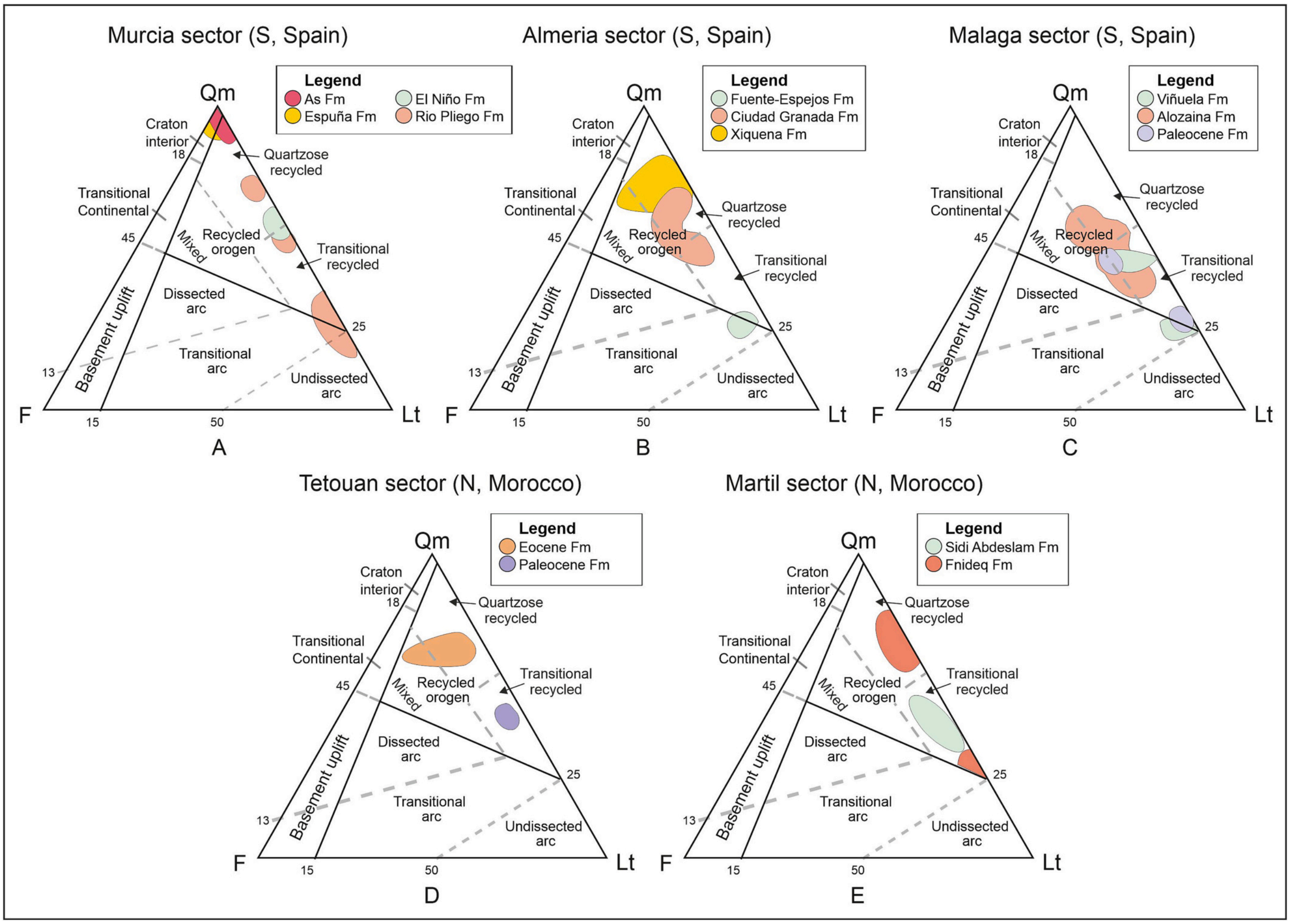

Fig. 6. Ternary discrimination diagrams of coarse rocks provenance (Perri et al., 2017; Critelli et al., 2021; Perri et al., 2022): A, Espuña sector; B, Almería sector; C, Málaga sector; D, Ghomaride of the Tetouan sector; and E, Ghomaride of the Martil sector. Qm (monocrystalline quartz), F (feldspars), Lt (total lithic fragments L + Qp), L (aphanitic lithic fragments), Qp (policrystalline quartz).

Table 1
Recalculated modal point-count data of the studied coarse rocks (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).

Sector	Formation		%			%			%		References
		NCE	CI	CE	Qm	F	Lt + CE	Qt	F	L	
Murcia	El Niño	62,4	0,0	37,6	61,0	0,0	39,0	60,0	0,0	40,0	Perri et al., 2017; Critelli, 2018
	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	
	Espuña	38,0	62,0	0,0	96,0	0,0	4,0	98,0	1,0	1,0	
Almería	Fuente-Espejos	82,0	8,0	9,0	73,0	7,0	20,0	73,0	12,0	15,0	Critelli, 2018; Critelli et al., 2021
	Ciudad Granada	85,0	6,0	9,0	81,0	8,0	11,0	78,0	9,0	13,0	
	Xiquena	69,0	17,0	14,0	66,0	7,0	27,0	76,0	7,0	17,0	
Málaga	Viñuela	92,0	8,0	0,0	58,0	4,0	38,0	73,0	12,0	15,0	Critelli, 2018; Critelli et al., 2021
	Alozaina	84,0	8,0	8,0	68,0	11,0	21,0	67,0	13,0	20,0	
	Paleocene	25,0	67,0	8,0	62,0	7,0	31,0	63,0	8,0	29,0	
Martíl	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	
Tetouan	Eocene	100,0	0,0	0,0	71,0	6,0	23,0	71,0	6,0	23,0	Perri et al., 2022
	Paleocene	43,0	21,0	36,0	49,0	2,0	49,0	49,0	2,0	49,0	

4.2. *Rif Chain*

In the Internal Rif Chain only the Ghomaride Complex and the Internal Front Units has preserved sedimentary suites from Paleocene to Lower Miocene detrital suites. This tectonic complex was studied in two sectors of the chain with 4 samples: Tetouan (western) and Martil (eastern) (Perri et al., 2022). The sandstones from the Tetouan sector (2 samples) are Paleogene in age, (Table 1; Fig. 6D) (Perri et al., 2022), evolving from (Qm49 F2 Lt49) (Paleocene) with dominance of sedimentary clasts (NCE) to (Qm71 F6 Lt23) (Eocene) with NCE as a unique component with an important quartzose contribution. The sandstones from the Martil sector (2 samples) are Oligocene to early Miocene (Table 1; Fig. 6E) (Perri et al., 2022) consisting in: quartzolithic (Qm62 F2 Lt36) (Oligocene-Aquitanian) (Fig. 6E) with high proportion of quartz and with sedimentary lithics (NCE) such as impure chert, argillite and siltstone in minor proportion; (Qm35 F2 Lt63) (Burdigalian) with an abrupt increasing of lithic content (Fig. 6E). Low-grade metamorphic lithic fragment and sedimentary lithics such as argillite and impure chert are dominant (NCE) in the Burdigalian sandstones. At the base of this formation, the carbonatic grains (dolomite, spiritic, micritic, biomicritic) were detected.

5. Geochemistry and mineralogy

5.1. Betic Cordillera

In the Betic Cordillera, the mudrock samples were collected in three sectors (18 samples): Murcia (eastern), Almería (eastern) and Málaga (central) (Perri et al., 2017; Critelli et al., 2021). The mineralogical analyses from the Murcia sector (7 samples) (Perri et al., 2017) (Table 2) indicate that quartz is the main mineralogical component in Oligo-Miocene formations, whereas carbonates (calcite and dolomite) are most abundant in Paleocene-Eocene formations. Feldspars (plagioclase and K-feldspar) are minor in the Paleocene-Eocene successions, and occur in higher amounts in the Oligo-Aquitanian ones. Phyllosilicates (illite, chlorite, kaolinite, C—S and I—S mixed layers) show higher percentages in the Oligo-Miocene in the older successions. Geochemical analyses indicate that the Oligo-Miocene mudrocks show high SiO_2, Al_2O_3, K_2O, Fe_2O_3 and Na_2O values whereas the Paleocene-Eocene samples are characterized by high CaO percentages. Among the trace elements, the Paleocene-Eocene mudrocks are characterized by higher values of Ni, Cr, V, La and Zr than the Paleocene-Eocene samples (Table 3). In particular, Ni and Cr values of the Oligo-Aquitanian successions are on average higher than those of the UCC (Upper Continental Crust; McLennan et al., 2006), whereas Ni and Cr values of the Burdigalian successions are sometimes higher than those of the UCC composition (McLennan et al., 2006). The mineralogical analyses from the Almería sector (3 samples) (Critelli et al., 2021) indicate that phyllosilicates and quartz are the main mineralogical components for the Oligo-Miocene formations, whereas carbonates (calcite with minor amounts of dolomite) are most abundant in the Paleocene-Eocene formations. Very few Burdigalian samples show high values of carbonates. Feldspars show on average higher percentages in the Oligo-Miocene formations than Paleocene-Eocene Fm (Table 2). Clay mineral association is mainly characterized by illite and micas prevailing on chlorite, kaolinite and mixed-layer phases. Geochemical analyses indicate that the Oligo-Miocene mudrocks show high SiO_2, K_2O and Na_2O values whereas the Paleocene-Eocene samples are characterized by high CaO percentages. Among the trace elements, the Oligo-Miocene mudrocks are characterized by higher values of Ni, Cr and V than the Paleocene-Eocene samples (Table 3). In particular, Ni and Cr values of the Oligo-Miocene Fms are on average higher than those of the UCC composition (McLennan et al., 2006).

The mineralogical analyses from the Málaga sector (4 samples) (Critelli et al., 2021) indicate that quartz and on average phyllosilicates are the main mineralogical components for the Oligo-Miocene formations, whereas carbonates (calcite with minor amounts of dolomite) are most abundant in the Paleocene-Eocene formations. Clay mineral association is mainly characterized by illite and micas prevailing on chlorite, kaolinite and mixed-layer phases. Feldspars (plagioclase and K-feldspar) are only present in the Oligo-Miocene successions, with major amounts in the lower part (Table 2). Geochemical analyses show that the Oligo-Miocene samples show high SiO_2, Al_2O_3, K_2O, MgO and Na_2O values whereas the Paleocene-Eocene mudrocks are characterized by high CaO percentages. Among the trace elements, the Oligo-Miocene samples are characterized by higher values of Ni, Cr, V and La than the Paleocene-Eocene mudrocks (Table 3). In particular, Ni and Cr values of the Oligo-Miocene samples are on average higher than those of the UCC composition (McLennan et al., 2006).

5.2. Rif Chain

In the Internal Rif Chain, the studied mudrocks were collected in two sectors of the chain (4 samples): Tetouan (western) and Martil (estern) (Perri et al., 2022). The mineralogical analyses from the Tetuán sector (2 samples) (Perri et al., 2022) indicate that phyllosilicates (illite and micas prevailing on mixed-layer phases, chlorite and kaolinite) and quartz are generally the main mineralogical components for the Eocene Fm, whereas carbonates (calcite with minor amounts of dolomite) occur only in the Paleocene Fm where are the most abundant phases. Feldspars (plagioclase and K-feldspar) occur only in the Eocene Fm (Table 2). Geochemical analyses indicate that the Eocene Fm shows higher SiO_2, Al_2O_3, TiO_2, K_2O, Fe_2O_3 and Na_2O than the Paleocene Fm samples that are characterized by very high CaO percentages (Table 3). Among the trace elements, the Eocene and Paleocene Fms are characterized by similar values of Ni, Cr, V, La and Zr that are on average compared to those of the UCC (McLennan et al., 2006) and PAAS (Post-Archean Australian Shales; Taylor and McLennan, 1985) compositions. The mineralogical analyses from the Martil sector (2 samples) (Perri et al., 2022) show that phyllosilicates (illite and micas prevailing on mixed-layer phases, chlorite and kaolinite) and quartz are generally the main mineralogical components for the both Oligo-Miocene formations with

Table 2
Mineralogical composition of the bulk fraction of the studied mudrock samples from the syn-orogenic and pre-orogenic successions.

Sector	Formation	Σphyllosilicates	Quartz	Feldspars	Calcite	Dolomite	References
Murcia	El Niño	23,7	47,3	5,2	18,2	5,5	Perri et al., 2017
	Río Pliego	36,3	38,9	14,2	3,8	6,7	
	Bosque	10,0	19,1	3,0	24,0	44,0	
	As	traces	33,2	0,1	66,3	0,0	
	Malvariche	11,4	15,6	0,3	67,6	4,7	
	Espuña	10,3	12,2	0,0	77,4	0,0	
	Mula	4,7	15,2	2,0	75,2	2,0	
Almería	Fuente-Espejos	28,7	24,3	8,3	35,0	3,7	Critelli et al., 2021
	Ciudad Granada	35,0	29,0	16,0	14,7	6,0	
	Xiquena	34,0	30,0	4,0	31,5	0,5	
Málaga	Viñuela	23,0	29,0	6,0	27,5	14,5	Critelli et al., 2021
	Alozaina	43,0	37,3	13,5	4,3	2,0	
	Eocene	30,5	22,5	0,0	47,0	0,0	
	Paleocene	4,5	7,0	0,0	88,5	0,0	
Martíl	Sidi Abdeslam	38,0	32,0	23,0	6,5	0,5	Perri et al., 2022
	Fnideq	43,6	32,6	11,2	10,8	1,8	
Tetouan	Eocene	47,5	41,0	11,5	0,0	0,0	Perri et al., 2022
	Paleocene	10,0	8,0	0,0	82,0	0,0	

Table 3
Chemical composition and chemical weathering indices (CIA and CIA'; see the text for the details) of the studied mudrock samples from the syn-orogenic and pre-orogenic successions.

Sector	Formation	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	L.O.I	Ni	Cr	V	La	Zr	CIA	CIA'	References
Murcia	El Niño	0,3	2,3	5,9	58,4	0,1	1,3	12,5	0,3	0,1	2,8	15,7	42,3	73,3	78,7	20,5	62,3	62	71	Perri et al., 2017
	Río Pliego	0,7	3,4	15,2	55,7	0,1	3,1	5,0	0,8	0,1	6,1	9,2	49,5	90,4	134,3	46,0	203,9	66	71	
	Bosque	0,1	6,9	4,7	25,3	0,0	1,1	27,7	0,3	0,0	1,9	31,3	16,3	23,5	56,0	<8	106,0	59	71	
	As	0,0	0,6	0,2	33,8	0,0	0,0	37,3	0,0	0,0	0,3	27,5	<8	<8	10,5	<8	12,0	54	78	
	Malvariche	0,0	1,3	3,9	16,1	0,0	0,9	39,8	0,2	0,0	2,4	34,6	12,3	25,0	65,0	<8	57,2	65	75	
	Espuña	0,0	1,0	2,7	12,5	0,1	0,7	43,7	0,1	0,0	1,2	37,3	16,2	8,0	60,7	<8	35,0	62	72	
	Mula	0,0	1,2	2,0	15,4	0,0	0,4	43,1	0,2	0,0	1,1	36,0	12,1	11,0	35,7	<8	39,0	62	76	
Almería	Fuente-Espejos	0,3	3,3	8,6	37,1	0,1	1,8	21,3	0,4	0,2	3,3	24,0	49,1	95,3	105,0	22,0	113,3	75	78	Critelli et al., 2021
	Ciudad Granada	0,5	5,0	13,7	47,0	0,1	2,7	11,1	0,7	0,0	4,6	15,1	44,0	96,3	141,0	31,3	192,3	75	78	
	Xiquena	0,4	3,3	12,0	40,4	0,1	2,1	18,5	0,6	0,0	4,0	19,0	32,5	78,0	121,0	41,0	197,5	77	80	
Málaga	Viñuela	0,2	10,0	6,3	30,5	0,1	1,8	20,6	0,3	0,1	2,9	27,5	45,3	90,5	91,5	33,5	85,5	71	74	Critelli et al., 2021
	Alozaina	0,7	2,8	16,6	56,6	0,1	3,0	3,7	0,8	0,0	5,7	10,0	42,4	103,3	134,0	37,8	266,3	74	79	
	Eocene	0,1	2,0	11,3	25,5	0,0	1,5	26,8	0,6	0,0	4,7	27,5	39,6	87,5	143,0	31,5	137,0	84	85	
	Paleocene	0,1	1,0	2,2	8,5	0,0	0,3	54,2	0,2	0,0	0,8	32,6	14,3	68,5	69,0	30,5	91,5	80	83	
Martil	Sidi Abdeslam	15,1	2,3	13,2	42,9	0,1	1,8	4,4	0,8	0,0	4,5	15,2	44,1	141,0	142,5	51,5	245,0	77	81	Perri et al., 2022
	Fnideq	3,2	2,6	16,3	49,0	0,1	2,9	7,0	0,7	0,1	6,5	11,7	61,1	138,4	154,6	38,4	181,4	76	80	
Tetouan	Eocene	0,6	1,6	19,7	60,9	0,0	2,9	0,4	0,8	0,0	6,5	6,7	44,5	116,0	170,0	52,5	268,5	80	83	Perri et al., 2022
	Paleocene	0,1	0,9	3,9	10,8	0,1	0,7	47,1	0,2	0,0	1,1	36,0	14,8	116,0	52,0	53,0	59,0	80	82	

minor abundances of carbonates (calcite with minor amounts of dolomite). Feldspars (plagioclase and K-feldspar) are on average more abundant in the Burdigalian than the Oligo-Aquitanian (Table 2). Geochemical analyses show that the Oligocene-Lower Miocene successions are characterized by similar elemental variations except for the Na_2O value that is higher in the Burdigalian. Among the trace elements, the Oligocene-Lower Miocene successions are characterized by similar values of Ni, Cr and V that are on average higher than those of the UCC (McLennan et al., 2006) and PAAS (Post-Archean Australian Shales; Taylor and McLennan, 1985) compositions.

6. Discussion

6.1. Provenance relations

The heterogeneous composition of the coarse detrital suites indicate that the Cenozoic studied successions had a multiple source area consisting in metamorphic, siliciclastic and carbonate rocks. The counted siliciclastic sandstones plot mainly in a wide area at the Qm-Lt side in a Qm-F-Lt diagram (Fig. 7), reflecting their typical suites in tectonic-controlled settings (e.g., Dickinson, 1985; Critelli and Criniti, 2021) transition between a craton, quartzose recycled, quartzose transitional orogenic, and finally lithic-quartzose provenance type (e.g. Dickinson, 1985). The basement of the Malaguide-Ghomaride Complexes mainly consists of a pre-Ordovician to Late Carboniferous siliciclastic, siliceous and metasedimentary (slate, phyllite, carbonate and quartzite) succession including thin carbonate lenses and conglomerate bodies with some clasts of acid plutonic rocks (Vera, 2004). This is overlain by a Late Triassic to Cretaceous thick carbonate succession with thin mudrocks and cherty mudrock intercalations. Related sedimentary successions also occur in other Alpine–Mediterranean Chains equivalent to the Malaguide-Ghomaride Complex, such as the Algerian Kabylides (Wildi, 1983), or the Italian Calabrian Terranes (Bonardi et al., 2001, 2002, 2003). The composition of Paleocene-Eocene rocks (Mula and Espuña Groups) is dominantly carbonatic, as highlighted by both petrographical and mineralogical-geochemical data (Tables 1 to 3). The siliciclastic samples highlight a high compositional maturity and indicate a clear provenance from a craton interior area in part of the Eocene samples of the Espuña Group (Dickinson, 1985). 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 Malaguide origin and may be identifiable with Calabro-Kabilide blocks (Martín-Algarra et al., 2000). A sharp increase of siliciclastic component starting from Oligocene formations suggests abrupt changes of the source area involving the Late Paleozoic to early Mesozoic metamorphic and terrigenous basement. Therefore, the Ciudad Granada Group samples (Upper Oligocene-Aquitanian) represents erosion from quartzose recycled to transitional recycled orogen. Moreover, the Viñuela Group samples (Burdigalian) mainly represents erosion from transitional recycled orogen.

During the early Miocene are abundant the quartzoarenite fragments indicating a main source from the Late Triassic arenites. Also carbonate fragments are very abundant derived from Mesozoic and Tertiary terrains. A significant increasingly contribution from low-medium grade metamorphic rocks during the early Miocene is also testified by the abundance of slate, phyllite and metarenite grains in sandstone and micro conglomerate strata indicating also erosion of metamorphic terranes.

In the case of mudrock samples, the heterogeneous composition also suggests multiple source areas derived from metamorphic, siliciclastic and carbonate rocks, with a minor supply of mafic rocks. The Cr/V vs. Y/Ni plot (e.g., Hiscott, 1984; Perri et al., 2016, 2017; Corrado et al., 2019; Cavalcante et al., 2011, 2023) shows that the Oligo-Miocene formations are characterized by higher Cr/V values than Paleocene-Eocene formations (Fig. 8A). The V-Ni-La*4 ternary diagram shows that the studied samples generally fall close to felsic sources with a trend towards the

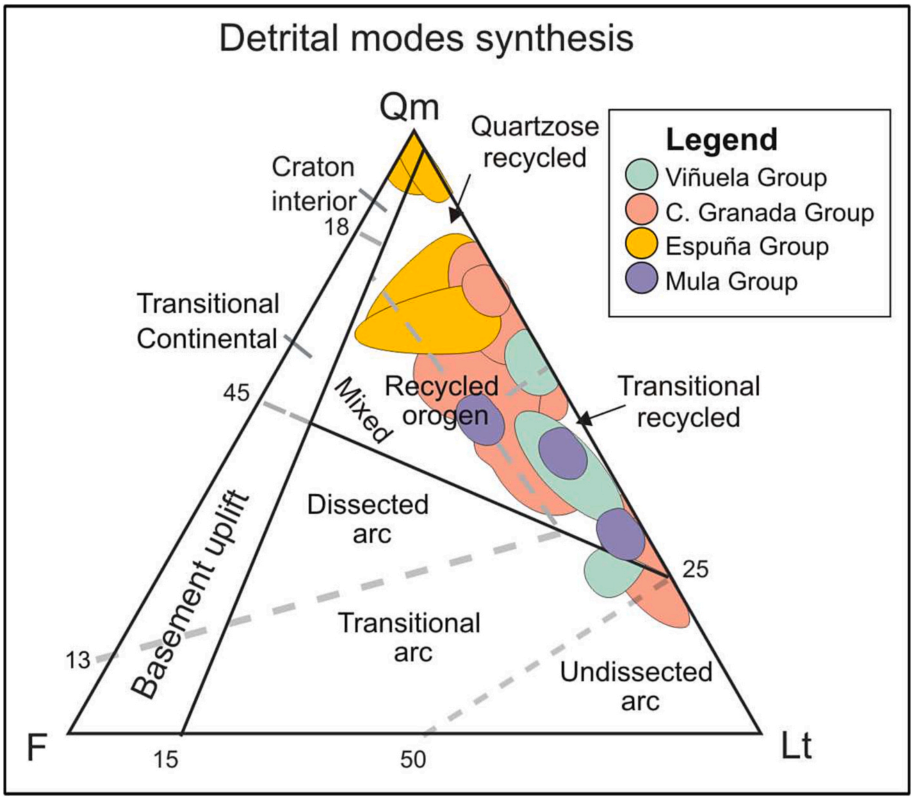

Fig. 7. Ternary discrimination synthesis diagram of coarse rocks provenance (Perri et al., 2017; Critelli et al., 2021; Perri et al., 2022). Qm (monocrystalline quartz), F (feldspars), Lt (total lithic fragments L + Qp), L (aphanitic lithic fragments), Qp (policrystalline quartz).

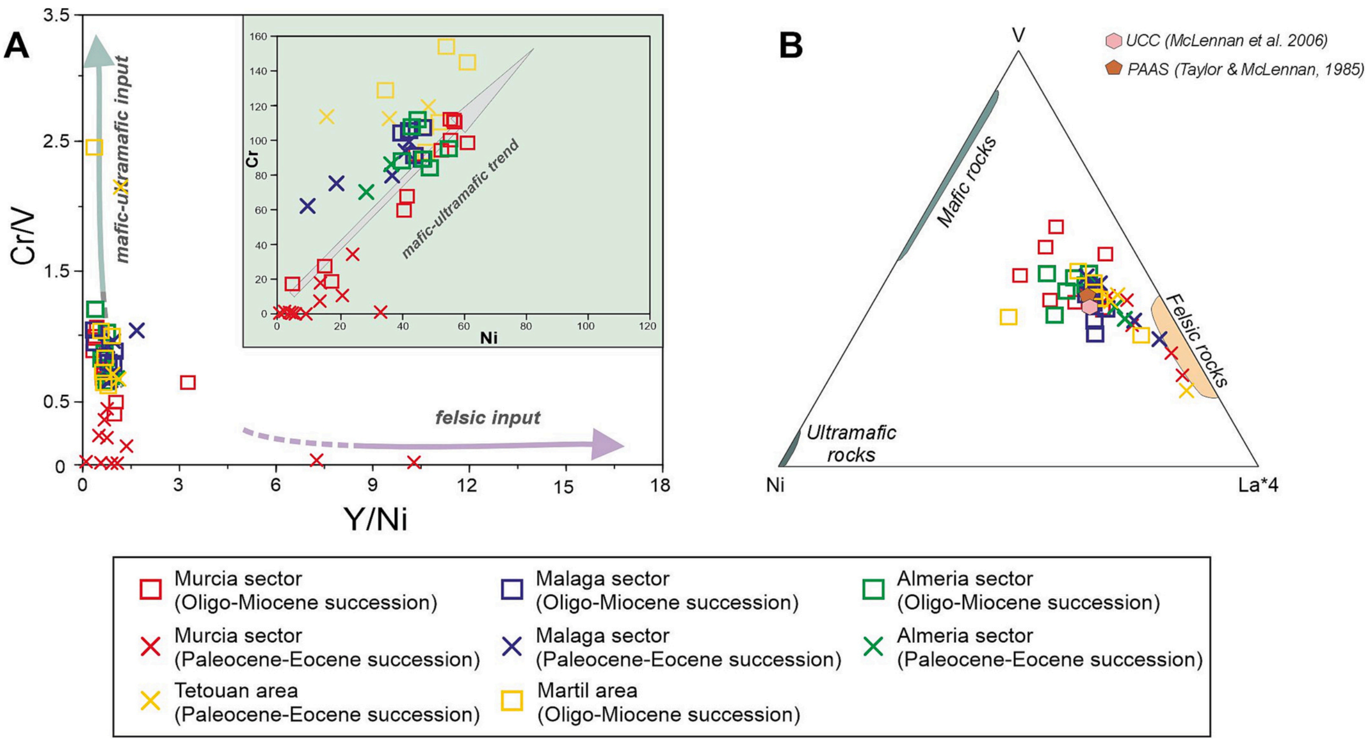

Fig. 8. A) Provenance diagrams based on the Cr/V vs. Y/Ni relationships (after Hiscott, 1984) and the Cr vs. Ni ratios; B) Ternary plot based on the V-Ni-La*4 proportions (modified after Perri et al., 2011) for the studied mudrock samples from the syn-orogenic and pre-orogenic successions.

mafic supply for the Oligo-Miocene mudrocks (Fig. 8B). Thus, the studied mudrocks are mainly related to felsic areas with minor mafic contributions mainly for the Oligo-Miocene successions. This mafic supply is negligible or absent in the studied sandstone suites.

6.2. Sorting and recycling

The studied coarse detrital suites of the studied successions testify a general decreasing sorting from Paleocene to Miocene suites in relations with major changes in detrital modes and growing orogen. However, sandstone composition along the studied sections have variable cycles in terms of sorting and increasing mineralogical maturity and recycling as follow: the Betic sector has two main sorting/recycling cycles, the Mula to As formations (Q96–92), where sorting and recycling abrupt decrease upsection, and a second cycle from Bosque to El Niño formations (Q96–61). Both cycles have a general mineralogical maturity decreasing upwardly as in response of changing sorting and increasing recycling. In the Almeria and Malaga sectors of Betic, from Xiquena to Fuente-Espejos (Almeria) (Q66–73) and Paleocene to Vinuela (Malaga) (Q62–68-58) there is a general trend of decreasing recycling and sorting. The Rif sector has similar trends (Q62–35) in the Martil section, while in the Tetouan section the Paleocene-Eocene arenites increase abruptly upward the Qm content (from 49 to 71) suggesting and upward increase of recycling and sorting.

The Paleocene-Eocene successions seem to be affected by higher weathering effects than the Oligo-Miocene ones. This is compatible with the climatic cadre of the westernmost Tethys where a warm climate prevailed during the Eocene followed by a cooling at the Oligocene (Tateo, 2020; Martín-Martín et al., 2021, 2022; Jafarzadeh et al., 2022; Tosquella et al., 2022). These changes can be also related to the sorting and recycling effects of sediments during their transport and deposition within a sedimentary basin, that commonly produce a fractionation of Al_2O_3 (clay minerals) from SiO_2 (quartz and feldspars) and TiO_2 (mostly present in clay minerals and Ti-oxides) from Zr (present in zircon, and sorted with quartz). Those relations were illustrated in a ternary plot based on Al–Ti–Zr variations (e.g., Garcia et al., 1991, 1994; Mongelli et al., 2006; Critelli et al., 2021; Cavalcante et al., 2023), where the studied sediments, in particular samples from the Paleocene-Eocene successions, fall in a trend towards the Zr apex, which could be related to sorting and recycling processes (Fig. 9). The Zr enrichment, mainly recorded in the Paleocene-Eocene successions, suggests several recycling and reworking processes before the final deposition within the studied sedimentary basin (e.g., Critelli et al., 2021).

6.3. Paleoweathering and paleotectonic features

Many works have shown that the variations of alkali and alkaline-earth elements in fine-grained sediments are generally related to chemical weathering processes in source areas producing a depletion of mobile elements (i.e. Ca, Na and K) and an enrichment of immobile elements such as Al (e.g., Fedo et al., 1995; Cullers, 2000; Scarciglia et al., 2007, 2016; Mongelli et al., 2006; Barbera et al., 2011; Perri et al., 2013, 2016, 2017; Corrado et al., 2019; Perri, 2014, 2018, 2020; Cavalcante et al., 2023 and many others), as illustrated by the Chemical Index of Alteration (CIA; Nesbitt and Young, 1982) calculated as follow:

$$CIA = Al_2O_3/(Al_2O_3 + K_2O + Na_2O + CaO) \times 100$$

The studied samples are characterized by high CaO values; thus, we also use a CIA' modified and calculated without the CaO content (e.g., Perri et al., 2012, 2014, 2015; Amendola et al., 2016) as follow:

$$CIA^{'} = Al_2O_3/(Al_2O_3 + K_2O + Na_2O) \times 100$$

The studied samples have moderate CIA and CIA' values and show high variability of those indices (Table 3). In detail, in the A-CN-K (Fig. 10A) and A-N-K (Fig. 10B) plots the samples fall in a wide group following a trend from the A apex towards the K apex close to the illite-muscovite points, being more evident for the Betic Cordillera Fms than the Rif Chain Fms. The trends showing in both A-CN-K and A-N-K plots

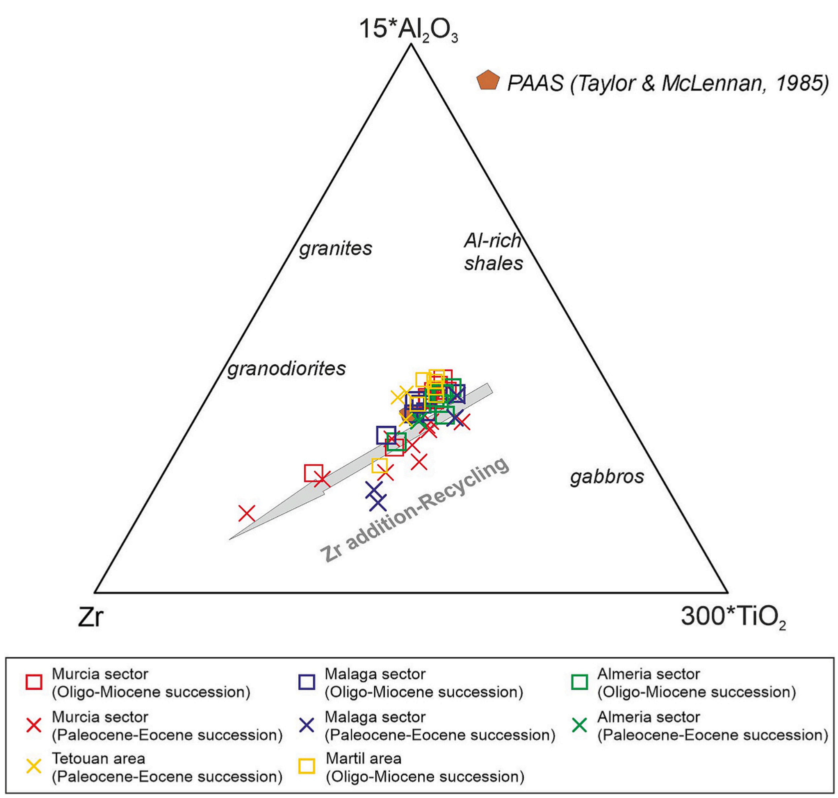

Fig. 9. Ternary plot based on the relative proportions of $15{*}Al_2O_3$, $300{*}TiO_2$ and Zr (see also Garcia et al., 1991, 1994) for the studied mudrock samples from the syn-orogenic and pre-orogenic successions.

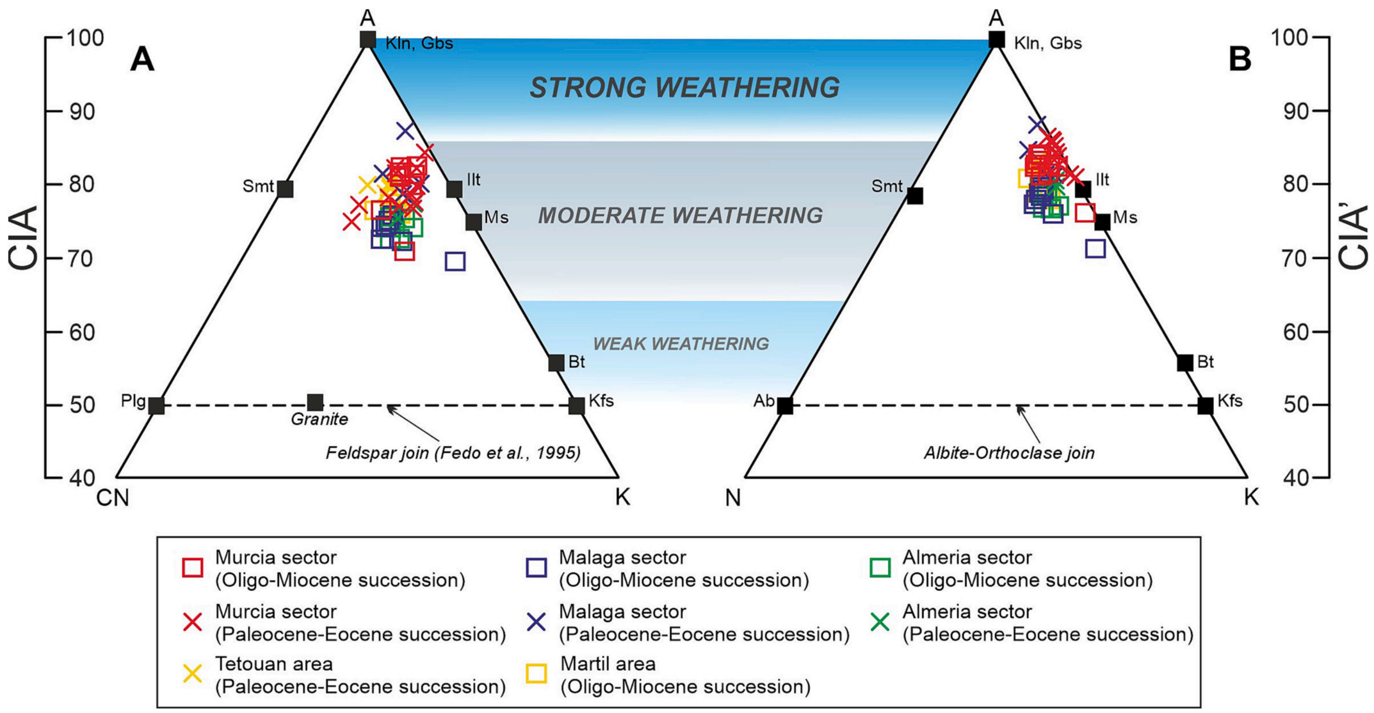

Fig. 10. A) Ternary A–CN–K (Nesbitt and Young, 1982); B) A-C-N (Perri et al., 2012, 2014, 2015; Amendola et al., 2016) diagrams. A, Al_2O_3; C, CaO; N, Na_2O; K, K_2O; Kln, kaolinite; Gbs, gibbsite; Ms., muscovite; Ilt, illite; Smt, smectite; Plg, plagioclase; Kfs, K-feldspar; Bt, biotite; Ab, albite.

indicate source areas characterized by non-steady-state weathering conditions which have slightly changed from the Paleocene-Eocene to the Oligo-Miocene successions and characterized by a progressive cooling period (e.g., Abbassi et al., 2021). Many works have also used the CIA values as estimation of paleoclimate variations (Nesbitt and Markovics, 1997; Cullers, 2000; Cullers and Podkovyrov, 2002; Li and Yang, 2010; Cao et al., 2019; Perri, 2020). In particular, Yang et al. (2014) showed that land surface temperatures are linearly related with CIA at a global scale, based on this relationship (e.g., Cao et al., 2019):

$$T(^{\circ}C) = 0.56 \times CIA - 25.7$$

The atmospheric paleotemperatures estimated using this CIA-temperature equation range from an average value of ~15 °C for the Paleocene-Eocene successions to an average value of ~13 °C for the Oligo-Miocene successions and, thus, testifying a relative cooling. Again, this is compatible with the climatic cadre of the westernmost Tethys where a warm climate prevailed during the Eocene followed by a cooling at the Oligocene (Tateo, 2020; Martín-Martín et al., 2020c, 2021; Tosquella et al., 2022). Moreover, the trend described in both diagrams is typical of source areas where active tectonism allows erosion of all zones within weathering profiles developed on source rocks (e.g., Nesbitt et al., 1997). Uplift and erosional processes of the studied formations during the Paleogene to Miocene transition were probably due to the activation of superficial tectonics in the studied areas (Perri et al., 2017).

6.4. *Paleogeographic-paleotectonic implications*

The studied sedimentation should be located in the southern margin of the *MM* (or *AlkaPeca* according to the models) (Fig. 11A) in transition to the *MFB* (Martín-Martín et al., 2006a, 2006b). The studied sedimentary record shows much less detritic supply during Paleocene-Eocene times when Eo-Alpine phase took place. Nevertheless, both mentioned tectonic phases (Eo- and Neo-Alpine) were responsible of the weathering a recycling of the studied sediments. During the Eo-Alpine phase (Paleocene-Eocene) the Mula and Espuña Groups are characterized by a main carbonate composition (Martín-Martín et al., 2020c).

In relation with the coarse detrital suites the entire succession reflects a craton, quartzose recycled to quartzose transitional orogenic provenance type (sedimentary or epimetamorphic Hercynian-like) during the Paleocene-Eocene (Fig. 11B) deposited in the active margin of a foreland-like basin (Perri et al., 2017, 2022; Critelli et al., 2021). On the contrary, during the Oligocene to Early Miocene a transitional-undissected arc provenance type is deduced, coincident with the wedge-top stage of the margin (Perri et al., 2017, 2022; Critelli et al., 2021) (Fig. 11B,C). This evolution is represented by the progressive dispersal pathways evolution from both quartz-rich arrival from flexure underplate to quartzolithic unroofing of the growth orogenic belt of the internal Rif and Betic thrust belts (e.g. Critelli and Criniti, 2021; Critelli and Martin-Martin, 2022). In the lower Miocene (mainly in Burdigalian) (Fig. 11D) coarse detrital suites, metamorphic clasts were recognized that could be related to the erosion of Upper Units of the Alpujarride and Sebtide Complexes (Martín-Martín et al., 2006a) or to an unknown deep Malaguide metamorphic Precambrian basement rocks (Martín-Algarra et al., 2000). The presence of abundant quartzoarenite fragments in the same period, indicates an additional source from the Late Triassic arenites (i.e. redbeds; Critelli and Le Pera, 1995, 1998; Critelli et al., 2008; Perri et al., 2013). Carbonate grains are also abundant in the Lower Miocene samples suggesting a provenance from the uplifted Mesozoic and Cenozoic terrains (Perri et al., 2017).

In the mudrocks, the scarce terrigenous elements found during the Paleocene-Eocene indicate erosion from a mainly felsic area (with minor mafic influence during the Oligo-Miocene) affected by high recycling conditions with moderate weathering (Fig. 11B). The origin of the minor mafic influence can be related to erosion of volcanic mafic rocks such as dikes in the Internal Betic Zone cropping out northeast of Malaga (e.g., Marchesi et al., 2012; Duggen et al., 2004) as well as to an unknown basement with affinity with the Calabro-Kabilide blocks, coupled with the deep levels of the Ghomaride-Malaguide Complexes (e.g., Perri et al., 2017, 2022; Critelli, 2018; Critelli and Criniti, 2021) (Fig. 11C,D).

All the above allows divide the succession into two sedimentary

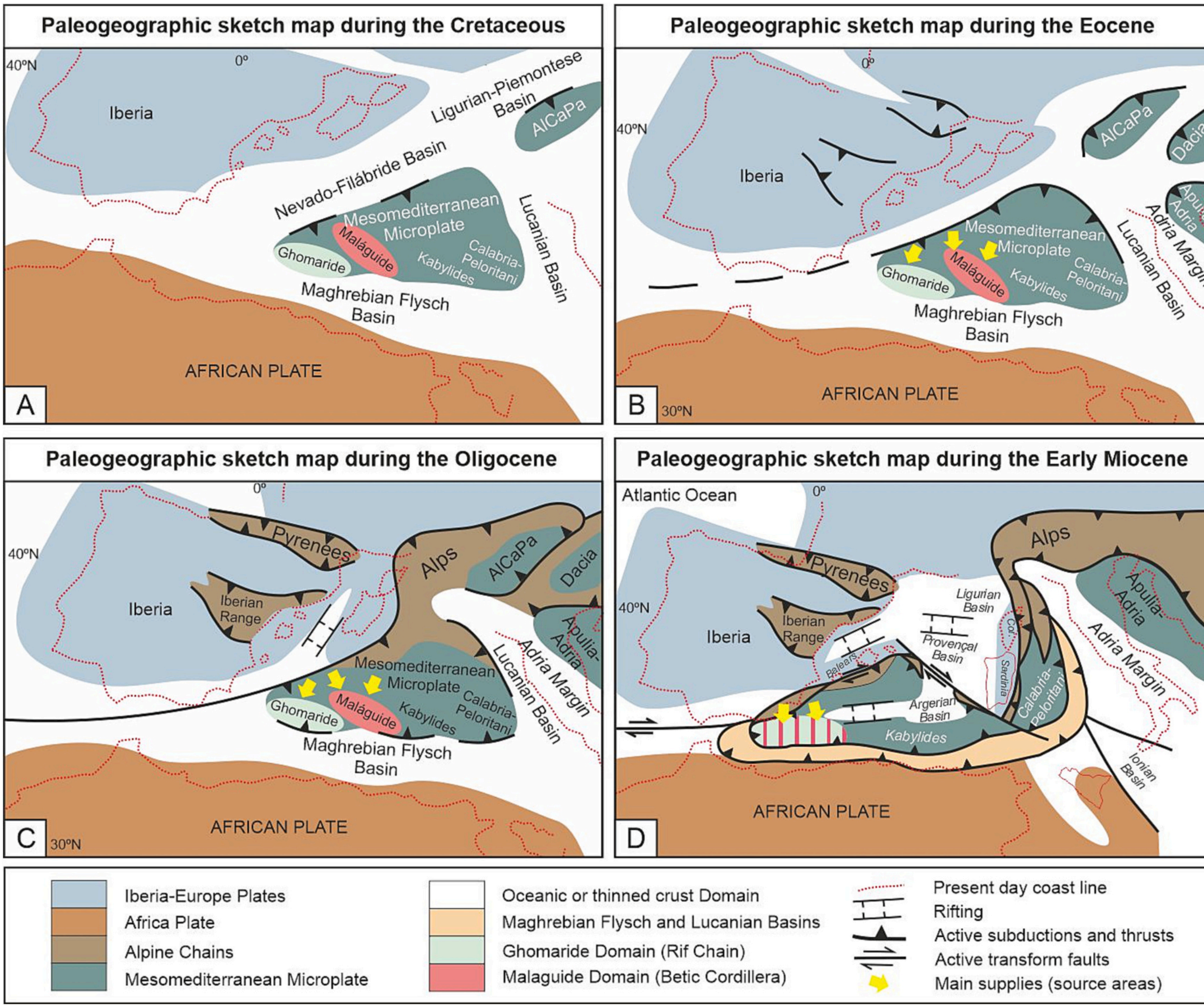

Fig. 11. Paleogeographic and paleotectonic evolutionary models for the Central-Western Mediterranean area during the Cretaceous to Early Miocene with location of the Malaguide and Ghomaride Domains, as well as, main supplies and source areas. A) Cretaceous times sketch map (70 Ma); B) Eocene times sketch map (35 Ma); C) Oligocene times sketch map (25 Ma); D) Burdigalian times sketch map (20 Ma).

cycles (Perri et al., 2017, 2022; Critelli, 2018; Critelli and Criniti, 2021). The lower cycle (Paleocene-Eocene) should be contemporaneous of the Eo-Alpine tectonic phase mainly affecting other remote regions (much less active in the study area). This cycle is interpreted as coeval of a soft deformation in the area consisting in basement folding in the Malaguide-Ghomaride domains, and mainly affected by deep tectonics with fault-propagation folds, accomplished of rising or reliefs and other subsiding areas (Fig. 11B,C). The *AlKaPeCa* model (Guerrera et al., 2021) supports a paleogeographic-geodynamic model without the existence of a northern oceanic Tethyan branch and therefore without a main deformation in the boundary with the Iberian Massif related to subduction, since it should be a continuation of this massif. Nevertheless, the data presented before indicate that although the terrigenous supply is lower to the carbonate content (and much lower to the Oligo-Miocene period), a not negligible terrigenous content is registered in that period that should be associated with the Eo-Alpine tectonics in the source areas located in the northern border of the *MM* or *AlCaPeKa* (according the models). This fit better with the *MM* paleogeographic-geodynamic model (Martín-Martín et al., 2006a,b, 2020a,b; Perrone et al., 2006; Critelli et al., 2008; Barbera et al., 2011; Perri, 2014; Perri et al., 2013, 2016; Guerrera and Martín-Martín, 2014; Critelli, 2018; Martín-Martín et al., 2020a, 2020b; Guerrera et al., 2021; Belayouni et al., 2023) supported by us. In the *MM* framework model, this tectonics should be contemporaneous to the subduction, closing of the northern Tethyan oceanic branch (Nevado-Filabride Basin) below the *MM* and nappe stacking in the northern border of the *MM* of lower units (Nevado-Filabride and Alpujarride-Sebtide Complexes) during Paleogene times (Fig. 11B,C). The closing of the northern oceanic branch in further eastern sectors meanwhile a subduction (Cretaceous-Paleogene) was also the responsible of other circum-Mediterranean mountain chains (Alps, Pyrenees, Iberian Range, etc.) (Fig. 11B). The upper cycle (Oligocene-Early Miocene) took place during the Neo-Alpine phase, when main deformation shifted to the southern part of the *MM* and the *MFB* (Fig. 11C,D). In this period, the closing of the southern oceanic branch (*MFB*) by another subduction (Oligocene-Early Miocene) took place mainly concerning the Betic-Maghrebian and Apennine mountain chains (Fig. 11C). In any way, Cenozoic oceanic closings were accomplished by a westward shifting of the *MM* (Critelli, 2018). During Neo-Alpine phase, in the Malaguide-Ghomaride domains, thrustings should become superficial while *MFB* subduction below the *MM* progressed and the accommodation of tectonic units took place giving a sharp increasing of rising areas reflected in the sedimentation by the occurrence of coarse terrigenous wedges (Ciudad Granada and Viñuela Groups). This period reflects the influence of volcanism in the area probably related to the Mediterranean back-arc type aperture, as well as, the erosion of metamorphic rocks derived from deep tectonic levels affected in the Eo-Alpine phase or belonging to a Hercynian basement (e.g., Fornelli et al., 2022; Jafarzadeh et al., 2022).

7. Conclusions

- The heterogeneous composition of the coarse detrital suites indicates a multiple source area for the studied successions consisting in metamorphic, siliciclastic and carbonate rocks. The counted siliciclastic sandstones plot mainly in a wide area at the Qm-Lt side in a Qm-F-Lt diagram reflecting their transition between a craton, quartzose recycled, quartzose transitional orogenic, and finally transitional-undissected arc provenance type.
- The mudrocks also show heterogeneous composition and suggesting multiple source areas derived from metamorphic, siliciclastic and carbonate rocks, with a minor supply of mafic rocks linked to the influence of a certain volcanism.
- The Paleocene-Eocene successions seem to be affected by higher weathering effects than the Oligo-Miocene ones in agreement with the warming climatic conditions in the Paleocene and mainly Eocene times in the western Tethyan area characterized by cooling effects from Eocene to Oligocene. Several recycling and reworking processes should take place mainly during the Paleocene-Eocene before the final deposition within the studied sedimentary basin.
- Source areas were characterized by non-steady-state weathering conditions which changed from the Paleocene-Eocene to the Oligo-Miocene successions characterizing a progressive cooling. This agrees with the climatic conditions in the western Tethyan area from Eocene to Oligocene, but also, reflects the typical evolution of the source areas where active tectonism allows erosion of all zones within weathering profiles developed on source rocks.
- A sharp increase of siliciclastic component starting from Oligocene formations suggests abrupt changes of the source area together with the above-mentioned changes in sorting-recycling-weathering. This change in sedimentation allows dividing the succession into two sedimentary cycles: the lower (Paleocene-Eocene) and the upper (Oligocene-Early Miocene).
- The lower cycle was contemporaneous to the Eo-Alpine tectonic phase when soft tectonic took place, which was reflected by basement folding and fault-propagation folds, accomplished by minor rising or reliefs and deepening of subsidence areas in the Malaguide-Ghomaride domains as part of a foreland system close to the active margin.
- The upper cycle took place during the neoAlpine phase, when main deformation shifted to the southern part of the *MM* and the *MFB*. In this period, in the Malaguide-Ghomaride domains, thrustings should become superficial while *MFB* subduction below the *MM* progressed and the stacking of tectonic units took place giving a sharp increasing of rising areas reflected in the sedimentation by the occurrence of coarse terrigenous deposits in wedge-top basins. This period reflects the influence of volcanism probably related to the Mediterranean back-arc type aperture, and/or the erosion of magmatic-metamorphic rocks derived from deep tectonic levels affected in the Eo-Alpine phase or belonging to a Hercynian basement.
- A not negligible terrigenous content is evidenced in the lower sedimentary cycle that should be associated with the Eo-Alpine tectonics in source areas. This could be contrary to the *AlKaPeCa* models supporting a paleogeographic-geodynamic model without the existence of a main deformation in the boundary with the Iberian Massif. Contrarily, the registered evolution seems to fit better with the paleogeographic-geodynamic models for the western-central Mediterranean area with the existence of the *MM* bounded by two oceanic branches. The closing of the northern oceanic branch during Cretaceous-Paleogene was the responsible of the Eo-Alpine deformation while the closing of the southern oceanic branch gave the Neo-Alpine phase mainly concerning the *MM* and the *MFB*. The studied sedimentation should be located in the southern margin of the *MM* in transition to the *MFB* since sedimentation shows much less tectonic influence during Paleocene-Eocene times.

Declaration of Competing Interest

Manuel Martín-Martín on behalf of all authors declare no conflict of interest. Also, the Funding are here mentioned:

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Data availability

Data will be made available on request.

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