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The Numidian formation and its Lateral Successions (Central-Western Mediterranean): a review

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ABSTRACT

The widely debated late Oligocene-middle Miocene Numidian Fm (*NF*) consists of supermature quartzose sediments deposited in the Maghrebian Flysch Basin (*MFB*) outcropping from the Betic Cordillera to the Southern Apennine passing by the Maghrebian Chain. The *NF* is commonly composed of three lithostratigraphic members and is characterized by two vertical successions (*Type A* and *Type B*) corresponding to different sedimentation areas in the *MFB*. It is noteworthy the occurrence of widespread lateral successions of the *NF* (*Types C, D* and *E*) indicating in some cases an interference of the Numidian sedimentation with other different depositional systems and supplies. The *Type C* 'Mixed Successions', deposited in depocentre areas, are composed of supermature Numidian supply interfingering with immature siliciclastic materials, coming from the internal portion of the *MFB*. The *Type D* consists of supermature Numidian materials supplied from the Africa Margin (external sub-domains) deposited in sub-basins on the Africa-Adria margins, outside the typical Numidian depositional area. The *Type E*, which stratigraphically overlies both the South Iberian Margin (*SIM*) and the Mesomediterranean Microplate (*MM*), represents the migration of the Numidian depositional system to reach the opposite margins of the *MFB*. The occurrence at a regional scale of all the above-mentioned lateral successions reveals a great evolutionary complexity resulting also from further constraints, which must be considered for palaeogeographic and palaeotectonic reconstructions. Another important point deals with the diachronism of the top of the *NF*, observed eastward from the Betic-Rifian Arc and the Algerian-Tunisian Tell (Burdigalian *p.p.*) to Sicily (Langhian *p.p.*) and up to the Southern Apennine (at least Langhian/Serravallian boundary) which can be related with eastwards delay in the *MFB* closure. The palaeogeographic reconstruction of the Numidian depositional area presented in this paper, which is also included into a global kinematic model, represents a first attempt to use the software GPlates for this subject.

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Introduction and aim

The meaning of the Numidian event has historically raised scientific discussions by different schools of thought about different features of the Numidian Formation (*NF*) and resulting interpretations terminology, age, sedimentological reconstructions, origin and radiometric age of the quartz, palaeogeographic and tectonic position, etc.). This subject has fascinated many authors, who over time have produced a very large literature and interpretative local models. However, basin-scale reconstructions based on appropriate data collected along the Maghrebian Chain (*MC*) and correlation with lateral sectors (Betic Cordillera and southern Apennine) are rare.

In fact, the *NF*, well represented in the southern side of the central-western Mediterranean area (Figure 1a), characterizes an orogenic belt constituted by three major tectonic complexes resulting from different palaeogeographic and palaeotectonic zones experiencing a Miocene structural evolution constituting the neo-Alpine Miocene orogenic system.

The tectonic complexes are constituted by: (i) the Internal Zones (Hercynian metamorphic units and related sedimentary cover), originated from the European Margin or from independent microplates located between the European and African plates (Figure 1b); (ii) the Intermediate Zone, corresponding to the Maghrebian Flysch Basin (*MFB*), constituted by

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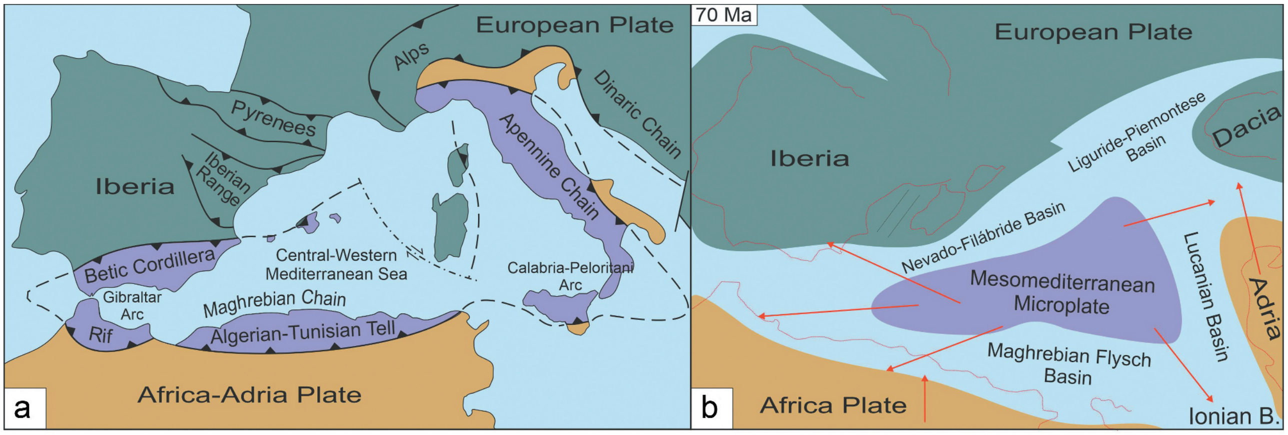

Figure 1. a) Simplified map of the main chains in the central-western peri-Mediterranean region (after Guerrera *et al.* 2021; modified); b) Palaeogeographic sketch map of the western Tethys at late cretaceous times (70 Ma).

sedimentary units deposited in one or more oceanic branches (or with thinned continental crust) of the western (Maghrebian) Tethys (Figure 1b); (iii) the External Zones consisting mainly of sedimentary units, originated from the evolution of the Adria-Africa and South Iberian margins (Figure 1b).

The *MFB* has been studied by many Authors (Durand-Delga 1980; Durand-Delga and Fontboté 1980; Wildi 1983; Bouillin 1986; Bouillin *et al*. 1986; Martín-Algarra 1987; Guerrera *et al*. 1993; Bonardi *et al*. 1996, 2001; Durand Delga *et al*. 2000; Perrone *et al*. 2008; among others), and represents an important Meso-Cenozoic domain. Its history is useful to reconstruct the geodynamic evolution of the central-western neo-Alpine chains. One of the most particular features of the *MFB* is related to its structural evolution, which originated (i) an internal sub-domain where sediments were supplied by units belonging to the internal margin of the basin, and (ii) an external sub-domain, with sediments coming from the erosion of units belonging to the Africa-Adria margin, as recognized for a long time (see Guerrera and Martín-Martín 2014, and references therein). This subdivision, which was useful in the past, appears more and more an unrealistic schematization mainly because significant lateral passages between sediments of these two sub-basins have been highlighted.

As regards the external sub-basin of the *MFB*, the typical Numidian depositional area, we emphasize the new results from more rigorous palaeoenvironmental reconstructions, and overall the increasing finding of significant and interesting lateral successions of the *NF*. These data shed more light on relationships between the *NF* and lateral successions deposited both in the internal sub-basin of the *MFB;* as well as towards the African-Adria external margin. These lateral relationships constitute new elements reflecting the occurrence of a more complex palaeogeographic setting of the depositional areas of the *NF*. Moreover, the stratigraphic and palaeogeographic reconstructions of these lateral successions out of the typical Numidian depositional area represent a possible interpretative key for a better understanding of the western Mediterranean subduction zones that caused the closure of the oceanic basins.

From another point of view, the presence of an intermediate microplate (*MM*) (Figure 1b), together with the subsequent tectonic evolution of the Western Mediterranean (south directed Alpine oceanic subduction of the northern Tethyan branch, located north of the *MM*), has been much debated (see Guerrera *et al*. 2019, 2021; and references therein). No definite agreements have been yet reached about the evolutionary frameworks, and we support the interpretation that the *MFB* constituted a depositional environment located between the African Plate and the *MM* (Figure 1b). The detailed reconstruction of the stratigraphy and provenance of the sedimentary units of the *MFB*, can be useful to solve a long debate.

The deposits of the *MFB* have long been distinguished in internal and external successions, which differ for their lithofacies and sedimentological characters, and also for the different source of sediment supply, which comes from the opposite margins of the *MFB*. These differences become more and more marked especially during the Oligo-Miocene, when contemporary but markedly different flysch families were generated (Guerrera and Martín-Martín 2014; and references therein).

The external upper Oligocene-lower Miocene sedimentation deposited in external sub-domain of the *MFB* is represented by the *NF*, which constitutes the most widespread formation known along the south-western Mediterranean area. The formation is well

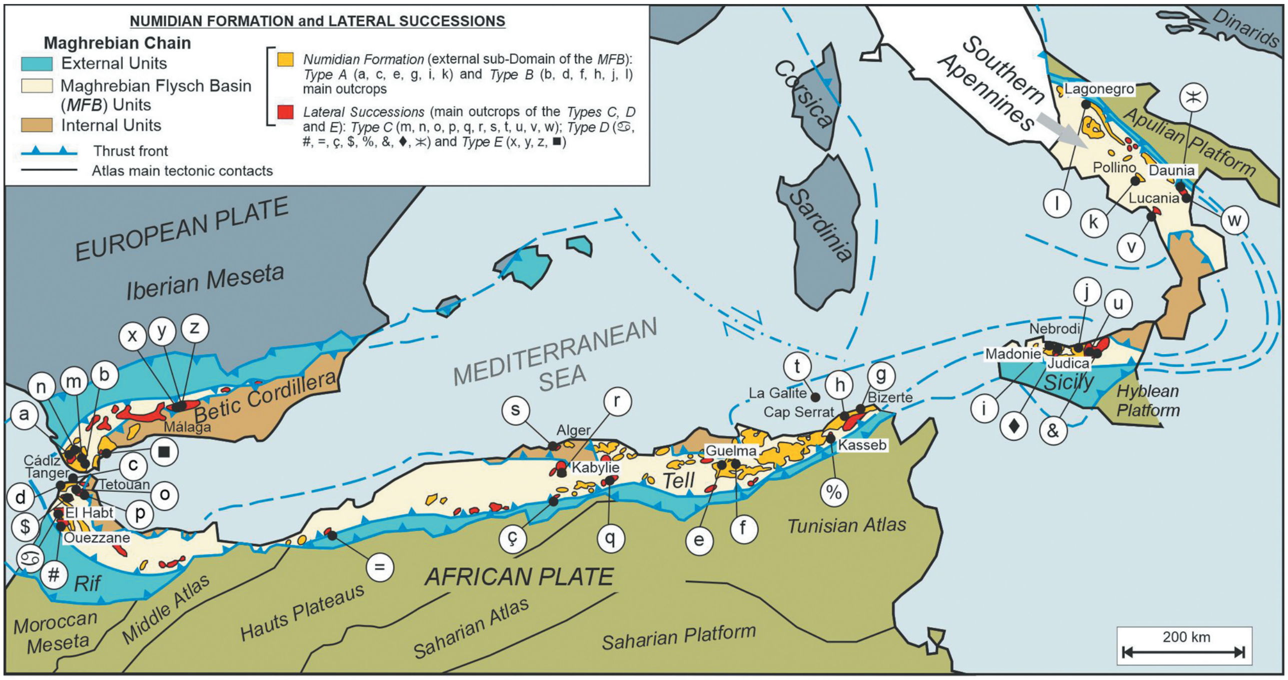

Figure 2. Areal distribution of the Numidian formation and Lateral Successions recognized in the Maghrebian chain and along its extent in betic cordillera and southern Apennines (data after Guerrera *et al.* 1992, 2012; Alcalà *et al.* 2013; D'errico *et al.* 2014; Abbassi *et al.* 2021; Belayouni *et al.* 2012, 2013; Butler *et al.* 2020; this paper).

preserved in the different sectors of the chains extending from the Betic-Rifian Arc up to the Southern Apennines (Figure 2). Its lateral extension is about 2,500 km and it may reach up to 3,000 m in thickness (e.g. Tunisian Tell), with a width roughly estimated around 150–200 km. However, the existence of different lithofacies characterizing other equivalent Numidian successions, as well as the above-mentioned Lateral Successions, implies a more articulated and complex shape of the basin, not yet defined.

Vertical and lateral reconstructions of the depositional processes, carried out through an integrated biostratigraphic control of these deposits, constitute the basis for the recognition of the main depositional systems and of their evolution in time, along the basin. In particular, detailed sedimentological studies of the turbidite successions, with a special emphasis on the identification of sand pathways, are key for achieving accurate palaeogeographic reconstructions despite the complex tectonic evolution. In this way, multidisciplinary studies of the *NF* represent a valuable support for the reconstruction of the related palaeogeographic basin. They are also needed to assess the characterization of the sedimentary and tectonic relationships between the internal and the external zones of the *MFB*, including its lateral extension in the Betic Cordillera and Southern Apennines. This general setting is supported by large amounts of accredited data.

The more recent identification in different areas of coeval Lateral Successions (Guerrera *et al.* 2012; Guerrera and Martín-Martín 2014; Alcalà *et al.* 2013; and references therein) introduced new elements which, henceforth, must be considered at the regional scale. Thus, a new research direction focusing on these new aspects of the Numidian issue, which are still little considered but, in which we are particularly interested, was undertaken. This renewed interest in the study of the *NF* results from recent interesting new data especially about the presence of Lateral Successions deposited in the margins of the typical Numidian depositional area (Boukhalfa *et al.* 2020; Butler *et al.* 2020; Riahi *et al.* 2021; Abbassi *et al.* 2022; Khomsi *et al.* 2022). We consider that a special focus on these successions may be useful to achieve a more detailed palaeogeographic and geodynamic reconstruction at the scale of the *NF* Basin.

The terminology used to distinguish the Numidian Fm (and its internal members) from other formations was based on the official Lithostratigraphy criteria, which result from lithofacies differences. In our work the main lithological features have been verified laterally along the chains where the Numidian Fm crops out (about 2,500 km), finding a substantial homogeneity despite variations deriving from the specific setting of depositional areas and from tectonic complexities. The application of official criteria became necessary towards the end of the last century to reduce the increase in terminology devoid of lateral correlations and without considering the great lateral extension of the formation.

We believe that such goals could only be reached through the realization of integrated multidisciplinary studies on the *NF* at a regional scale, rather than through local studies which, although extremely useful, are not methodologically adequate for drawing conclusions on the Numidian event at the basin scale.

The present study aims to propose an update of the different lithofacies types of the Numidian Successions (for which we propose the categorization as *Type A* and *Type B*) as well as of its Lateral Numidian Successions (for which we propose the categorization as *Type C*, for the 'Mixed Successions'; and *Type D* and the local Betic *Type E* for the "Lateral Marginal Successions"). The latter are considered much useful because they can provide further valuable information on the palaeogeographic extension of the *NF*.

A special attention will be given to the palaeogeographic and palaeotectonic evolution of the central-western Mediterranean area, which we will attempt to reconstruct using the software GPlates (Müller *et al.* 2018) based on the recent compilation of Le Breton *et al.* (2021), implemented in the global plate model of Müller *et al.* (2019).

The reconstructions will integrate data we newly collected in different sectors of the chain, as well as literature data.

Geological setting

The *NF* is one of the most typical, thickest and widestoutcropping unit of the external Maghrebian Chain and is a part of the widespread allochthonous complex of Betics, Maghrebids, and Southern Apennine (Durand-Delga 1980; Wildi 1983; Didon *et al.* 1984; Carbone *et al.* 1987; Cazzola and Critelli 1987; Martín-Algarra 1987; Hoyez 1989; Moretti *et al.* 1991; Guerrera *et al.* 1992, 1993, 2012; Stromberg and Bluck 1998; Yaich *et al.* 2000; Riahi *et al.* 2007, 2010, 2014, 2021; Fildes *et al.* 2010; Thomas *et al.* 2010a, 2010b; Belayouni *et al.* 2012, 2013; Alcalà *et al.* 2013; Thomas and Bodin 2013; Barbera *et al.* 2014; D'errico *et al.* 2014; Ben Yahia *et al.* 2019; Butler *et al.* 2020; Martín-Martín *et al.* 2020; Abbassi *et al.* 2022; Belhajtaher *et al.* 2023; among others).

Broad agreement has been reached in the literature regarding the structural framework of the Betic-Maghrebian-Southern Apennine (neo-alpine) chains and the subdivision into three main tectonic complexes (internal, basinal or intermediate, and external zones), strongly deformed during the Miocene. However, many discrepancies concerning the palaeogeographic reconstructions and other different topics continue to be debated. These latter are especially related to the distribution of the alpine oceanic branches, to the presence and distribution of continental elements (microplates) between the European and African Plates and to the age and origin of the Numidian quartz (cfr., Guerrera *et al.* 2021; and references therein).

The location of the *MFB*, which opened in the Jurassic-Cretaceous after the Pangea break-up (Durand-Delga 1980; Durand-Delga and Fontboté 1980; Wildi 1983) is still a matter of controversy. For some authors, the *MFB* was located between Europe and Africa Plates (e.g. Bouillin 1986; Bouillin *et al.* 1986; Viti *et al.* 2009; van Hinsbergen *et al.* 2014; among others). Instead, according to other authors it constituted a southern oceanic branch, which was separated from a northern one, corresponding to the Jurassic Nevado-Filabrides and Piemontese-Ligurian Ocean (Eo-Tethys), by a microplate (Doglioni 1992) named 'Mesomediterranean Microplate' (*MM*) (Guerrera *et al.* 1993, 2005, 2012; Michard *et al.* 2002, 2006; Critelli *et al.* 2017; Carminati and Doglioni 2012; Puga 2017; Critelli 2018; among others).

Since the Early Cretaceous, the *MFB* kept receiving sediment supplies in its both internal and external subdomains (Bouillin *et al.* 1970; Durand Delga 2006; and references therein), and the successions thus accumulated have been later on (substantially during Miocene) deformed. However, it should be mentioned that the sedimentation of this southern oceanic domain was not homogenous. Such observation is attested by the lateral lithofacies variations recognized between the western branch (Betic and Maghreb) and the eastern one (Sicily and South Apennine) (Guerrera *et al.* 1993, 2005; de Capoa *et al.* 2000, 2004; Lentini *et al.* 2002; D'errico *et al.* 2014; Perrone *et al.* 2008; Ben Yahia *et al.* 2019; among others).

Despite some controversies, which continue to animate the debates about the origin of the siliciclastic supply, the main Numidian depositional area is increasingly considered to correspond to the external subdomain of the *MFB*, with a sediment supply from the African margin. On the opposite, the internal subdomain, which is the site of the internal flysch sedimentation, has been fed by the internal margin of the *MFB* which we identify as corresponding to the *MM* interposed between European and African Plates (Guerrera *et al.* 1993).

Accordingly, during the latest Oligocene-middle Miocene *p.p.*, the main Numidian depositional area was invaded by ultra-mature polycyclic quartz supply and the pronounced variations in thickness resulting from the reconstructed Numidian successions deposited, depended largely on lateral palaeogeographic variations differences of the basin (see later).

The lithostratigraphy of the *NF* prevalently consists of three stratigraphic members, recognizable especially when the outcropping successions are complete and not tectonically reduced (see later).

Even if the age of the *NF* is set between the late Oligocene *p.p.* and the middle Miocene *p.p.*, a probable diachronism has been found between the successions outcropping in Betic-Africa branch and those of Sicily and Southern Apennine (see Figure 4).

The *NF* of the Southern Apennines (Carbone *et al*. 1987; Lentini *et al*. 2002; among others) shows some differences with respect to the characters recognized in North Africa and Sicily. In fact, here the age of the formation is middle-upper Miocene *p.p.* and mineralogical-petrographic analyses indicate a gradually more arkosic and less quartzarenitic deposition (Fornelli 1998; D'errico *et al*. 2014; Fornelli *et al*. 2015, 2019). Such data are clearly in favour of a clastic supply from the external Apennine zones and maybe even from the Calabria-Peloritani domain. However, in general, the clastic provenance does not change, and according to these authors the prevailing quartzose sediment supply has always an African origin. For this reason the observed differences are to be interpreted as mainly due to the palaeogeographic setting and to the vertical evolution of the Numidian sedimentation.

As for the evolutionary models of the central-western Mediterranean area applied to the reconstruction of the *MFB* evolution, they often result from very different methodological approaches, which sometimes lead to opposite point of view and different interpretations. However, such approaches are always useful because they contribute to provide a more exhaustive overview (van Hinsbergen *et al*. 2014; Leprêtre *et al*. 2018; Guerrera *et al*. 2020, 2021; Romagny *et al*. 2020; among others).

Methodological approach

This paper presents a regional-scale review of the Numidian subject carried out considering old (literature) and new data and based on methods that merge classical geology with more modern approaches such as the use of the software GPlates.

Such regional-scale review will be attempted through the presentation and discussion of the following aspects related to:

- Field analysis including lithostratigraphy, structural observations, reconstruction of representative stratigraphic successions and lithofacies characterization;

- Laboratory analyses including biostratigraphy/chrono-stratigraphy, sandstone petrography and clay mineralogy;

- Identification and correlation at different scales of the main geological and tectonic events recognized along different sectors of the Maghrebian Chain;

- Interdisciplinary data integration and processing;

- Redefinition of some aspects concerning the *NF*, especially those about the increasingly recognized Lateral Successions;

- And the use of the software GPlates (Müller *et al*. 2018, 2019) to elaborate palaeogeographic and palaeotectonic reconstructions of the western Mediterranean area.

The revision of stratigraphic (*NF* and Lateral Successions), mineralogical-petrographic and geochemical features of the main lithofacies, together with the identification of the special type of Numidian quartz grains, and the radiometric dating are quite useful for the identification of major interpretative constraints. This review integrates and updates previous analyses, and palaeogeographic and palaeotectonic reconstructions carried out by previous authors, by means of a comparison with general evolutionary models known in literature. In particular, some risks related to the U-Pb detrital Zircon geochronology measured on specific quartz crystals (Zimmermann *et al*. 2015) from different Numidian lithofacies of the central-western peri-Mediterranean chains are also highlighted.

State of knowledge on the Numidian subject: a synthetic revision

In this section we will summarize and revise some main general regional features related to the *NF*. We will start by reinterpreting the lithostratigraphic and biostratigraphic results, distinguishing two different Numidian successions whose palaeoenvironmental setting is not yet well defined. Then we will consider the biostratigraphic framework with paying a particular attention to probable diachronic phenomena. Follow the discussion of some general considerations on the depositional systems characterizing the *NF*. Finally, we will examine the significance of the three different types of Lateral Successions, both forming Numidian-like intervals, recognized in different and opposite palaeogeographic positions. These successions are probably located towards the internal side of the typical Numidian depositional area which is known as 'Mixed Successions' (named here as *Type C*), towards external side of the main Numidian depositional area (Africa Margin), and here named 'Marginal Successions' (named here as *Type D*), and on the internal/external zone boundary of the Maghrebian Chain (named here as *Type E*). All these Lateral Successions seem to indicate lateral interfingering phenomena, which still await a more precise definition.

Lithostratigraphy

The lithostratigraphy of the typical *NF* reconstructed in different sectors of the involved chains, shows that this formation prevalently consists of three main stratigraphic members (Lower, Intermediate and Upper). This subdivision is recognizable especially when the outcropping successions are complete and not tectonically reduced.

(1) The Lower Numidian *Mb* consists of prevailing pelites with rare intercalations of thin orange-colour quartzarenites, and sometimes calcarenites. Pelites can be represented by (1a) characteristic brownish (tobacco) pelites or (1b) varicoloured clays (*VC*) (containing T*ubotomaculum sp*.) with interbedded thin quartzarenite beds. (2) The Intermediate Numidian *Mb* is mainly made up of peculiar orange-colour ultra-mature quartzarenite turbidites, alternating with brownish pelites or *VC*. This member is the one that best characterizes the formation, due to its high thickness, which may reach up to few thousand metres, and sometimes it has been considered as the whole *NF*. (3) The Upper Numidian *Mb* is mainly constituted by a brownish pelitic-marly interval containing minor quartzarenite beds than the previous member. In the uppermost part, this member is often characterized by the presence of an important regional (e.g. Sicily, Tunisia, etc.) greenish-whitish siliceous marker-level ('silexites'). These members are recognizable in different sectors of Maghreb and Southern Apennine but the complete succession can be found only when not reduced by tectonic elisions or by paleo-physiographic constraints.

The most peculiar lithofacies are represented by the prevalent ultra-mature orangish quartzarenites containing typical well-rounded frosted quartz grains and enriched by the presence of heavy minerals as Zircon-Rutile-Tourmaline (ZRT series). The thicknesses of the formation and of the single members vary laterally along the chains probably due to: (i) relationships between the morphology of depositional environments, source location and terrigenous supply direction; (ii) amount of clastic transport; and (iii) reduction of the original successions by tectonic deformations causing dismemberment and mechanical transport. The two types of *NF* normally are recognizable in all the considered chains even if the absence of outcrops and/or of specific studies in some sectors do not allow them to be distinguished (i.e. western Algerian Tell).

The *NF* outcropping in the Southern Apennines (Carbone *et al*. 1987; Guerrera *et al*. 1992; Patacca *et al*. 1992, 2012; Festa *et al*. 2006; Lentini *et al*. 2002; Lirer *et al*. 2007; Patacca and Scandone 2007; D'errico *et al*. 2014; among others) shows some differences with respect to the characters recognized in North Africa and Sicily. In fact, its age is here much younger and set to middle-upper Miocene *p.p.* and the mineralogical-petrographic analyses indicate a gradually more arkosic and less quartzarenitic contribution (Fornelli 1998; D'errico *et al*. 2014; Fornelli *et al*. 2015, 2019). Such characteristics clearly indicate a clastic supply in this sector, from the external Apennine zones and may be even from the Calabria-Peloritani domains.

The pronounced variation in thickness shown by the reconstructed Numidian successions depends largely on lateral palaeogeographic differences in the basin (see later).

As attested by literature and as mentioned above, the *NF* is usually marked by ultra-mature quartzarenites with well-rounded frosted quartz grains, which sedimented in the external domain of the *MFB*. These specific features are common to the *NF* outcropping throughout the central-western Mediterranean area, from the Southern Spain (e.g. Didon *et al*. 1984; Stromberg and Bluck 1998) to the Northern Morocco (e.g. Leblanc and Feinberg 1982; Cazzola and Critelli 1987; Zaghloul *et al*. 2005; Abbassi *et al*. 2021), and in Northern Algeria (e.g. Moretti *et al*. 1991; Mauffret *et al*. 2004), Northern Tunisia (e.g. Yaich 1992; Riahi *et al*. 2007; Belayouni *et al*. 2010, 2012, 2013), Sicily, and Southern Apennines (e.g. Wezel 1970; Carbone *et al*. 1987; Fornelli 1998; Guerrera *et al*. 2021; and references therein). Only a few works (Fornelli and Piccarreta 1997; Fornelli 1998; and references therein) indicate in some samples from Southern Apennines (Italy) a marked grain-size bimodality: rounded quartz grains and subangular ones (see below the 'Numidian quartz and petrographic analyses' section).

The enormous amount of the Numidian quartz deposited, implies the erosion of a continental source area, grossly evaluated from 200,000 to 10^6 km^2 if covered by a regolith layer not less than 50 m thick. In present days, an agreement emerges more and more recognizing the African craton as representing the main source of the Numidian quartz. Furthermore, an origin from Africa has also been suggested based on the strong textural and compositional similarities of the *NF* with the Nubian Sandstones *s.l.*, which extend from Algeria to

Somalia (Guerrera and Puglisi 1984; Guerrera *et al*. 1992; and references therein).

Several authors, considering the homogenous regional character of the Numidian quartz as deduced from mineralogical, petrographic, geochemical, and radiometric studies, proposed an African cratonic source area for clastic materials constituting the *NF* (Lancelot *et al*. 1977; Fornelli 1998; Thomas *et al*. 2010, 2010; Belayouni *et al*. 2012, 2013; Guerrera *et al*. 2012; Alcalà *et al*. 2013; Thomas and Bodin 2013; D'errico *et al*. 2014; Guerrera and Martín-Martín 2014; Fornelli *et al*. 2015, 2019); among others). However, other authors have formulated alternative hypotheses based mainly on sedimentological reconstructions and/or radiometric analyses, proposing a northern European origin for the Numidian supply (i.e. Parize *et al*. 1986; Yaich *et al*. 2000; Boukhalfa *et al*. 2009; Riahi *et al*. 2010; Fildes *et al*. 2010; Stow *et al*. 2010; among others).

In the Betic Cordillera, Rif and Tell the maximum contribution of quartzarenites (Intermediate *Mb*) results mainly from a coeval unique Aquitanian *p.p.*-Burdigalian *p.p.* mega-event that registered a progressive delay in Sicily and Southern Apennine (Guerrera and Martín-Martín 2014).

The lithostratigraphy of the typical *NF* shows at least two main types of vertical successions (*Type A* and *Type B*; Figure 3), recognized along the chains (Guerrera *et al*. 2012; and references therein). Each type normally displays the three previously described typical stratigraphic members. The distinction is based on difference concerning the lithofacies association, the frequency of quartzarenite bodies and some sedimentological features. Both types normally display the three members but the successions mainly differ above all in their pelite components. From the bottom to the top the *Type A* succession shows: (1) Lower Numidian *Mb*. Homogeneous varicoloured clays (*VC*) with rare intercalations of thin quartzarenite turbidites (prevailing $T_{a\text{-}b}$, T_b intervals of *Bouma Sequence*); (2) Intermediate Numidian *Mb*. Typical orange-coloured quartzarenite turbidites (prevailing $T_{a\text{-}b}$, $T_{a\text{-}c}$, $T_{a\text{-}d}$, $T_{a\text{-}e}$ of *Bouma Sequence*) alternating with varicoloured clays (*VC*); and (3) Upper Numidian *Mb*. Siliceous green pelites with intercalations of quartzarenite turbidites (prevailing $T_{a\text{-}b}$, $T_{a\text{-}c}$, $T_{a\text{-}d}$ of *Bouma Sequence*), and containing a regional siliceous marker-bed upwards. The *Type B* succession shows: (1) Lower Numidian *Mb*. Thin laminated brownish pelites ('tobacco') with interbedded quartzarenite turbidites and sometimes associated calcarenite beds (prevailing T_a, $T_{a\text{-}b}$, T_b of *Bouma Sequence*); (2) Intermediate Numidian *Mb*. Typical orange-coloured thick quartzarenite turbidites (prevailing $T_{a\text{-}b}$, $T_{a\text{-}c}$, $T_{a\text{-}d}$, $T_{a\text{-}e}$ of *Bouma Sequence*), sometimes representing channelized beds and with basal erosion surfaces, alternating with brownish ('tobacco') thin laminated pelites; (3) Upper Numidian *Mb*. Siliceous green pelites and marls with intercalations

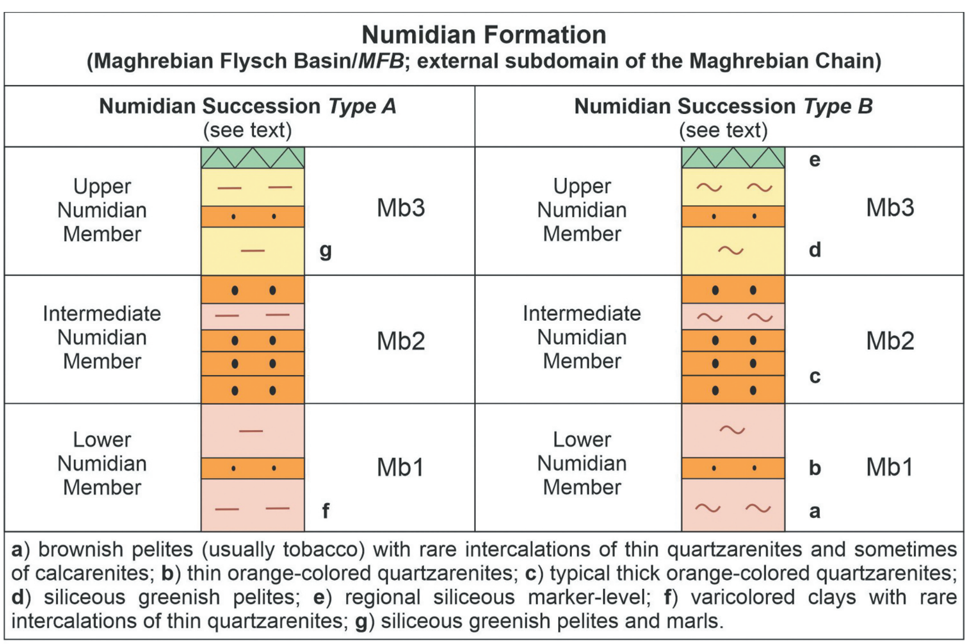

Figure 3. Regional lithological characterization of the two main vertical successions (*Type A* and *Type B*) of the Numidian Fm, which probably deposited in different depositional areas of the Numidian basin (external sub-domain of the *MFB*) (after Guerrera *et al*. 1992, 2012; Riahi *et al*. 2010, 2014, 2021; Belayouni *et al*. 2012, 2013); (D'errico *et al*. 2014; Guerrera and Martín-Martín 2014; Pinter *et al*. 2016).

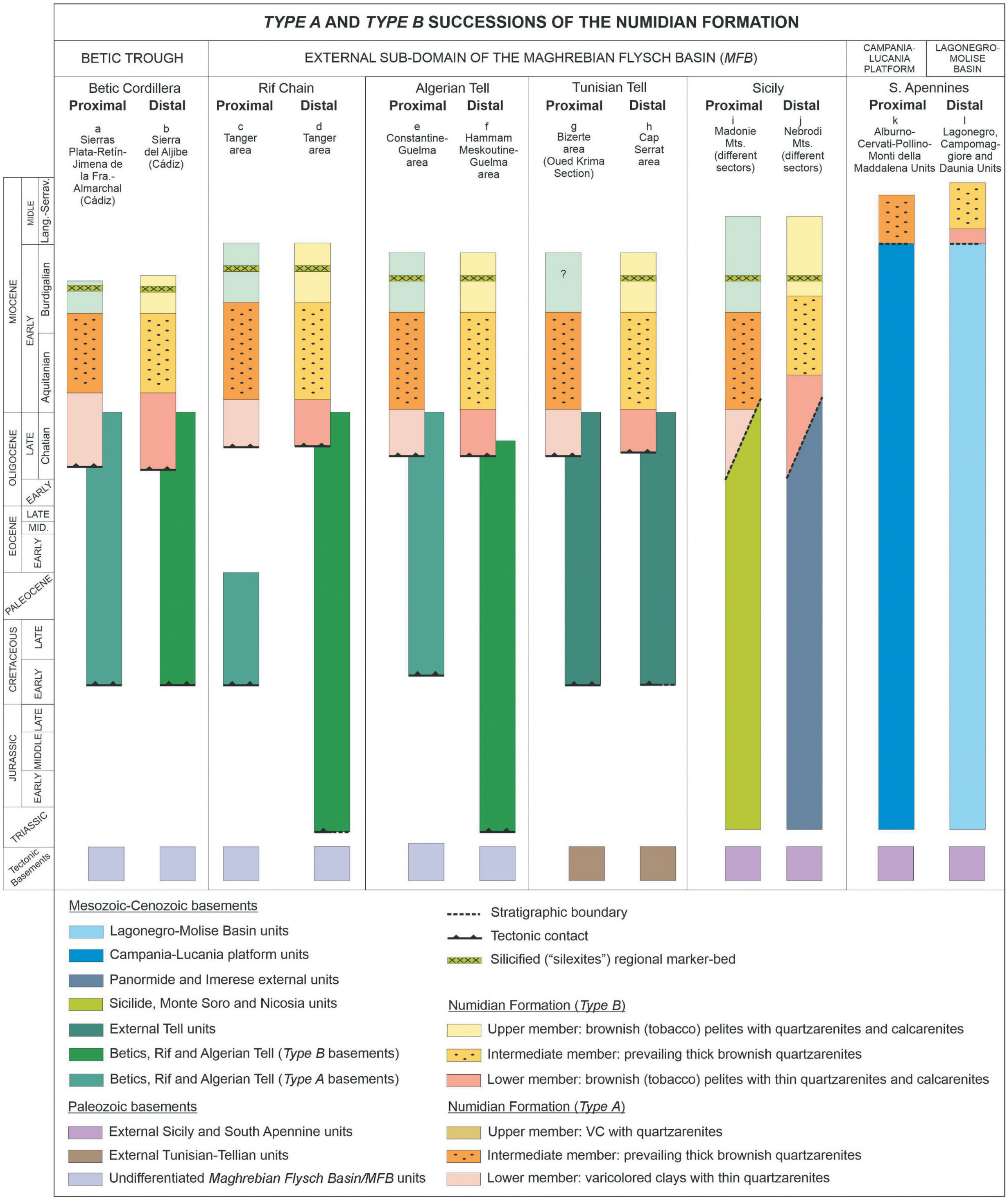

Figure 4. Distribution of the *Type A* and *Type B* successions of the Numidian Fm (external sub-Domain of the *MFB*) recognized along the Betic, Maghrebian, and Southern Apennine chains (data after Guerrera *et al*. (2012); Guerrera and Martín-Martín (2014) Maaté *et al*. (2017) Abbassi *et al*. (2021) updated, and new observations). Types of basal contacts with the substratum are also shown. In Sicily and Southern Apennine, the Numidian successions deposited in more complex palaeogeographic contexts (e.g. D'errico *et al*. 2014; Pinter *et al*. 2016).

of thin quartzarenite turbidites (prevailing T_{a-b}, T_{a-c}, T_{a-d} of *Bouma Sequence*) and the regional siliceous marker-bed upwards.

In our opinion, the features of the two types of successions (*Type A* and *Type B*) are controlled by their specific sediment supply systems together with paleo-physiographic conditions of the depositional area (distance from source areas, topographic irregularities of the basin floor, etc.), assuming a significance and importance still to be clarified.

Even if found in different sectors of the chains, however the described distinction cannot always be considered valid everywhere, due to the great lateral variability of the *NF* and the frequent dismemberment by tectonics. From a sedimentological point of view, we believe that the succession *Type A* can be considered a more basinal one (may be abyssal plain), with respect to the *Type B*, whose characteristics (Bouma sequences) seem to indicate a slope environment with the occurrence of canyons, rise, etc. Such assertion is supported by the fact that *Type B* succession includes in its Lower *Mb*, calcarenite beds which are always absent in the lower *Mb* of *Type A*, because presumably they deposited in a deeper environment under the Calcite Compensation Depth (CCD) level. In the same way, the different microfauna assemblage checked in the varicoloured clays (common in the *Type A*) and in the brownish pelites (common in the *Type B*) indicate a different depth index.

An attempt of synthesis at regional scale was carried out by Guerrera and Martín-Martín (2014; and references therein), who summarize the main stratigraphic records showing a geological evolution similar to the *NF* in different sectors of Betics, Maghrebids and Southern Apennine.

On a regional scale the boundary between the *NF* and the underlying units is mainly a tectonic contact and in most cases the successions are found to be uprooted from their originary stratigraphic substratum. However, in some sectors of the Sicilian Maghrebids (Guerrera and Martín-Martín 2014), Tunisian Tell (Hoyez 1975; Belayouni *et al*. 2010, 2012; Riahi *et al*. 2010), Betic Cordillera (Alcalà *et al*. 2013) and Rif (Abbassi *et al*. 2021; and present paper) the original substratum can be occasionally preserved, or its nature can sometimes be interpreted (Figure 4). Such rare cases, are useful because they provide new elements of knowledge on the areal distribution of the *NF*, and especially because they allow reaching more consistent palaeogeographic and palaeotectonic reconstructions.

Frequently the Numidian successions have been dismembered and mainly displaced towards the external zones during the Miocene deformation phases.

Biostratigraphy

The biostratigraphic studies about the *NF*, which have been consolidated over time by means of integrated analyses mainly based on planktonic foraminifera and calcareous nannoplankton, have a long history that is not easy to reconstruct. The biostratigraphic researches have produced up to now, many results regarding the age of *NF*, which provide a fairly coherent even if not yet an exhaustive picture.

Considering the total extension of the *NF* (from the Betic Cordillera to the Southern Apennines) the set of biostratigraphic datings indicates that the age of the formation ranges from upper Oligocene *p.p.* to middle Miocene *p.p.* In Betic Cordillera and North Africa, the age has been set more precisely to be Chattian *p.p.*-Burdigalian *p.p.* (Didon *et al*. 1984), thus marking a more or less substantial penecontemporaneity. Recently, Belhajtaher *et al*. (2023) using calcareous nannofossils date some stratigraphic sections (Tunisian Tell) to the Oligocene *p.p.*-lower Miocene *p.p.*, also including intervals stratigraphically underlying those previously studied by Belayouni et al. (2013). These results agree with those found in the Betic-Rif sectors. Moreover, the Intermediate (quartzarenitic) Numidian *Mb* of North Africa was set to be restricted to the upper Aquitanian-lower Burdigalian, thus supporting the interpretation that it represents a single event.

On the other hand, the top of the *NF* is dated Langhian *p.p.* In Central Sicily the NF is younger than in North Africa with ages reaching the Late Langhian (Pinter *et al*. 2016). Also in Southern Apennines, the top of the *NF* is also found to be slightly younger than in North Africa with an age set within the Langhian/Serravallian time interval (e.g. Patacca *et al*. 1992; La Manna *et al*. 1995; Guerrera *et al*. 2012).

These results clearly point out a substantial diachronism in the deposition of the *NF* when progressing from the Betic-Africa branch to the Sicily-Southern Apennines branch of the basin, and hence pinpoint a progressive eastward migration of the deformation.

Despite the *NF* age differences observed, it is not yet possible to appreciate in more detail the diachronism rate neither between the two main branches, nor between the Numidian in Sicily and southern Apennine. To achieve this goal, it would be necessary to carry out integrated biostratigraphic analyses considering the variability of the lateral and vertical extension of the *NF* members at a regional scale.

A possible explanation of this difference in age can be searched in the progressive greater distance (referred to North Africa) between the African sediment source areas and the sedimentary depositional basins. This distance is controlled by the progressive eastward migration of the deformation and/or to the occurrence of palaeogeographic barriers or other unknown obstacles, as suggested by D'errico *et al*. (2014).

The age of the Numidian successions checked in the different chains is reported in Figure 4, which represents a synthetic framework at regional scale.

Depositional systems and palaeoenvironments

Numerous studies were addressed to the reconstruction of the depositional palaeoenvironments of the *NF* in all sectors of the Betic, Maghrebian and the South Apennine chains (Wezel 1970; Durand-Delga 1980; Guerrera 1981/82; Hoyez 1989; Moretti *et al*. 1991; Guerrera *et al*. 1992, 2012; Fildes *et al*. 2010; Riahi *et al*. 2010; Thomas *et al*. 2010; Belayouni *et al*. 2013; Thomas and Bodin 2013; Barbera *et al*. 2014; D'errico *et al*. 2014; Riahi *et al*. 2014, 2021; Pinter *et al*. 2016, 2017, 2018; Butler *et al*. 2020; Abbassi *et al*. 2021, among others).

Briefly, data from great majority of papers point out that the main depositional environments of the *NF* range from the slope domain (and related sub-environments such as channels, overbank areas, etc.) to a more or less deep environment located near the slope bordering the abyssal plain (deep sea fans and continental rise). The Numidian lithofacies associations (predominantly clastic turbidite deposits) referable to these environments, have been recognized in all segments of the chains.

However, it is often not possible to reconstruct the lateral and vertical distributions of the original successions, due to the tectonic transport, which caused their expulsion from the depositional basins (as frequently indicated by their tectonic position in the superstructure). Only in a few sectors the different depositional environments of the Numidian successions are recognizable, especially in the Tunisian Tell. Here, continental and shelf deposits are represented by the Glauconititic Fm (external shelf) of the Bejaoua Group (Rouvier 1977), the fluvio-deltaic sands of the Fortuna Fm, the fluvial sands of the Cherichira Fm (Yaich 1992), and the paleo-dunes (fossil barkane systems; uncertain age) observed in many southern Tunisia Tellian areas (Zaier and Belayouni 2000; Guerrera *et al*. 2012).

Recent studies addressed to the different depositional palaeoenvironments of the *NF* at regional scale highlighted interesting aspects concerning the distribution of Numidian flows. These were obviously controlled by palaeogeographic factors (i.e. physiography of the margin/basin systems), structural elements (i.e. syn-sedimentary tectonics) and mineralogical-petrographic characters of the different sediment contributions related to the specificity of the source area.

For example, according to Thomas *et al*. (2010) the *NF* should be related to a major Cenozoic drainage system, located on the North African Margin during the regional Atlas uplift phases. The formation would be interpretable as resulting from a passive margin deposition, mainly controlled by hinterland uplift and climatic fluctuations. According to Butler *et al*. (2020), the Numidian flows, which are axially fed from North Africa, were confined along sinuous corridors related to active submarine thrusting. 2021), in their study of different successions in the Tunisian Tell, concluded to the existence of depositional processes typical 'bypass channel' (proximal deposition). Such finding indicates that facies distribution, depositional environment, and sedimentary features, were controlled by topographic highs and by the occurrence of inherited faults.

According to Alcalà *et al*. (2013), the quartz supply occurring during the Burdigalian, is related to the erosion of the Atlas area, favoured by a forebulge uplift of the African Margin due to the subduction of the *MFB* below the *MM* in the context of a complex foreland basin system evolution.

Evidently, it appears more clearly that the depositional environments reconstructed for the *NF* are different, and they vary according to the relationships between paleo-physiographic features and the main processes acting both in source areas and depositional basins. On a larger scale, such features and processes depended on the general palaeogeography. Obviously, it seems that each chain sector experienced its own peculiar evolution that controlled the main parameters and features of the depositional systems (distance between erosion areas and depositional zones, amount of sediment supply, distribution and features of hydrographic networks, energy of relief, etc.). This resulted in the deposition of different lithofacies associations, as attested by the abundant literature.

The different sedimentological interpretations of the Numidian depositional systems show lateral and transversal differences in the shape of the paleo-basinal areas, which result into a different width values and cause different relationships with the internal (Internal Flysch of the *MFB*) and external (African Margin) subdomains, respectively. For example, the presence of confined paleo-basin was highlighted in Sicily, while an enlargement of the paleo-basin towards the African palaeomargin is very probable in the Rif and especially in the Tunisian Tell, as evidenced by the literature reported in this section. As can be inferred from numerous sedimentological studies, the *NF* prevalently represents a turbidite succession deposited in deep marine palaeoenvironments (prevailing slope and abyssal plain) but with many lateral variations mainly controlled by active tectonics (Guerrera *et al*. 2012; Pinter *et al*. 2016; Abbassi *et al*. 2021). Really, the palaeoenvironments reconstructed over time by the different authors along the sectors of the implicated chains, show a wider and detailed variety.

Lateral Successions

A rather underestimated subject concerning successions interpreted as lateral ones with respect to the *NF*, and already pointed out by some authors (e.g. Didon 1969; Laval 1970; Didon *et al*. 1973; Hoyez 1976; Didon and Hoyez 1978; Guerrera 1981/82; Guerrera *et al*. 1986, 2012; Grasso *et al*. 1987; Carmisciano *et al*. 1989; Belayouni *et al*. 2010; Alcalà *et al*. 2013; Guerrera and Martín-Martín 2014; Abbassi *et al*. 2021), is relaunched here because it allows expanding the Numidian theme establishing new interpretative constraints.

In the last years, some Numidian-like successions have acquired increasing importance especially because they can provide new palaeogeographic information useful to clarify some relationships between the sedimentation in the *MFB* and the deposition characterizing lateral sedimentary basins. In general, these lateral successions consist of stratigraphic intervals containing Numidian lithofacies interfingering with lithofacies fed by different source areas. In fact, in each sector, the Lateral Successions show the interdigitation and/or stratigraphic alternances with lithofacies of other nature and origin.

On the basis of the available data, we propose to distinguish three main types of Lateral Successions, deposited in different sectors of the Numidian depositional area. The innermost type is already known as "Mixed Successions", and is here called *Type C*, (Guerrera *et al*. 2012; *and references therein*). The second outermost one (*Type D*) is known as 'Marginal Successions'. It is represented by different lithologic successions, associated with *NF* lithofacies and fed from local areas of the North African Margin (*NAM*). The framework is completed by a third type of lateral succession also representing another type of 'Marginal Successions' (here *Type E)*, which deposited far from the *MFB* only in the Betic area. The provisional terminology adopted in this paper is reported in Table 1.

More in detail, the *Type C* Successions known along the considered chains, consist of stratigraphic alternances between Numidian lithofacies and pelite and arenite intervals, which are completely different regarding their mineralogical and petrographic characters (Didon and Hoyez 1978; Guerrera 1981/82; Guerrera *et al*. 1986, 1992, 1993, 2005, 2012 (a, b); (Grasso *et al*. 1987; Carmisciano *et al*. 1989; Hoyez 1989; Belayouni *et al*. 2010, 2013; Guerrera and Martín-Martín 2014); and references therein). The arenites show two different compositions (hyper- and hypo-mature), which result from the erosion of the opposite continental margins of the *MFB* (*MM* and Africa Craton). Alternances of different petrofacies are recognizable in the same stratigraphic succession (Figure 5), such as: (i) immature lithic arkoses and litharenites derived from the erosion of internal crystalline belts and their carbonate cover; (ii) typical Numidian ultra-mature quartzarenites resulting from the erosion of external cratonic areas. Therefore, the *Type C* Successions were supplied alternatively from the opposite (internal and external) margins of the *MFB*, to indicate a lateral interference and interfingering of two different sedimentary systems, probably developed in depocentre areas.

In the La Galite Archipelago (Tunisian Tell), Belayouni *et al*. (2010) described a 45 m thick Numidian succession tectonically overlying the La Galite Flysch Fm (i.e. an internal unit of the *MFB*). Such observation supposes the possible presence at this locality of *Type C* Succession deposits, in agreement with previous observations made by Durand Delga (1956).

The thickness and the vertical development of the different *Type C* lithofacies along the chain probably depend on the prevalence of one depositional system with respect to the other, which is controlled by the palaeogeographic setting, tectonic activity and

Table 1. Palaeogeographic relationships between the Numidian Fm (*Types A* and *B*) and Lateral (*Types C*, *D* and *E*) Successions. The terminology for Lateral Successions is still informal.

Relationships between Numidian Fm (*Type A* and *Type B)* and Lateral Successions (*Types C, D* and *E)*
(*NB*, Numidian Basin; *MFB*, Maghrebian Flysch Basin)

Type C **Lateral 'Mixed Successions'** (deposited between the *NB* and the internal sub-Domain of the *MFB*)	*Type A* **and** *Type B* **Numidian Formation** (*NB*)	*Type D* **and** *Type E* **Lateral 'Marginal Successions'** (prevalently deposited on Africa-Adria-Iberia Margins)
Stratigraphic alternances of lithofacies fed by the opposite (internal and external) margins of the *MFB*	Upper Numidian Member Intermediate Numidian Member Lower Numidian Member	Numidian successions mainly deposited on External units (Betic, Maghrebian and Southern Apennine chains)
Probably deposited in depocentral areas of the *MFB*	Two main Numidian Successions characterized by lithofacies associations related to different depositional environments of the *NB*	Mainly shelf/basin systems located on continental margins

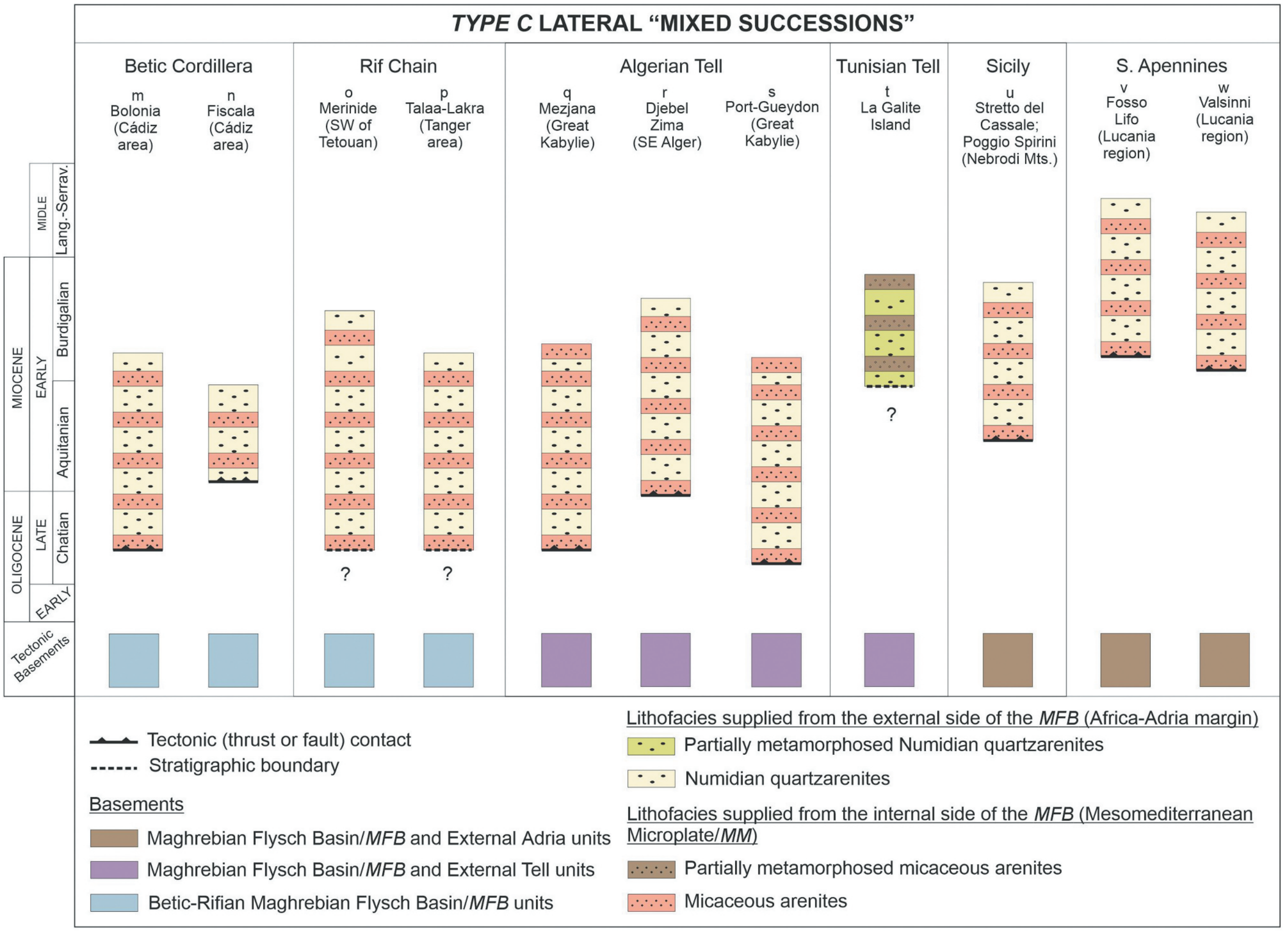

Figure 5. Distribution of the Numidian Lateral 'Mixed Successions' (*Type C*) recognized along the Betic, Maghrebian and Southern Apennine Chains, and demonstrating the interfingering between the depositional systems of the internal (Internal Flysch) and external (Numidian Fm) sub-domains of the Maghrebian Flysch Basin (*MFB*). The successions are characterized by a stratigraphic alternance of intervals and/or a few beds of very different petrofacies, consisting of immature (Internal supply), and supermature (External supply) deposits. Depocentral depositional areas located between the internal and external sub-Domains of the *MFB* seem to be the most suitable sedimentation sites for this type of Lateral Succession (data after, Hoyez 1976; Didon and Hoyez 1978; Guerrera 1981/82; Guerrera *et al*. 1986; Carbone *et al*. 1987; Grasso *et al*. 1987; Carmisciano *et al*. 1989; Moretti *et al*. 1991; Fornelli 1998; Belayouni *et al*. 2010; Guerrera *et al*. 2012; Guerrera and Martín-Martín 2014, updated and integrated with new observations).

sediment amount that favour a heteropic deposition. Normally, at regional scale, the *Type C* lithofacies are transported tectonically towards the external zones, consistently with the local tectonic polarity, and they were recognized in every sector of the considered chains (Figure 5). However, our statement does not exclude that the contact between *Type C* Mixed Successions and their substratum could be locally stratigraphic as in the Tanger area (Talaa-Lakra and Mérinides), where the basal contact of the *Type C* Mixed Successions has been recently settled as stratigraphic (Abbassi *et al*. 2022). As regards the age of *Type C* Mixed Successions, although some studies have attributed an Early Burdigalian age (Alcalà *et al*. 2013; Abbassi *et al*. 2022), a definite age is not yet well defined everywhere. However, the age should remain inside the age-interval comprised between the base and the top of the Numidian Fm (Middle Miocene). Moreover, despite the different structural position (uprooted or rooted) of *Type C* Mixed Successions, their ages and contact types depend on the local palaeogeography (source/deposition relationships) and on the beginning of the deformation in each specific sector, and therefore it is not necessarily synchronous everywhere.

The distinction between *Type D* and *Type E* successions, which are both 'Lateral Marginal succession', is made upon their depositional palaeoenvironments, the age, as well as upon their lithostratigraphic characteristics which are slightly different.

Type D are Lateral Marginal Successions deposited on the African-Adria margin areas (External Zones of the Maghrebian Chain). They are characterized by a lithostratigraphic suite displaying Numidian features with clastic materials fed from the Africa cratonic area, but, sometimes, associated to carbonate lithofacies with larger benthic foraminifera and glauconites, and having a more local origin (non-flysch successions). Good examples recognized in the El Habt and Ouezzane units (External Intrarif) and in the External Tanger Unit (Internal Intrarif), according to Maaté *et al*. (2017) and Martín-Martín *et al*. (2022). In the Rif a controversy exists about the palaeogeographic position of the External Tanger Unit. This unit is considered by several authors as a part of the African Margin (Maaté *et al*. 2017; Martín-Martín *et al*. 2022, among others), while others (Durand Delga 2006; Abbassi *et al*. 2022) consider it as a part of the shallow and marginal southern sector of the *MFB*. In any case, *Type D* Successions are characterized by a lithostratigraphic suite displaying some Numidian features (supermature arenites with rounded quartz grains) but deposited outside the deep areas of *MFB*, where the Numidian Fm usually occurs, and with an age ranging from lower Oligocene to upper Burdigalian (Figure 6). These successions usually show older ages than *Type A* and *B* successions. This can be explained considering that the distribution paths of the Numidian supplies should be very complex, due to their intermittent activity in time and space. Moreover, in proximal areas the lateral Numidian lithofacies could be slightly older, due to their closer position to the source areas. Later, these supplies will arrive at the deep *MFB* where the Numidian *Type A* and *B* occur with a slight younger age.

Other examples of Type D successions could be documented also at the Algerian (Oranais and Boghari stratigraphic sections) and Tunisian (Kasseb-Fortuna sections) Tell (i.e. Flandrin 1955; Rouvier 1977; Lahondère 1987; Hoyez 1989; Yaich *et al*. 2000; Belayouni *et al*. 2010, 2012, 2013); (Riahi *et al*. 2021); Sicily (i.e. Wezel 1970; Guerrera *et al*. 1992; Barbera *et al*. 2014; Guerrera and Martín-Martín 2014); and also at Southern Apennines (i.e. Perrone 1981; Fornelli 1998; D'errico *et al*. 2014; Fornelli *et al*. 2015, 2019). In these cases, the *NF* was fed (Table 1; Figure 6) by the African cratonic area with the potential addition of carbonate lithofacies having a more local origin. However, the *Type D* deposits are not constituted by the typical Numidian quartzarenites but they contain quartz-rich litharenites. The Numidian Lateral Successions here considered as *Types D* reported in the Rif Chain stratigraphically cover some external units representing their original substratum (i.e. Intrarif Subdomain) on the African palaeomargin (Maaté *et al*. 2017; Martín-Martín *et al*. 2020, 2022, 2023 Tanger Unit; Abbassi *et al*. 2021). The subsequent tectonic evolution deformed these successions to generate tectonic slices mainly transported on units of the External Zones. Moreover, a revision of the relationships between the *Type D* Lateral Marginal Successions and the underlying formations is required to clarify whether the contact is tectonic (uprooted tectonic slices) or sedimentary (deposition within minor basins located in an intermediate position between the source areas of the Numidian quartz and the deeper main Numidian depositional area).

One of the recent results is represented by the *Type E* Lateral Marginal Successions, which deposited on the internal/external zone boundary of the Maghrebian Chain, and associated to supplies from the innermost and western parts of the *SIM* and also the Mesomediterranean Microplate (*MM*) in the Betic Cordillera during Burdigalian times. These deposits represent an interesting element that allow to better define the palaeogeographic framework of the Numidian evolution (Alcalà *et al*. 2013). In particular, the *Type E* deposits show Numidian turbidite quartzarenites interbedded with deposits related to an external supply from the Subbetic-Penibetic Zones of the Betic Cordillera and also as part of the Frontal Units of the Internal Betic Zone (Numidoide from Martín-Algarra 1987). However, the *Type E* Successions are not characterized by the typical Numidian quartzarenites because they contain instead quartz-rich litharenites. In this case, the external Betic sediment supply must be considered from the External Zones of the Iberia Plate. This type represents the migration of the Numidian depositional system to reach the opposite margins of the *MFB* and is mainly associated to supplies from innermost and western parts of the SIM of the Betic Cordillera in the final period of the Numidian deposition in this area. The post-collisional (extensional) emplacement event for *Type E* successions is considered a gravitational back-slide process (Hlila *et al*. 2008). The second post-collisional event is represented by the Argüelles succession (Betic Cordillera, North of Gibraltar), which stratigraphically rests on the Frontal Units of the Internal Zones (Martín-Algarra 1987; Alcalà *et al*. 2013).

These Lateral Successions introduce new aspects concerning the Numidian *'scenario'*. In fact, the research advancements on the *Type C, Type D* and *Type E* Successions, which deposited laterally to the typical Numidian depositional area, introduce new complex elements useful for a better definition of the Numidian evolution in general. The different families of lateral successions occupy different and opposite palaeogeographic positions. We believe that the deposition of Type C successions could have resulted from an interference of opposite depositional systems located in intermediate areas of the basin. However, for the depositional systems of *Type D* and *Type E* Successions the situation is different. We believe that a more complex palaeogeography of the shelf/basin

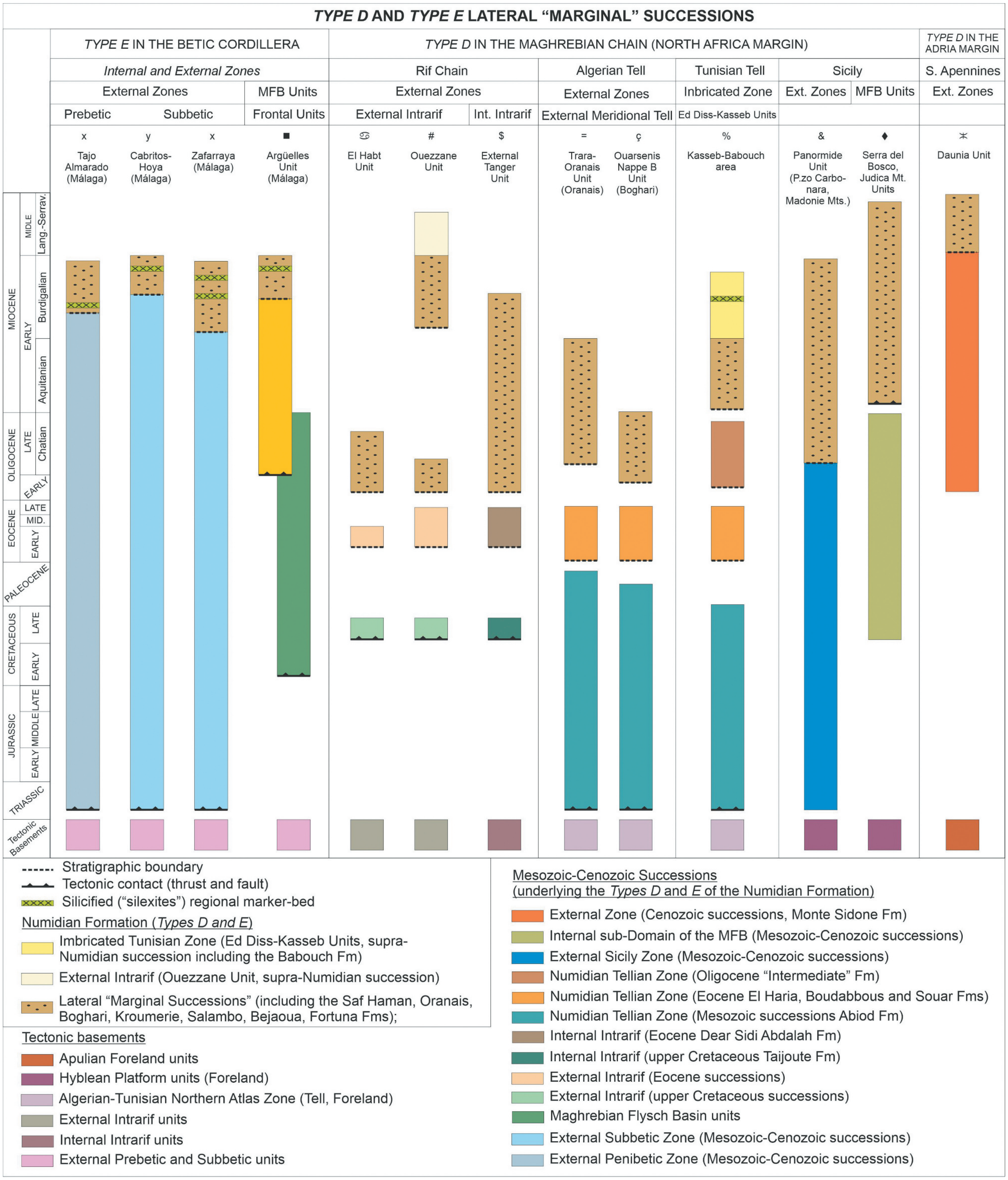

Figure 6. Distribution of the *Type D* and *Type E* Lateral 'Marginal Successions' recognized along the Betic, Maghrebian and Southern Apennine Chains, and deposited outside the Numidian Basin. Normally these successions stratigraphically lie above the Africa-Adria external units of the *MFB*, and emphasize the African provenance of the Numidian supply (data after Belayouni *et al.* (2012; Belayouni *et al.* 2013); Guerrera *et al.* (2012); Alcalà *et al.* (2013); Barbera *et al.* (2014); D'errico *et al.* (2014); Maaté *et al.* (2017);2020), updated with new observations).

system was at the origin of favouring a supply of the cratonic Numidian quartz from different locations.

Numidian quartz, shales and U-Pb zircon: a synthetic revision

One of the most interesting long-term debate regarding the Numidian Fm of the *MFB* deals with the sediment provenance (from the North and/or South) and the location of the source region. Among the multiple analytical studies that might help solving this debate, petrographic, mineralogical and geochemical studies of arenites and shales coupled to geochronological studies (U-Pb Zircon dating) of quartz minerals were of a special interest. These studies brought significant elements and criteria to prioritize one source area over others.

Numidian quartz and petrographic analyses

The petrographic study of Quartz crystals of the Numidian sandstones evolved as a valuable tool that can provide precious information on provenance and transport of these grains from the source area to the Numidian depositional Basin (Dickinson and Suczek 1979; Fornelli 1998; Thomas *et al*. 2010).

It is now well established that the Numidian clastic sediments deposited in all the considered chains consist predominantly of Quartz (often more than 90%) associated with minor minerals. The latter are mainly represented by Feldspars, Micas, Clays and a suite of heavy minerals including Zircon, Rutile Tourmaline (ZRT), Garnet, Monazite and Iron Oxide (Wezel 1970; Gaudette *et al*. 1979; Puglisi 1994; Fornelli and Piccarreta 1997; Fornelli 1998; Belayouni *et al*. 2010; Fildes *et al*. 2010). As a matter of fact, the determination of textural features of quartz by means of an integrated petrographic, mineralogical and geochemical studies, has provided precious indications about their specific source areas (Schwab 1975; Roser and Korsch 1986; Fornelli and Piccarreta 1997; Fornelli 1998; Thomas *et al*. 2010; among others).

A review of specific studies has led to determine common features of Quartz grains. Interpretations of Quartz-Feldspar-Lithic (QFL) diagrams obtained for different Numidian arenites from the western-central peri-Mediterranean chains have been successfully attempted with the aim to trace the source of sandstone materials (i.e. Carbone *et al*. 1987; Moretti *et al*. 1991; Fornelli and Piccarreta 1997; Fornelli 1998; Johansson *et al*. 1998). Based on the results obtained, all these authors pointed out that more than 55% and up to 97% of QFL plots lie within the quartzarenite domain. In particular, Thomas *et al*. (2010) and Thomas (2011), who studied using the X-ray diffraction the QFL composition of *NF* arenite samples collected in Sicily and Tunisia, found that all the analysed samples plot in the quartzarenite pole, with an average bulk composition of Q_{92},F_2,L_6. The same authors pointed out the occurrence of a bimodality, which is expressed by two quartz grain-size classes: fine to very fine quartz grains (100 µm to 300 µm) and coarse to highly coarse quartz grains (500 µm to 2 mm). While the latter are composed by a polycyclic polycrystalline quartz, the finer fraction, which is constituted by microcrystalline quartz associated to minor amounts of Feldspar, Glauconite, Mica, and lithic grains, might be related to flow processes rather than to a distinct source area or to a direct supply to the basin (Thomas *et al*. 2010, 2010).

Similarly, a pure quartzarenite composition has been suggested by several authors in for the *NF* in Tunisia (Yaich 1992; Belayouni *et al*. 2010; Fildes *et al*. 2010), Morocco (Leblanc and Feinberg 1982), Algeria (Moretti *et al*. 1991), and Sicily (Johansson *et al*. 1998; Barbera *et al*. 2014).

However, with a special reference to the quartz fraction of the Numidian deposits in Italy, a marked grain-size bimodality and a dominant population in the range of sublitharenite and quartzarenite (Wezel 1970; Didon *et al*. 1984; Puglisi 1994; Fornelli and Piccarreta 1997; Fornelli 1998) clearly attest a significant difference with respect to the Maghrebian *NF*. In fact, Fornelli (1998), in his study on the Numidian deposits of southern Apennines, observed that Quartz grains belong to two distinct classes. The first one is represented by undeformed rounded grains inherited from plutonic rocks or high-grade metamorphic rocks. They are interpreted as resulting from a polycyclic origin or derived from a long continental or marine reworking. On the other hand, the second one is represented by deformed frequently subangular grains. They are interpreted as polycyclic grains highly shattered during final transport or as materials reworked from an ancient plutonic/metamorphic basement affected by strong chemical alteration and a rapid final transport.

Similarly, Belayouni *et al*. (2010) in their petrographic study of the arenites of the internal (La Galite Flysch Fm) and the external (Numidian Succession) deposits of the *MFB* of La Galite Archipelago (offshore Tunisia), recognized three different petrofacies. Two of these petrofacies characterize well the La Galite Flysch Fm, and consist of immature litharenites, which have been transported over a short distance from a source area located close to the sedimentary basin. These deposits are characterized by clastic deposits supplied from crystalline magmatic or metamorphic rocks. In particular, the petrographic composition shows various angular-shaped elements cemented by a fine-grained mesostasis. Such a petrographic composition allowed considering the La Galite Flysch as a formation belonging to the syn-orogenic flysch succession of the internal sub-domain of the *MFB* (*sensu* Guerrera *et al*. 1993, 2005). The third petrofacies, which constitutes the *NF* is quite different because it shows specific features of supermature quartzarenites affected by heating and deformation (contact metamorphism). In fact, this petrofacies consists of the 96.8–97.6% of well-sorted quartz grains (average size 0.3 mm). In addition, quartz grains are limpid and show some solid (zircon and biotite) and fluid (monophasic and biphasic) inclusions.

Recent petrographic studies on Lateral Numidian successions of the External Rif Zones (*ERZ)* have also provided some differences (Maaté *et al*. 2017; Martín-Martín *et al*. 2020, 2022) with respect to the clastic sedimentation of the *NF s.s*. Although in these cases the main component is always quartz (more than 40%), the value of the average content is lower with respect to the Numidian successions. These Successions consist of arenites, hybrid arenites and calcarenites. The QFL diagrams allowed classifying arenites and hybrid arenites as sub-litharenites and litharenites.

Mineralogy and geochemistry of Numidian shales

The chemical composition of shales is an important record of the geological evolution of the continental crust through time, because some elements are transported within the terrigenous fine fraction (Taylor and McLennan 1985). Accordingly, major and trace elements analyses, and especially rare earth elements (REE) analyses, could be of precious help to unravel the past history of resedimented clastic materials.

Indeed, the calculation and interpretation of the Chemical Index of Alteration allow determining the source area as well as the degree of chemical weathering during the transport (McLennan *et al*. 1993; Fedo *et al*. 1996; Mongelli *et al*. 1996; Hassan *et al*. 1999; Bauluz *et al*. 2000; Cullers 2000; Condie *et al*. 2001; Mongelli 2004; Barbera *et al*. 2011, 2014). Also, the paleo-climate characterizing the source areas at the time of deposition (Nesbitt and Young 1982) can be recognized.

Shales represent an important portion of the *NF*, and studies addressed to determine the source areas have been mainly based on petrographic/geochronological approaches and only a few studies have been devoted to mineralogical/geochemical analysis. In the last decades, the renewed interest in mineralogical/geochemical analyses of the Numidian shales (i.e. Fiore *et al*. 2000; Cavalcante *et al*. 2003; Mongelli 2004; Barbera *et al*. 2014; Ben Yahia *et al*. 2019) brought valuable results on sediment provenance, through the identification of many mineralogical/geochemical criteria.

Clay minerals are materials inherited from the continent and constitute the final products of the siliciclastic weathering process. The study of their assemblage in clastic sediments can provide significant information about the continental weathering intensity, as well as on variations and changes in the continental runoff. The Numidian shales analysed for mineralogy, and especially for clay minerals assemblage, have shown a common feature expressed by a Kaolinite-rich signature (Mongelli 2004; Barbera *et al*. 2011, 2014). In fact, Barbera *et al*. (2014) observed that kaolinite and smectite are the most abundant phases (up to 50%) among the clay minerals of the *NF* in Sicily, while illite and chlorite are subordinated. According to these authors, such mineralogical fingerprints are in total contrast with the composition of the older Alpine Tehyan deposits, whose provenance from the European crust has been already constrained (Barbera *et al*. 2009, 2011). Therefore, an alternative provenance from the Africa craton of the *NF* shales has been favoured, however clearly confirmed also by geochemical analysis.

Recent mineralogical studies (Maaté *et al*. 2017; Martín-Martín *et al*. 2020, 2022) have also been carried out in the Lateral Numidian successions of the *ERZ*. The bulk mineralogy of clays was found to be rich in quartz and phyllosilicates associated to minor amounts of calcite and dolomite. The clays are rich in illite and I-S mixed-layers and have lower average values of smectite, kaolinite and palygorskite. For the same authors, the low values of the ratio of I(002):I(001) peaks of illite indicate a mature sedimentation, while the XRD parameters indicate the presence of detrital quartz and illite without any signs of a secondary origin due to diagenesis or incipient metamorphism.

U-Pb Zircon geochronology

U-Pb detrital Zircon geochronology rapidly evolved into a valuable and powerful tool for determining provenance of clastic materials deposited in sedimentary basins. Especially U-Pb detrital zircon geochronology techniques were applied successfully on clastic sediments of the *NF* in order to determine their provenance through an accurate dating of the associated zircon crystals (main results in Table 2). Confidence allowed to the use of U-Pb Zircon dating on clastic sediments is based on the fact that weathering of source rocks, during the transport processes has no or little effect on the alteration of the specific age of Zircon crystals. This

Table 2. U-Pb detrital Zircon geochronology measured on quartz crystals from different successions of the Numidian Formation outcropping in the central-western peri-Mediterranean chains.

Formation	Chain sector	Radiometric dating (kMa)	References
Numidian Fm	Betic Cordillera and Maghrebian Chain	1.83 ± 0.1 (90–95% Zr)	Lancelot *et al.* (1976)
Aljibe Formation	Betic Cordillera (Southern Spain)	(0.602–0.576) (47–54% Zr) (1.87–2.048) (18–24% Zr) (2.5–3.3) (<10% Zr)	Daudet (2019)
Numidian Sandstones (Tanger Unit)	Rif Chain (Northern Morocco)	2.5 to 0.5	Abbassi *et al.* (2022)
Maghrebian Flysch Complex (Numidian Fm)	Rif Chain (Northern Morocco)	2.28 to 0.347	Azdimousa *et al.* (2019)
Numidian Fm (Khroumirie Member)	Tellian Chain (Northern Tunisia)	1.75 ± 0.1	Gaudette *et al.* (1975), Gaudette *et al.* (1979)
		0.514 ± 0.019	Fildes *et al.* (2010)
Numidian Fm (Nicosia Unit)	Sicilian Maghrebids (Sicily, Italy)	0.55 ± 0.028 1.35 ± 0.1 (5–10% Zr)	Lancelot *et al.* (1977)
Bifurto and Numidian fms	Campania – Lucania and Adria platforms (Southern Apennines, Italy)	3.047 ± 0.013 to 0.516 ± 0.019 Mainly 2.5 to 1.6	Fornelli *et al.* (2015), Fornelli *et al.* (2019)

implies that the frequency distribution of the age of these crystals in the host sediments will remain representative, and now it is used to trace accurately the provenance of the Numidian materials (Thomas *et al.* 2010, 2010; Thomas 2011). However, as noticed by 2015), it is possible that some sedimentological processes, sorting effects (e.g. graded beds), as well as sampling might alter the confidence in dating accuracy and affect the provenance interpretation. Particularly, changes of sediment transport system will extremely and profoundly impact the provenance of the formation (Zimmermann *et al.* 2015). In the same respect, Kielman (2018) argued that further complications arise from the use of U-Pb detrital zircon to determine material provenance, when an unknown number of source rocks contribute to the detrital sediments, or when source rocks are absent. Therefore, the author concludes that to be credible, ancient detrital zircon populations require extensive data filtering in order to produce reliable results for age comparison.

In addition, Tokiwa *et al.* (2017) reported that zircon ages do not directly indicate the depositional age; but instead, the crystallization age, and thus, it is possible that a large age gap exists between the depositional ages and zircon ages. Therefore, in order to ensure a reliable determination of the depositional age based on U-Pb Zircon analytical method, these authors recommend to insure first its effectiveness. This could be achieved through the comparison of detrital zircon ages with those deduced from other geochemical, biostratigraphic, and/or mineralogical studies, performed on the same materials.

However, despite these relevant remarks regarding the reliability on U-Pb detrital zircon geochronology, we do believe that in the present case-study, some confidence can be given to detrital zircon data interpretation for differencing European ages (Hercynian-Variscan) from African ages (Caledonian and older). Two reasons could be advanced to justify our assertion. The first one deals with the wide gap existing between the detrital U-Pb zircon ages sourced from the European craton compared to that sourced from the African craton. While for an African craton source area, detrital zircon ages are quoted in thousands million years (Paleoproterozoic to Mesoproterozoic), those inherited from the European craton source area are quoted in hundreds of millions of years (not older than Late Palaeozoic). We think that these differences are several magnitudes higher than the uncertainty values (e.g. 650) due to interferences from sampling or sedimentary processes. In addition, even if the shift in U-Pb zircon ages, due to sedimentary interference, reported by Zimmermann et al. (2015), is relatively high (Neoproterozoic to Paleoproterozoic), the determined ages always lie in a time interval not younger than the Precambrian. The second one deals with the fact that our interpretation of source of origin of *NF* sandstones is not quoted only based on detrital U-Pb zircon geochronology but is supported and confirmed by data deduced from other geochemical, mineralogical and petrographic studies. Such approach gives much more credibility to the interpretations and conclusions reached in this study regarding the source provenance of the Numidian sandstones.

One of the first attempts to determine the provenance of the *NF* was carried out by Lancelot *et al.* (1977), who measured the U-Pb isotope ratios on Zircon crystals collected from the *NF* of the Betic Cordillera and Maghrebian Chain (Table 2). Their results pointed out to the occurrence of two populations of ages: the first one, which accounts from 90 to 95% of Zircon crystals indicates an age of 1830 ± 100 Ma (Paleoproterozoic) and the second one, accounting for 5 to 10% of crystals, indicates an age of 1350 ± 60 Ma (Mesoproterozoic). Both classes clearly attest to a Precambrian age of Zircon crystals.

Daudet (2019), who measured the U-Pb isotope ratios in Zircon crystals collected from the Numidian successions of the Betic Cordillera, confirmed these data. Similarly, three populations of ages have been distinguished. The first population accounting for 47 to 54% of crystals indicates an age between 603 and 576 Ma (Caledonian); the second one, which represents 18 to 24% of crystal indicates and age between 1.870 and 2.048 Ma. Instead, the last population, 10%, indicates ages from 2.500 to 3.300 Ma. Such ages point again to the Precambrian units as the main source for the Betic *NF*.

Gaudette *et al*. (1975), who reported a Zircon age of 1.750 ± 100 Ma (Paleoproterozoic), on the *NF* of Tunisia, have obtained comparable results and similar ages earlier.

More recently, results of U-PB Zircon measurements performed on the Numidian deposits of Tunisia and Sicily (Fildes *et al*. 2010) show younger (Caledonian) ages referable to the early Phanerozoic (i.e. 514 ± 19 Ma for Tunisia and 550 ± 28 Ma for Sicily). These authors interpreted their results as an indication of a northern provenance from the European Plate of the Numidian sandstones. Their interpretation refers to the Rb/Sr isotope dating of mica crystals (505 Ma) obtained by Bossiere and Peucat (1985, 1986) on the Kabyle basement block considered as a part of the European Domain.

In their study of U-Pb detrital Zircon ages from Numidian sandstones in Southern Apennines, Fornelli *et al*. (2015) measured an age varying from 3.047 ± 1 Ma (Mesoarchean) to 516 ± 19 Ma (Cambrian), with maximum values comprised between 2.500 and 1.600 Ma, attesting a Paleoproterozoic age. These authors have reported no values that might refer to a Hercynian alpine age. In addition, the same authors pointed out the existence in another sample, of a cluster of ages at 773 ± 24 Ma and 668 ± 17 Ma, calculated on Zircon domains with magmatic zoning, which attest to an important contribution from Neoproterozoic granitic rocks widely outcropping in the North African Craton.

Similar results have been obtained from the U-PB detrital Zircon measurements performed on the Quartz-rich Bifurto Sandstones Fm of southern Apennines (Fornelli *et al*. 2019). Indeed, the U-Pb detrital Zircon ages are found to range between 2.551 ± 40 Ma and 425 ± 9 Ma, with 93% of the age data comprised in the same time span of the detrital Zircon ages (3.047 ± 13 Ma to 516 ± 19 Ma) of the Numidian sandstones of the Southern Apennines (Fornelli *et al*. 2015). In a quite recent publication, Fornelli *et al*. (2022) reported new U-Pb zircon measurements on Oligocene to Miocene sandstone suites of the Southern Apennines foreland basin system and found that in the Numidian Flysch formation, the prevalent zircon ages are clustered at 661 ± 10 Ma, 607 ± 8 Ma and 547 ± 8 Ma. They interpreted their results as indicating a provenance of the *NF* from the African Craton without evidence of Variscan or Alpine signatures.

Abbassi et al. (2020) and Abbassi et al. (2021, 2022) studied the provenance of the Burdigalian Numidian sands sampled in the Tanger Unit (Intrarif sub-Domain, External Rifian Zones, Morocco) by using the U-Pb Zircon geochronology technique. They concluded that the recorded ages of the detrital Zircon U-Pb (older than 500 Ma) clearly indicate a provenance of the *NF* quartzarenites from the African Craton.

In their study of U-Pb ages of the detrital Zircon in the Maghrebian Flysch Complex of the external Rif Belt (Morocco), Azdimousa *et al*. (2019) reported very similar U-Pb ages (2.280 Ma to 347 Ma) distributed as follows: Paleozoic (5%), Neoproterozoic (49%), Paleoproterozoic (31%), Neoarchean (5%) and Mesoarchean (10%). These results strongly suggest that the External Rif and the entire Maghrebian Complex belonged to the same NW African Palaeomargin.

Discussion

On the basis of the above reported data, some considerations can constrain the evolutionary geological context concerning the Numidian scenario. For this purpose, some aspects considered qualifying of the Numidian history have been selected. The available litho- and biostratigraphic data allow a preliminary framing of the *NF* and Lateral Successions, which is not yet complete, especially in less studied sectors (e.g. Algerian Tell). Therefore, considering the lateral extension of this formation (about 2.500 km), data will have to be enriched.

Depositional systems and sediment supplies

Numerous studies were addressed to the reconstruction of depositional environments of the *NF* and its Lateral Successions in all sectors of the Betic-Maghrebian-South Apennine chains (Wezel 1970; Didon and Hoyez 1978; Durand-Delga 1980; Martín-Algarra 1987; Hoyez 1989; Guerrera *et al*. 1992, 1993, 2012; Fildes *et al*. 2010; Riahi *et al*. 2010, 2014, 2021; Thomas *et al*. 2010; Belayouni *et al*. 2013; Thomas and Bodin 2013; Barbera *et al*. 2014; D'errico *et al*. 2014; Pinter *et al*. 2016, 2017; Pinter 2017;

Critelli *et al*. 2017; Critelli 2018; Butler *et al*. 2020; Matano *et al*. 2020; Abbassi *et al*. 2021); among many others and references therein).

There is, indeed, a wide agreement considering the reconstructed depositional environments of the Numidian Fm as varying from a slope domain bordering the abyssal plain (and related sub-environments such as channels, overbank areas, etc.) to confined basins located at different depths near the slope, and to a proper continental rise bordering the abyssal plain.

Some studies have focused on the assessment of different depositional systems of the *NF* at regional scale in order to better highlight the distribution of Numidian flows and their control factors. Among these, the main considered are palaeogeography (e.g. physiography of the margin/basin system); structural elements (e.g. tectonic activity and syn-sedimentary tectonics); and potential source area, as deduced from mineralogical-petrographic-geochemical characteristics of sediments.

According to Thomas *et al*. (2010) the *NF* should be related to a major Cenozoic drainage system located on the North African Margin during the regional Atlas uplift phases. Therefore, the *NF* is interpretable as the result of a passive margin deposition fed by variety of small and separated unconfined submarine fans (Guerrera *et al*. 2012)controlled primarily by hinterland uplift and climatic fluctuations. According to Butler *et al*. (2020) the Numidian flows, axially fed from the North Africa, were confined along sinuous corridors related to active submarine thrusting. By examining different successions of the Tunisian Tell, Riahi *et al*. (2021) identified depositional mechanisms according to which the facies distribution, the depositional environment, and sedimentary features appear to be controlled by the occurrence of topographic heights and inherited faults. According to 2013) the main (Burdigalian) Numidian quartz supply is related to the erosion of the Atlas area, favoured by a forebulge uplift of the African Margin due to the *MFB*-subduction under the *MM* during the complex geodynamic evolution of the foreland basin system.

Moreover, the lateral and vertical distribution of the originary Numidian successions cannot be easily reconstructed, due to the tectonic transport and related deformation. Only in a few sectors, different depositional palaeoenvironments are recognizable, especially in the Tunisian Tell where the Numidian Fm deposited in deep depositional environments, but also shelf and continental realms. They are represented by four lithostratigraphic Fm from distal to proximal areas:

-the so-called Glauconititic Fm (external shelf) belonging to the Bejaoua Group (Rouvier 1977; Boukhalfa *et al*. 2015);

- the fluvio-deltaic sands of the Fortuna Fm (Yaich 1992);

- the fluvial sands of the Cherichira Fm (Yaich 1992);

- the paleo-dunes (fossil barkane systems of uncertain age), which have been observed in some areas of the southern Tell (Zaier and Belayouni 2000; Guerrera *et al*. 2012).

The different palaeoenvironments reconstructed for the *NF* reflect the intertwining of some dominant control factors for deposition (paleo-morphology, distance between erosion and depositional areas, energy of the relief, volume and amounts of sediment supply, hydrographic networks, syn-sedimentary tectonics, geology and tectonics of the source areas, palaeoclimatic conditions, etc.). Each sector experienced its own peculiar evolution that caused the deposition of a characteristic lithofacies association, as attested by the literature.

Even if at present, a representative palaeoenvironmental reconstruction of all sectors of the *NF* is not possible, the available data point out to a large variety of depositional palaeoenvironments. Therefore, a generalized palaeoenvironmental attribution does not appear possible, and the reconstructions concerning single sectors (even if always precious) cannot be extended neither to the whole Maghreb nor to further areas.

Diachronism of the Numidian event

The age of the *NF* considered from the Betic Cordillera to the Southern Apennines ranges from late Oligocene *p.p.* to Langhian/Serravallian (Guerrera and Martín-Martín 2014; and references therein). However, this age range varies between the Betic-Rif-Tell sector (late Chattian *p.p.*-Burdigalian *p.p.*), where it marks a substantial penecontemporaneity, and the Sicilian (Aquitanian *p.p.*-Langhian *p.p.*) and Southern Apennines (Aquitanian *p.p.*-Langhian/Serravallian boundary, at least) areas. The Intermediate Numidian *Mb* appears to be restricted to the upper Aquitanian-lower Burdigalian, thus supporting the idea of a unique contemporaneous event. On the other hand, the younger age of the *NF* in the northern sector would result from the growing distance (with respect to North Africa) of sedimentation areas, due to the progressive migration of deformation eastwards (Figure 7).

As regards the palaeogeography of the *NF* depositional area in the Southern Apennines, the presence of the *NF* both on the Campania-Lucania platform units and on the more external Lagonegro-Molise Basin (D'errico *et al*. 2014) was evidenced. This double position does not find a palaeogeographic correspondence with

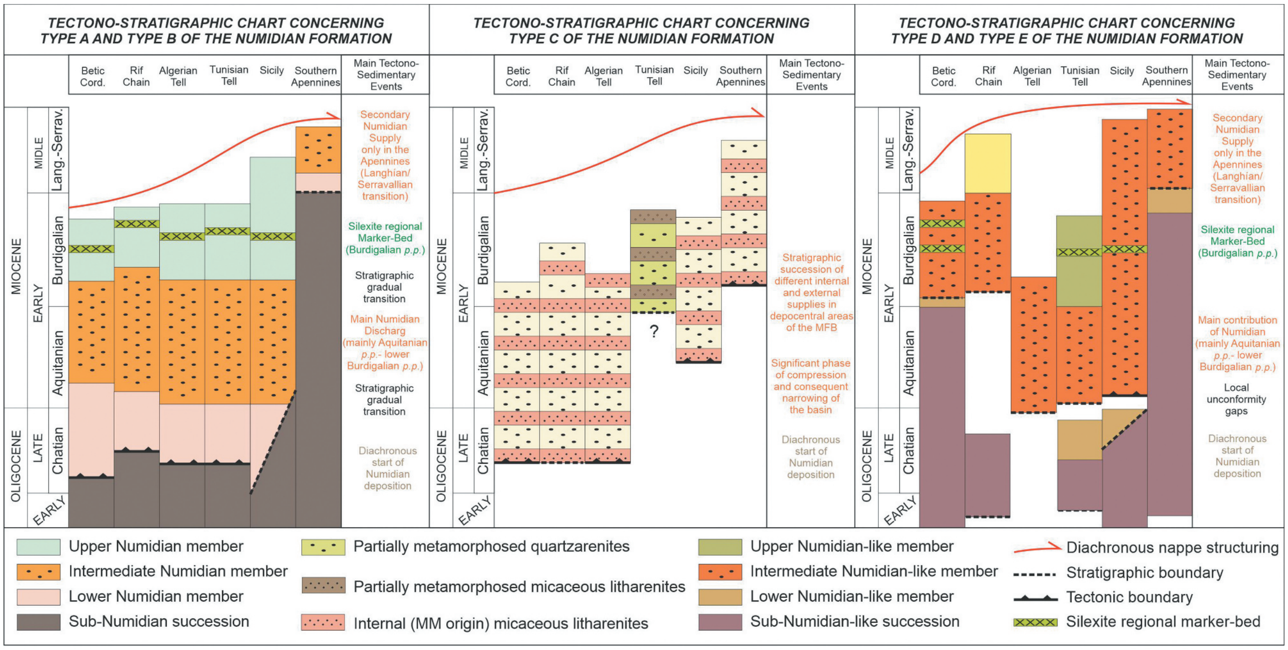

Figure 7. Tectono-stratigraphic charts concerning the *Type aA* to *Type E* of the Numidian Formation depicting the lateral and vertical variability of the lithofacies, significant stratigraphic markers, surfaces and gaps of the stratigraphic record. The tectonic propagation along the chain is also represented.

the classical location of the Numidian depositional area in the external sub-domain of the *MFB*. This reconstruction indicates a northward extension of the Numidian sedimentation (Molise Basin), where the *NF* gradually thins out and disappears (D'errico *et al*. 2014). This could also represent a further confirmation of the southern provenance of the Numidian supply. A comparable palaeogeography can be found in the Sicilian Maghrebides (Madonie Mts) where the upper part of both the Imerese Basin and the Panormide Platform successions show Numidian-like deposits (Barbera *et al.* 2014).

A general terminology proposal for the lithostratigraphy of the different successions of the *NF*, considering also its vertical and lateral variations, is currently missing. New researches addressed to different chain sectors can be useful to fill this gap and to improve the regional framework and correlations. Data reported in this paper are to be considered only as a first contribution to the discussion.

Figure 7 shows some tectono-stratigraphic charts related to the different types of Numidian Fm and lateral successions. The main findings are: (1) The starting of Numidian deposition can be placed at the upper Oligocene *p.p.*; (2) usually, a gradual stratigraphic transition takes place among the three Numidian members; (3) the main Numidian discharge is Aquitanian *p.p.* -Burdiagalian *p.p.* in age; (4) a regional silexite marker-bed is located inside the Burdigalian; (5) In the easternmost Apennine sectors a secondary event of Numidian discharge is registered in the Middle Miocene *p.p.*; and (6) diachronic tectono-sedimentary events have been recorded from internal to external zones and mainly between the E-W branch of the North Africa and that which includes the Sicilian Maghrebids and the southern Apennines (from Burdigalian to Serravallian).

Lateral Successions

As regards the different types of Lateral Successions, the *Type C* successions are already partially documented, even if they have been little considered in literature. Instead, the *Type D and Type E* successions are practically unknown, and only now we are starting the debate.

The *Type C* consists of a stratigraphic alternance of different lithofacies normally belonging to the internal and external sub-domains of the *MFB*, which show lateral passages and deposition in intermediate depocentral areas of this basin. This reconstruction appears quite plausible, at least on the basis of known data. Conversely, the *Type D and Type E* are still little known and poorly documented. However, the scenarios that the latter could involve concern the palaeogeographic relationships between elements of the *MFB* and sedimentary domains located outside of very marginal to the *MFB*. In fact, the presence of Numidian successions and of lateral facies with variable thickness, stratigraphically lying, sometimes over external units (D'errico *et al*. 2014; Maaté *et al*. 2017; Pinter 2017; Martín-Martín *et al*. 2020, 2022; Abbassi *et al*. 2021; among others), and sometimes over internal/external zone boundary units (Alcalà *et al*. 2013) (Figure 6), are still to be defined much better through advanced multidisciplinary data.

The *Type D*, is often supposed to be deposited in shallow-water environments (shelves, fan-deltas with quartzose conglomerates, and pro-delta pelites) or in continental realms (fluvial channelized quartz-rich sedimentary bodies and fossilized dunes, such as in the Tunisian Tell) of the N African margin. These features clearly support the idea of an origin of the clastic supply from the African Plate. Furthermore, the *Type D* is frequently rooted on units of the External Maghrebian Zones.

The *Type E* represents one exception, being a new Lateral Successions checked along the Internal/External Zones Boundary of the Betic Cordillera, and consisting of Numidian quartzarenites interbedded with external lithofacies of the Subbetic-Penibetic Zones (Alcalà *et al*. 2013) or making part of Frontal Unit of the Internal Betic Zone (Martín-Algarra 1987). This anomalous position is probably due to the presence of a 'triple junction' in the Betic-Rifian Arc, which is associated to a dextral transform fault located between the *SIM* and *MM-MFB* system (for a more detailed explanation see Figure 7 in Alcalá *et al*. Alcalà *et al*. 2013).

Type C, *Type D* and *Type E* have a relevant palaeogeographic significance related to the marked palaeoenvironmental diversity resulting from different depositional systems, and therefore can provide further constraints for geological reconstructions.

A first preliminary framework of part of the Lateral Successions at regional scale was presented by Guerrera *et al*. (2012). New data have made possible to recognize other Lateral Successions in new palaeogeographic positions (Alcalà *et al*. 2013).

In short, a better identification and understanding of these Lateral Successions can represent a further useful step for a more advanced evolutionary interpretation of the Numidian depositional area and neighbouring palaeogeographic sectors.

The Numidian clasts are made up predominantly of polycrystalline quartz with a polycyclic origin (often over 90%), with the exception of the southern Apennines where D'errico *et al*. (2014) have found that the monocrystalline quartz is more abundant than the polycrystalline quartz. This observation somehow was confirmed later by Fornelli and Micheletti (2021). In addition, the quartz in the Numidian clasts is often found to be associated with minor minerals, mainly represented by Feldspars, Micas, Clays and a suite of heavy minerals including Zircon, Rutile, Tourmaline (ZRT), Garnet, Monazite and Iron Oxide (Fildes *et al*. 2010; and references therein).

Various studies highlighted the specificities of the Numidian quartz in the different sectors of the examined chains (Riahi *et al*. 2010; D'errico *et al*. 2014; Fornelli and Micheletti 2021). Despite some genetic specificities, all the Numidian quartz can be considered referable to the same quartz family.

Petrographic studies on the Numidian Lateral Successions (*Type D* and *Type E*) pointed out some differences between these successions and the Numidian *s.s.* clastic sedimentation both in Southern Apennines, and Betic Cordillera and *ERZ*. In the Southern Apennine deposits, which show a marked bimodal grain-size distribution, the samples are comprised in the range of sublitharenite and quartzarenite (Wezel 1970; Didon *et al*. 1984; Puglisi 1994; Fornelli and Piccarreta 1997; Fornelli 1998). In the Betic Cordillera (Alcalà *et al*. 2013), and in the *ERZ* the quartz average is lower than in the *NF* (Maaté *et al*. 2017; Martín-Martín *et al*. 2022), probably due to the absence of siliciclastic sorting. In these types of the Numidian successions, the *ERZ* sandstones are arenites and hybrid arenites and, more in detail, sublitharenites and litharenites.

In both cases, the results seem to indicate that in *Type D* and *Type E* the quartz of Numidian origin is mixed with other components. Therefore, in these external lateral depositional areas, the Numidian supply systems have not supplied the Numidian quartz to the same extent as in the Numidian *s.s.* depositional area.

In any case, Barbera *et al*. (2014) in their mineralogical and geochemical study of the *NF* of Sicily observed that the Quartz is the most abundant component within the non-clay fractions. Moreover, Quartz exhibits a high compositional maturity, due to the high abundance of detrital quartz grains as well as to its high roundness. The authors have interpreted such properties as testifying prolonged transports, thus confirming the polycyclic origin of sandstones. Such results are in contrast with the composition of the older Alpine Tethys sediments, whose provenance from the European crust has been constrained (Barbera *et al*. 2009, 2011, 2014).

The strong composition similarity (mineralogical, petrographic, geochemical, geochronological, and type of quartz data) between the Numidian siliciclastic sediments and the Nubian Sandstones family, which extends from Algeria to Somalia (Guerrera and Puglisi 1984; Guerrera *et al*. 1992; Barbera *et al*. 2014; among others) is an additional support to the provenance of the Numidian clastic materials from the African Craton.

Numidian shales

A main provenance from the African craton (Nubian clastic sediments) has been also attested for the Numidian shales, based on the excellent match between the distribution of trace elements in the Numidian muddy rocks and the Nubian kaolinite (Barbera *et al.* 2014). The same match is also observed when comparing geochemical data from Nubian sandstones and Numidian sandstones, thus attesting the close relationship existing between the two facies. This relationship is also clearly expressed in the Zr/Y-Zr/Nb diagram (Barbera *et al.* 2014), where the two formations are found to lie along the same trend.

In the *ERZ* (Maaté *et al.* 2017; Martín-Martín *et al.* 2022) the bulk mineralogy of clays was found to be rich in quartz and phyllosilicates. The clay mineralogy is rich in illite and I-S mixed-layers related to a mature sedimentation. Mongelli (2004) in his study of the distribution of rare-earth elements in the Oligo-Miocene pelitic sediments of the Lagonegro Basin (southern Apennines), identified in those pelites, the occurrence of a particular rare-earth geochemical signature which perfectly fits the average composition of Phanerozoic cratonic sandstones (Condie 1993). The available geochemical results on the Numidian shales clearly show their provenance from the south. They also indicate that the reworking of older sedimentary successions was a likely process for the origin of the Numidian clasts, and that one of the most likely source rocks might be represented by the Nubian Sandstones and perhaps by their southern equivalents (Guerrera and Puglisi 1984).

Radiometric age and provenance

Studies carried out in the Betic Cordillera and Maghrebian Chain indicate the occurrence of two populations of ages of Zircon crystals dated to 1800–1700 Ma (Paleoproterozoic), and 1350 Ma (Mesoproterozoic), respectively. Similar Paleoproterozoic ages have been furnished (1750 Ma) for Tunisia. A more wideness of ages results for the Numidian sandstones of the Southern Apennines, with a range from 3.000 Ma (Mesoarchean) to 400 Ma (Early Palaeozoic) (Fornelli *et al.* 2015, 2019, 2022).

Similar results and comparable ages from the *NF* of Tunisia attest a provenance of the Numidian supply from the African Craton (Gaudette *et al.* 1975, 1979). Thomas *et al.* (2010) and Thomas (2011), attempted an interesting literature review of radiometric U-Pb Zircon ages determined on Numidian deposits from Spain, Morocco, Tunisia, Sicily and Southern Apennines. In particular, they discussed the significance of these ages in relation to the origin from the south or north of the Numidian supply. They concluded that the three main populations of ages established for the *NF* (i.e. Paleoproterozoic, late Mesoproterozoic and late Neoproterozoic to Cambrian) refer to a source in which Eburnian and Panafrican events are represented, but neither Hercynian nor Alpine events are recognizable. They based their interpretation considering that the African basement contains only Zircon with an age ranging from Precambrian to Cambrian, while European basements contain minor amounts of Precambrian Zircons, and relatively high frequencies of Zircons of Panafrican age (550–650 Ma). In particular, such age intervals (514 Ma to 550 Ma) have been recognized both in European and African basements (Fornelli *et al.* 2015) and considering their frequency distribution is statistically far more likely (Thomas *et al.* 2010).

Accordingly, these authors concluded to a provenance of both Numidian sandstones and shales, which deposited in the external sub-domain of the *MFB* from Precambrian to Cambrian sediments outcropping across the African Craton, thus excluding any contribution from the European basement.

This review of the U-Pb Zircon data from supermature Numidian arenites highlights a major agreement of most of the authors in considering the African Craton as the predominant source area of the Numidian supplies. Contributions from the European basement are denied, since the most reasonable European possible older source areas are made of Hercynian rocks (about 350 Ma: Late Palaeozoic). Only in the Britain Island and Scandinavian Peninsula, Caledonian ages (500–600 Ma; Early Palaeozoic) can be found, but a source area from these so far regions seems impossible for the Numidian deposition.

Data from Fornelli *et al.* (2015) and Fornelli *et al.* (2022) also attest an important contribution from the Neoproterozoic granitic rocks widely outcropping in the North African Craton. On the other hand, datings performed on the Internal Flysch families of the *MFB* (internal sub-domain) provided radiometric ages lying between 332 ± 6 Ma and 290 ± 6 Ma. Such ages refer clearly to the Hercynian cycle (Azdimousa *et al.* 2019; Fornelli *et al.* 2020, 2022) and therefore point to the European basement as a source area for these materials. In summary, all data discussed above, are clearly in favour of a provenance of the clastic sediments of the *NF* from the African craton rather than from the European basement.

Palaeogeographic and palaeotectonic reconstruction (software GPlates)

The palaeotectonic reconstructions of the study area from Cretaceous to Miocene are shown in Figure 7. These reconstructions were made with the software GPlates (Müller *et al*. 2018) and are based on the recent compilation of Le Breton *et al*. (2021), which is implemented in the global plate model of Müller *et al*. (2019). This software allows calculating the past motion of plates according to geological and geophysical data using Euler's rotation theorem. It is also possible to reconstruct the motion and palaeogeographic position of blocks that are now part of the mountain chains (*MM*). The past motion of the major plates (Europe, Iberia and Africa) is based on the reconstruction of magnetic anomalies from the Atlantic Ocean (Müller *et al*. 2019; and references therein). In Figure 7, Europe is always considered as the fixed plate. The past motion of the Adria Plate and the Corsica-Sardinia block is based on an elaboration of geological and geophysical data from Ligurian-Provençal Basin, Provence, Alps, Apennines, Dinarides and Sicily Channel (Le Breton *et al*. 2017, 2021; and references therein). The past location of the Betic-Rif-Kabylide-Peloritani-Calabria-Tuscany units belonging to the *MM* were modified according to the geological record described in this study and previous papers (Martín-Martín *et al*. 2020, 2020; Guerrera *et al*. 2021).

Figure 8a shows the western Mediterranean palaeogeographic-palaeotectonic picture at 70 Ma (Latest Cretaceous). In particular, the western Tethyan area showed several oceanic branches (Nevado-Filabride, Ligurian-Piemontese, *MFB*, Lucanian and Ionian basins) to surround the *MM* microplate, the latter including different internal crustal elements (i.e. at least the Betic-Rifian Arc, Alboran, Rif, Tell, Calabria-Peloritani Arc). At this time, a tectonic inversion from extension to compression occurred, due to the northward motion of Africa relative to Europe, and related to the opening of the southern Atlantic Ocean. Figure 8b presents the palaeogeographic-palaeotectonic stage at 25 Ma (Late Oligocene). At this stage, the northern Tethyan branch (Nevado-Filabride and Ligurian-Piemontese oceans) closed by a subduction towards SE and the deformation migrated to the SE into the *MFB* (acting as a complex foreland basin) and towards the African margin. During the late Oligocene-Aquitanian, another subduction process started in the southern margin of the *MM*. This subduction closed progressively the *MFB* and deformed the *MM* to form thrust nappes that were stacked to trigger uplift and relief formation.

In this phase, the *MM* and the North Africa acted as sediment source areas for their respective marginal basins and especially for the internal and external subdomains of the *MFB*. The Internal Flyschs (internal subdomain of the *MFB;* Mauritanian subdomain) derived from different elements (Rif, Betic, Kabylide, Peloritani and Calabria units) of the southern margin of *MM*. Instead, the *NF* (*Type A* and *Type B*) together with the *Type C* of the central part of the *MFB* and the *Type D* external Lateral Successions, which deposited in coalescent areas were fed from the African craton. The Numidian Succession (*s.l.)* occurred both in continental areas, marine platforms, slopes and basin areas of the *MFB* (foredeep) with a broad variety of lithofacies. In the same period, a tectonic extension began in the Valencia Gulf and Ligurian-Provençal Basin. Figure 8c shows the situation at 20 Ma (Burdigalian), when the westernmost area (Maghreb) of the *MFB* was almost closed and the Numidian deposits reached the opposite basin margins (South Iberian and South-*MM* margins). During this phase the main sedimentary event resulted in the deposition of huge amounts of the Numidian quartz caused by a rising of the North African Plate (forebulge deformation). In a similar way to the previous period, the *NF* (*Type A* and *Type B*) together with the *Type C* occupied the central part of the *MFB*, and the *Type D* external Lateral Successions deposited in the North African Margin/*NAM*. During this period the *Type E* appears for the first time in the triple junction *SIM, NAM* and the *MM*. The formation of Iberian reliefs and the forebulge of the African Margin, which resulted from the closure by subduction of the *MFB*, probably favoured the migration of the Numidian depositional system to reach the far side of the *MFB*.

At the end of this period, the Numidian deposition moved eastward and northward, due to the closure of the western side of the *MFB*. This migration explains the diachronism observed in the *NF* of the eastward branch (Sicily and Southern Apennines). Figure 8d shows the situation at 15 Ma (Langhian), when the *NF* (*Type A* and *Type B*), as well as the Internal Flysch deposition and *Type C* Mixed Successions, migrated to the Lucanian Basin, where the age reaches the early Serravallian *p.p*. In this period, the *Type D* external Lateral Successions were deposited in the Hyblean Platform (Sicily) and Calabria. Finally, the back-arc extension affecting the Western Mediterranean progressed to form the Algerian and Alboran basins, as the Apennine subduction zone and related slab retreated.

Conclusions

Despite the extensive literature published over many decades, the Numidian theme always comes back to

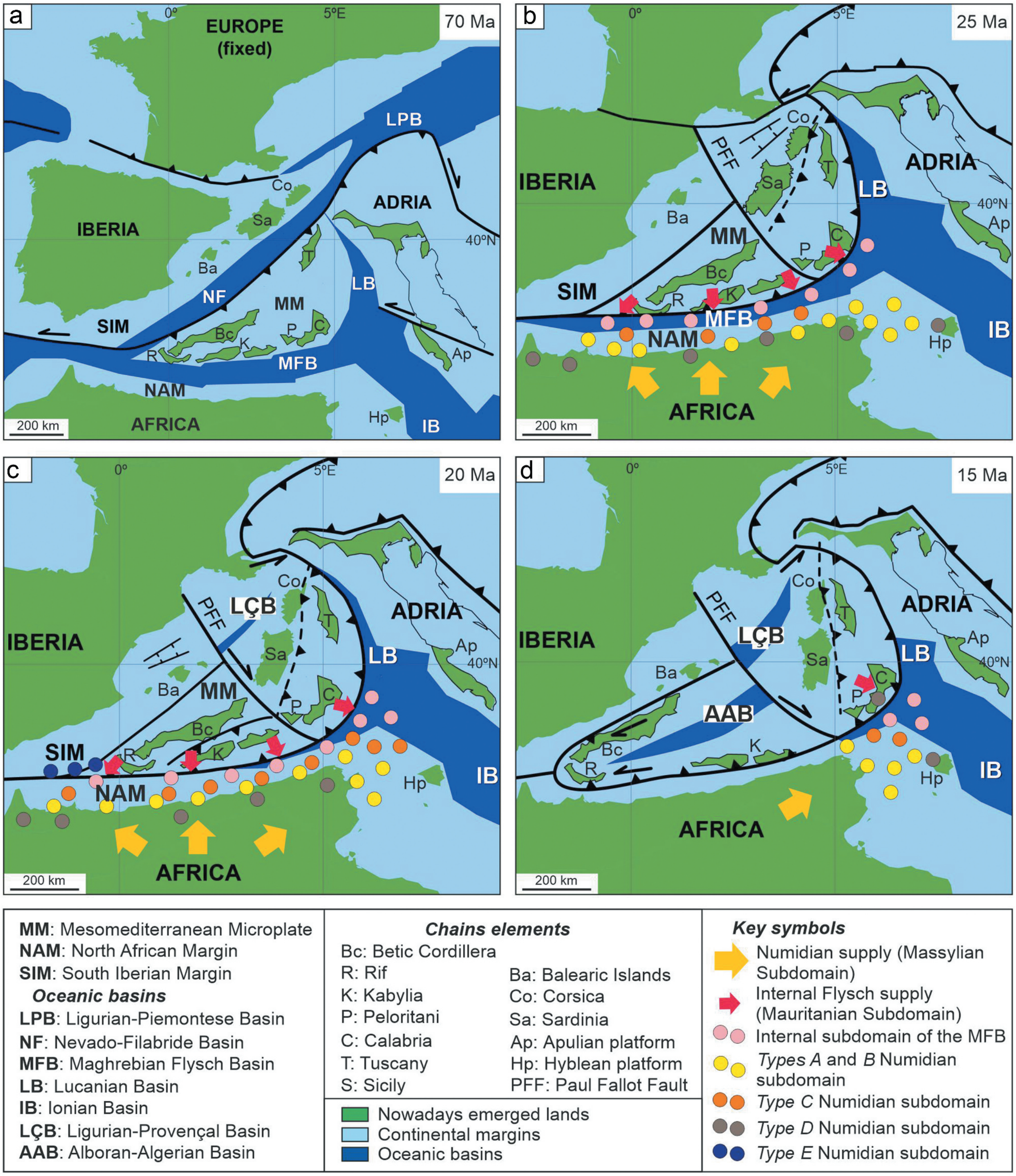

Figure 8. Palaeogeographic and palaeotectonic reconstructions of the western Tethyan area from Late Cretaceous to Middle Miocene. Reconstructions were developed with the software GPlates (Müller *et al*. 2018), following the models after Müller *et al*. (2019) and Le Breton et al. (2017, 2021) for Iberia, Europe, Africa, and Adria plates, as well as those for Balearic, Corsica and Sardinia islands. Past location of the Betic-Rif-Kabylide-Peloritani-Calabria-Tuscany units belonging to the *MM* are according to Guerrera *et al*. (2021) and Martín-Martín et al. (2020, 2020), with changes. A) Late Cretaceous (70 Ma); B) Chattian (25 Ma); Early Burdigalian (20 Ma); Langhian (15 Ma).

the foreground, due to the geological complexity of the chains where the *NF* is represented, which have been affected by a strong syn- and late-orogenic tectonics. However, despite these complications, which are amplified by both the considerable lateral extension (about 2,500 km) of the *NF* and the huge number of outcrops to be reconstructed and correlated, the Numidian history seems already sufficiently reconstructed, and shared by a part of the scientific community.

The current stratigraphic documentation of the *NF*, although still not complete, provides a vertical and lateral stratigraphic record and a reference palaeogeographic framework from the Gibraltar Arc to the Southern Apennines. Many of the Numidian outcrops that were already studied in the past are now better defined, although as many remain to be assessed.

Our review, which have been addressed to many sectors of Maghreb and neighbouring chains, was based on data obtained from similar and comparable methodologies, and seems to indicate at least in our opinion that the following knowledges of the Numidian event are supported by consolidated data.

(1) The biostratigraphic age of the *NF*, and of the single members may be considered sufficiently validated by different groups of fossils. A consistent amount of biostratigraphic results indicate that the *NF* is substantially coeval (upper Oligocene *p.p.*-lower Miocene *p.p.*) in North Africa and Betic Cordillera. In particular, the Intermediate (quartzarenitic) *Mb*, can be considered an upper Aquitanian-lower Burdigalian single homogeneous sedimentary event. Instead, the *NF* results a little younger in Sicily and southern Apennines, where the formation reaches the Langhian *p.p.* and Serravallian *p.p.*, respectively. This diachronism is probably related to the progressive basin migration towards the foreland, due to the tectonic deformation that caused a lateral migration of deposition (Butler *et al*. 2020) towards areas located at progressively greater distances with respect to source areas.

(2) The typical *NF* is characterized by at least two different vertical successions showing different lithofacies associations and sedimentary structures (Figure 3), and probably indicating basinal (*Type A*) and more marginal (Type B) deposition areas. Both successions are made by three stratigraphic members, except when they are incomplete and reduced because of tectonic deformation and/or palaeoenvironmental factors. In fact, the *NF* has been frequently tectonically transported outside its depositional area, to form differently thick tectonic wedges overriding External Zones units.

(3) Most of authors refer the Radiometric age (U-Pb zircon dating) and the origin of the Numidian quartz to the Precambrian and to the African area, respectively. This origin is related to the tectogenetic propagation towards the African foreland, which caused a forebulge of the latter triggering the erosion of quartz-rich sediments (such as the Nubian Sandstones, among others). Only in a few cases, a minor arkosic or litharenitic component is added to the quartzarenitic supply.

(4) The origin of the Numidian sediments and the source of the special quartz (real 'trademark') are to be located in the African Craton, as attested by different radiometric ages defined in several sectors by numerous interdisciplinary regional studies. Contrary opinions are increasingly rare. On the other hand, the huge amount of the Numidian quartz (millions of km^3), which is well represented along about 2.500 km, and the formation thickness that can exceed 3 km mark the most abundant clastic supply of the peri-Mediterranean chains. This very large amount of sediments makes it difficult to outline another different source area that could have provided such a huge quantity of quartz mainly during the late Aquitanian-early Burdigalian. Moreover, we must also consider in this evaluation the amount of the erosion of the Numidian successions after their Plio-Quaternary emersion. In fact, this value should be added to the previous ones.

(5) At the regional scale, the basal contact of the *NF* is usually a tectonic contact, as attested by an extensive literature and geological cartography. However, the *NF* and Lateral Successions stratigraphically rooted to their substratum have been recognized recently in different chain sectors (e. g. Rif and Tunisian Tell), affected by a gentler deformation. This implies that the sedimentation on most external areas represents a palaeogeographic constraints for the determination of the external boundary of the *MFB*.

(6) The large distribution of the *Type C* and especially of the *Type D* and also the local Betic *Type E* successions favours a new thematic approach addressed to palaeogeographic implications. The presence of the *Type C* indicates a lateral passage between different depositional systems, which are fed from opposite directions, and probably are located in depocentre areas of the *MFB*. These deposits often appear as tectonic slices overriding other *MFB* units. The *Type D*, which

deposited on the external margin of the *MFB,* is composed of Numidian Succession stratigraphically interbedded with a variable thickness in successions of different palaeoenvironments ranging from continental (i.e. palaeodunes) to external shelf margin (i.e. glauconitites) settings. Furthermore, the facies and distribution of the *Type D* constitute a further and clear indication of the location of the Numidian source in a southern cratonic area. Therefore, subsequent reconstructions of Lateral Successions (outside the typical Numidian depositional area) could provide useful steps forward in the knowledge of the Numidian theme. The *Type E* corresponds to a new Lateral Succession checked along the Internal/External boundary of the Betic Cordillera. The succession consists of a Numidian quartzarenite succession, which is associated with external lithofacies the Subbetic-Penibetic Zones or as Frontal Units of the Internal Zone. This anomalous position is probably due to the occurrence of a 'triple junction' in the Betic-Rifian Arc, which is associated to a dextral transform fault located between the *SIM, MFB-NAM* and *MM* system. The formation of Iberian reliefs and the forebulge of the African Margin resulting from the closure by subduction of the *MFB* have presumably favoured the migration of the Numidian depositional system to reach the opposite margins of the *MFB*.

(7) The relationships between the depositional environments of the *NF* and the Lateral Successions remain substantially unknown in many details. For example, it is not clear if the depositional environments of the *Type C* were represented by wide and open ephemeral depositional areas or by deeper minor depocentres, as it would be more logical to expect. The *Type D* could be deposited in more or less deep basins and shallow basins located on the African Margin, fed by supply coming from southern source areas. Instead, the *Type E* represents a deposition of the *NF* in the far side of the *MFB*, probably related to the closure of the basin during the latest evolutionary stages of the western area.

(8) As considered by most authors, the palaeogeographic location of the typical Numidian depositional area corresponds to the external subdomain of the *MFB*, which represents a southwestern branch of the Tethys Ocean. The Numidian depositional area is characterized by oceanic and/or thinned crust, and deformed asynchronously during the Miocene. More in detail, the age of deformation results to be latest Oligocene-Burdigalian *p.p.* in the Betic Cordillera and North Africa, while reaches the Langhian *p.p.* in Sicily and the Serravallian *p.p.* in Southern Apennines. This 'segmented' diachronism is probably related to a gradual expansion of the Numidian depositional area to occupy a progressively wider palaeogeographic space. This progressive evolution should justify also the great thickness of the *NF* near the sediment source area (e.g. Tunisian Tell).

(9) As regards the regional palaeogeographic and palaeotectonic model framing the Numidian event, we do believe in the existence of an intermediate and independent Mesomediterranean Microplate/*MM*) located between European and African plates. This microplate partially separated a northern oceanic basin experiencing the late Trias-Palaeogene *p.p.* alpine history from a southern basin with oceanic and/or thinned crust, which was involved in the Cretaceous-Miocene *p.p.* Apennine-Maghrebian evolution. This reconstruction, which reflects better the geological reality described in the previous decades, appears the more probable and is adopted by various authors. However, new interdisciplinary data and interpretation on a regional scale are still necessary. As regards the basement of the *MFB*, recent studies highlighted the presence of oceanic branches separating some sectors of the External Rif (Benzaggag *et al*. 2013; Michard *et al*. 2014, 2018; Benzaggag 2016; Boukaoud *et al*. 2021; Haissen *et al*. 2022). These new and interesting features cannot be ignored. These studies attest that the *MFB* oceanic branch had probably further ramifications. This further fragmentation of the African Margin, which generated sub-basins where the lateral Succession of the *NF* may have deposited, could also be found in other sectors of the Maghrebides, Betic Cordillera and southern Apennines.

(10) A lot of knowledge about the *NF* have already been acquired but many others useful for a better and more definitive comprehension in the evolutionary framework are necessary. Therefore, it seems evident that researches addressed to the Numidian subject are destined to continue. In fact, many secrets and surprising discoveries are still hidden, such as details about the Numidian extra-basinal successions deposited on the Cretaceous-upper Oligocene stratigraphic substratum. Moreover, an increase of researches concerning the Cretaceous-upper Oligocene original stratigraphic

substratum of the *NF*, as well as a more definitive shared terminological approach facilitating the not always easy data comparison, would be greatly needed.

As final remark, it would be desirable in future researches to achieve the following main challenges: (i) to comply with a general common terminological rigour, the only one able to allow effectively comparing results from different research groups; (ii) to define and share scientific aspects that are sufficiently clear, in order to plan and trace a common study pathway which might be adopted as a reference by the scientific community; (iii) to perform a palaeogeographic and palaeotectonic reconstruction of the Numidian depositional area considering further important recognized geological events, which can integrate the present knowledge.

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