Marine and Petroleum Geology 156 (2023) 106426

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

# Cenozoic tectono-sedimentary evolution of the onshore-offshore Tunisian Tell: Implications for oil-gas research

Habib Belayouni [a], Francesco Guerrera [b], Manuel Martín-Martín [c,*], Mario Tramontana [d], Manuel Bullejos [e]

[a] Ex- Département de Géologie, Université de Tunis El Manar, Campus Universitaire, 2092, Tunis, Tunisia
[b] Ex-Dipartimento di Scienze Della Terra, Della Vita e Dell'Ambiente (DiSTeVA), Università Degli Studi di Urbino Carlo Bo, Campus Scientifico E. Mattei, 61029, Urbino, Italy
[c] Departamento de Ciencias de LaTierra y Medio Ambiente, University of Alicante, AP 99, 03080, Alicante, Spain
[d] Dipartimento di Scienze Pure e Applicate (DiSPeA), Università Degli Studi di Urbino Carlo Bo, Campus Scientifico E. Mattei, 61029, Urbino, Italy
[e] Departamento de Álgebra, University of Granada, 18010, Granada, Spain

ARTICLE INFO

*Keywords:*
Tunisian paleomargin evolution
Stratigraphic reconstruction
GPlates paleogeographic reconstruction
Oil and gas research
Petroleum resources

ABSTRACT

A review of the paleogeographic and tectonic reconstruction of the onshore and offshore Tunisian margin during the Cenozoic is discussed. Five unconformities (A to E) and associated stratigraphic gaps of various vertical extents allow subdivision of the stratigraphic record into depositional units in the following time intervals: (i) Paleocene-Oligocene, (ii) Oligocene-early Aquitanian, (iii) early Aquitanian-Burdigalian, (iv) late Burdigalian-Langhian and (v) Langhian-late Miocene. These intervals can in turn be grouped into four main sedimentary cycles (SC1–SC4) dated to the (1) Paleocene-Oligocene, (2) Oligocene–Burdigalian, (3) Burdigalian-Langhian and (4) Langhian-late Miocene. The oldest depositional unit reflects Eo-Alpine tectonics in the Maghrebian Flysch Basin (*MFB*); the others are related to the Neo-Alpine syn- and late orogenic tectonic deformation affecting the *MFB*. The uppermost unit represents post-orogenic deposition. Early Miocene synsedimentary tectonism led to (1) deposition of thick successions owing to a large sediment supply and (2) the occurrence of various tectofacies (unconformities, slumps, mega-turbidites, olistostromes, growth folds, chaotic intervals and heterogenous lithofacies), that all, together with the occurrence of lateral change of facies, clearly indicate non-cyclical sedimentation. During the middle Miocene the Tunisian Tell underwent polyphase thrust tectonism, followed by late Miocene strike-slip deformation with contemporaneous rejuvenation of halokinetics and magmatism (the La Galite Archipelago) that may be traced as far as the Algerian Tell. The margin experienced deep-seated compressional tectonism during the Paleogene, a foreland basin during the early Miocene, and nappe stacking during the middle Miocene, with the occurrence of wedge-top sub-basins. The evolution of the region makes the existence of petroleum resources within either the thrust belt, the foredeep and/or the foreland systems plausible. Oil and/or gas may have been trapped in either i) deep buried allochthonous thrust wedges that are located below the Numidian Nappes, and/or in ii) the imbricate Medjerda Valley domain of the Tell foredeep. The offshore area between northern Tunisia and the La Galite Archipelago may also hold potential for large oil/gas fields, as has been confirmed by exploration of the same overthrust belt in other areas such as in Sicily and the Southern Apennines.

## 1. Introduction

A crucial element for palaeogeographic and paleotectonic reconstructions of the central–western Mediterranean Alpine area (Fig. 1) is the Maghrebian Chain, which outcrops along the northern African Margin, the Betic Cordillera (southern Spain), Sicily and the southern Apennines (Italy). The Maghrebian Flysch Basin (*MFB*) represents a Mesozoic–Cenozoic domain sandwiched between the internal and external tectonic complexes of this chain (Durand Delga, 1980; Guerrera et al., 1993, 2005, 2019, 2020; Guerrera and Martín-Martín, 2014; Critelli and Martín-Martín, 2022). Several authors have supported the occurrence of a late Eocene major deformation affecting the Atlas and

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

https://doi.org/10.1016/j.marpetgeo.2023.106426
Received 4 July 2023; Received in revised form 20 July 2023; Accepted 21 July 2023
Available online 26 July 2023

External Tell domains in Tunisia, Algeria and Morocco in the perimediterranean chains (Bracène and Frizon de Lamotte, 2002; Benaouali-Mebarek et al., 2006; Talbi et al., 2008; Khomsi et al., 2016; Lepretre et al., 2018; Khomsi et al., 2022). In particular, these authors observed that in the Tunisian and Algerian Atlas systems, the Eocene–Oligocene boundary is marked by a regional angular unconformity related to an important deformation (the Atlas phase). This phase occurred before the emplacement of the Tell units and was recorded in the Tunisian Tell, Atlas belt and their respective foreland basins. Nevertheless, such an angular unconformity has not been definitively confirmed in the Tunisian Tell nappes, where the boundary between the late Eocene and Oligocene is mostly transitional (Rouvier, 1977; Belayouni et al., 2012, 2013). This stratigraphy implies that the Maghrebian Chain was mainly built by one major deformation phase, which developed in the early middle Miocene (Guerrera et al., 1993, 2005, 2019; Guerrera and Martín-Martín, 2014). Different authors separate the Alpine history *s.s.* (vergence to the north) from the Maghrebian one (vergence to the south), framing the relative evolutions in two main different domains. These domains represent a northern and a southern oceanic branch of the western Tethys, which are separated by an independent Mesomediterranean Microplate (*MM*) (Doglioni, 1992; Martín-Algarra, 1987; Guerrera et al., 1993; Critelli, 2018; Critelli and Martín-Martín, 2022). The latter comprises pre-Alpine basements (Variscan) and a Meso–Cenozoic sedimentary cover locally affected in the northern part by Alpine metamorphism. Hence, within this general setting, the *MFB* has constituted the entire southernmost branch of the western Tethys since the Jurassic.

The different Cretaceous–Paleocene successions of the MFB sedimentary cover have traditionally been referred to as internal and external basin subdomains tectonically displaced on the more External Zones of the African Margin. This was first outlined in the Algerian Tell (Durand Delga and Fontboté, 1980; Wildi, 1983) and later recognised in many sectors of the Betic–Maghrebian and Apennine systems through multidisciplinary approaches (Durand Delga et al., 2000; Zaghloul et al., 2002; Belayouni et al., 2006, 2010, 2012, 2013; Thomas et al., 2010; Alcala et al., 2013; Barbera et al., 2014; Guerrera and Martín-Martín, 2014; Fornelli et al., 2015, 2019; Critelli, 2018). In recent times, another important discovery has resulted from comparative studies across the Maghrebian Chain (Bonardi et al., 1996, 2001, 2002; de Capoa et al., 2003, 2005, 2014; Perrone et al., 2006, 2008, 2014; Di Staso et al., 2009; Matano et al., 2020; Fornelli et al., 2022). These studies revealed (particularly in the Apennine successions) a rejuvenation at the top of the MFB sedimentation as well as thrusting and folding age towards the east (Guerrera et al., 2012, 2021). This age, coeval along the western branch of the Maghrebian Chain (Algerian Tell, Rif and Betic Cordillera), was slightly young in Sicilian Maghrebids and even more young in the southern Apennines. Both the widespread internal and external successions of the southern Apennines, which were deposited on the Lucanian Ocean (LO) as an extension of the Maghrebian Ocean to the north, have been well correlated with those of the MFB (Bonardi et al., 1996), even if the North African terminology was not always clearly considered and adopted. In the MFB (and in the Lucanian Ocean), the tectono-sedimentary evolution was controlled by internal (northern) and external (southern) basin margin activity, which led to very different geological characters between internal and external pene-contemporaneous stratigraphic records, tectonically stacked by the same Miocene tectonic phases. In short, the internal sub-domain deposition was predominantly controlled by the MM tectonics (Perri et al., 2017, 2022; Critelli et al., 2021; Martín-Martín et al., 2023c), while the external one (and its External Lateral successions; Guerrera et al., 2012; Martín-Martín et al., 2023b; Belayouni et al., 2023) was influenced by the tectonic activity of the northern African Margin. The so-called Lateral (internal) Mixed Successions recognised in different sectors of the MFB (Hoyez, 1976; Guerrera et al., 1986; Grasso et al., 1987; Guerrera and Martín-Martín, 2014) represent an intermediate sub-domain with respect to the previous ones. These deposits comprise stratigraphic alternances of intervals fed by both the internal and external basin margins and interfingering in the intermediate portion of the depocentral area.

Within this general setting, the onshore–offshore Tunisian Tellian domain constitutes a key area for the reconstruction of the paleogeographic and paleostructural Cenozoic evolution of the *MFB* owing to its transitional position between the western branch of the Maghrebian Chain (Algerian Tell, Rif and Betic Cordillera) and the eastern branch of the Maghrebian Chain (Sicily and southern Apennines). The *MFB* successions and lateral equivalents in the northern African Margin, cropping out in the Tunisian Tell, belong only to the external sub-domain (Sub-Numidian, Numidian and Supra-Numidian formations; lateral

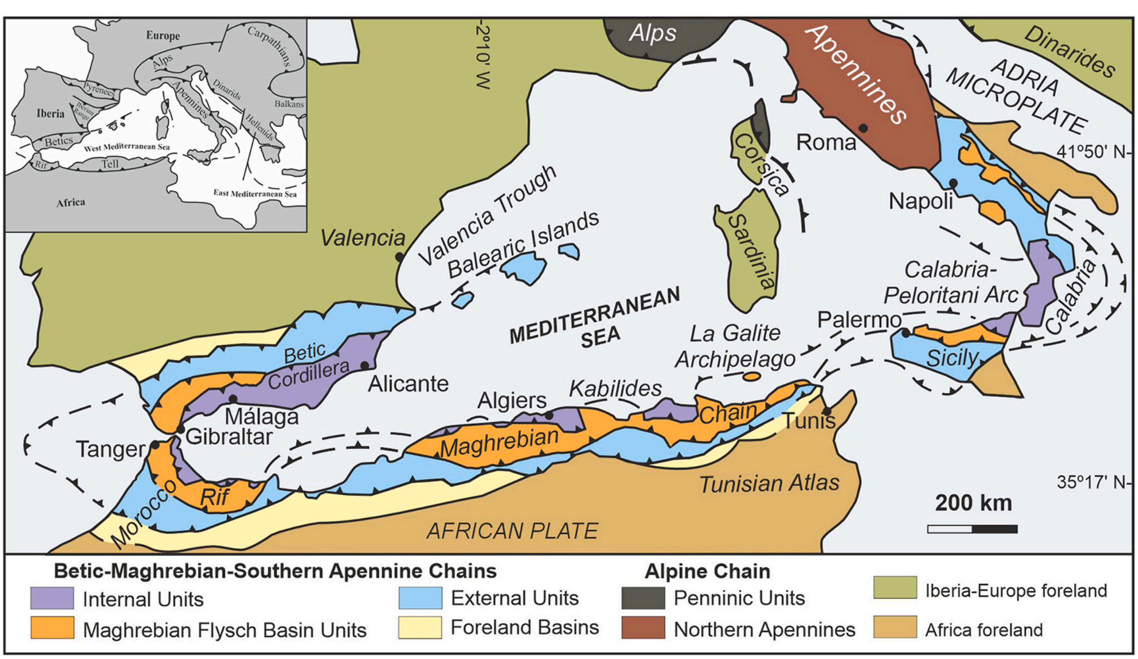



**Fig. 1.** Geological sketch map showing the Betic–Maghrebian–Apennine Chains (after Martín-Martín et al., 2022, 2023b, revised).

equivalents in the northern African Margin and related Cretaceous or older substratum rocks), which are related to the northern Tunisian margin evolution (Belayouni et al., 2012, 2013). Instead, the units of the *MFB* internal sub-domain and the units of the Internal Zones of the Maghrebian Chain are probably submerged in the Mediterranean Sea (Belayouni et al., 2010).

## 2. Geological setting

The Central and Western Mediterranean geology is strongly influenced by the presence of the plate boundary zone between Africa and Eurasia, constituted by the Alpine Thrust Belt. This mountain belt extends southward from the Strait of Sicily to the Moroccan Rift and the Spanish Betic Cordillera (Fig. 1) through northern Tunisia and northern Algeria. In northern Tunisia, the WSW–ENE-trending 'Nappes Zone', characterised by widespread successions of allochthonous uppermost Oligocene–Miocene Numidian Formation overriding folded and faulted autochthonous to para-autochthonous Cretaceous to Eocene units, represents the most obvious local expression of this geodynamic system (Fig. 2). Northern Tunisia has a complex geological history owing to the continuous evolution of the region as either a passive or active continental margin.

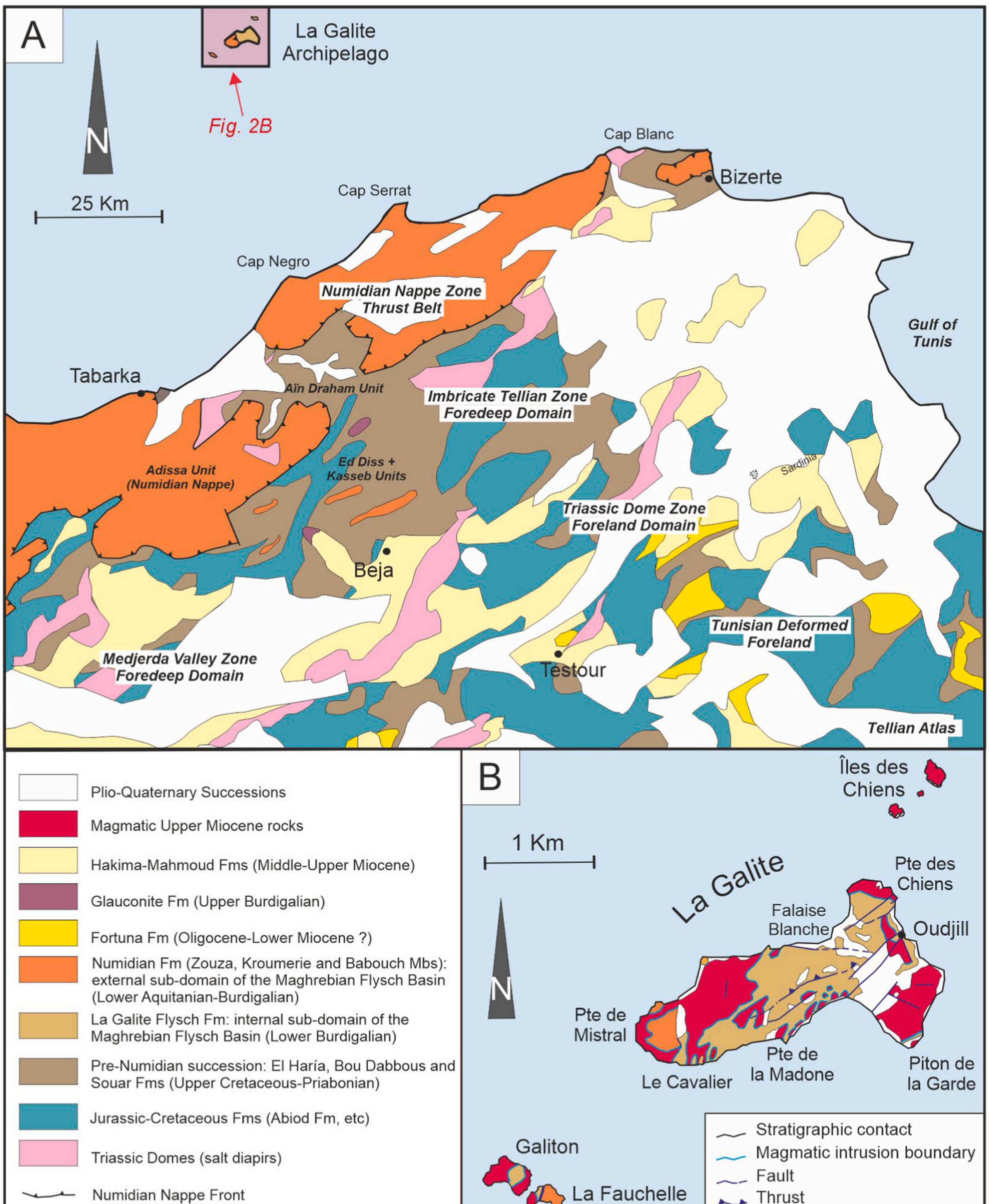



**Fig. 2.** Geological–structural schematic map of Tunisian Tell (A) and a geological sketch of La Galite Archipelago (B) located on the Tunisian Margin.

The Tunisian Tell encompasses the La Galite Archipelago, the La Galite Corridor, the northern coast and the hinterland. It forms the suture between the North African plate and the east–west-trending continental *MM* (Guerrera et al., 2005). During the latest Oligocene, the internal units constituting the southern margin of the *MM* (Kabylie massifs and lateral equivalents) progressively began to override the *MFB* units (intermediate oceanic domain), subsequently reaching the External Zones (Africa Margin) and completing the structural building of the Maghrebian Chain.

The Tunisian Tell constitutes the easternmost portion of the North Africa 'Maghrebides' fold–thrust belt and comprises two main zones characterised by folded thrust sheets displaced southeastwards (Fig. 2A). These zones are: (1) the Numidian Nappe Zone, comprising the Ain Draham, Adissa, Ed Diss and Kasseb allochthonous thrust units, overlain by the more recently displaced Numidian unit (Rouvier, 1985) and (2) the Imbricate Tellian Zone, comprising para-autochthonous and autochthonous formations showing folds, imbricate structures and superimposed molassic basins. The Imbricate Tellian Zone extends SW-ward to the Medjerda Valley Zone, representing a foredeep basin filled with Mio–Pliocene deposits. The latter is sandwiched to the northwest between the Tellian Numidian fold-and-thrust belts (i.e. the Tunisian Nappe Zone) and the 'Triassic Dome Zone' to the SE (Baird et al., 1990; Moody and Sutcliffe, 1994; Moody et al., 2006; Booth-Rea et al., 2023) (Fig. 2A). During the last decades, the Medjerda Valley Zone, which was referred to as part of the Triassic Dome Zone, has been individualised as a foredeep petroleum play and fully recognised as a separate sub-domain from the southeastern foreland domain. The Medjerda Valley Zone contains a Mio–Pliocene sedimentary basin in front of the SE-directed thrust sheets. The thickness of its sediments may reach several thousand metres, as deduced from seismic line interpretation (Chaari et al., 2004; Chaari, 2005; Chaari and Belayouni, 2005). These thrust sheets were mainly displaced during the Langhian/Tortonian compression and folded again during the late Miocene–Pliocene shortening. Detachment levels are represented by 'allochthonous' Triassic salt, resulting in different diapirism phases or Cretaceous/Paleogene shales. The Triassic Dome Zone, known as 'the Salt Dome Zone' (Perthuisot, 1981; Snoke et al., 1988; Booth-Rea et al., 2023), lies to the SE of the most external Tellian Atlas thrust. It is bounded to the SE by NE–SW-trending tectonic accidents, herein designated as the 'Teboursouk Accident' (Fig. 2A). These Triassic outcrops have been defined as evaporite (halite) diapirs. The Triassic Dome Zone is also characterised by long, straight and closely spaced anticlines and synclines, concentrated in an approximately 60 km wide zone from eastern Algeria to the Gulf of Tunis in the NE. These structures are occasionally symmetric but more commonly asymmetric and often display a box-like geometry with steep limbs and a narrow hinge zone, indicating that they are fault-bend folds. Oil seeps and/or oil stains are frequently encountered on the southeastern steep and sometimes overturned flanks of these anticlines (Belayouni et al., 1992; Saidi et al., 2008). Many of these anticlines are cored by a Triassic succession of shales and evaporites and are tectonically and/or unconformably (stratigraphic unconformities) overlaid by Mesozoic–Cenozoic suites (Snoke et al., 1988; Bouhlel, 1993; Saidi et al., 2008). The 'Deformed Tunisian Foreland' or Tunisian Northern Atlas is located to the SE of the Triassic Dome Zone (Fig. 2A). The boundary between Deformed Tunisian Foreland and Triassic Dome Zone roughly corresponds to the NE–SW-trending Teboursouk Accident, which approximately marks the southernmost limit of the major outcrops of the Triassic that characterise the Triassic Dome Zone (Moody et al., 2006). The Deformed Tunisian Foreland domain mainly comprises Cretaceous to Paleogene–Neogene autochthonous successions. Jurassic rocks occur in the core of some major folds, while Triassic rocks locally occur along NE–SW Accidents.

## 3. Aim and methodological approach

A revision and fine-tuning of the knowledge concerning the Tunisian Tell seem appropriate to address future research on persistent scientific problems. This revision is also useful for oil research in the Mediterranean area. The aim of this work is as follows: (1) to provide an update on the geological setting of the Tunisian Tell, particularly during the Cenozoic, in the context of the geodynamic evolution of the Maghrebian Chain; (2) to evaluate implications for oil exploration (onshore and offshore) in the Africa Margin. This paper aims to thoroughly define the Cenozoic tectono-sedimentary evolution of the *MFB* and the northern African Margin from the end of their extensional evolutionary phase (the latest Cretaceous) to the nappe stacking of the Miocene, going through a Paleogene phase with gentle deformation (deep-seated basement tectonics). A comparison of the oil potential was also carried out between different Iberia–Africa–Adria Plate margins. This is important considering that the Tellian domain remains an underexplored area for oil and gas despite several encouraging features, such as widespread occurrences of live oil seeps onshore and gas/oil discoveries in nearby geological provinces. In short, this work intends to provide an update on the Cenozoic geological setting of the onshore–offshore Tunisian Tell and to evaluate opportunities for oil and gas exploration in relation to their discoveries in the neighboring domains of the Maghrebian Chain.

The methodology used for fine-tuning the proposed theme includes the following aspects: (1) an updated geological framework of the examined area in its broader context; (2) an updated stratigraphic framework through synthetic columns representing the main examined sectors of the Tunisian Tell (this is complemented by a synoptic framework, highlighting the sedimentary units characterising the onshore and offshore areas); (3) an updated structural setting highlighting the main tectonic structures that are most interesting for the Cenozoic evolution; (4) a discussion about the main stratigraphic and tectonic implications, extended to a general paleogeographic and geodynamic reconstruction at a regional scale based on GPlates-type processing; (5) considerations concerning some implications for Tunisian oil–gas research offshore; (6) comparisons regarding the petroleum resource potential in different Iberia–Africa–Adria Plate margins. In particular, the comparison with Sicily and the Apennines, where numerous oil/gas fields have been discovered, can be important because the Tunisian Tell remains an underexplored area despite the numerous oil infiltrations already identified (Saidi et al., 2008).

In addition, a 3D HTML (Leifeld, 2013; Li et al., 2019; Gur et al., 2022) interactive structural model of the study area has been developed using Python libraries, following the methodology implemented by Bullejos et al. (2022a, 2022b, 2023) and Martín-Martín et al. (2023a). The model is provided in the Supplementary Materials (3D_Tunisia_structural_ model.html). Python (http://www.python.org) is a common, user-friendly programming language with many open-source libraries (packages and modules) (Yukun et al., 2019). Furthermore, the HTM file of this model allows it to be viewed with a conventional web browser. The user can view different perspectives of the model, hide some elements, zoom in or out on an area and take a picture from a specific perspective. The model can also be rotated to provide a more precise view.

## 4. Cenozoic stratigraphic framework

The Tunisian Tell exhibits onshore and offshore sedimentary and orogenic cycles of the Maghrebian Chain, including the La Galite Archipelago and Sardinia Channel (Table 1; Figs. 2 and 3). Further, a well-developed Cenozoic sedimentary cover is displaced (thrust-nappes) towards the external domains. The presence of the La Galite Flysch Formation on La Galite Island (Fig. 2B) belonging to the internal subdomain of the *MFB* (Belayouni et al., 2010), plays an important role. This indicates the paleogeographic existence of the internal portion of the *MFB* in this area, which is also present in other sectors of the Maghrebian Chain. According to Belayouni et al. (2010), potassic peraluminous magmatism in the La Galite Archipelago indicates a late intrusion in the internal portion of the *MFB*. The different deposits

**Table 1**
Main Cenozoic stratigraphic framework and orogenic cycles recognised in the Tunisian Tell (data after Talbi et al., 2005; Belayouni et al., 2010, 2012, 2013; and references therein).

| **Maghrebian Chain: onshore and offshore Tunisian Tell stratigraphic framework** | | | | | | |
|---|---|---|---|---|---|---|
| **Internal Zones** | **Maghrebian Flysch Basin** | | **North African Margin** | | | **Sedimentary cycles** |
| Units related to Meso-Mediterranean Microplate (metamorphic units and Cretaceous carbonate cover) Not checked (below the Mediterranean Sea) | Internal Subdomain (La Galite Archipelago) | External Subdomain Numidian Nappe Zone | External Zones Tunisian Dome Zone | | Deformed Tunisian Foreland | |
| | Plio-Quaternary | | Upper Miocene post Numidian succession | Late Miocene-Early Pliocene? | Late Miocene-Early Pliocene ? | *Post-Orogenic Sedimentary Cycle (SC4)* |
| | Upper Miocene magmatic rocks | Continental calc-alkaline to alkaline magmatism | Medjerda Group, Middle-Tortonian-Messinian Molasses, Hakima-Mahmoud, Oued el Melah, Kechabta, Oued Bel Khédim, Chaabet Tebbala fms | Continental deposits (Mellegue Group) Pliocene-Villafranchian | (Beglia & Segui Fm) Mio-Pliocene | |
| | Not known | Glauconite Fm (late Burdigalian- Langhian) | Not known | | | *Late-Orogenic Sedimentary Cycle (SC3)* |
| | La Galite Flysch Fm (lower Burdigalian) | Numidian Fm (Oligocene-lower Miocene) | Oligocene-lower Miocene Marine succession (Salambo-Béjaoua Group); Intermediate Interval (Oligocene); O1 of Rouvier (1977) (pelites and reworked Glauconite) | | Oligo-Miocene Fortuna Fm (shales, fluvial to continental sandstones) | *Syn-Orogenic Sedimentary Cycle (SC2)* |
| | Not known | Sub-Numidian succession (Paleocene-Ypresian-lower Oligocene); Tellian trough deposits (Paleocene El Haria "boules jaunes"; Ypresian Boudabous bituminous limestones; and Boudabous distal facies; upper Eocene Souar shales "boules jaunes" | Tunisian Trough Successions (Paleocene – Upper Eocene) Paleocene El Haria Shales "boules jaunes"; Ypresian Boudabous proximal facies; Upper Eocene Cherahil littoral shales Fm (Souar equivalent) | | Shallow marine deposits: Paleocene *p.p.*- Upper Eocene: Paleocene El Haria shales, Ypresian El Gueria nummulitic limestones, Upper Eocene shallow marine shales including Reneiche coquina marker-member (Souar equivalent) | *Pre-Orogenic Sedimentary Cycle (SC1)* |
| | Not known | Upper Triassic-Jurassic, Cretaceous sedimentary substratum | Permo-Triassic-Jurassic, Cretaceous sedimentary substratum | | | Pre-Cenozoic Substratum |
| Not known | Oceanic and/or thinned crust | | Continental crust, African Plate | | | Basement |

recognised in the Tunisian Tell, associated with the paleogeographic and paleotectonic history of the African Margin, exhibit marked differences in lithofacies, sedimentological features, minero-petrostratigraphy (petrofacies) (e.g., Critelli et al., 2023), sediment source areas and tectonic evolution (Belayouni et al., 2012, 2013; Berrocoso et al., 2013; Marzougui et al., 2014; Riahi et al., 2014; Atawa et al., 2016; Essid et al., 2016; Booth-Rea et al., 2018; Lepretre et al., 2018; Frifita et al., 2020). The Cenozoic stratigraphy of the *MFB* in Tunisia is schematically represented by four main stratigraphic successions (Fig. 3). One of these successions is located offshore (La Galite Island) and the other three are deposited on a common Cretaceous substrate, referring to different tectonic zones (Numidian Nappe Zone, Triassic Dome Zone and Deformed Tunisian Foreland) (Fig. 2). These successions are separated by different para-conformities and unconformities with varying temporal gaps (Fig. 3). The presence of five unconformities (A–E) and associated gaps, along with terrigenous supply due to tectonic implications, allows for the division of the Cenozoic sedimentary record into four main sedimentary cycles onshore: (1) the Paleocene–Oligocene Pre-Orogenic Cycle (*SC1*), which unconformably and/or transitionally overlies Mesozoic successions and shows no terrigenous input during pre-orogenic deposition; (2) the Oligocene–Burdigalian Syn-Orogenic Cycle (*SC2*), characterised by the maximum amount of terrigenous supply and representing syn-orogenic sedimentation; (3) the Burdigalian–Langhian Late-Orogenic Cycle (*SC3*); and (4) the Langhian–late Miocene Post-Orogenic Cycle (*SC4*). The latter two cycles represent minor cycles corresponding to recognisable tectogenetic phases at a regional scale. In particular, Pre-Orogenic Cycle shows low and fine terrigenous supply (pelites); Syn-Late Orogenic Cycles contain the most significant clastic supply; in Post-Orogenic Cycle, the terrigenous supply is consistent but discontinuous, heterogeneous and decreases upwards. Moreover, successions of these cycles exhibit frequent lateral heteropy of lithofacies and thickness variations at different stratigraphic intervals. The Numidian Formation is a typical example of such deposition (Belayouni et al., 2012, 2013; Guerrera et al., 2012; and references therein). Typically, this sedimentary unit tectonically overrides the External Zones or the foreland (Table 1).

The Paleocene–Oligocene Sub-Numidian Succession (Pre-Orogenic Cycle), well represented in the Numidian Nappe Zone and Triassic Dome Zone (Fig. 2A), generally comprises para-autochthonous units consisting of different formations: El Haria with 'boules jaunes' (Paleocene), Bou Dabbous bituminous limestones (Ypresian), Souar shales with 'boules jaunes' (upper Eocene) and the Intermediate Member of the Salambo shales (Oligo–early Miocene) deposited in the northern African Margin. The characteristics of the pelitic–carbonate lithofacies, absence of considerable terrigenous contributions and structural arrangement indicate a pre-orogenic cycle. The widespread occurrence of 'boules jaunes' was interpreted as slumping related to margin/basin system instability (Belayouni et al., 2012). The Oligocene–Burdigalian 'Numidian' Succession, including the Intermediate Interval, is well represented in the Numidian Nappe Zone, where allochthonous and locally para-autochthonous units are present. These deposits belong to the Syn-Orogenic Cycle and correspond to the Numidian nappe unit. They

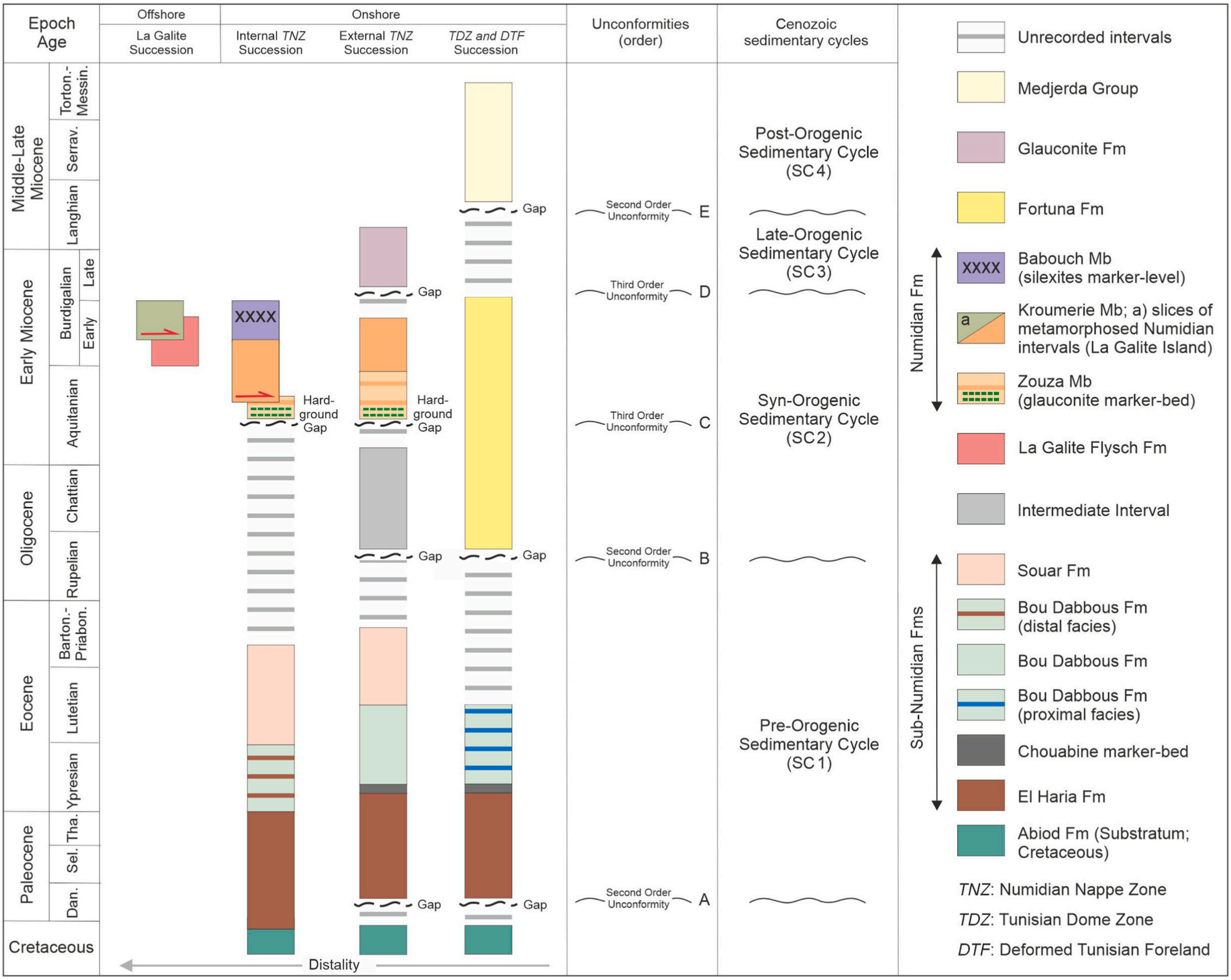



**Fig. 3.** Synthetic Cenozoic stratigraphic columns, representing the sedimentary successions reconstructed in the Tunisian Tell (onshore) and in the La Galite Archipelago (offshore) based on previous data after Belayouni et al. (2010, 2012, 2013; revised). The recognised main events (i.e., unconformities and sedimentary gaps) are also shown.

consist of three members deposited over an Intermediate Interval (Belayouni et al., 2012, 2013), which are termed Lower Numidian Member, Numidian Member and Upper Numidian Member (locally known as Zouza Member, Khroumirie Member and Babouch Member, respectively) when not tectonically elided. These units are deposited in the external sub-domain of the *MFB* (Guerrera et al., 2012; Belayouni et al., 2012, 2013, 2023). In the Tunisian Tell, the Numidian Formation exhibits lateral successions such as the para-autochthonous and autochthonous Salambo–Bejaoua–Fortuna formations (Rouvier, 1977; Yaich et al., 2000; Riahi et al., 2010; Boukhalfa et al., 2015).

In general, the differences between internal and external sedimentations of the *MFB* become particularly evident during the late Oligocene–early/middle Miocene. Terrigenous sedimentation of immature sandstones occurs in the internal sub-domain (only represented by the La Galite Flysch Formation, while highly supermature quartzarenitic Numidian successions are contemporaneously deposited in the external sub-domain) (Guerrera et al., 2005, 2012; Belayouni et al., 2012, 2013; Guerrera and Martín-Martín, 2014; Belayouni et al., 2023). The deposits in the *MFB*'s internal sub-domain originate from the erosion of pre-Alpine metamorphic units and related Mesozoic carbonate cover, which constituted the northern margin of the basin (Guerrera et al., 2021). These internal deposits are common in all lateral sectors (from the Betic–Rifian Arc to the southern Apennines), while in the Tunisian segment, they are only recognised in the La Galite Archipelago (Fig. 2B). Therefore, the identification of this internal sedimentation is crucial for paleogeographic constraints in evolutionary reconstructions.

The Burdigalian–Langhian Late-Orogenic Cycle comprises a unique formation (Glauconite Formation), poorly represented and only recognised in the Triassic Dome Zone. Conversely, the middle–late Miocene Post-Orogenic Cycle is well represented in the Triassic Dome Zone and Deformed Tunisian Foreland (Table 1; Figs. 2A and 3), predominantly composed of the Medjerda Group. This group includes the Hakima-Mahmoud, Oued el Melah, Kechabta, Oued Bel Khédim, Chaabet Tebbala Formations, the Mellegue Group and the Beglia and Segui Formations. All these units were deposited in the northern African Margin.

## 5. Tectonic framework

Fig. 4 depicts different screenshots of the interactive 3D HTML structural model of the Tunisian Tell, showcasing zenithal and southwest lateral views along with the location of structural elements. These screenshots can be found in the Supplementary Materials under the file name '3D_Tunisia_structural_model.html'. The primary tectonic characteristic of the Tunisian Tell is the presence of a major NE–SW-trending

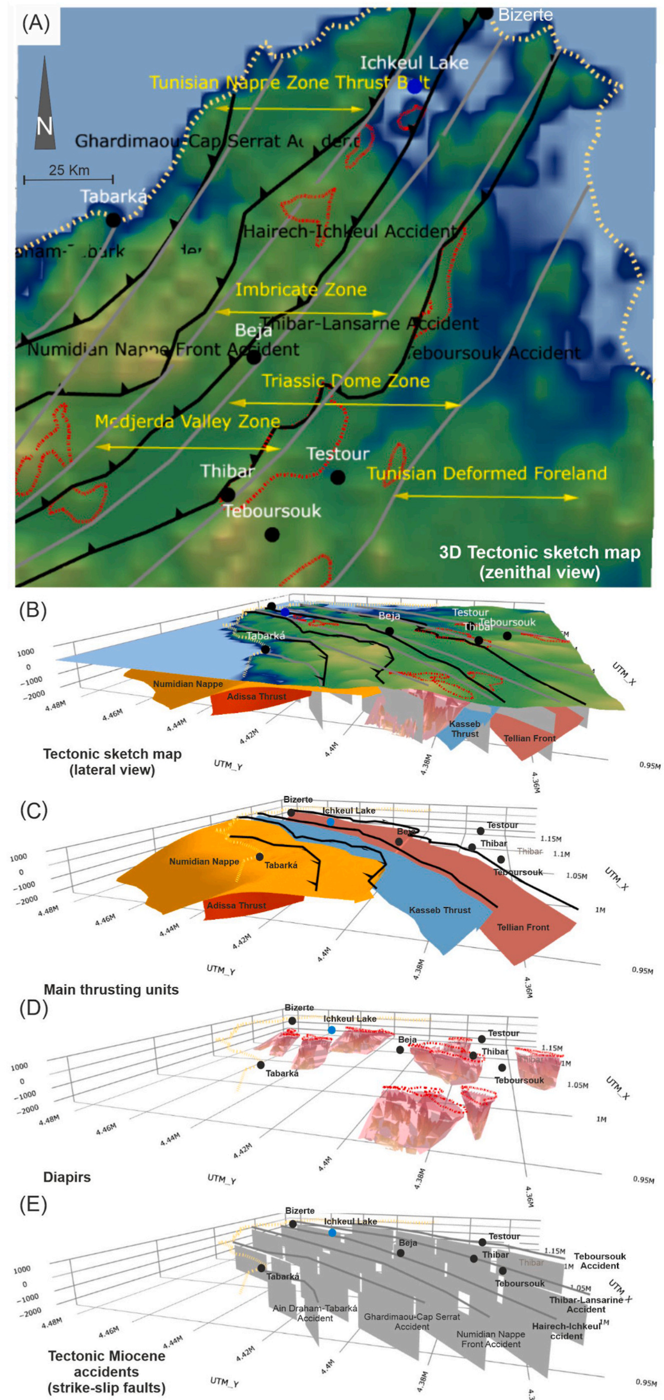



**Fig. 4.** Screenshots of the interactive 3D HTML structural model of the Tunisian Tell provided in Supplementary Materials (3D_Tunisia_structural_model.html). (A) Zenithal view with the location of all structural elements; (B) southwestern lateral view with the location of all structural elements; (C) southwestern lateral view with the location of main thrust contacts (Numidian, Adissa, Kasseb and Tellin front); (D) southwestern lateral view with the location of diapirs; (E) southwestern lateral view with the location of the main structural accidents (Tabarka, Cap Serrat, Numidian Front, Ichkeul, Thibar and Teboursouk).

tectonic thrust sheet of the Numidian Formation. This thrust sheet represents the highest structural unit in the area (Fig. 2A), which has been frequently verified in the Maghrebian Chain. In the footwall of this thrust sheet, there is an older succession primarily consisting of Eocene–Paleocene terrains. The superposition of younger rocks over older ones is interpreted owing to out-of-sequence SE-vergent thrusting (Moody and Sutcliffe, 1994; Moody et al., 2006). This interpretation contrasts with that of Rouvier (1977), who considered a gravity-emplacement of the Numidian thrust sheet. However, regardless of whether the emplacement mechanism of the Numidian sheet has been accomplished by an out-of-sequence thrust tectonic, the minimum estimated amount of displacement, which is given by the distance from the exposed front of the sheet to the northern Tunisian coast, is about 40 km (Rouvier, 1977, 1985). Irrespective of how the Numidian thrust sheet was emplaced, the structure of the footwall succession is generally believed to reflect thrust tectonics with a major detachment surface in Triassic evaporites. The NE–SW-trending thrusts are characterised by folds and scarps. The belt is further distinguished by SE-vergent imbricate folds and thrusts, often intersected by E–ESE-trending dextral wrench faults and less common NS-trending sinistral faults.

The overall structural framework is completed by several main tectonic accidents (lineaments or axes in local literature), now consisting in strike–slip faults zones. From north to south, these tectonic accidents are as follows (Fig. 2A): (1) the Ghardimau–Cap Serrat Accident affecting the Numidian Nappe Zone; (2) the Numidian Nappe Front Accident affecting the Numidian Nappe Zone; (3) the Hairech Ichkeul Accident serving as the boundary between the Numidian Nappe Zone and the Triassic Dome Zone; (4) the Thibar–Lansarine Accident affecting the Triassic Dome Zone; and (5) the Teboursouk Accident serving as the boundary between the Triassic Dome Zone and the Deformed Tunisian Foreland. These tectonic accidents depict a complex geological history with different kinematics overlapping in time. So, they were believed to have firstly functioned as NW-vergent listric NE–SW normal faults during the Mesozoic extension. These faults led to the formation of half-graben basins where thick Cretaceous successions, including potential source and reservoir rocks, were deposited. Later, these faults experienced inversion tectonics due to the NW–SE-trending Cenozoic compression. They transformed into reverse faults and SE-vergent thrusts and finally (during the Plio-Quaternary period), they evolved into wrench sinistral strike–slip faults.

From Late Miocene, the general compression direction changed from NW–SE to N–S (Chaari and Belayouni, 2000, 2005). In the 'La Galite Archipelago' (Fig. 2B), Belayouni et al. (2010) identified folds and thrusts with various orientations, ranging from E–W to SE–NW and generally exhibiting a S–SW vergence. In addition, a NE–SW to E–W trending thrust fault has been recognised in the Oudjill area, considered the most significant compressional feature of La Galite Island (Fig. 2B).

## 6. Discussion

This section considers the implications of three main subjects: Cenozoic stratigraphy, tectonic structures, and Tunisian Tell paleogeography and geodynamic evolution.

### 6.1. Cenozoic stratigraphy

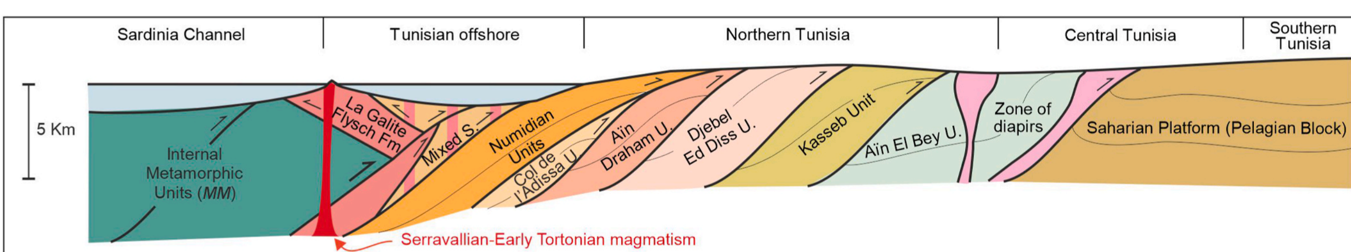
The reconstructed Tunisian Cenozoic stratigraphic framework (Fig. 3) reveals several unconformities that bound different sedimentary cycles, which have also been recognised through the analysis of tectonic/sedimentary processes (Belayouni et al., 2012, 2013; Khomsi et al., 2016, 2022; Lepretre et al., 2018). The oldest unconformity separates the Paleogene pre-orogenic deposits (Souar, Bou Dabbous and El Haria formations) from the Cretaceous sedimentary substratum (Belayouni et al., 2013). This unconformity is well represented in external Numidian Nappe Zone, Triassic Dome Zone and Deformed Tunisian Foreland (Talbi et al., 2008; Melki et al., 2010; Dhraief et al., 2017; Ben Abid et al., 2022) and is likely related to regional tectonics. This unconformity becomes a conformity surface in the deepest zones (internal Numidian Nappe Zone), as is typical in basinal areas (Khomsi et al., 2016, 2022). However, the other unconformities (Belayouni et al., 2013) (Fig. 3) are not present throughout the entire area and can thus be considered minor unconformities. However, these unconformities allow for dividing the stratigraphic record into five Cenozoic depositional units. These units, in turn, can be grouped into four main sedimentary cycles (Pre- Syn- Late- and Post-Orogenic) that are separated by unconformities with considerable tectonic implications. These cycles are related to different tectonic contexts that developed during sedimentation in the *MFB* and northern African Margin. The magmatic emplacement (late Serravallian–early Tortonian extensional event) on La Galite Island, as observed at the base of the La Galite Flysch Formation and near some Numidian shavings, indicates contact metamorphism in an active geodynamic context.

The heteropic tendency of many lithofacies clearly indicates non-cylindrical (highly fragmented) sedimentation, which characterises the stratigraphic record of this sector of the Maghrebian Chain. Moreover, the presence of various features in these successions indicates a tectonic control on sedimentation, supported by the widespread occurrence of tectofacies (e.g., slumps, turbidites, olistostromes and growth folds), even in the Pre-Orogenic Cycle. An example of mass flow deposits (slumps) is provided by the so-called 'boules jaunes' recognised in the El Haria (Paleocene) and Souar (upper Eocene) formations. Tectofacies are also well represented in the Kroumerie Member (lower Miocene) of the Numidian Formation (Belayouni et al., 2012). Based on available dating (Guerrera and Martín-Martín, 2014; and references therein), the top of the correlated successions outcropping in North Africa and the Betic Cordillera appears slightly older compared to those of the Sicilian Maghrebids (Langhian) and southern Apennines (early Serravallian). This age difference between the east and west branches seems to be related to paleogeographic constraints, such as the greater width of the *MFB* towards the east (Guerrera et al., 2012, 2021).

### 6.2. Cenozoic tectonics

Fig. 5 proposes a synthetic and schematic structural section of the Tunisian margin, integrating offshore and onshore data (Belayouni et al., 2010, 2012: 2013). The Cenozoic evolution of the Tunisian Tell, as an integral part of the Maghrebian Chain, is similar to the evolution of the lateral branches of the chain. It has been controlled by the convergence between the Europe and Africa–Adria plates, which caused the subduction of the oceanic crusts of *MFB* and Lucanian Ocean beneath the southern continental margin of the Africa–Adria plates. This subduction was responsible for generating a complex orogenic setting, giving rise to the Maghrebide Chain. The tectonic inversion (beginning of convergence) started in the latest Cretaceous and continued as a result of the early to mid-Paleocene propagation of rifting from the Central Atlantic onto the northern Atlantic Ocean (Rosenbaum et al., 2002; Nielsen et al., 2005, 2007; Ellis and Stoker, 2014). Within this setting, the *MM* (an independent and intermediate microplate) started drifting southeastward through the Western Tethyan Domain. At the end of the middle Miocene, the thrusting and building of the Kabylie massifs (a fragment of the *MM*) began, marking the beginning of the Tellian Atlas orogeny. The Tellian Numidian System, which shows a decreasing deformation magnitude towards the southeast, evolved as a NE–SW-oriented SE-ward vergent fold-and-thrust belt resulting from remobilising former NE–SW-trending listric normal faults as reverse and thrust faults. The generated thrust sheets were mainly displaced during the Langhian/Tortonian compression and were folded again during the late Miocene–Pliocene shortening. As mentioned above, detachment levels are represented either by 'allochthonous' Triassic salt resulting in different diapirism phases or Cretaceous/Paleogene shales. The thrusts and folds of the whole system were later dissected by numerous E–W dextral and N–S sinistral strike–slip faults, which brought the area to its present structural setting.

In the context of this general framework, the sedimentation of the *MFB* was controlled by progressive tectonic events that generated sedimentary successions and unconformities, which characterise the Tunisian Tell from the Upper Cretaceous to the Miocene. Therefore, the Cretaceous–Cenozoic unconformity observed in the Maghrebian domain seems to be related to tectonic inversion from extension to compression in the Alpine Tethys, linked to the beginning of the opening of the southern Atlantic and the anticlockwise rotation of Africa (Stampfli and Borel, 2002; Melki et al., 2010; Dhraief et al., 2017; Ben Abid et al., 2022). Instead, the unconformity covering the late Eocene–early Oligocene period appears to be related to the Eo-Alpine tectonic phase affecting mainly the Iberian-Europe continental margin and the northern branch of the western Tethys (Martín-Martín et al., 2001; Khomsi et al., 2016, 2022; Guerrera et al., 2021) and is also reflected in flexure of the Atlas front domain (Khomsi et al., 2006, 2009). Finally, the unconformities affecting the Burdigalian and Langhian are probably related to the thrust-nappe phase of the Tunisian Tell (Belayouni et al., 2013; Khomsi et al., 2021, 2022). The Paleogene deformation observed in the Tunisian Tell should be interpreted as a reflection of the Eo-Alpine phase in the northern African Margin, which resulted in the basement folding controlling the appearance of lithofacies lateral changes and growth in the Paleogene sedimentary record. The geodynamic framework is completed with the late-orogenic deformation (post--thrust-nappe phase), mainly represented by strike–slip faulting and halokinetic processes. The emplacement of potassic peraluminous magmatism (late Serravallian–early Tortonian extensional event) on La Galite Island is probably owing to the opening of slab break-off in the deep subduction system (Belayouni et al., 2010). In the area between the




**Maghrebian Chain**

| Domains | Mesomediterranean Microplate (MM) | Maghrebian Flysch Basin (MFB) | | | External Zones | Foreland | | |
|---|---|---|---|---|---|---|---|---|
| Sub-Domains | Internal Zone *p.p.* | Mauretanian (Internal) | Mixed Successions (lateral transition) | Massylian (External) | Allochthonous Units | Deformed Tunisian Foreland | Undeformed (or slightly deformed) Tunisian Foreland | |
| Tectonic Zones | Internal Zone | Basin Zone | | | Tellian Numidian Zone | Tunisian Dome Zone | Intermediate Atlas Zone | Saharian Platform Zone |

**Fig. 5.** Schematic north–south geological section showing the relationships between different paleogeographic domains and subdomains recognised in the onshore and offshore Tunisian Tell on the basis of interdisciplinary previously collected data (Belayouni et al., 2010, 2012: 2013; revised).

La Galite Archipelago and the Tunisian onshore, *MFB* units (mainly comprising the Numidian Formation and 'Mixed Successions') are also expected.

### 6.3. Paleogeography and geodynamic evolution

In the Tunisian Tell, the units belonging to the *MFB* internal sub-domain are not present onshore, unlike what is observed in the other sectors of the northern African Margin (Guerrera and Martín-Martín, 2014). Only successions clearly belonging to the internal sub-domain and some small elements of the intermediate sector of the *MFB* are recognised offshore in the La Galite Archipelago (Belayouni et al., 2010). These are represented by 'La Galite Flysch Fm' deposits and by the lateral Mixed Succession deposits, the latter characterising a tectonic slice. In addition, the terrains that crop out at La Galite Island are intruded by plutonic rocks (the roof of a large batholith of high-K cordierite/garnet-bearing granitoids: Belayouni et al., 2010). The emplacement of these rocks, which occurred during the Serravallian–early Tortonian period (14-10 Ma), is probably because of the local extension resulting from the roll-back of the subducted *MFB* below the *MM,* causing local metamorphism. The features of this intrusion show elements from cordierite-bearing granitoids from the continental crust (Kabylide-like), as previously proposed by some authors (Fourcade et al., 2001; Belayouni et al., 2010). Therefore, the La Galite Archipelago represents a portion of the internal *MFB* (southern oceanic branch of the Tethys) located at the footwall of overriding internal pre-alpine metamorphic units belonging to the *MM* (Guerrera et al., 2005). Owing to the absence of offshore seismic data, the La Galite Archipelago provides a unique opportunity for the geological reconstruction of the occurrence of the northern African Margin in the Sardinia Channel. The internal zone units and some of the *MFB* units are not observable between the Algerian Tell and Sicily. Therefore, only three possibilities can be considered: (1) an interruption of the northern African Margin caused by the subduction of the African Margin below the *MM*; (2) a partial interruption of the chain due to underfeeding of internal and external depositional systems and also related to palaeo-physiographic and/or tectonic conditions; (3) no interruption of the chain. In this case, the non-outcropping portion of the chain must be considered to continue offshore in the Mediterranean Sea, ensuring the lateral extension of isopic bands. In our opinion, the last hypothesis is more plausible due to the above-mentioned geological features of La Galite Island (Belayouni et al., 2010). The N–S interpretative geological cross-section reconstructed from offshore to onshore (Figs. 4 and 5) assumes the presence of all the units that usually form the northern African Margin. Furthermore, the same magmatic activity (Abbassene et al., 2016) observed in the Algerian Tell in the La Galite Archipelago is another element of lateral correlation.

Regarding the evolution of the offshore Tunisian margin, Fig. 6 shows a hypothetical tectono-sedimentary reconstruction of the *MFB* during the late Oligocene to late Miocene. Also, the geology of the La Galite Archipelago and the possible continuation offshore of the internal *MFB* sub-domain, considering its presence both in the Algerian Tell and the Sicilian Maghrebids, has been considered. In particular, the Numidian Fm outcropping onshore represents deep marine sedimentation (slope–basin system) arranged in a regressive-transgressive trend deposited in the *MFB* external sub-domain, where internal and external successions can be distinguished. These latter units are found at least in all Betic, Maghrebian and Southern Apennine chains. This mega-basin received a considerable amount of quartz-rich supply from external areas (the African craton), particularly during the Miocene and is representative of syn-orogenic sedimentation occurring under compressional deformation during Oligocene to early Miocene times (Fig. 6).

Fig. 6 (lower section) shows the transition from the northern African Margin to the *MFB*. This transition is influenced by Paleogene deep-seated tectonic activity, which induces changes in sedimentation and the development of lithofacies heteropy and growth folds in a passive-like margin. The intermediate section of the same figure illustrates the transformation of the entire *MM*–*MFB*–northern African Margin area (representing the Maghrebian Chain system) into a foreland basin during the early Miocene. This transformation is caused by the subduction of MFB beneath the *MM,* resulting in the uplift of a forebulge in the northern African Margin. The upper section shown in Fig. 6 presents the interpretation of thrust-nappe formation in the Tunisian area (offshore and onshore), primarily occurring during the middle Miocene, where wedge-top basins may have formed.

Based on available data and considering the extension of geological equivalent bands in the Algerian Tell and Sicily, a paleogeographic framework and the paleotectonic evolution of the onshore and offshore Tunisian Tell have been reconstructed (Fig. 7). This reconstruction at 70 Ma (Figs. 7A), 20 Ma (Fig. 7B) and 0 Ma (Fig. 7C) is based on the analysis of numerous multidisciplinary data using the GPlates software (Müller et al., 2018; Müller et al., 2019) and models proposed by Müller et al., 2019. These models utilise the recent compilation by Le Breton et al. (2021) for Iberia, Europe, Africa and Adriatic plates as well as Balearic, Corsica and Sardinia Islands. The software enables the calculation of past motion of plates based on geological and geophysical data, employing Euler's rotation theorem. In addition, it allows for the reconstruction of the motion and paleogeographic positions of blocks that currently form the chains (*MM*). The reconstruction presented in Fig. 7 is a work in progress and should be considered a hypothesis.

## 7. Implications for Tunisian oil exploration

Despite the presence of at least three active petroleum systems linked to three well-developed mature source rocks (i.e. upper Albian–Vraconian shales of the Mouelha member, upper Cenomanian–Turonian euxinic limestones and marls of the Bahloul horizon as well as Ypresian Globigerina bituminous limestones of the Bou Dabbous Formation), which have generated oil and gas in the Tunisian Tell Domain, as evidenced by numerous gas, oil and bitumen seepages, the Tunisian Tell remains an underexplored area for oil and gas exploration (El Euchi et al., 2004; Mejri et al., 2006; Saidi et al., 2008; Roure et al., 2019; Khomsi et al., 2022**).** The findings of this study provide preliminary implications for potential oil exploration in northern Tunisia. New considerations about the non-tabular stratigraphy and the presence of remarkable lithofacies lateral changes, thickness variations, diachronous boundaries, etc., are crucial elements for better understanding the active petroleum systems in the area, including source rocks, reservoir rocks, seal rocks, overburden rocks, trap formation and generation migration–accumulation timing processes. Although it is considered a frontier zone, the Tunisian Tell has the potential for commercial oil and gas accumulations. Several studies have already examined the petroleum potential of the Tunisian Tellian domain, particularly in relation to the Mesozoic–Cenozoic period (El Euchi et al., 2004; Mejri et al., 2006; Khomsi et al., 2018, 2019a, 2019b, 2021). These studies have discussed the possible occurrence of potential oil/gas accumulations in the Tellian domain and concluded that the most promising areas are likely to be found in northern Tunisia offshore. The Meso–Cenozoic petroleum systems in this region are expected to be highly interesting and potentially very productive (Fernandes, 2015; Khomsi et al., 2019a, 2019b, 2021, 2022).

Regarding the onshore Tellian domain, although no exploration wells have been drilled thus far, it is worth mentioning the results obtained from a soil gas geochemical study conducted throughout the Tunisian Tell (Chaari and Belayouni, 2000, 2005) during a seismic acquisition campaign conducted by an oil company in 1999 across the Tabarka block, using dynamite as an energy source. The analytical results revealed the presence of several surface geochemical hydrocarbon gas anomalies along most seismic lines. Two of these anomalies were considered particularly interesting as they were located on the Numidian Formation outcrops above two potential plays. These anomalies

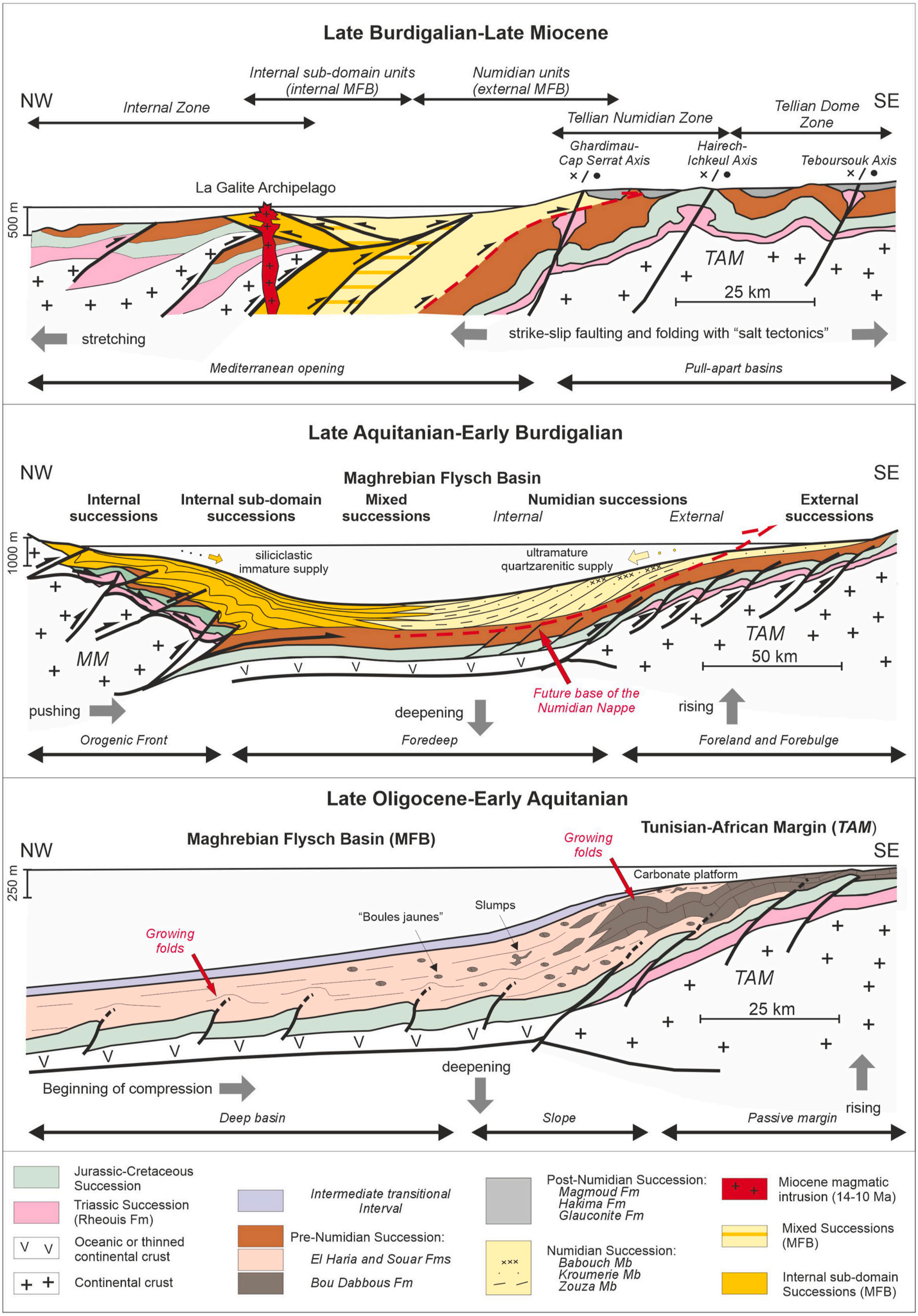



**Fig. 6.** Hypothetical offshore tectono-sedimentary evolution of the Tunisian margin (after Belayouni et al., 2013; revised).

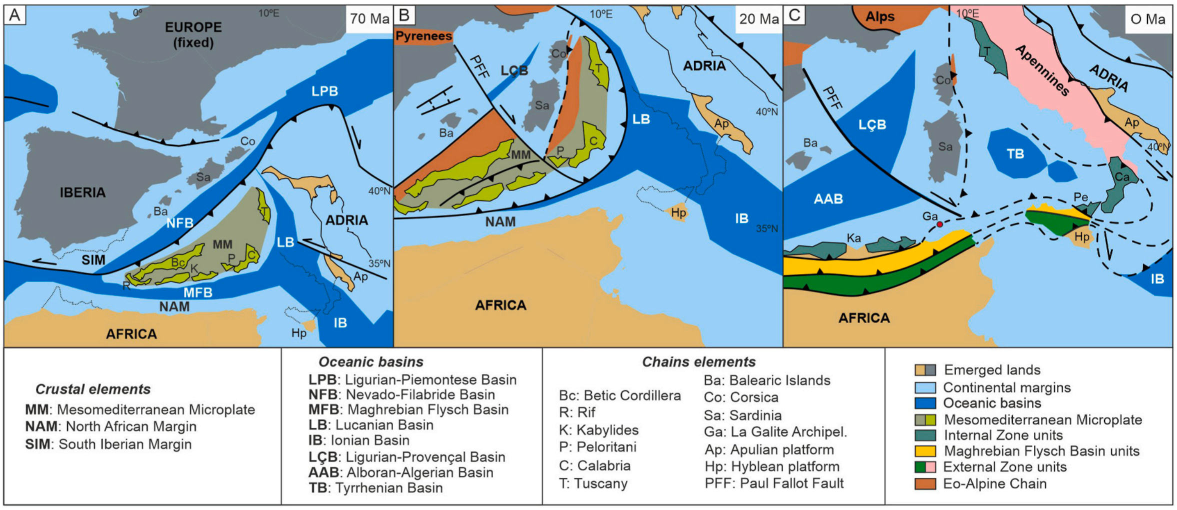



**Fig. 7.** Paleogeographic and paleotectonic GPlates reconstructions. (A) Late Cretaceous (70 Ma); (B) early Miocene (20 Ma); (C) present day.

were interpreted as potentially indicating the presence of significant oil and/or gas accumulations. However, it should be noted that conclusions drawn from surface geochemistry exploration techniques must be approached with caution, as delineating a surface geochemical anomaly does not always guarantee the presence of subsurface petroleum accumulation but could be attributed to various other phenomena.

In terms of exploration, northern Tunisia offshore (Fig. 8A) has not been extensively investigated for hydrocarbon resources, unlike the notable studies conducted in the Sicily Channel and Sicilian onshore (Grant, 1998). Northern offshore Tunisia encompasses six shallow-water open blocks, covering an approximate area of 30,000 sq km. PGS Geophysical AS, in collaboration with ETAP-Tunisia, acquired 2D seismic data and 1000 sq km of 3D seismic data in the region. Despite the presence of a thick Messinian Salt succession, which acted as a barrier, the pre-reprocessed 2D seismic data already indicated a series of undrilled leads on a NE–SW trend along a thrust belt–foredeep setting (Wolden and Jones, 2005; Fernandes, 2015) overlying presumably Mesozoic–Cenozoic potential active petroleum systems (Fig. 8B). Such a setting holds the potential for the discovery of large oil/gas fields, as demonstrated by exploration activities in the same thrust belt that led to the discovery of the giant Val d'Agri oil field in the southern Apennines and the Gagliano gas condensate field in central Sicily. However, confirming the presence of such potential plays and prospects requires acquiring new 2D/3D seismic data and applying more modern reprocessing techniques in northern Tunisia offshore. The primary objectives are to explore oil and gas in the Miocene to Cretaceous carbonates and gas in the Oligocene–Miocene turbidite fan deposits.

## 8. Petroleum resource potential: comparison between different margins of Iberia and Africa–Adria plates

The Cenozoic structural evolution reconstructed in the onshore–offshore Tunisian Tell Domain and its relevance for the highly plausible existence of potential subsurface petroleum resources, either within the thrust belt–foredeep system or in the foreland region, can be compared with other sectors of the Africa–Adria Plate margins along the Betic–Maghrebian–Apennine chains (South Iberia, Moroccan Rif, Algerian and Tunisian Tell as well as Sicily and Apennines). The broad categories of tectonic provinces where numerous oil and gas discoveries have been made along the Africa–Adria Plate margin (e.g., Rif Chain, Algerian Tell, Sicily and Apennines) belong to the thrust belt, foredeep and foreland domains. Analogous provinces can be found within northern Tunisia (i.e., the Tunisian Tell Domain, including the Tunisian Nappe Zone (Thrust Belt); the Imbricate Tellian Zone together with Medjerda Valley Zone (Foredeep Domain), the Tunisian Dome Zone: Triassic Dome Zone (Foreland Domain and Deformed Tunisian Foreland). However, no oil or gas discoveries have yet been made in northern Tunisia, which remains an underexplored area up to the present time. This is because it continues to be considered a highly risky frontier domain, mainly due to its highly tectonised nature and complex geology, which are unfavourable for trap integrity preservation. First, we will highlight the main features of the different margins (South Iberian, Moroccan Rif, Algerian and Tunisian Tell, Sicilian Maghrebids as well as Apennine–Adria) in relation to their oil potential. Further, we will discuss the main similarities and singularities of the Tunisian margin with respect to neighboring margins, particularly the southern Apennines and Sicily, where considerable amounts of oil and gas have been or are being produced.

### *8.1. Betic Cordillera*

Comparably with the Tunisian Tell Margin, the Betic Cordillera shows different tectonic provinces, which are from south to north (Vera et al., 2005): (i) the Internal Domain, which corresponds to the *MM* and primarily comprises three nappe complexes (Fernandez et al., 1998; Crespo-Blanc and Frizon de Lamotte, 2006); (ii) the so-called 'Flysch Trough Units', which constitute early Cretaceous to Miocene deep-water deposits (Biju-Duval et al., 1978; Dercourt et al., 1986; Durand-Delga et al., 2000), representing an equivalent of the Numidian fold-and-thrust belt described in the Tunisian Tell; (iii) the 'Fold-and-Thrust Belt' of the external domain, which is made up of Triassic to Neogene deposits (Crespo-Blanc and Frizon de Lamotte, 2006); (iv) the Guadalquivir 'Foredeep Complex', located further north. This complex is mainly composed, in the eastern and southern sectors, of a typical olistostrome deposited in a foredeep basin during the Burdigalian to Serravallian and in the western sector by a chaotic mixture of highly deformed Triassic evaporites with scattered younger rocks (Sierro et al., 1996); (v) the Guadalquivir 'Foreland Domain' bordering the Betic Chain towards the north. This foreland domain comprises autochthonous deposits, which, overall in the Iberian Massif, range in age from Early Tortonian to Recent (Crespo-Blanc and Frizon de Lamotte, 2006). Among the numerous oil/gas exploration wells drilled in the Betic Cordillera, which covered the 'Flysch Trough Domain', the 'Fold-and-Thrust Belt Domain', the Guadalquivir 'Foredeep Complex' and the 'Foreland Basin' (Fernandez et al., 1998), only a few gas/condensate discoveries have been made, mostly located in the Guadalquivir foreland basin. Indeed, in that domain, more than 29 commercial biogenic gas fields (3 offshore and 26 onshore) have been found within the Upper Miocene sandy turbidites

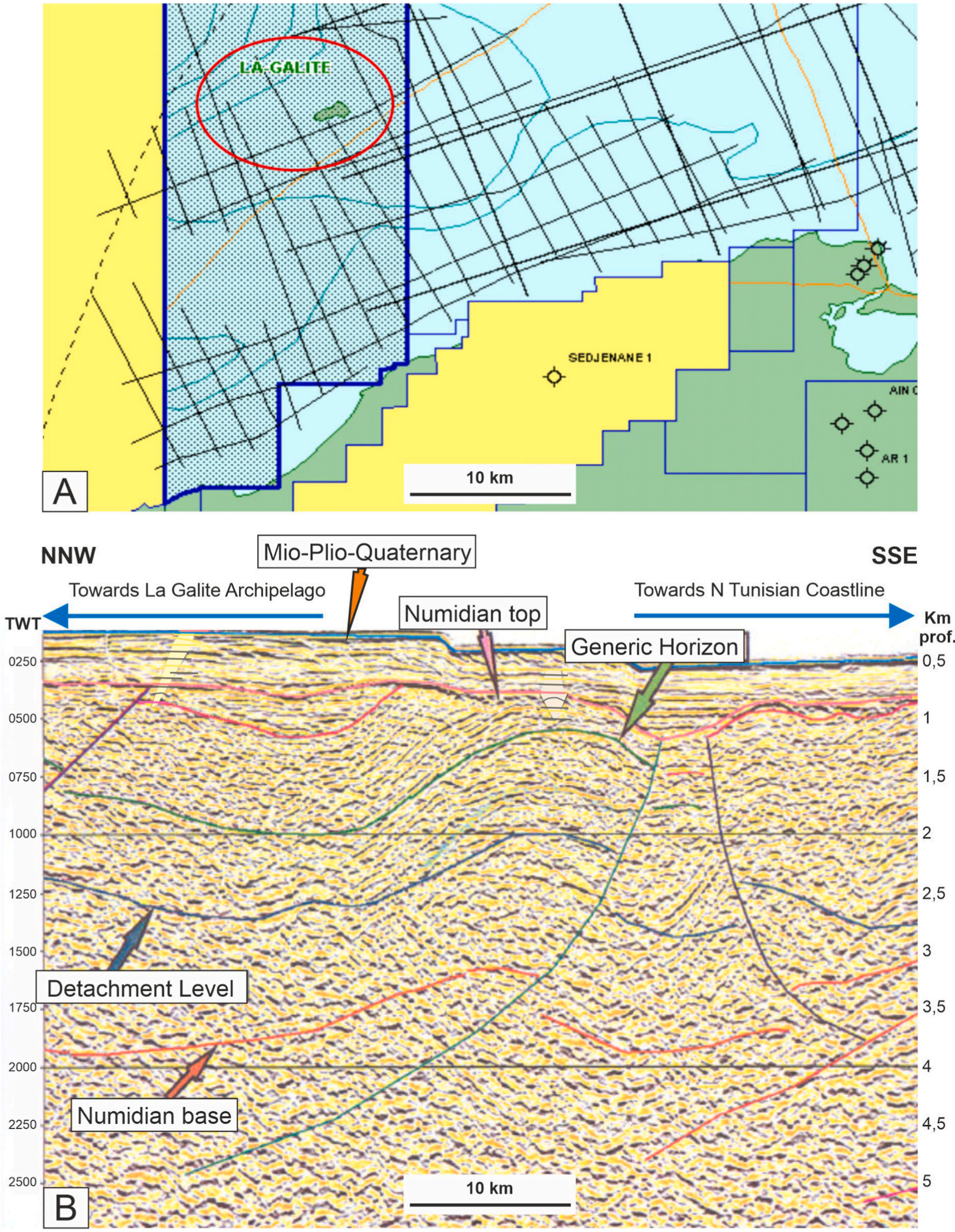



**Fig. 8.** PGS Geological acquisition through la Galite Archipelago Block (after Wolden and Jones, 2005). (A) Location of the PGS 2D Seismic profile across La Galite Archipelago Block, offshore northern Tunisia. (B) PGS 2D Seismic profile interpretation across the La Galite Archipelago Block (offshore northern Tunisia), showing multiple traps within both the Tertiary and Cretaceous intervals. (TWT: Two-way-time vertical scale).

(Guadalquivir Sandstones Fm), with a total and accumulated production of 115 billion cubic feet, sourced from organic-rich marine clays located just a few meters under the sandstone turbidite reservoir (Martínez Del Olmo et al., 1998; Motis and Martínez del Olmo, 2012; Motis and Martínez Del Olmo, 2013; Martinez Del Olmo, 2013, 2019). In the fold-and-thrust belt domain, the Prebetic Outer Platform–Slope (Betic Ranges) has also shown a certain interest as an exploratory area for oil/gas. The existence of an active petroleum system was confirmed with the drilling of the Rio Segura G-1 well, where gas has been discovered within the Barremian limestone (2000 m deep) and the Valanginian turbidite thin sand (4000 m deep). The hydrocarbon type found is wet gas (Martinez Del Olmo, 2019). In addition, high potentialities are expected from the Burdigalian–Serravallian olistostrome deposited in the Guadalquivir ‘Foredeep Complex‘. Indeed, hanging wall anticlines are a promising new play identified in the seismic images in the area, with an excellent shale and salt seal (the Miocene Olistostrome) sitting above a thick Mesozoic series in four-way-closure fault propagation anticlines.

### 8.2. Rif Chain

Like the Algerian/Tunisian Tell, the Moroccan Rif represents the orogenic system that lies south of the West Mediterranean Sea. It comprises three major tectonic provinces, listed from north to south: (i) the Internal Domain (Critelli et al., 2018), which originated from the *MM*; (ii) the 'Flyschs Thrust Belt', composed of displaced nappes/units from the *MFB*; (iii) the External Zones, characterised by three paleogeographic zones known as the Intrarif, Mesorif and Prerif (Lepretre et al., 2018; Gimeno-Vives et al., 2020). During the first half of the last century, petroleum exploration in the Moroccan Rif domain focused on the External Rif Zone, primarily in the proximal Prerifian domain and the Gharb Basin (the southern foreland basin). This exploration involved the drilling of several shallow wells (Jobidon and Dakki, 1993; Tawadros, 2011). The campaign resulted in the identification of four uneconomic occurrences of hydrocarbons: two at Djebel Tselfat, one at Djebel Bou Draa and one at Djebel Outita. These occurrences are in the 'Prerif Ridges', part of the southwestern front of the Rifian Fold-and-Thrust belt. Subsequent exploration efforts have led to the discovery of several oil and gas fields in the Prerif Ridges and the Sidi Fili trend, which represents a NE–SW fault trend that separates the Gharb foreland basin from the Prerif Ridges. Oil production has occurred in thrust-faulted Jurassic carbonates and fractured metamorphic Paleozoic rocks (Jobidon and Dakki, 1993; Tawadros, 2011). More recently (2008–2009), considerable amounts of gas have been discovered NE of Rabat by Circle Oil Company in the Foredeep Gharb Basin, which is in the External Zone of the 'Rif Folded Belt'.

### 8.3. Algerian Tell

The Algerian Tell is a complex orogen where recognisable features can be observed from north to south. These include (i) the Internal Zone (Kabylides), which is part of the *MM* and (ii) the sedimentary units of the *MFB,* representing the cover of the Maghrebian Basin (Numidian Fold-and-Thrust Belt). As in Tunisia, these units are likely flanked by small–narrow foredeep basins in front of the thrust belt; (iii) the external Tell (External Zones and Foreland), which derives from the African Palaeomargin (Benaouali-Mebarek et al., 2006). This subdivision aligns well with the one described for the Tunisian Tell, including the La Galite Archipelago, the Numidian Fm imbricate thrusts and the Triassic Dome Zone. Above this structural domain, a post-orogenic Neogene basin, such as the Chelif Basin and Hodna Basin, has been established (Derder et al., 2013; Arab et al., 2015). In addition to the existence of oil shows in the regions of Ain Zeft and Tliouanet, several modest discoveries have been made in the basin, confirming the presence of remarkable oil potential in those areas. Exploration in the Hodna Basin began in the 1940s, when the Oued Gueterini oil deposit was discovered. It represented a small oil-producing field in the Neogene sandstone, producing approximately 3000 $m^3$ of light oil annually. The presence of heavy oil was also detected (ALNAFT Publication). However, despite these small discoveries, the oil potential of the Algerian Tell domain has not yet been fully revealed owing to its complex geology. The most important Algerian production is related to gas extraction from the giant fields in the Algerian Sahara (Hassi Messaoud, Hassi R'mel, Ourhoud and Hassi Berkine), with no production from the Algerian Tell domain. Gas is supplied to Europe through different pipelines.

### 8.4. Sicily

The southeast-vergent External Zones of the Sicilian Maghrebids mainly crop out in the western sector of Sicily (Madonie Mountains) and show a similar evolution to the previously described External Zones of other sectors. Two main successions deposited in a margin-basin system characterise these zones: (i) the middle Triassic–Oligocene Panormide carbonate platform succession and (ii) the middle Triassic–Oligocene Imerese Basin deep-water succession. The latter (Sicano Basin) passes laterally to sectors bordered by shallow water and pelagic platforms (Trapani-Saccense and Iblean Foreland). The Panormide Unit overrides the Imerese Unit (Henriquet et al., 2020). Regarding oil potentialities in Sicily, the most important discoveries have been made within the onshore Sicilian thrust belt (mostly southern Sicily), where active petroleum systems with proven hydrocarbon potential have been assessed within Late Triassic–Liassic intra-platform basins (Caldarelli and Smith, 2012). Oil fields in Sicily have been discovered either in the foredeep or in the foreland domains, such as in the Ragusa onshore platform, where heavy oil from Triassic and Jurassic source rocks has been trapped in similarly aged, fractured carbonate mound reservoirs (Granath and Casero, 2004; Casero, 2004). In such foreland domains, oil/gas fields are generally found in close proximity to the margins to allow interdigitation of the source, reservoir and seal (Mattavelli et al., 1993). Regarding oil/gas discoveries produced from foredeep plays in Sicily, the most famous one is represented by the Gagliano–Bronte onshore oil field located in north–central Sicily. It produces thermogenic gas and condensate (55°API) within different sandstone levels of the para-autochthonous Miocene Numidian Formation, at a depth of 3000 m. Finally, biogenic gas is also produced in Sicily from foredeep plays. The onshore Catania and Cisina Gas Fields are the most popular from the Pliocene–Pleistocene Foredeep of Gela (Hyblean Plateau).

### 8.5. Apennines

The Apennines represent a Neogene and Quaternary orogenic thrust belt that links the western Alps to the Maghrebian orogeny. It is the important orogenic belt of the central Mediterranean, resulting from the collisional events between the African and European plates. To the east, the Adria plate represents the foredeep and foreland regions of the orogenic belt (De Alteriis, 1995; Nicolai and Gambini, 2007; Vitale et al., 2018; Tripodi et al., 2018; Mangano et al., 2023). The east-vergent External Zones of the Apennines are represented by two sectors belonging to the Adria Margin, located north and south of the Ancona–Anzio tectonic line: (i) the northern, more external Umbria-Marche Domain (distal) and the southern, more internal Lazio-Abruzzi (proximal); (ii) the Campania-Lucania Domain. Even though these areas show some paleogeographic peculiarities, their general evolution is comparable to the one reported above for the chain sectors of the South Iberian and African margins. Regarding petroleum resource potentialities, the specificity in the southern Apennines is that there are two regional nappes (the internal carbonate platform and the Lagonegro nappes), which have been thrust-faulted, overriding eastward during the late Neogene above the foreland region of the Apulia Platform (e.g. Borrelli et al., 2022; Criniti, 2023). The Apulia Platform holds one of the most significant petroleum systems in the region. Maturation of Triassic shales, the source rock, occurred under the effect of the overburden created by the displaced nappes, generating oil and giving rise to several fields discovered beneath the nappes in the buried Apulia Platform. The Costa Molina field (southern Apennines) is the most famous sub-thrust play, with reservoirs consisting of carbonates sealed by Miocene tight limestones and fault-bounded traps (reverse and normal faults). Migration from the mature source rock of Triassic organic shales occurred during the late Pliocene (Mattavelli et al., 1993). In the Southern Apennine foredeep, in an area located east of Napoli, the Candela-Palino gas field (mostly of biogenic origin) is produced from turbidite sand bodies, which were deposited in front of the advancing nappes during the middle–late Pliocene and sealed by alternating clays (e.g., Civitelli et al., 2023). In the upper producing levels of the major Candela field, light oil (42°–58°API) and thermal gas, possibly issued from shaly tertiary shale rocks containing terrestrial organic matter, have mixed with the biogenic gas (Novelli et al., 1988).

### 8.6. Synthesis of this comparison

The comparison between the different external margins of the Betics–Rif–Tell–Sicily–Apennines in relation to petroleum resource potential, clearly indicates that these margins are favourable for generating and accumulating oil and gas (both thermogenic and/or biogenic). This is supported by several oil/gas discoveries made in thrust-plays, foredeep plays and foreland plays, mainly sourced from Triassic/Jurassic and Cenozoic mature source rocks. However, due to their location in highly tectonically deformed zones, these areas are considered frontier risky zones for oil and gas exploration. This explains why hydrocarbon-producing areas are mainly located in Sicily and Apennines, with few or no significant discoveries in the Betic–Rif–Tell domains. Nevertheless, several differences exist between the Tunisian Tell, Prerif, Prerif Ridges, Sicily and Apennines. First, the Triassic/Jurassic successions in the Tunisian Tellian domain show no evidence of potential source rocks, as they were deposited in highly oxic environments unfavourable for organic matter preservation. Second, the Numidian Tellian Nappe successions in the area, with a thickness of over 3000 m, have severely burned the underlying Cretaceous source rocks, rendering them over-mature/spent source rocks. Consequently, no oil/gas has been preserved in this area. However, this is not the case for the tertiary source rock (Ypresian bituminous limestones of the Bou Dabbous Formation), which is found to be mature and has generated light oil. This is evident from numerous live seeps flowing through the fracture network and affecting the source rock. Finally, the flexuration resulting from the thrust-sheet load, which in Sicily produced thick Mio–Pliocene successions consisting of organic-rich shales and sands generating commercial concentrations of biogenic gas, is absent in onshore northern Tunisia. Therefore, the generation of biogenic gas in that area is highly improbable.

## 9. Conclusions

Recent interdisciplinary studies have led to a better definition of *MFB* (which is the main frontal belt) and northern African Margin (Northern Apennines–Maghrebides). These studies have provided valuable insights, particularly focused on the Cenozoic period in the onshore and offshore Tunisian Tell (Table 2). Based on current knowledge, it is evident that the main paleogeographic and paleotectonic elements of the *MFB* are also present on the Tunisian margin. In fact, the reconstruction of these elements in the region, considering their evolution to the south of the northern African Margin, indicates their consistency with features found both laterally in the western branch (Algerian Tell, Rif and Betic Cordillera) and in the north-eastern branch (Sicily and South Apennine) of the Maghrebian Chain.

**Table 2**
Main geodynamic events and related basinal evolutionary stages of the Maghrebian Chain in the Tunisian paleomargin.

| Time range/Age | | Main Geodynamic events | Basinal evolutionary stages |
|---|---|---|---|
| Late Miocene –Pliocene | | Extensional and strike-slip deformation | Molassic and/or intramontane basins (new sedimentary cycle) |
| Middle Miocene | Serravallian Langhian | Late-orogenic phase (continental collision) | Thrust-top basins, piggy-back basins, gravity sliding |
| Early Miocene | Burdigalian Aquitanian | Syn-orogenic phase Subduction (Neo-Alpine orogenic phase) | Foredeep stage (huge amount of siliciclastic supply with subordinate volcaniclastites ?) |
| Paleogene | Late Oligocene | | |
| | Early Oligocene Paleocene, Eocene | Start of tectonic inversion (compressional phase: unconformities, gentle folding and blind thrusts) (Eo-Alpine orogenic phase) | Fine terrigenous supply (pre-foredeep stage) |
| Late Cretaceous | | | |

The Cenozoic stratigraphic framework reveals the presence of five unconformities, each with its own meaning and interpretation. The oldest unconformity (unconformity A) is located at the boundary between the Cretaceous–Cenozoic periods and is likely associated with the tectonic inversion (from extension to compression) in the Alpine Tethys, which is related to the opening of the southern Atlantic Ocean. The unconformity observed across the Eocene–Oligocene boundary (unconformity B) is linked to the Eo-Alpine tectonic phase, which primarily affected the Iberian-Europe domain and the northern branch of the western Tethys. However, the unconformity (C) identified at the base of the Aquitanian succession is considered to be the result of flexure in the Atlas Chain front, possibly connected to the aforementioned tectonic phase. The remaining two unconformities (D and E), which affect the Miocene succession, are not found throughout the entire area and are likely associated with basinal processes resulting from the emplacement of thrust-nappes in the Tunisian Tell.

The recognition of these unconformities has facilitated the division of the Cenozoic stratigraphic record into five depositional units grouped into four main sedimentary cycles: (SC 1) Paleocene–Oligocene, (SC 2) Oligocene–Burdigalian, (SC 3) Burdigalian–Langhian and (SC 4) Langhian–late Miocene. Based on the different lithofacies, variations in terrigenous supply and timing of thrust-nappe emplacement, the sedimentary cycles can be interpreted as representing the following evolutionary stages: (SC 1) Pre-orogenic phase, (SC 2) Syn-orogenic phase, (SC 3) Late-orogenic phase and (SC 4) Post-orogenic phase.

The widespread occurrence of syn-sedimentary structures, such as unconformities, slumps, turbidite successions, olistostromes, growth folds and chaotic intervals, clearly indicates various amounts of tectonic control on sedimentation, supporting the proposed distinction between pre-, syn-, late- and post-orogenic cycles. Formations and members often exhibit lateral heteropies, characterised by diversification of lithofacies within depositional units and sedimentary cycles. This heteropic stratigraphic framework clearly indicates that the Tunisian stratigraphic record is characterised by non-cylindrical sedimentation.

The studied area displays a polyphase tectonic evolution, including: (1) gentle folding of the Paleogene basement; (2) a tectonic phase of thrusting and nappe emplacement during the middle Miocene; (3) a late Miocene strike–slip phase accompanied by halokinetic processes, concurrent with the magmatic event of La Galite Archipelago, which extends into the Algerian Tell. Petrographic and geochemical data from these magmatic rocks indicate the existence of a tectonic wedge comprised of Internal Zone (*MM*) units overriding the lower *MFB* units, which in turn underlie the upper *MFB* units and are affected by a backthrust.

The tectono-sedimentary evolution of the *MFB*-northern African Margin Tunisian system indicates the presence of a passive continental margin during the Paleogene, a foreland basin system during the early Miocene and thrust and nappes development during the middle Miocene, as indicated by the occurrence of wedge-top sub-basins. Preliminary paleogeographic and paleotectonic reconstructions of the onshore and offshore Tunisian Tell at 70, 20 and 0 Ma have been conducted using GPlates software. These reconstructions are based on extensive multidisciplinary data and consider the geological equivalent bands known in the Algerian Tell and Sicily. Considering the numerous oil and gas discoveries in various tectonic provinces along the Africa-Adria Plate margin (including different thrust belts, foredeep and foreland), it is conceivable that considerable accumulations of oil and gas exist in similar tectonic contexts within the Tunisian Tell. The Cenozoic structural evolution reconstructed in the onshore–offshore Tunisian Tell highlights remarkable indicators of potential petroleum resources. Therefore, substantial amounts of oil and gas may be trapped in deeply buried allochthonous thrust wedges underlying the Numidian Nappes, and/or in the imbricate Tellian foredeep domain located in the extreme

NW of the Medjerda Valley foredeep domain. These targets would be analogous to the Candela-Palino field in the Apennines. Another similarity to the oil/gas producing provinces in Sicily and the southern Apennines is the existence of the aforementioned foredeep belt identified in northern Tunisia offshore, south of the La Galite Archipelago. This area has the potential to contain considerable oil/gas accumulations, as demonstrated by exploration activities in the same thrust belt, which have led to the discovery of giant oil fields in Sicily and the southern Apennines.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

## Acknowledgements

Research supported by Research Project PID2020-114381 GB-I00, Spanish Ministry of Education and Science; Research Groups and Projects from M. Martín-Martín, Alicante University (CTMA-IGA). We also acknowledge the help from Eline Le Breton (Freie Universität Berlin, Germany) with the paleogeographic and paleotectonic GPlates reconstructions. The improvements due to two reviewers are greatly acknowledged.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2023.106426.

## References

Abbassene, F., Chazot, G., Bellon, H., Bruguier, O., Ouabadi, A., Maury, R.C., et al., 2016. A 17Ma onset for the post-collisional K-rich calc- alkaline magmatism in the Maghrebides: evidence from Bougaroun (northeastern Algeria) and geodynamic implications. Tectonophysics 674, 114–134.

Alcala, F.J., Guerrera, F., Martín-Martín, M., Raffaelli, G., Serrano, F., 2013. Geodynamic implications derived from numidian-like distal turbidites deposited along the internal–external domain boundary of the betic Cordillera (S Spain). Terra. Nova 25, 119–129.

Arab, M., Bracène, R., Roure, F., Zazoun, R.S., Mahjoub, Y., Badji, R., 2015. Source rocks and related petroleum systems of the Chelif Basin, (western Tellian domain, north Algeria). Mar. Petrol. Geol. 64, 363–385.

Atawa, M., Zouaghi, T., Souei, A., 2016. Gravity constraints on the underground structural framework and associated volcanism of the Maghrebian allochthonous domain: the Sejnene Numidian flysch, Tunisian Tell, Journ. African Earth Sci. 116, 248–263.

Baird, A.W., Grocott, G.G.J., Moody, R.T.J., Sandman, R.L., 1990. Structural Evolution of the Medjerda Zone, Northern Tunisia. AAPG Intern. Conf., London, Program and Abstracts.

Barbera, G., Barone, G., Mazzoleni, P., Puglisi, D., Khozyem, H.M., Mashaly, O., 2014. Mineralogy and geochemistry of the Numidian Formation (Central-Northern sicily): intra-formation variability and provenance evaluation. Ital. Journ. of Geosciences 133 (1), 13–26.

Belayouni, H., Chandoul, H., Mrad, R., 1992. Oil seeps and associated phenomena in Northern Tunisia. Field trip guidebook. IIIèmes journées de Géologie Tunisiennes appliquées à la Recherche des Hydrocarbures. ETAP, pp. 1–41.

Belayouni, H., Di Staso, A., Guerrera, F., Martín-Martín, M., Serrano, F., Tramontana, M., 2006. New data about the piedimonte formation (monte soro unit): insights and constraints to the geodynamic evolution of the Sicilian Maghrebids. Geodinam. Acta 19 (2), 117–133.

Belayouni, H., Brunelli, D., Clocchiatti, R., Di Staso, A., Amrani El Hassani, El, Iz, E., Guerrera, F., Kassaa, S., Laridhi Ouazaa, N., Martín-Martín, M., Serrano, F., Tramontana, M., 2010. La galite Archipelago (Tunisia, North Africa): stratigraphic and petrographic revision and insights for geodynamic evolution of the maghrebian chain. J. Afr. Earth Sci. 56, 15–28.

Belayouni, H., Guerrera, F., Martín-Martín, M., Serrano, F., 2012. Stratigraphic update of the cenozoic sub-numidian formations of the Tunisian tell (North Africa): tectonic/sedimentary evolution and correlations along the maghrebian chain. J. Afr. Earth Sci. 64, 48–64.

Belayouni, H., Guerrera, F., Martín-Martín, M., Serrano, F., 2013. Paleogeographic and geodynamic Miocene evolution of the Tunisian tell (numidian and post-numidian successions): bearing with the maghrebian chain. Intern. J. Earth Sci. 102 (3), 831–855. https://doi.org/10.1007/s00531-012-0824-x.

Belayouni, H., Guerrera, F., Martín-Martín, Le Breton, E., Tramontana, M., 2023. The numidian formation and its lateral successions (Central-Western mediterranean): a review. Int. Geol. Rev. https://doi.org/10.1080/00206814.2023.2199429.

Ben Abid, O., Ouali, J.A., Mahroug, A., Sarsar-Nouali, B., Ahmadia, R., 2022. Insights on the late Cretaceous-Eocene event in the Tunisian eastern foreland using subsurface data. J. Afr. Earth Sci. 196 (4), 664–677.

Benaouali-Mebarek, N., Frizon de Lamotte, D., Roca, E., Bracène, R., Faure, R., Sassi, J.L. W., Roure, F., 2006. Post-Cretaceous kinematics of the Atlas and Tell systems in central Algeria: early foreland folding and subduction-related deformation. CR Geosci., Themat. Issue: Some Recent Dev. Geodyn. Maghreb 338, 41–49.

Berrocoso, A.J., Bodin, S.W., Wood, J., Calvert, S.E., Mutterlose, J., Petrizzo, M.R., Jonathan Redfern, J., 2013. Dynamic sedimentary conditions during periods of enhanced sequestration of organic carbon in the central southern Tethys at the onset of the Cenozoic global cooling. Sediment. Geol. 290, 60–84.

Biju-Duval, B., Letouzey, J., Montader, L., 1978. – Structure and evolution of the Mediterranean basin. – Proceed. ODP, Initial Report 42, 951–984.

Bonardi, G., Giunta, G., Messina, A., Perrone, V., Russo, S., 1996. The calabria-peloritani arc and its correlation with northern Africa and southern Europe. IGCP Proj. 276, 27–86. Newsletter 6 spec. issue, Messina.

Bonardi, G., Cavazza, W., Perrone, V., Rossi, S., 2001. Calabria-Peloritani terrane and northern Ionian sea. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins. kluwer academic publishers, Dordrecht/Boston/London, pp. 287–306.

Bonardi, G., de Capoa, P., Di Staso, A., MartÍn-Martín, M., Martín-Rojas, I., Perrone, V., Tent-Manclús, J.E., 2002. New constraints to the geodynamic evolution of the southern sector of the Calabria-Peloritani Arc (Italy). Com. Ren. Acad. Sci. Paris 334, 423–430.

Booth-Rea, G., Gaidi, S., Melki, F., Marzougui, W., Azanon, J.M., Zargouni, F., F Galvé, J. P., Pérez-Pena, J.V., 2018. Late Miocene extensional collapse of northern Tunisia. AGU 100. Tectonics 37 (6), 1626–1647. https://doi.org/10.1029/2017TC004846.

Booth Rea, G., Gaidi, S., Melki, F., Marzougui, W., Ruano, P., Nieto, F., Azañón, J.M., J, M., Galvé, J.P., J, P., Hidas, K., K Garrido, C.J., 2023. Metamorphic domes in Northern Tunisia: exhuming the roots of nappe belts by widespread post-subduction delamination in the Western Mediterranean. Tectonics 42, e2022TC007467. https://doi.org/10.1029/2022TC007467.

Borrelli, M., Perri, E., Morsilli, M., Critelli, S., 2022. Late Permian-Triassic sedimentary evolution of the Southern Adriatic area based on wells and cores analysis. Mar. Petrol. Geol. 150, 106154 https://doi.org/10.1016/j.marpetgeo.2023.106154.

Bouhlel, S., 1993. Gîtologie, minéralogie et essai modélisation des minéralisations à F-Ba-Sr-Pb-Zn-(S°) associées aux carbonates (jurassiques et crétacés) et aux diapirs triasiques: gisements de Stah-Kohol, Zriba, Guebli, Bou Jaber et Fedj el Adoum (Tunisie septentrionale). Thèse d'État, Faculty of Sciences of Tunis. Tunisia, pp. 1–303.

Boukhalfa, K., Amorosi, A., Soussi, M., Ben Ismail-Lattrâche, K., 2015. Glauconitic-rich strata from Oligo-Miocene shallow-marine siliciclastic deposits of the northern margin of Africa (Tunisia): geochemical approach for basin analysis. Arab. J. Geosci. 8, 1731–1742.

Bracène, R., Frizon de Lamotte, D., 2002. The origin of intraplate deformation in the Atlas system of eastern and central Algeria: from Jurassic rifting to Cenozoic-Quaternary inversion. Tectonophysics 357, 207–226.

Bullejos, M., Cabezas, D., Martín-Martín, M., Alcalá, F.J., 2022a. A Python application for visualizing the 3D stratigraphic architecture of the onshore llobregat river delta in NE Spain. Water 14, 1882. https://www.mdpi.com/2073-4441/14/12/1882.

Bullejos, M., Cabezas, D., Martín-Martín, M., Alcalá, F.J., 2022b. A K-nearest neighbors algorithm in Python for visualizing the 3D stratigraphic architecture of the llobregat river delta in NE Spain. J. Mar. Sci. Eng. 10, 986. https://doi.org/10.3390/jmse10070986.

Bullejos, M., Cabezas, D., Martín-Martín, M., Alcalá, F.J., 2023. Confidence of a k-nearest neighbors Python algorithm for the 3D visualization of sedimentary porous media. J. Mar. Sci. Eng. 11, 60. https://doi.org/10.3390/jmse11010060.

Caldarelli, C., Smith, D., 2012. Hydrocarbon systems in the onshore and offshore Sicilian fold and thrust belt: new constraints from geochemical data. In: Adapted from Extended Abstract Prepared in Conjunction with Oral Presentation at AAPG International Conference and Exhibition. Milan, Italy, October 23-26, 2011.

Casero, P., 2004. Structural Setting of Petroleum Exploration Plays in Italy. Special volume of the Italian Society for the IGC 32 Florence, pp. 189–205, 2004. http://www.pierocasero.it/dowload/V-Structural%20Setting.pdf.

Chaari, Gh, 2005. Northern Tunisia Nappes Zone. Internal Presentation. Carthago Oil Company, pp. 1–79.

Chaari, Gh, Belayouni, H., 2000. Soil Gas Geochemistry in Petroleum Exploration – Tabarka Permit – Tunisia. Internal Report. Carthago Oil Company, pp. 1–25.

Chaari, Gh, Belayouni, H., Soussi, M., 2004. Geochemistry and Petroleum Systems of Jebel Goraa Area – Salt Dome Zone, a New Play Concept for Northern Tunisia. 9th Tunisian Petroleum Exploration and Production Conference – ETAP. October. 2004.

Chaari, Gh, Belayouni, H., 2005. Source rock evaluation in Northern Tunisia: relevance to oil exploration in an underexplored area. In: Internal Presentation. Carthago Oil Company, pp. 1–71.

Civitelli, M., Ravidà, D.C.G., Borrelli, M., Criniti, S., Falsetta, E., 2023. Diagenesis and Petrophysics of Miocene Sandstones within Southern Apennines Foreland, Italy. Marine and Petroleum Geology (in press).

Crespo-Blanc, A., Frizon de Lamotte, D., 2006. Structural evolution of the external zones derived from the Flysch trough and the South Iberian and Maghrebian paleomargins

around the Gibraltar arc: a comparative study. Bull. Soc. géol. Fr., t. 177 (5), 267–282.
Criniti, 2023. Detrital modes of buried permian sandstones of the puglia 1 well (puglia region, southern Italy). Rendiconti Online della Società Geologica Italiana 59, 119–124. https://doi.org/10.3301/ROL.2023.19.
Critelli, S., 2018. Provenance of Mesozoic to Cenozoic Circum-Mediterranean sandstones in relation to tectonic setting. Earth Sci. Rev. 185, 624–648.
Critelli, S., Martín-Martín, M., 2022. Provenance, Paleogeographic and paleotectonic interpretations of Oligocene-Lower Miocene sandstones of the western-central Mediterranean region: a review. in: "the evolution of the tethyan orogenic belt and, related mantle dynamics and ore deposits". J. Asian Earth Sci. Spec. Issue X8, 100124. https://doi.org/10.1016/j.jaesx.2022.100124.
Critelli, S., Perri, F., Arribas, J., Herrero, M.J., 2018. Sandstone detrital modes and diagenetic evolution of Mesozoic continental redbeds from western-central circum-Mediterranean orogenic belts. In: Ingersoll, R.V., Lawton, T.F., Graham, S. (Eds.), Tectonics, Sedimentary Basins and Provenance: A Celebration of William R. Dickinson's Career. Geological Society of America Special Paper 540, pp. 119–132. https://doi.org/10.1130/2018.2540(06.
Critelli, S., Martin-Martin, M., Capobianco, W., Perri, F., 2021. Sedimentary history and palaeogeography of the cenozoic clastic wedges of the malaguide complex, internal betic Cordillera, southern Spain. Mar. Petrol. Geol. 124/2 https://doi.org/10.1016/j.marpetgeo.2020.104775.
Critelli, S., Criniti, S., Ingersoll, R.V., Cavazza, W., 2023. Temporal and Spatial significance of volcanic particles in sand (stone): implications for provenance and paleotectonics. In: Di Capua, A., De Rosa, R., Kereszturi, G., Le Pera, E., Rosi, M., Watt, S.F.L. (Eds.), Volcanic Processes in the Sedimentary Record: when Volcanoes Meet the Environment, vol. 520. Geological Society of London Special Publication, pp. 311–325. https://doi.org/10.1144/SP520-2022-99.
De Alteriis, G., 1995. Different foreland basins in Italy: examples from the central and southern Adriatic Sea. Tectonophysics 252 (1), 349–373.
de Capoa, P., Di Staso, A., Guerrera, F., Perrone, V., Tramontana, M., 2003. The Extension of the Maghrebian Flysch Basin in the Apenninic Chain: Palaeogeographic and Palaeotectonic Implications, vol. 21. Travaux Institute Scientifique Rabat, Géologie, pp. 77–92.
de Capoa, P., D'Errico, M., Di Staso, A., Perrone, V., Perrotta, S., Tiberi, V., 2005. The succession of the Val Marecchia Nappe (Northern Apennines, Italy) in the light pf new field and biostratigraphic data. Swiss Journ. Geosciences 108, 35–54.
de Capoa, P., D'Errico, M., Di Staso, A., Morabito, S., Perrone, V., Perrotta, S., 2014. Biostratigraphic and petrographic study of the Oligocene-lower Miocene successions of the external oceanic units in the Apennines and Sicilian Maghrebides. Rev. Soc. Geol. Espana 27 (1), 151–173.
Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.M., Boulin, J., Sibuet, J.C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M., Lauer, J.P., Biju-Duval, B., 1986. – geological evolution of the Tethys belt from the atlantic to the pamirs since the lias. Tectonophysics 123, 241–315.
Derder, M.E.M., Henry, B., Maouche, S., Bayou, B., Amenna, M., Besse, J., Bessedik, M., Belhai, D., Ayache, M., 2013. Transpressive tectonics along a major EeW crustal structure on the Algerian continental margin: blocks rotations revealed by a paleomagnetic analysis. Tectonophysics 193, 183–192.
Dhraief, W., Dhahri, F., Chalwati, I., Boukadi, N., 2017. Tectonosedimentary framework of Upper Cretaceous –Neogene series in the Gulf of Tunis inferred from subsurface data: implications for petroleum exploration. Geol. Carpathica 68 (2), 97–108.
Di Staso, A., Perrotta, S., Guerrera, F., Perrone, V., Tramontana, M., 2009. New biostratigraphic and petrographic data from the poggio carnaio sandstone Fm (val marecchia nappe): insights into the tectonic evolution of the northern Apennines. Ital. Journ. Geosciences 128 (2), 443–454.
Doglioni, C., 1992. Main differences between thrust belts. Terra. Nova 4, 152–164.
Durand-Delga, M., 1980. La Méditerranée occidentale: étapes de sa genèse et problémes structuraux liés à celle-ci. Mém. hors-série Soc. Géol. France 10, 203–224.
Durand-Delga, M., Fontboté, J.M., 1980. Le cadre structural de la Méditerranée occidentale. Mémoire B.R.G.M. Serv. Géol. National 115, 67–85.
Durand Delga, M., Rossi, M., Olivier, P., Puglisi, D., 2000. Situation structurelle et nature ophiolitique des roches basiques jurassiques associées aux flychs maghrébins du Rif (Maroc) et de Sicile (Italie). C.R. Acad. des Science, Ser. IIA-Earth Planet Sci. 331, 29–38.
El Euchi, H., Saidi, M., Fourati, L., El Marhessi, Ch, 2004. Northern Tunisia thrust belt : deformation models and hydrocarbon systems. In: Swennen, R., Roure, F., Granath, J.W. (Eds.), Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold-And-Thrust Belts: AAPG Hedberg Series, vol. 1, pp. 371–380.
Ellis, D., Stoker, M.S., 2014. The faroe–shetland basin: a regional perspective from the Paleocene to the present day and its relationship to the opening of the North Atlantic Ocean. Geological Society, London, Special Publications 397, 11–31.
Essid, E., Kadri, A., Inoubli, M.H., Zargouni, F., 2016. Identification of new NE-trending deep-seated faults and tectonic pattern updating in northern Tunisia (Mogodos-Bizerte region), insights from field and seismic reflection data. Tectonophysics 682, 249–263.
Fernandes, J., 2015. Structural Insights on the Offshore Northern Tunisia Margin and the Petroleum System Implications. European Regional Conference and Exhibition, Lisbon Portugal. Abstract. http://www.searchanddiscovery.com/abstracts/html/2015/90226erm/abstracts/10342316.html.
Fernandez, M., Berastegui, X., Puig, C., Garcia-Castellano, D., Jurado, M.J., Torné, M., Banks, C., 1998. Geophysical and geological constraints on the evolution of the Guadalquivir foreland basin, Spain. In: Mascle, A., Puigdefabregas, C., Fernandez, M. (Eds.), Cenozoic Foreland Basins of Western Europe, vol. 134. Geological Society of Special Publications, pp. 29–48.
Fornelli, A., Micheletti, F., Langone, A., Perrone, V., 2015. First U-Pb detrital zircon ages from numidian sandstones in southern Apennines (Italy): evidences of african provenance. Sedim. Geology 320, 19–29.
Fornelli, A., Gallicchio, S., Micheletti, F., 2019. U-Pb detrital zircon ages and compositional features of Bifurto quartz-rich sandstones from Southern Apennine (Southern Italy): comparison with Numidian Flysch sandstones to infer source area. Ital. Journ. Geosciences 138. https://doi.org/10.3301/IJG.2019.02.
Fornelli, A., Micheletti, F., Gallicchio, S., Tursi, F., Criniti, S., Critelli, S., 2022. Detrital zircon ages of Oligocene to Miocene sandstone suites of the southern Apennines foreland region, Italy. J. Palaeogeogr. 11 (2), 222–237.
Fourcade, S., Capdevila, R., Ouabadi, A., Martineau, F., 2001. The origin and geodynamic of the alpine cordierite-bearing granitoids of northern Algeria. A combined petrological, mineralogical, geochemical and isotopic (O,H,Sr,Nd) study. Lithos 53 (2–3), 187–216.
Frifita, N., Mickus, K., Gharbi, M., 2020. Gravity contribution to the Mejerda foreland basin, Northwestern region of Tunisia. Journ. African Earth 171, 103956.
Gimeno-Vives, O., Frizon de Lamotte, D., Leprêtre, R., Haissen, F., Atouabat, A., Mohn, G., 2020. The structure of the central-eastern external Rif (Morocco); poly-phased deformation and role of the under-thrusting of the North-west african paleo-margin. Earth Sci. Rev. 205, 103198.
Granath, J.W., Casero, P., 2004. Tectonic setting of the petroleum systems of Sicily. In: Swennen, R., Roure, F., Granath, J.W. (Eds.), Deformation, Fluid Flow, and Reservoir Appraisal in Foreland Fold and Thrust Belts: AAPG Hedberg Series, vol. 1, pp. 391–411.
Grant, J., 1998. Geosciences exploring the Atlas trend offshore Northern Tunisia. Offshore magazine 1–4. https://www.offshore-mag.com/home/article/16759339/geosciences-exploring-the-atlas-trend-offshore-northern-tunisia.
Grasso, M., Guerrera, F., Loiacono, F., Puglisi, D., Romeo, M., Balenzano, F., Carmisciano, R., Di Pietro, M., Gonzalez Donoso, J.M., Martín-Algarra, A., 1987. Caratterizzazione sedimentologica, biostratigrafica e mineralogico-petrografica di "Successioni Miste'' inframioceniche affioranti in Spagna (Catena Betica) e in Italia meridionale (M.ti Nebrodi e Appennino lucano). Boll. Soc. Geol. Ital. 106, 475–516.
Guerrera, F., Loiacono, F., Grasso, M., 1986. Dati preliminari sulle successioni oligomioceniche "miste" affioranti lungo la Catena Betico-Maghrebide-Appennino meridionale: una famiglia di flysch con evidenti implicazioni paleogeografiche e paleotettoniche. Boll. Soc. Geol. Ital. 105, 99–110.
Guerrera, F., Martín-Algarra, A., Perrone, V., 1993. Late oligocene-miocene syn- late-orogenic successions in western and central mediterranean chains from the betic Cordillera to the southern Apennines. Terra. Nova 5, 525–544.
Guerrera, F., Martín-Martín, M., Perrone, V., Tramontana, M., 2005. Tectono-sedimentary evolution of the southern branch of the western Tethys (maghrebian Flysch Basin and Lucanian Ocean): consequences for western mediterranean geodynamics. Terra. Nova 17, 358–367.
Guerrera, F., Martín-Algarra, A., Martín-Martín, M., 2012. Tectono-sedimentary evolution of the 'Numidian Formation' and Lateral Facies (southern branch of the western Tethys): constraints for central-western Mediterranean geodynamics. Terra. Nova 24, 34–41.
Guerrera, F., Martín-Martín, M., Tramontana, M., 2019. Evolutionary geological models of the central-western peri-Mediterranean chains: a review. Intern. Geol. Rev. https://doi.org/10.1080/00206814.2019.1706056.
Guerrera, F., Martín-Martín, M., Tramontana, M., 2020. Evolutionary models of the cenozoic basins of central-western mediterranean area: a review of methodological approaches. Geosciences 10, 366. https://doi.org/10.3390/geosciences10090366.
Guerrera, F., Martín-Martín, M., Tramontana, M., 2021. Evolutionary geological models of the central- western peri-Mediterranean chains: a review. Int. Geol. Rev. 63 (1), 65–86.
Guerrera, F., Martín-Martín, M., 2014. Geodynamic events reconstructed in the betic, maghrebian, and apennine chains (Central-Western Tethys). Bull. Soc. Géol. France 185, 329–341.
Gur, I., Nachum, O., Miao, Y., Safdari, M., Huang, A., Chowdhery, A., Narang, S., Fiedel, N., Faust, A., 2022. Understanding HTML with Large Language Models. https://doi.org/10.48550/arXiv.2210.03945 arXiv.
Henriquet, M., Dominguez, S., Giovanni, B., Malavieille, J., Monaco, C., 2020. Structural and tectono-stratigraphic review of the Sicilian orogen and new insights from analogue modeling. Earth Sci. Rev. 208 (148), 1–96.
Hoyez, B., 1976. Précisions stratigraphiques, sédimentologiques et tectoniques sur les massifs du flysch au Nord de Medjana (Wilaya de Sétif, Algérie). Ann. Soc., géol. Du Nord 96, 89–97. Python programing language. https://www.python.org.
Jobidon, G., Dakki, M., 1993. The external Rif of Morocco and its hydrocarbon potential. AAPG (Am. Assoc. Pet. Geol.) Bull. 77, 9. AAPG Conference: mid-continent section meeting, Amarillo, TX (United States), 10-12 Oct 1993; Journal ID: ISSN 0149-1423.
Khomsi, S., Bédir, M., Soussi, M., Ben Jemia, M. Gh, Ben Ismail-Lattrache, K., 2006. Mise en évidence en subsurface d'événements compressifs Éocène moyen–supérieur en Tunisie orientale (Sahel): généralité de la phase atlasique en Afrique du Nord. C. R. Geosci. 338, 41–49.
Khomsi, S., Soussi, M., Mahersi, C., Fakhfakh-Ben Jemia, H., Riahi, S., Bou Khalfa, K., 2009. New insights on the structural style of the subsurface of the Tell units in north-western Tunisia issued from seismic imaging: geodynamic implications. C.R. Geosci. 341, 347–356. https://doi.org/10.1016/j.crte.2009.01.002.
Khomsi, S., Frizon de Lamotte, D., Bédir, M., Echihi, O., 2016. The late Eocene and late Miocene fronts of the Atlas belt in eastern maghreb: integration in the geodynamic evolution of the mediterranean domain. Arab. Journ. Geosci. 9, 650–670.
Khomsi, S., Roure, F., Khelil, M., Frizon de Lamotte, D., Zargouni, F., 2018. Thrust belt systems of Northern Africa petroleum implications. Field trip guide, CAJG 2018: 1st, 2018 Conf. Arabian Journ. Geosciences (Nov. 12–15, 1–109.

Khomsi, S., Roure, F., Khelil, M., Mezni, R., Echihi, O., 2019a. A review of the crustal architecture and related pre-salt oil/gas objectives of the eastern Maghreb Atlas and Tell: need for deep seismic reflection profiling. Tectonophysics 766, 232–248. https://doi.org/10.1016/j.tecto.2019.06.009.
Khomsi, S., Roure, F., Brahim, N.B., Maherssi, C., Arab, M., Khelil, M., 2019b. Structural styles, petroleum habitat and traps in the Pelagian-Sirt Basins, Northern Africa: an overview and future exploration developments. In: Rossetti, F. (Ed.), The Structural Geology Contribution to the Africa-Eurasia Geology: Basement and Reservoir Structure, Ore Mineralization and Tectonic Modelling. CAJG 2018. Advances in Science, Technology & Innovation (IEREK Interdisciplinary Series for Sustainable Development). Springer, Cham. https://doi.org/10.1007/978-3-030-01455-1_33 et al.
Khomsi, S., Khelil, M., Roure, F., Zargouni, F., 2021. Surface and subsurface architecture of the Kasseb structures: implications for petroleum exploration beneath the Tellian allochthon, the easternmost portion of the Maghrebides. Arab. Journ. Geosci. 14 https://doi.org/10.1007/s12517-020-06388-2.
Khomsi, S., Roure, F., Vergès, J., 2022. Hinterland and foreland structures of the eastern Maghreb Tell and Atlas thrust belts: tectonic controlling factors, pending questions, and oil/gas exploration potential of the Pre-Triassic traps. Arab. Journ. Geosci. 15, 462. https://doi.org/10.1007/s12517-022-09707-x.
Le Breton, E., Brune, S., Ustaszewski, K., Zahirovic, S., Seton, M., Muller, R.D., 2021. Kinematics and extent of the piemont–liguria basin – implications for in the Alps. Solid Earth 12, 885–913.
Leifeld, P., 2013. Texreg: conversion of statistical model output in R to LATEX and HTML tables. J. Stat. Software 55, 1–24.
Lepretre, R., Frizon de Lamotte, D., Combie, R.V., Gimeno-Vives, O., Mohn, G., Eschard, R., 2018. The Tell-Rif orogenic system (Morocco, Algeria, Tunisia) and the structural heri- tage of the southern Tethys margin. Bull. Soc. Géol. Fr. Earth Sciences Bulletin 189, 1–10. https://doi.org/10.1051/bsgf/2018009.
Li, Y., Yang, Z., Chen, X., Yuan, H., Liu, W., 2019. A stacking model using URL and HTML features for phishing webpage detection. Future Generat. Comput. Syst. 94, 27–39.
Mangano, G., Alves, T.M., Zecchin, M., Civile, D., Critelli, S., 2023. The rossano-san nicola fault zone evolution impacts the burial and maturation histories of the crotone basin, calabrian arc, Italy. Petrol. Geosci. 29 (2), 1–22.
Martín-Algarra, A., 1987. Alpine Geological Evolution of the Internal-External Betic Zones Contact (Central and Western Sector). PhD thesis, University of Granada, Spain, pp. 1–1171.
Martín-Martín, M., Rey, J., Alcala, F.J., Tosquella, J., Deramond, J., Lara-Corrona, E., Duranthon, F., Antoine, P.O., 2001. Tectonic controls on the deposits of a foreland basin: an example from the Eocene Corbieres-Minervois basin, France. Basin Res. 13, 419–433.
Martín-Martín, M., Guerrera, F., Maaté, A., Hlila, R., Serrano, F., Cañaveras, J.C., Paton, D., Alcalá, F.J., Maaté, S., Tramontana, M., Martín-Pérez, J.A., 2022. The cenozoic evolution of the Intrarif (Rif, Morocco). Geosphere 18 (2), 850–884. https://doi.org/10.1130/GES02199.1.
Martín-Martín, M., Bullejos, M., Cabezas, D., Alcalá, F.J., 2023a. Using python libraries and k-Nearest neighbor algorithms to delineate sy-sedimentary faults in sedimentary porous media. Mar. Petrol. Geol. 153, 106283.
Martín-Martín, M., Guerrera, F., Cañaveras, J.C., Alcalá, F.J., Serrano, F., Maaté, A., Hlila, R., Maaté, S., Tramontana, M., Sánchez-Navas, A., Le Breton, E., 2023b. Paleogene evolution of the External Rif Zone (Morocco) and comparison with other western Tethyan margins. Sediment. Geol. 448, 106367.
Martín-Martín, M., Perri, F., Critelli, S., 2023c. Cenozoic detrital suites from the Internal Betic-Rif Cordilleras (S Spain and N Morocco): implications for paleogeography and paleotectonics. Earth Sci. Rev. 243, 104498 https://doi.org/10.1016/j.earscirev.2023.104498.
Martinez Del Olmo, W., 2019. The Spanish petroleum systems and the overlooked areas and targets. Bol. Geol. Min. 130 (2), 289–315.
Martínez Del Olmo, W., Torrescusa, S., Riaza, C., García, C., 1998. Stratigraphy and Turbidite Reservoir Characterization of Biogenic Gas Fields in the Guadalquivir-Gulf of Cadiz Miocene Basins, SW Spain. Am. Ass. Petroleum Geologist. Rio de Janeiro, Brasil, p. 692.
Marzougui, W., Melki, F., Arfaoui, M., Houla, Y., Zargouni, F., 2014. Major faults, salt structures and paleo-ridge at tectonic nodes in Northern Tunisia: contribution of tectonics and gravity analysis. Arab. Journ. Geosciences. https://doi.org/10.1007/s12517-014-1698-y.
Matano, F., Di Nocera, S., Criniti, S., Critelli, S., 2020. Geology of the epicentral area of the 1980 earthquake (Irpinia, Italy): new stratigraphical, structural and petrological constrains, 247 MDPI Geosci. 10 (6), 1–33. https://doi.org/10.3390/geosciences10060247. https://www.mdpi.com/2076-3263/10/6/247?utm_source=releaseissue&utm_medium=email&utm_campaign=releaseissue_geosciences&utm_term=doilink37.
Mattavelli, L., Pieri, M., Groppi, G., 1993. Petroleum exploration in Italy: a review. Mar. Petrol. Geol. 10, 410–425.
Mejri, F., Burollet, P.F., Ben Ferjani, A., 2006. Petroleum geology of Tunisia. A renewed synthetis. ETAP Memoir 22, 1–233.
Melki, F., Zouaghi, T., Ben Chelbi, M., Bédir, M., Zargouni, F., 2010. Tectono-sedimentary events and geodynamic evolution of the mesozoic and cenozoic basins of the alpine margin, Gulf of Tunis, north-eastern Tunisia offshore. Compt. Rendus Geosci. 342 (9), 741–753.
Moody, R.T.J., Sutcliffe, P.J.C., 1994. The unroofing of the Medjerda zone. In: Chine, A., Ben Hassine, K. (Eds.), Proceedings of the 4th Tunisian Petroleum Exploration Conference (1994), vol. 7. ETAP Memoir n°, pp. 39–53.
Moody, R.T.J., Sandman, R.I., Belayouni, H., 2006. Field Trip Guide Book to Northern Tunisia, 2006, pp. 1–93. Oct. 13-18.
Motis, K., Martínez del Olmo, W., 2012. Los Cabalgamientos ciegos del Alto Guadalquivir (Provincia de Jaén). VIII Congreso Geológico de España. Geotemas 13, 154–158. Oviedo.
Motis, K., Martínez Del Olmo, W., 2013. Three different exploration plays in the marine Guadalquivir foreland basin in the context of the late Miocene closure of the thethys ocean (south of Spain). In: Adapted Oral Presentation. AAPG European Regional Conference & Exhibition, Barcelona, Spain, pp. 1–23. April 8-10.
Müller, R.D., Cannon, J., Qin, X., Watson, R.J., Gurnis, M., Williams, S., Pfaffelmoser, T., Seton, M., Russell, S.H.J., Zahirovic, S., 2018. GPlates: building a virtual earth through deep time. G-cubed 19, 2243–2261. https://doi.org/10.1029/2018GC007584.
Müller, R.D., Zahirovic, S., Williams, S.E., Cannon, J., Seton, M., Bower, D.J., Tetley, M. G., Heine, C., Le Breton, E., Liu, S., Russel, S.H.J., Yang, T., Leonard, J., Gurnis, M., 2019. A global plate model including lithospheric deformation along major rifts and orogens since the triassic. Tectonics 38, 1884–1907. https://doi.org/10.1029/2018TC005462.
Nicolai, C., Gambini, R., 2007. Structural architecture of the Adria platform-and-basin system. Boll. Soc. Geol. Ital. 7, 21–37.
Nielsen, S.B., Thomsen, E., Hansen, D.L., Clausen, O.R., 2005. Plate-wide stress relaxation explains European Palaeocene basin inversions. Nature 435 (7039), 195–198. https://doi.org/10.1038/nature03599.
Nielsen, S.B., Stephenson, R., Thomsen, E., 2007. Dynamics of Mid-Palaeocene North Atlantic rifting linked with European intra-plate deformations. Nature 450 (7172), 1071–1074. https://doi.org/10.1038/nature 06379.
Novelli, L., Welte, D.H., Mattavelli, L., Yalcin, M.N., Cinelli, D., Schmitt, K.J., 1988. Hydrocarbon generation in southern sicily. A three-dimensional computer aided basin modelling study. In: Organic Geochemistry in Petroleum Exploration; Pergamon, pp. 153–164. Great Britain, UK; 13.
Perri, F., Critelli, S., Martin-Martin, M., Montone, S., Amendola, U., 2017. Unravelling hinterland and offshore palaeogeography from pre-to-syn-orogenic clastic sequences of the Betic Cordillera (Sierra Espuña), Spain. Palaeogeogr. Palaeoclimatol. Palaeoecol. 468, 52–69.
Perri, F., Martin-Martin, M., Maaté, A., Hlila, R., Soufian Maaté, S., Criniti, S., Capobianco, W., Critelli, S., 2022. The Cenozoic sedimentary cover from the Ghomaride Complex (Internal Rif Belt, Morocco): implications on unravelling hinterland and offshore palaeogeography. Mar. Petrol. Geol. 143 (105811), 1–25.
Perrone, V., Martín-Algarra, A., Critelli, S., Decandia, F.A., D'Errico, M., Estevez, A., Iannace, A., Lazzarotto, A., Martín-Martín, A., Martín-Rojas, I., et al., 2006. Verrucano" and "pseudoverrucano" in the central-western mediterranean alpine chains: paleogeographical evolution and geodynamic significance. In: Chalouan, A., Moratti, G. (Eds.), Tectonics of the Western Mediterranean and North Africa, vol. 262. Geol. Soc. London, U.K., pp. 1–43
Perrone, V., Di Staso, A., Perrotta, S., 2008. The evolution of the Western Adriatic Margin and contiguous oceanic area: open problems and working hypotheses. Boll. Soc. Geol. Ital. 127, 357–373.
Perrone, V., Perrotta, S., Marsaglia, K., Di Staso, A., Tiberi, V., 2014. The Oligocene ophiolite-derived breccias and sandstones of the val marecchia nappe: insights for paleogeography and evolution of northern Apennines (Italy). Paleo. Paleo. Paleo. 394, 128–143.
Perthuisot, V., 1981. Diapirism in northern Tunisia. Journ. Struct. Geol. 3, 231–235.
Riahi, S., Soussi, M., Boukhalfa, K., Ben Ismail-Lattrache, K., Stow, D., Khomsi, S., Bedir, M., 2010. Stratigraphy, sedimentology, and structure of the Numidian flysch thrust belt in northern Tunisia. J. Afr. Earth Sci. 57, 109–126.
Riahi, S., Uchman, A., Stow, D., Soussi, M., Lattrache Kmar, B.I., 2014. Deep-sea trace fossils of the oligocene-miocene Numidian Formation, northern Tunisia. Paleo. Paleo. Paleo. 414, 155–177.
Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during alpine orogeny. Tectonophysics 359 (1–2), 117–129. https://doi.org/10.1016/S0040 -1951(02)00442-0.
Roure, F., Khomsi, S., de Lamotte, D.F., Leprêtre, R., 2019. Tethyan and Alpine controls on the crustal architecture of the Tunisian and Algerian Atlas and Tell: needs for coupled deep seismic soundings and tomography. In: Rossetti, F., et al. (Eds.), The Structural Geology Contribution to the Africa-Eurasia Geology: Basement and Reservoir Structure, Ore Mineralisation and Tectonic Modelling. CAJG 2018. Advances in Science, Technology & Innovation (IEREK Interdisciplinary Series for Sustainable Development). Springer, Cham. https://doi.org/10.1007/978-3-030-01455-1_3.
Rouvier, H., 1977. Géologie de l'Extrême Nord Tunisien: tectoniques et paléogéographies superposées à l'extrémité orientale de la chaîne nord-maghrébine. Thèse doctorat es-sciences Univ, Paris VI, pp. 1–703.
Rouvier, H., 1985. Géologie de l'extrême-nord tunisien: tectonique et paléogéographies superposées à l'extrémité orientale de la chaîne nord-maghrébine. PhD Thesis. Min. Géol., Ann, pp. 1–427. Tunis.
Saidi, M., Bélayouni, H., Meskini, A., 2008. Oil seeps and source rocks in northern Tunisia; fieldtrip guidebook. EPC' 2008 28, 1–39. Tunis, Oct. 16-18, 2008. Etap Mem.
Sierro, F.J., González-Delgado, J.A., Dabrio, C.J., Flores, J.A., Civis, J., 1996. Late Neogene depositional sequence in the foreland basin of Guadalquivir (SW Spain). In: Friend, P.F., Dabrio, C.J. (Eds.), Tertiary Basins of Spain. The Stratigraphic Record of Crustal Kinematics. Cambrige University Press, 399-345.
Snoke, A.W., Schamel, S., Karasek, R.M., 1988. Structural evolution of Djebel Debadib anticline: a clue to the regional tectonic styles of the Tunisian Atlas. Tectonics 7 (3), 497–516.
Stampfli, G.M., Borel, G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic. Earth Planet Sci. Lett. 196, 17–33.

Talbi, F., Jaafari, M., Tlig, S., 2005. Magmatisme néogene de la Tunisie septentrionale: petrogenese et evénements géodynamiques. Rev. Soc. Geol. Espana 18 (3–4), 241–252.
Talbi, F., Melki, F.K., Ismail-Lattrache, B., Alouani, R., Tlig, S., 2008. Le Numidien de la Tunisie septentrionale: données stratigraphiques et interprétation géodynamique. Estud. Geol. 64 (1), 31–44.
Tawadros, E.E., 2011. Geology of North Africa, first ed. CRC Press Taylor & Francis Group. London 930pp. (eBook ISBN9780429217227). https://www.taylorfrancis.com/books/mono/10.1201/b11419/geolo-gy-north-africa-edward-tawadros.
Thomas, M.F.H., Bodin, S., Redfern, J., Irving, D.H.B., 2010. A constrained Africa-craton source for Cenozoic Numidian Flysch: implications for the paleogeography of the western Mediterranean basin. Earth Sci. Rev. 101, 1–23.
Tripodi, V., Muto, F., Brutto, F., Perri, F., Critelli, S., 2018. Neogene-Quaternary evolution of the forearc and backarc regions between the Serre and Aspromonte Massifs, Calabria (southern Italy). Mar. Petrol. Geol. 95, 328–343. https://doi.org/10.1016/j.marpetgeo.2018.03.028.
Vera, J.A., Arias, C., García-Hernández, M., López-Garrido, A.C., Martín-Algarra, A., Martín-Chivelet, J., Molina, J.M., Rivas, P., Ruiz-Ortiz, P.A., Sanz De Galdeano, C., Vilas, L., 2005. Las zonas externas Béticas y el paleomargen Sudibérico. In: Vera, J.A. (Ed.), Geología de España. Sociedad Geológica de España-Instituto Geológico y Minero de España, Madrid, pp. 409–422, 2004.
Vitale, S., Filomena Amore, O., Ciarcia, S., Fedele, L., Grifa, C., Paolo Prinzi, E., Tavani, S., D'Assisi Tramparulo, F., 2018. Structural, stratigraphic, and petrological clues for a Cretaceous-Paleogene abortive rift in the southern Adria domain (Southern Apennines, Italy). Geol. J. 53 (2), 660–681.
Wildi, W., 1983. La chaîne tello-rifaine (Algérie, Maroc, Tunisie): structure, stratigraphie et évolution du Trias au Miocène. Rev. Geogr. Phys. Geol. Dyn. 24, 201–297.
Wolden, T., Jones, M.S., 2005. Offshore Northern Tunisia MC2D. N1 La Galite Block and N4 Rafraf Block. PGS N1_N4 Flyer Publication. Internal document – ETAP, pp. 1–4.
Yaich, Ch, Hooyberghs, H.J.F., Durlet, Ch, Renard, M., 2000. Corrélation stratigraphique entre les unités oligo-miocènes de Tunisie centrale et le NumidienStratigraphic correlation between the Numidian formation (North Tunisia) and Oligo–Miocene deposits of central Tunisia. C. R. Acad. Sci. Paris 331 (7), 499–506.
Yukun, L., Zhenguo, Y., Xu, C., Huaping, Y., Wenyin, L., 2019. A stacking model using URL and HTML features for phishing webpage detection. Future Generat. Comput. Syst. 94 (27–39) https://doi.org/10.1016/j.future.2018.11.004. ISSN 0167-739X.
Zaghloul, M.N., Guerrera, F., Loiacono, F., Maiorano, P., Puglisi, D., 2002. Stratigraphy and petrography of the beni ider flysch in the tétouan area (Rif chain, Morocco). Boll. Soc. Geol. Ital. 121, 69–85. https://www.python.org.