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New insights on the Oligo-Miocene succession bearing phosphatic layers of the Maltese Archipelago

Nuovi dati sulla successione oligo-miocenica dell'Arcipelago Maltese contenente livelli fosfatici

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ABSTRACT

The Maltese Archipelago sedimentary succession is nowadays very well studied and known, mostly due to the excellent exposures of the outcrops, the well-preserved calcareous microfossil content, and the cyclic lithological pattern of most of the stratigraphic intervals. Therefore, the Maltese sediments have been studied to establish updated calcareous plankton biostratigraphic schemes, and the Ras il Pellegrin section, along the western coast of Malta Island, has been chosen to host the Global Stratigraphic Section and Point of the Serravallian Stage.

This paper focuses on the Maltese Oligo-Miocene succession bearing well-developed phosphatic beds, with particular attention to the evaluation of the associated sedimentary hiatuses. To achieve this goal, the calcareous nannofossils content of the marine sediments inter-bedded to the phosphatic horizons has been analysed in two key sections: Il Blata (W of the Malta Island) and Qammieh (N of the Malta Island). Furthermore, the good correspondence of the examined succession with the third-order sequences of the New Jersey passive margin, allowed a more refined definition of the intervals characterized by absence of "normal" marine sedimentation.

Dissimilarities in the number of the phosphatic horizons characterizing the two sections have been explained supposing different locations of the two depositional areas within the sedimentary basin, probably affected by local syn-sedimentary tectonic activity.

Finally, the correlation of the two investigated successions with the stable Oxygen isotope curve provided relationships between the origin of the phosphatic layers and global sea-level changes.

KEYWORDS

Maltese Archipelago, phosphatic horizons, calcareous nannofossils, late Oligocene-middle Miocene, sea-level changes

RIASSUNTO

La successione sedimentaria che costituisce le isole dell'Arcipelago Maltese risulta ad oggi molto ben studiata e conosciuta, soprattutto per le ottime esposizioni degli affioramenti, l'eccellente conservazione dell'abbondante contenuto di microfossili calcarei e la ciclicità litologica riconoscibile nella maggior parte degli intervalli stratigrafici. In virtù delle loro caratteristiche, lo studio di questi sedimenti è alla base della definizione di schemi biostratigrafici integrati a plancton calcareo, e una sezione Maltese (quella di Ras Il Pellegrin) è stata scelta per ospitare il "Global Stratigraphic Section and Point" del piano Serravalliano (Miocene medio).

Questo articolo riporta i risultati di uno studio stratigrafico eseguito sulla successione oligo-miocenica maltese contenente livelli fosfatici, con particolare attenzione alla valutazione delle lacune sedimentarie ad essi associate. A tale scopo, è stato eseguita l'analisi biostratigrafica quantitativa dei nannofossili calcarei presenti nei sedimenti marini intercalati agli orizzonti fosfatici in due sezioni chiave, quella de Il Blata (affiorante lungo la costa occidentale dell'Isola di Malta) e quella di Qammieh (affiorante lungo la costa settentrionale della medesima isola). Inoltre, la buona corrispondenza della successione qui esaminata con le sequenze di terzo ordine del margine passivo del New Jersey, ha contribuito a ottenere una stima ancora più dettagliata degli intervalli caratterizzati da assenza di sedimentazione marina "normale".

Le differenze nel numero di orizzonti fosfatici riconosciuti nelle due sezioni sono state giustificate supponendo, per le due aree di sedimentazione, differenti posizioni all'interno dell'originario bacino di deposizione, probabilmente interessato da tettonica sinsedimentaria locale.

Infine, attraverso la correlazione delle due successioni con la curva degli isotopi dell'ossigeno, è stata riconosciuta una connessione tra l'origine dei livelli fosfatici e le fluttuazioni a scala globale del livello del mare.

PAROLE CHIAVE

Arcipelago Maltese, orizzonti fosfatici, nannofossili calcarei, Oligocene superiore-Miocene medio, oscillazioni del livello del mare

INTRODUCTION

During the latest Paleogene-Neogene epochs, a series of important climate modifications occurred (e.g. RAYMO, 1994; ZACHOS *et alii*, 2001; ABELS *et alii*, 2005; MOURIK, 2010), mostly driven by changes in ocean-circulation (WOODRUFF & SAVIN, 1989; WRIGHT *et alii*, 1992; FÖLLMI *et alii*, 2008) or by shifts in the organic carbon accumulation rates (VINCENT & BERGER, 1985; FRANCE-LANORD & DERRY, 1997). According to the literature, this period is characterised by an increase of the phosphate content of the world oceans, which is linked to the weathering and erosion processes involving the continental deposits (e.g. FÖLLMI *et alii*, 1994; JACOBS *et alii*, 1996; JOHN *et alii*, 2003).

One of the most strategical areas for understanding these dynamics is the central Mediterranean, namely the Maltese Archipelago, where a well-developed succession of phosphatic beds, late Oligocene to middle Miocene in age, occurs (JACOBS *et alii*, 1996; JOHN *et alii*, 2003; FÖLLMI *et alii*, 2008).

The Maltese sedimentary succession, very well studied from a litho- and biostratigraphic point of view, covers the late Oligocene-early Messinian time span (GIANNELLI & SALVATORINI, 1972, 1975; PEDLEY, 1976, 1987; OIL EXPLORATION DIRECTORATE, 1993; MAZZEI, 1986; JACOBS *et alii*, 1996; FORESI *et alii*, 2007, 2011; MOURIK *et alii*, 2011; BALDASSINI *et alii*, 2013); it exhibits shallow water carbonate deposits in its older and younger terms (Lower and Upper Coralline Limestone formations) and marly-carbonate to marly-clayey sediments in the intermediates (Globigerina Limestone, Blue Clay and Greensand fms). The transition from the Lower Coralline to the Globigerina Limestone is marked by a phosphatised surface, reported as Basal Globigerina Limestone Phosphatic Bed (BGLPB in CARBONE *et alii*, 1987, see tab. 1 for acronyms). The Chattian–Langhian Globigerina Limestone fm is characterised by a number of hiatal surfaces, often accompanied by phosphate-rich deposition (e.g. GRUSZCZYNSKI *et alii*, 2008; FÖLLMI *et alii*, 2008); it is subdivided into three members (Lower, Middle and Upper) mainly on the basis of two main phosphorite conglomerate beds, named after ROSE *et alii* (1992) as "Qammieh" and "Xwieni" conglomerate beds (QCB and XCB, respectively).

Along the western coast of the Malta Island, in the neighbourhoods of the Victoria Line Fault (*Auct.*), the Globigerina Limestone fm displays two further phosphatic beds, here described for the first time in detail and named QCB1 and XCB1.

In this paper we illustrate two sections showing well developed phosphatic intervals, with the aim of evaluating the corresponding hiatuses (GIANNELLI & SALVATORINI, 1972; MAZZEI, 1986; REHFELD & JANSSEN, 1995; GRUSZCZYNSKY *et alii*, 2008) from a bio-chronostratigraphic point of view. For this purpose we performed a quantitative study of the calcareous nannofossils content in two sections, namely Qammieh (NW of the Maltese coast) where ROSE *et alii* (1992) formalised the QCB level, and Il Blata (W of the Maltese coast) where the four phosphatic horizons (QCB, QCB1, XCB and XCB1) well outcrop.

Subsequently we attempted the comparison of our results with the stable Oxygen isotope curve for establishing correspondences between the genesis of the phosphatic levels and global climatic excursions. A more accurate definition of the chronostratigraphy of the sedimentary successions comprised between the phosphatic layers, has been obtained comparing them with the Oligo-Miocene third-order eustatic sequences of the New Jersey passive margin re-described by BOULILA *et alii* (2011), which seem to fit well the stratigraphic arrangement of the Maltese succession.

GEOLOGICAL SETTING

The Maltese Archipelago (about 90 km south of Sicily and 300 km east of the Tunisian coast) is part of the Pelagian carbonate platform and consists of two major islands, Malta and Gozo, and several smaller islands.

From the Late Mesozoic and during the Cenozoic, the Mediterranean area has undergone a compressive N-S geodynamic regime driven by the convergence between the African and Eurasian plates (e.g. GUEGUEN *et alii*, 1998; GOES *et alii*, 2004; CARMINATI & DOGLIONI, 2005). During Neogene and Quaternary, the central Mediterranean area, and thus the Maltese islands, have suffered intense tectonic stresses (e.g. FINETTI, 1984; DART *et alii*, 1993; FINETTI *et alii*, 2005; CATALANO *et alii*, 2009; DE GUIDI *et alii*, 2013). The main resulting structural elements are the

Pantelleria, Linosa and Malta troughs (as parts of the Pantelleria Rift), which have developed in a context of stretched and thinned African continental crust (BOCCALETTI *et alii*, 1984; SCARASCIA *et alii*, 2000; CATALANO *et alii*, 2009).

From a geodynamic point of view a pre-rift (older than 21 Ma) and an early syn-rift (21-6 Ma) phases are distinguishable (ILLIES, 1980; PEDLEY, 1990; GARDINER *et alii*, 1995), characterised by the development of neptunian dykes. The acme of the tectonic activity is represented by a late syn-rift phase (older than 5 Ma) which gave rise to the Maltese Graben, and a post-rift phase (last 1.5 Myr). The Maltese Graben lies within the African Plate, foreland of the Apenninic-Maghrebian chain, and its geodynamic evolution has been driven by two different regional normal fault systems, respectively ENE-WSW and NW-SE oriented, affecting the Sicily Channel (e.g. ILLIES, 1981; FINETTI, 1984; BOCCALETTI *et alii*, 1987; REUTHER, 1990; DART *et alii*, 1993; ROBERTSON & GRASSO, 1995; FINETTI & DAL BEN, 2005; FINETTI *et alii*, 2005; CORTI *et alii*, 2006; CATALANO *et alii*, 2009).

According to CATALANO *et alii* (2009), in late Quaternary the normal faults were reactivated by dextral strike-slip motions.

LITHOSTRATIGRAPHICAL FEATURES OF THE SAMPLED SECTIONS

Il Blata section crops out in the western sector of the Maltese Island, south of Fomm Ir-Rih Bay (figs. 1, 2), while the Qammieh section rests in the northern part, along the Rdum il-Qawwi coast (figs. 1, 3). A lithostratigraphic description of the two sections follows.

Il Blata

The section, 55 m thick, is characterised in its basal part by the transition between the Lower Coralline Limestone (LCL) and the Globigerina Limestone (GL) fms, marked by the BGLPB (fig. 2, tab. 1).

The Lower Globigerina Limestone member (LGLm) consists of about 3.50 m of fine grained, massive light yellow limestone, harder and darker down-section, where high concentrations of macrofossils (particularly pectinids and *Scutella*) are organized into layers. Hardened and protruding levels, a few centimetres thick, highlight the quasi-horizontal stratification. A deeply irregular erosional surface (ES in fig. 2, tab. 1) affecting the uppermost layers, is followed by coarse to medium-grained carbonatic sediments, brown-yellow in colour, with abundant macrofossils (mainly pectinids), displaying maximum thickness of 50 cm. Scattered carbonatic fragments (from few centimetres to about 10 cm) and phosphatic pebbles (from few millimetres to 4 cm) are present, mainly concentrated immediately above the ES. The top of the LGLm is marked by the so-called "Terminal Lower Globigerina Limestone Hardground" (TLGLHg, GRUSZCZYNSKY *et alii*, 2008, fig. 2, tab. 1), a weakly phosphatised, highly eroded and shaped surface, showing a hummocky with convolute morphology, and intensively penetrated by *Thalassinoides* burrows (fig. 4).

The base of the Middle Globigerina Limestone member (MGLm, fig. 2) is highlighted by the QCB (GIANNELLI & SALVATORINI, 1972; ROSE *et alii*, 1992), a 10 to 30 cm thick horizon unconformably lying on the TLGLHg (fig. 4, tab. 1). The QCB consists of sub-angular dark brown phosphatic pebbles and sub-rounded light brown phosphatised cobbles (maximum diameter of 15 cm) immersed in a whitish marly limestone matrix, with both phosphatised (molluscs, echinoids, pteropods, corals, etc.) and non-phosphatised (molluscs, mainly represented by *Nautilus*, *Spatangus* and *Eupatagus*, and bryozoans) fossils. Glauconite occurs directly above the hardground surfaces as small sub-spherical pellets or replacement of the micritic matrix (e.g.

Pedley & Bennett, 1985; Rose *et alii*, 1992). The top of this bed (Qammieh Conglomerate Hardground, QCHg of Rose *et alii*, 1992) is planar (fig. 4) due to marine erosion in a hardground environmental context, and the clasts are hardly cemented by polycyclic films of phosphate (Pedley & Bennett, 1985).

The MGLm, 40 m thick, is characterised by about 10 metres of massive whitish limestone with sparse phosphatic particles and pebbles, cut at the top by an irregular erosional surface corresponding to the so-called Fomm-ir-Rih Local Hardground (FiRLHg, Gruszczynsky *et alii*, 2008; fig. 2, tab. 1). In the upper half these deposits are deeply eroded displaying an irregular surface (ES1 in fig. 2, tab. 1) filled with about 2 metres of brown-yellow biodetritic carbonatic sands, thinning upward. The deposits of the QCB1 (phosphatic pebbles and sub-rounded phosphatised cobbles immersed in a grey matrix), which directly lie above the FiRLHg, exhibit a weakly phosphatised planar top.

Homogeneous compact light grey calcareous marls, displaying flint layers in the middle part (fig. 2), represent the remnant 30 m of the MGLm.

The top of the MGLm is marked by a further highly bioturbated (*Planolites* and *Thalassinoides* burrows) erosional surface, reported as Terminal Middle Globigerina Limestone Omissionground (TMGLOg, Gruszczynsky *et alii*, 2008, fig. 2, tab. 1), which shows similarities with the FiRLHg (Gruszczynsky *et alii*, 2008).

The base of the Upper Globigerina Limestone member (UGLm) is marked by the XCB (Giannelli & Salvatorini, 1972; Rose *et alii*, 1992), a horizon from 15 to 30 cm thick, lying above the TMGLOg (fig. 2, tab. 1). This bed is formed by phosphatic particles (about 1 mm in diameter) and sub-angular pebbles, immersed in a yellow-ochre limestone, with phosphatised (pteropods as *Vaginella* and *Cavolinia*, corals, echinoids, brachiopods, balanids, shark teethes, and molluscs as *Aturia*, *Conus* and *Xenophora*) and not phosphatised (molluscs, mainly represented by pectinids, ostreids and gastropods; echinoids, such as *Hemiaster* and *Echinolampas*, and bryozoans) fossils.

Above the XCB, the UGLm consists of about 2.5 m of marly limestone, which are planar, indurated and phosphatised at the top. This hardened surface, here described for the first time as Upper Globigerina Limestone Hardground (UGLHg in fig. 2, tab. 1), is capped by a second phosphatic bed reported as XCB1 (fig. 2, tab. 1), from 10 to 15 cm thick, consisting of phosphatic pebbles and sub-rounded phosphatic cobbles included in a brown-yellow matrix. It follows about 3 metres of bioclastic calcarenite and about 4 metres of grey calcareous marls, corresponding to the Clay Rich Interval of John *et alii* (2003) (fig. 2). The topmost part of the section is represented by about 1.5 metres of marly limestones.

Qammieh

The section is 38 metres thick and, as the previously described, shows in the basal portion the transition from LCL to GL marked by the BGLPB (fig. 3, tab. 1). Two prominent hard beds, corresponding to QCB and XCB, are visible respectively at 6 and 26 metres, highlighting the LGLm/MGLm and MGLm/UGLm transitions.

The LGLm is about 6 m thick and consists of medium- to fine-grained yellowish limestone with abundant pectinids, bryozoans, *Scutella* and widespread both horizontal and vertical bioturbations. At the top, the TLGLHg (fig. 3, tab. 1) is represented by a widely eroded and phosphatised surface, affected by *Thalassinoides* burrows, filled with phosphatic pebbles immersed in a whitish-grey marly matrix.

The QCB, topped by the planar and phosphatised Qammieh Conglomerate Hardground (QCHg of Rose *et alii*, 1992) is followed by a second phosphorite conglomerate bed, here reported as QCB1 (fig. 3, tab. 1), up to 20 cm thick, discontinuously outcropping in the area. The QCB1, whose fossiliferous content is represented only by phosphatised corals, consists of small and rounded elements and sub-angular phosphatic pebbles, included within a yellowish-grey calcareous marly matrix. The following deposits consist of 20 metres of massive light grey calcareous marls, topped by a highly eroded erosional surface (TMGLOg in fig. 3 and tab. 1).

The UGLm, 12 metres thick, is characterised by yellow-ochre marly limestones, more or less indurated, interbedded by about 4 metres of grey calcareous marls (fig. 3).

INTERPRETATIONS OF THE MALTESE PHOSPHATIC LAYERS

Starting from the second half of the nineteenth century, different interpretations have been provided for the Maltese phosphatic layers (e.g. Wright, 1855; Murray, 1890; Cooke, 1896a, 1896b; Rizzo, 1932), but it is only since the '70s of the last century that the interpretations on their genesis and geologic significance have become more accurate (e.g. Giannelli & Salvatorini, 1972, 1975; Felix, 1973; Pedley & Bennett, 1985; Carbone *et alii*, 1987; Rose *et alii*, 1992; Rehfeld & Janssen,1995; Föllmi *et* alii, 2008; Gruszczynski *et alii*, 2008).

Felix (1973) considered the pebbles forming the phosphatic layers as derived from the underlying surface (TLGLHg) during non-deposition periods or in a shallow water environment, where the hardground was modelled by chemical and biochemical actions, as well as wave activity. Bennett (1979) suggested a deeper depositional environment and highlighted a NW provenance for the elements of QCB and XCB observing the east- and south-ward decreasing of the pebble size. PEDLEY & BENNETT (1985) interpreted the phosphatic layers as largely formed by allochthonous pebbles and partly by subautochthonous phosphatised elements, recognizing a vertical variation in the clast size; the finer elements (<1 cm) filled the excavations in the underlying hardground and were followed by intensely mineralised conglomerates. The finer material underwent a more complex story, with multiple stages of sedimentation, lithification, boring, embossing and mineralization. The phosphatization process, preceded by phases of glauconitization, realised in a complex series of "stop-and-go" events, each characterised by clast reworking, faunal encrustation and boring phases, as well as development of phosphoritic films. The characters of XCB are very similar to that of QCB, thus suggesting a similar origin for the two beds. Based on the clast size and layer thickness, the authors supported the existence of a phosphogenetic province along the western margin of the Malta-Ragusa Rise (as also hypothesized by BENNETT, 1979), which represented the source area of clasts to the islands. CARBONE *et alii* (1987), linked the genesis of the Maltese phosphoritic layers to shallow water environment during periods of sea-level lowstand, testified by the presence of the bryozoan *Metrarabdutus*, rhodolites and coralline algae. Even ROSE *et alii* (1992) recognised a western source for the Maltese phosphatic layers, but considered the storm activity during sea-level lowstands, rather than currents, the mechanism triggering the clast transport. The authors, based on the biostratigraphic data provided by GIANNELLI & SALVATORINI (1972) and MAZZEI (1986), related the TLGLHg to a late Oligocene sea-level fall. Furthermore they interpreted the QCB as a condensed sequence cupped by a smooth and hummocky surface, probably linked to a sea-level fall, followed by the transgressive deposits of the MGLm. Similarly, the TMGLOg has been interpreted as the result of a late Burdigalian sea-level fall, and the XCB as a condensed sequence followed by the deposition of the UGLm during a sea-level rise (GRASSO *et alii*, 1994, correlated this event with the global eustatic onlap TB 2.3 of HAQ *et alii*, 1987). According to REHFELD & JANSSEN (1995) the TLGLHg formed during a prolonged sea-level lowstand, which activated strong currents at the bottom with a consequent reduction or interruption of sedimentation; QCB is referred as a condensed succession, and a second hardground marking the top of this bed is interpreted as the evidence of a transgressive phase. JACOBS *et alii* (1996), linked the development of the Maltese phosphatic layers to alternating periods of deepening and sea-level rise, and recognised a connection to the western North Atlantic phosphogenetic episodes highlighted by COMPTON *et alii* (1990, 1993) and STILLE *et alii* (1994). Following GRUSZCZYNSKI *et alii* (2008), the LGLm is characterised, in its higher layers, by an increasing upward series of erosional surfaces related to episodic storm events. The development of the TLGLHg, would be linked to the increased hydraulic energy forced by the sea-level fall. A similar genesis, at least in the initial stages, has also been recognised for the other two surfaces (FiRLHg and TMGLOg).

The most recent interpretation of the phosphatic layers is provided by FÖLLMI *et alii* (2008), who reported the QCB as a condensed interval related to gravity flows. According to this interpretation, the gravity flows were responsible for transporting the allochthonous phosphates in association with reworked autochthonous phosphates and the crustaceans responsible for the *Thalassinoides* burrows. Flow episodes were interrupted by a series of prolonged erosional and/or non-depositional phases. Concerning the XCB, FÖLLMI *et alii* (2008) recognised exclusively allochthonous phosphatic pebbles, which could be originated from a phosphate-producing area as hypothesized by PEDLEY & BENNETT (1985).

In synthesis, three main phases of phosphogenesis (25-21 Ma, 17.2-15 Ma, and 10.9-9.8 Ma) and two major phases of condensation (QCB: 23.2-22 Ma, and XCB: 17-15 Ma) were recognised in the Maltese Archipelago (FÖLLMI *et alii*, 2008).

BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

The numerous bio-chronostratigraphic studies performed on the deposits of the GLf, reported a late Chattian age (latest Oligocene) for the LGLm (e.g. GIANNELLI & SALVATORINI, 1972; MAZZEI, 1986; FORESI *et alii*, 2008; BALDASSINI *et alii*, 2013), a Burdigalian age (early Miocene) for the calcareous marls of the MGLm (e.g. GIANNELLI & SALVATORINI, 1972; THEODORIDIS, 1984; MAZZEI, 1986; FÖLLMI *et* alii, 2008; GRUSZCZYNSKI *et alii*, 2008; FORESI *et alii*, 2014), and a middle to late Langhian age for the UGLm (e.g. GIANNELLI & SALVATORINI, 1972; THEODORIDIS, 1984; MAZZEI, 1986; FÖLLMI *et* alii, 2008; GRUSZCZYNSKI *et alii*, 2008; MOURIK *et alii*, 2011). Previous studies concerning the sediments outcropping in the neighborhoods of the Victoria Line Fault, ascribed the basal deposits of the MGLm (between the QCB and the QCB1) to the Aquitanian stage (GIANNELLI & SALVATORINI, 1972; MAZZEI, 1986), and those of the UGLm (between the XCB and XCB1) to the early Langhian stage (GIANNELLI & SALVATORINI, 1972; MAZZEI, 1986).

For the present study, quantitative analyses on the calcareous nannofossil assemblages (figs. 5, 6) were performed on 101 samples (50 from Il Blata and 51 from Qammieh). Smear slides were prepared following standard methods and analysed under optical microscope (transmitted light and crossed nicols) at 1000X magnification. Furthermore, following RIO *et alii* (1990) and FORNACIARI *et alii* (1996), a targeted counting was performed on 50 and 30 specimens of *Helicosphaera* and *Sphenolithus* respectively. We adopted the calcareous nannofossil scheme for the Mediterranean region of FORNACIARI and RIO (1996) and of FORNACIARI *et alii* (1996), modified after DI STEFANO *et alii* (2008) (fig. 7, tab. 2), and compared with the standard "oceanic" biozonation of MARTINI (1971). The bioevents used as zonal markers, and thus considered for the evaluation of hiatuses, are chronologically constrained following the most recent literature (tab. 2).

Our analyses reveal that both at Il Blata and Qammieh, samples from MGLm and UGLm yield common to abundant, well preserved and diversified nannofossil assemblages, while are less common and poorly preserved in the LGLm. Reworking is confined to samples close to the phosphatic layers. The assemblages are mainly represented by placoliths, helicoliths and sphenoliths, and rare and badly preserved *Discoaster*.

In both sections, the deposits of LGLm (figs. 5, 6 and 7) belong to the MNP25a Zone of FORNACIARI & RIO (1996), late Chattian in age. This attribution is supported by the presence of *Sphenolithus ciperoensis* and the absence of *Sphenolithus distentus* (tab. 2).

At Il Blata, the oldest deposits of MGLm are represented by a calcareous interval, missing at Qammieh, comprised between the QCB and QCB1 layers, further subdivided by the ES1 erosional surface (MGLm2a and MGLm2b; figs. 2, 5 and 7).

MGLm2a and MGLm2b are respectively ascribed to the latest Oligocene MNN1b Subzone and to the middle-late Aquitanian MNN1d Subzone (figs. 5, 7). The first attribution is based on the presence of *Sphenolithus delphix* (zonal nominal taxon), while the second is sustained by the discontinuous presence of *Helicosphaera carteri* (fig. 5). This finding represents a noteworthy result, as for the first time, the basal interval of MGLm has been ascribed to the latest Oligocene on the basis of calcareous nannofossils, even if a similar age, for the same interval, is reported by JANSSEN (2012) on the basis of the study of the pteropods content.

In both sections, the MGLm1 interval is referable to the middle Burdigalian MNN3a Zone ~~of~~ (FORNACIARI & RIO, 1996), attribution supported by the continuous presence of *Sphenolithus belemnos* (figs. 5, 6 and 7).

At Il Blata, the UGLm is represented by few metres of calcareous deposits sandwiched between the XCB and the XCB1 levels (UGLm2), missing at Qammieh. This interval has been attributed to the upper Burdigalian MNN4a Subzone (DALL'ANTONIA *et alii*, 2001; DI STEFANO *et alii*, 2008) on the basis of rare and discontinuous *Helicosphaera ampliaperta* and abundant *Sphenolithus heteromorphus* (figs. 5, 7). The younger sediments of UGLm (UGLm1) are ascribed to the middle-upper Langhian MNN5a Subzone (DI STEFANO *et alii*, 2008) (fig. 7) for the common and continuous occurrence of *Helicosphaera waltrans* (figs. 5, 6).

EVALUATION OF THE BIOSTRATIGRAPHIC DURATION OF HIATUSES

As described above, the two investigated successions show a different number of phosphatic horizons and/or erosional surfaces, thus indicating that the duration of the relative sedimentary lacunas is different in the two sections.

In spite of the different thickness, the discontinuity levels show similar features, being composed by a hard- or omission-grounds, deeply eroded, bioturbated and (as concerns TLGLHg and FiRLHg) slightly phosphatised, followed by an interval of phosphatised pebbles and cobbles, very often smoothed at the top. According to GRUSZCZYNSKY *et alii* (2008), TLGLHg and FiRLHg represent two hardgrounds (sensu BROMLEY 1975) formed as the result of synsedimentary lithification, with bivalve borings and encrustations, whereas TMGLOg is interpreted as a firmground, without borings and encrustations~~,~~ but with widespread bioturbations. The genesis of these surfaces is commonly associated to non-depositional/erosional phases, linked to sea-level lowstand (ROSE *et alii*, 1992; REHFELD & JANSSEN, 1995; GRUSZCZYNSKY *et alii*, 2008) (fig. 4). Our findings of *Lithophaga* bores (fig. 3), which according to the existent literature (e.g. GALINOU-MITSOUDI & SINIS, 1995; STIROS *et alii*, 2000; PIRAZZOLI *et alii*, 2004; VACCHI *et alii*, 2012) is indicative of shallow water, in association to specimens of *Ostrea*, supports this interpretation.

The phosphatic beds (QCB, QCB1, XCB, XCB1), which directly overly the above described surfaces (respectively TLGLHg, MGLHg, TMGLOg and UGLHg), are interpreted as condensed intervals (ROSE *et alii*, 1992; REHFELD & JANSSEN, 1995; FÖLLMI *et alii*, 2008), whilst the planar phosphatised surface at the top of these latter phosphatic bed should reflect a sea-level shallowing (ROSE *et* alii, 1992) (fig. 4). The following transgressive episodes characterised by rapid sea-level rise (HANCOCK, 1989; PEDLEY & BENNETT, 1985; ROSE *et alii*, 1992), allowed the onset of a deeper marine deposition (fig. 4).

The present study allowed the biostratigraphic attribution of the sedimentary intervals composing the sections, and consequently the evaluation of the depositional lacunas corresponding to the phosphatic or erosional levels. In fact, these are chronologically constrained by the ages of the bioevents defining the biozones, which are not represented in the sedimentary succession (fig. 7, tab. 2).

At Il Blata, the biostratigraphic hiatus between the LGLm and the MGLm2b (embracing the TLGLHg/QCB interval; figs. 2 and 7) covers a time span of at least 1.02 Myr, calculated between the LO of *S. ciperoensis* (24.40 Ma, base of MNP25b) and the FO of *S. delphix* (23.38 Ma, base of the MNN1b Subzone) (fig. 7, tab. 2), and highlighted by the absence of the late Oligocene MNP25b - MNN1a zonal interval. The hiatus between the MGLm2b and the MGLm2a (at the ES1), is constrained within the early-middle Aquitanian, as it includes at least the MNN1c Subzone, (corresponding to 0.65 Myr, between the LO of *S. delphix* at 23.06 Ma, and the FO of *S. disbelemnos* at 22.41 Ma, tab. 2) and the lower part of the MNN1d Subzone, based on the comparison with the New Jersey third-order sequences (see next section). The hiatus between MGLm2a and MGLm1 (encompassing the FiRLHg/QCB1 interval) includes the MNN2a and MNN2b zones, covering a time span of 1.88 Myr, from the AE of *H. euphratis* (20.89 Ma, late Aquitanian) to the FO of *S. belemnos* (19.01 Ma, early Burdigalian, fig. 7, tab. 2). Between MGLm1 and UGLm2 (affecting the TMGLOg/XCB interval) the lacuna embraces at least the middle to late Burdigalian MNN3b Zone, corresponding to not less than 0.44 My (LCO of *S. belemnos* 18.43 Ma – FCO *S. heteromorphus* 17.99 Ma) (fig. 7, tab. 2). The youngest hiatus, between UGLm2 and UGLm1 (embracing the UGLHg/XCB1 interval), involves at least the late Burdigalian-Langhian MNN4b-MNN4c interval (0.79 Myr, LCO of *H. ampliaperta* 16.05 Ma - PE of *S. heteromophus* 15.26 Ma) (fig. 7, tab. 2).

At Qammieh, only two hiatuses are detectable. The first, between the LGLm and MGLm1 (encompassing the TLGLHg/QCB interval), covers a time span of 5.39 Myr (base of MNN25b, LO *S. ciperoensis* 24.40 Ma - base of MMN3a, FO of *S. belemnos* 19.01 Ma), from the late Oligocene to the middle Burdigalian. The second, between the MGLm1 and UGLm1 (affecting the TMGLOg/XCB interval), involves the interval from the MNN3b Zone (marked at the base by the *S. belemnos* LCO at 18.43 Ma) to the MNN4c Subzone (defined at the top by the *S. heteromoprhus* PE at 15.26 Ma), and has a duration of 3.17 Myr (middle Burdigalian - middle Langhian).

Our findings are basically in agreement with the results of previous authors (JACOBS *et alii*, 1996; FÖLLMI *et alii*, 2008), who, on the basis of the $^{87}Sr/^{86}Sr$ isotope ratio, recognised an older major phase of phosphogenesis in the late Oligocene-early Miocene interval, between 24.5±0.74 and 21.0±0.74 Ma (QCB+QCB1), and a younger phase in the middle Miocene, between 15.5±1.36 and 14.0±1.36 Ma (XCB+XCB1).

The dissimilar number of phosphatic horizons and/or erosional surfaces affecting the two sections can be explained supposing different positions of the two sections within the sedimentary basin, probably affected by an ongoing tectonic activity (PEDLEY, 1990; DART *et alii*, 1993). In this framework, a more distal depositional environment has been hypothesised for Il Blata with respect to Qammieh. In this latter section, the regressive/transgressive cycles, and the associated erosional surfaces, condensed phosphatic intervals and inter-bedded marine sediments, are only partially documented (fig. 7). On the contrary, in more distal areas, as in the case of Il Blata, lower amplitude episode of transgression and regression (fig. 4, 7), resulting in alternating "normal" marine sediments and condensed phosphatic horizons, are recorded (fig. 7).

SIMILARITIES BETWEEN THE MALTESE SEQUENCES AND PASSIVE MARGIN-TYPE SUCCESSIONS

As highlighted in the previous chapters, the "normal" marine depositional intervals here described are sandwiched by erosional, non-depositional and/or condensed phosphorite intervals, linked to sea-level shifts (e.g. ROSE *et alii*, 1992; REHFELD & JANSSEN, 1995; SCASSO & CASTRO, 1999; fig. 7) and associated to sedimentary hiatuses.

This characteristic sedimentary configuration, which well records the eustatic fluctuations, is due to the particular geodynamic context in which the succession deposited, corresponding to a tectonically almost stable foreland environment. For this reason the Oligo-Miocene successions of the Maltese Archipelago show similarities with the coeval deposits of the passive margin of New Jersey, where depositional intervals are often interrupted by unconformities associated to variable hiatuses (e.g. MILLER *et alii*, 1998; STECKLER *et alii*, 1999; BOULILA *et alii*, 2011). The sequences recognised are hierarchically framed within the third-order, and are separated by unconformities linked to minima insolation episodes within 1.2 Myr long obliquity cycles (BOULILA *et alii*, 2011).

In this context the LGLm, which falls within the MNP25a and has an age younger than 24.4 Ma, corresponds to sequence O6 (fig. 7), which embraces the time interval between 25.5 Ma and 24.3 Ma. The interval MGLm2b, recognised at Il Blata and attributed to the MNN1b Zone (between 23.38 Ma and 22.41 Ma), can be correlated to the uppermost part of sequence O7 (fig. 7), developed between 24.3 Ma and 21.99 Ma. Similarly, the MGLm2a interval (deposited between 22.41 Ma and 20.89 Ma) is comparable to the Kw1a sequence (corresponding to the time interval among 21.2 Ma and 20.99 Ma), and thus confined to the upper part of the MNN1d Subzone (fig. 7).

The MGLm1 depositional interval, referred to the MNN3a Zone, and thus deposited between 19.01 Ma and 18.43 Ma, is comparable to the Kw2a sequence (fig. 7) framed between 19.06 Ma and 18.07 Ma. The UGLm2 interval, only present at Il Blata and deposited between 17.99 Ma and 16.05 Ma, has been compared to the Kw2b (fig. 7), embracing the time interval between 17.58 Ma and 16.48 Ma.

The youngest UGLm1 interval, ascribed to the MNN5a Subzone and thus deposited since 15.26 Ma, shows a good fitting with the Kw3 sequence (fig. 7) framed between 14.67 Ma and 12.94 Ma.

COMPARING THE MALTESE SUCCESSION WITH THE GLOBAL OXYGEN ISOTOPE CURVE

The phosphogenic episodes characterising the Maltese succession are related to rapid and frequent sea-level changes, probably enhanced by an early syn-rift tectonic activity (DART *et alii*, 1993; KIM *et alii*, 2003).

The chronostratigraphic evaluation of the hiatuses associated to the phosphatic levels, gives the opportunity to establish a possible link between their genesis and global sea-level changes, through the comparison with the Oxygen isotopes curve (PEKAR & DE CONTO, 2006; BOULILA *et alii*, 2011; Fig. 7).

The interruption of "normal" marine sedimentation, after the LGLm deposition, could be associated to the sea-level lowering produced by the cold Oi2d event (MILLER *et alii*, 1991) framed at the MNP25a/25b transition. In the area where the Qammieh section deposited, the sediment starving persisted probably for the more proximal environment and/or the establishment of tectonic uplift (fig. 7). In the more distal Il Blata section, the temporarily deeper marine sedimentation, represented by MGLm2b and MGLm2a, was probably interrupted by the sea-level lowering associated to an increase of bottom currents energy, respectively forced by the latest Oligocene Mi1 and the late Aquitanian Mi1a events (fig. 7). After the Mi1a event, the transgression involved also the areas where the Qammieh section deposited, giving rise to the MGLm1 succession, whose deposition was stopped by the regressive phase linked to the middle Burdigalian Mi1ab event. The UGLm2 sedimentary interval was probably stopped by the late Burdigalian sea-level lowering associated to the Mi2 cooling event (fig. 7). Finally, the transgressive phase following the Mi2a event likely results in the establishment of a pelagic environment (UGLm1), which persisted longer on with the deposition of the Blue Clays fm.

CONCLUSIONS

The detailed litho-, bio- and chronostratigraphic study carried out on two sections representative of the late Oligocene-middle Miocene succession of the Maltese Archipelago, allowed a better definition of the phosphatic layers and the associated sedimentary hiatuses, inter-bedded within the pelagic carbonate sediments.

The two sections, Qammieh (N Malta Island) and Il Blata (W Malta Island), are respectively characterised by the presence of two (QCB and XCB) and four phosphatic levels (the previous mentioned plus two here described for the first time, named as QCB1 and XCB1).

The depositional lacunas have been indirectly constrained through the bio-chronostratigraphic definition of the carbonate intervals sandwiched within the phosphate horizons, and even better constrained through the comparison with successions deposited within a similar geodynamic setting, namely the third-order sequences of the of New Jersey passive margin. The estimated ages of hiatuses at Il Blata are the following: QCB= 24.40-23.38 Ma, QCB1= 20.89-19.01 Ma, XCB= 18.43-17.99 Ma, XCB1= 16.05-15.26 Ma.

At Qammieh the estimated ages of hiatuses associated to the QCB and XCB horizons are respectively 24.40-19.01 Ma and 18.43-15.26 Ma, thus involving also the QCB1 and XCB1 time spans.

The dissimilarities between the two sections can be explained supposing different locations within the depositional basin, being more distal for Il Blata, and more marginal for Qammieh, probably in a context of local synsedimentary tectonic activity.

Finally, the correlation of the investigated successions with the stable Oxygen isotopes curve allowed to establishing a connection between the development of the phosphate horizons and global sea-level changes.

Our results highlight that the deposition of "normal" marine sediments is always followed by a major cooling phase ("Miller events"). Thus, hard- or omissiongrounds representing the basal surfaces of the phosphatic horizons, that are recognised to be associated to sea-level lowering, may have been triggered by a major cooling event. In this context, the condensed phosphatic interval are related to subsequent rapid and low-amplitude transgressive/regressive phases, followed by a further sea-level rising responsible for the re-onset of the "normal" open-sea deposition. In this framework, some authors recognise in the smooth upper surface of the phosphatic bed, the evidence of a sea-level lowering that precedes the main latter transgression.

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FIGURE CAPTIONS

Fig. 1 - Location map of the studied sections and geological features of the considered areas.

Fig. 2 – Lithostratigraphic log of Il Blata section. Pictures on the right, illustrate the main lithological features.

Fig. 3 – Lithostratigraphic log of Qammieh section. Pictures,-on the right, illustrate the main lithological features.

Fig. 4 – Deposition, non-deposition/erosion, phosphating and condensation evidences within marine sediments during a "normal" marine sedimentation. The photo shows the transition between LGLm and MGLm, marked by the phosphatic bed QCB, at Il Blata. On the right, the relationships between the different depositional/non-depositional phases and the sea-level fluctuations are shown.

Fig. 5 – Quantitative distribution patterns of selected species within the *Helicosphaera* and *Sphenolithus* genera at Il Blata section.

Fig. 6 - Quantitative distribution patterns of selected species within the *Helicosphaera* and *Sphenolithus* genera at Qammieh section.

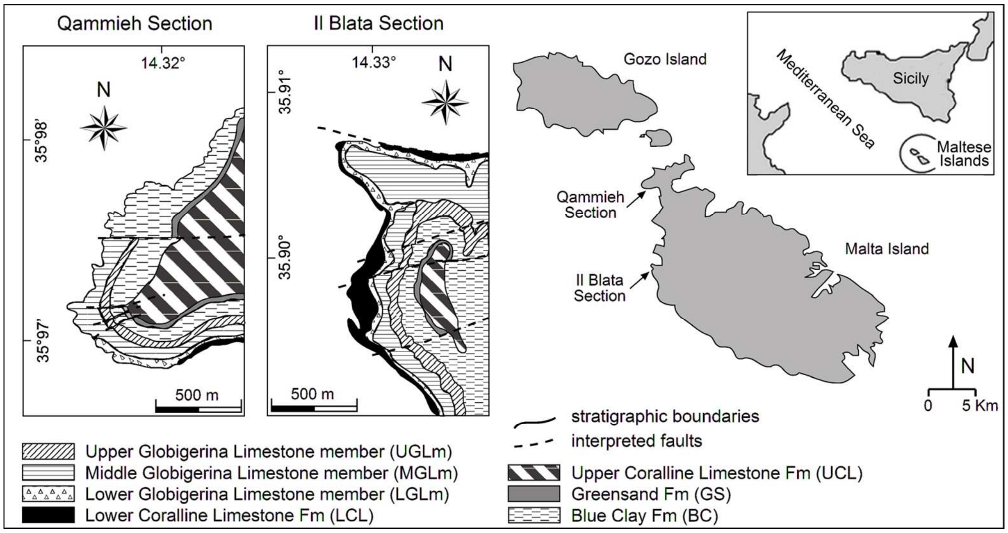
Fig. 7 - Bio-chronostratigraphic framework adopted in the present study. The different depositional intervals recognised in the two areas are compared to the main Oligo-Miocene cooling events of MILLER *et alii* (1991) (light grey line: PEKAR & DECONTO, 2006; dark grey and black lines: BOULILA *et alii*, 2011) and to the New Jersey third-order sequences recalibrated by BOULILA *et alii* (2011). M71=MARTINI (1971); MNZ=Mediterranean Nannofossil Zonation includes FORNACIARI & RIO (1996) and DI STEFANO *et alii* (2008). Bioevents chronology from RAFFI *et alii* (2006), DI

STEFANO *et alii* (2008), IACCARINO *et alii* (2011), BACKMAN *et alii* (2012) and FORESI *et alii* (2014).

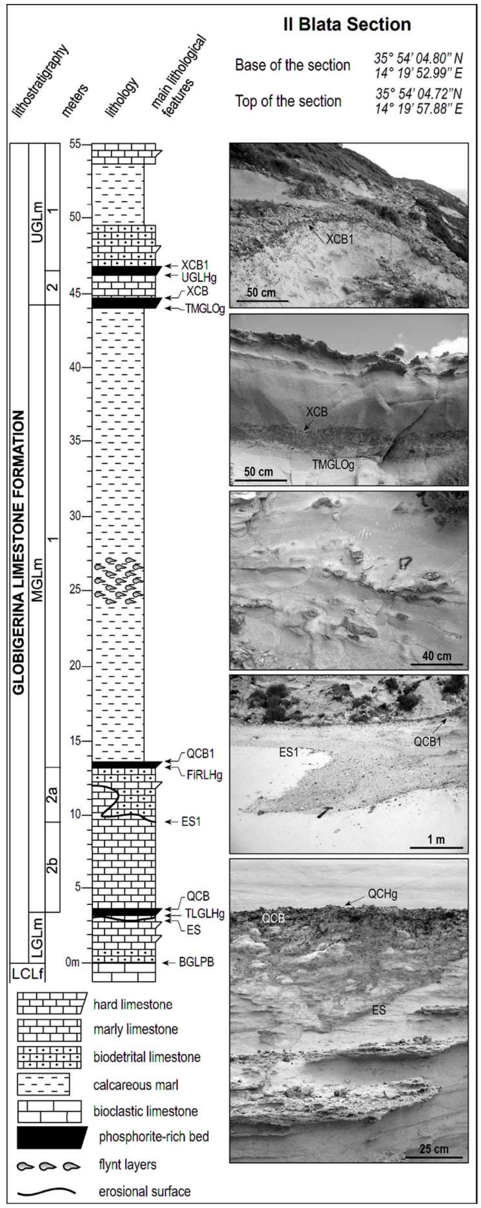
Table 1 - Lithostratigraphic and biostratigraphic acronyms adopted in the present paper.

Table 2 – Bioevents considered in the present study, with relative ages and references.

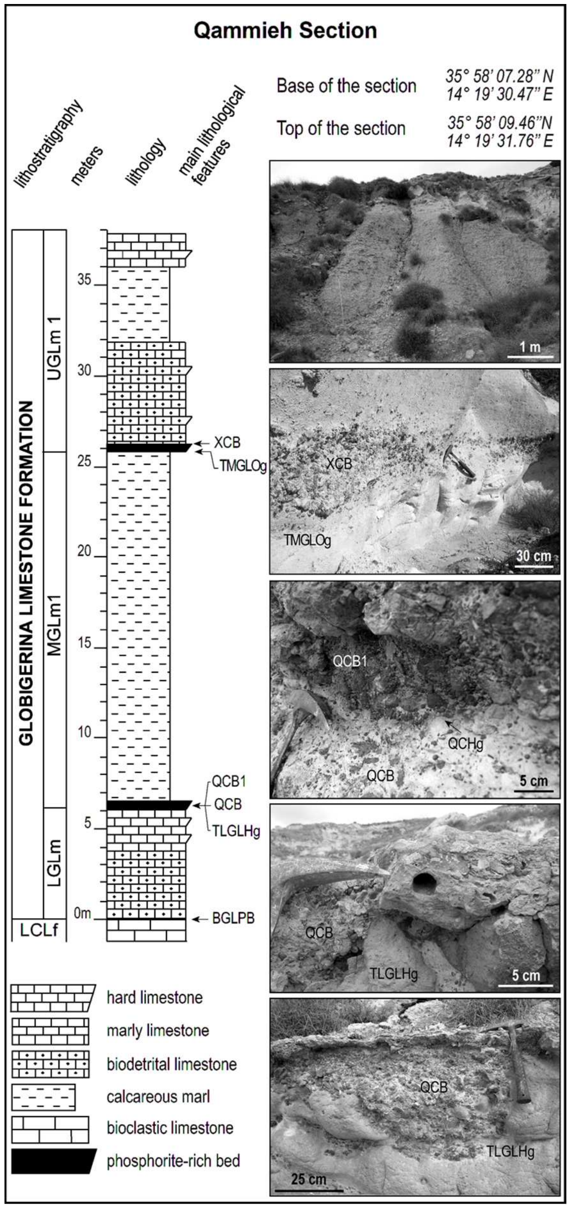
1=FORNACIARI & RIO (1996), 2=DI STEFANO *et alii* (2008), 3=RAFFI *et alii* (2006), 4=BACKMAN *et alii* (2012), 5=FORESI *et alii* (2014), 6=IACCARINO *et alii* (2011).



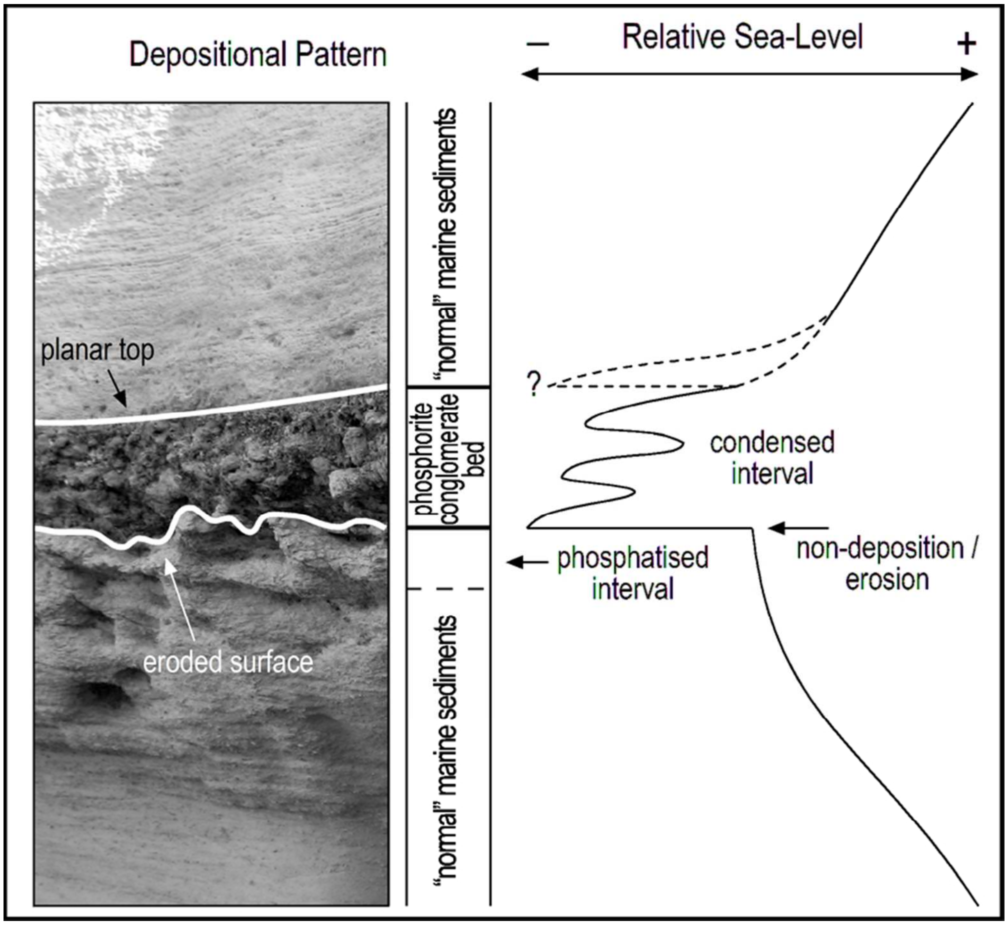
Location map of the studied sections and geological features of the considered areas.
180x94mm (250 x 250 DPI)



Lithostratigraphic log of Il Blata section. Pictures, on the right, illustrate the main lithological features.
90x230mm (250 x 250 DPI)



Lithostratigraphic log of Qammieh section. Pictures, on the right, illustrate the main lithological features.
88x189mm (250 x 250 DPI)



Deposition, non-deposition/erosion, phosphating and condensation evidences within marine sediments during a "normal" marine sedimentation. The photo shows the transition between LGLm and MGLm, marked by the phosphatic bed QCB, at Il Blata. On the right, the relationships between the different depositional/non-depositional phases and the fluctuations in sea-level are shown.
90x82mm (250 x 250 DPI)

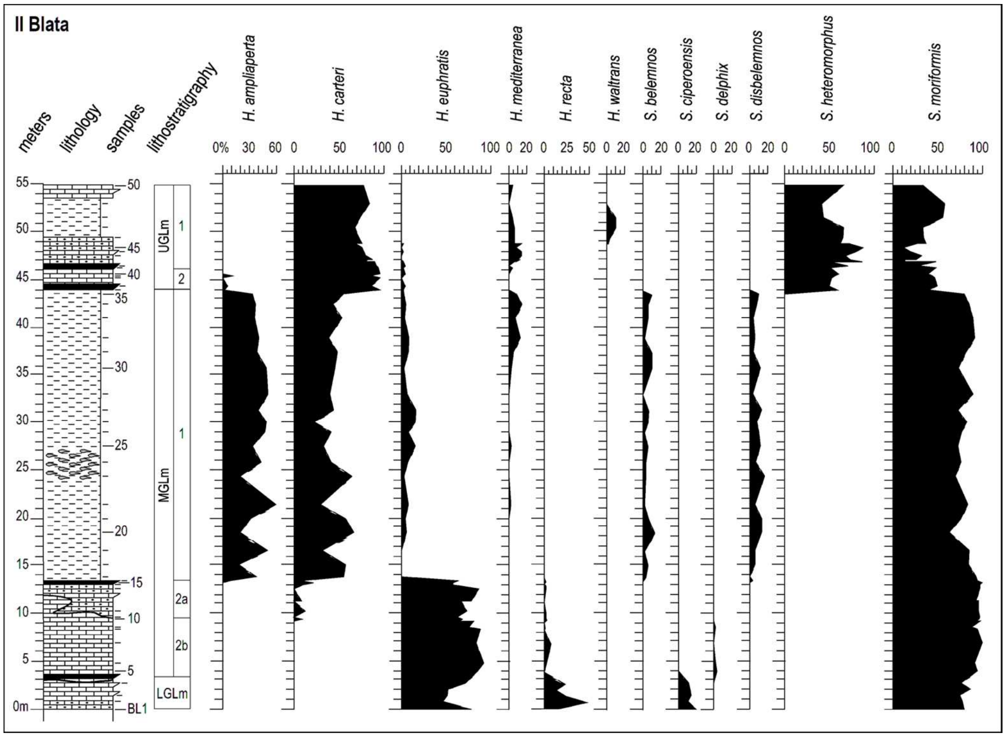
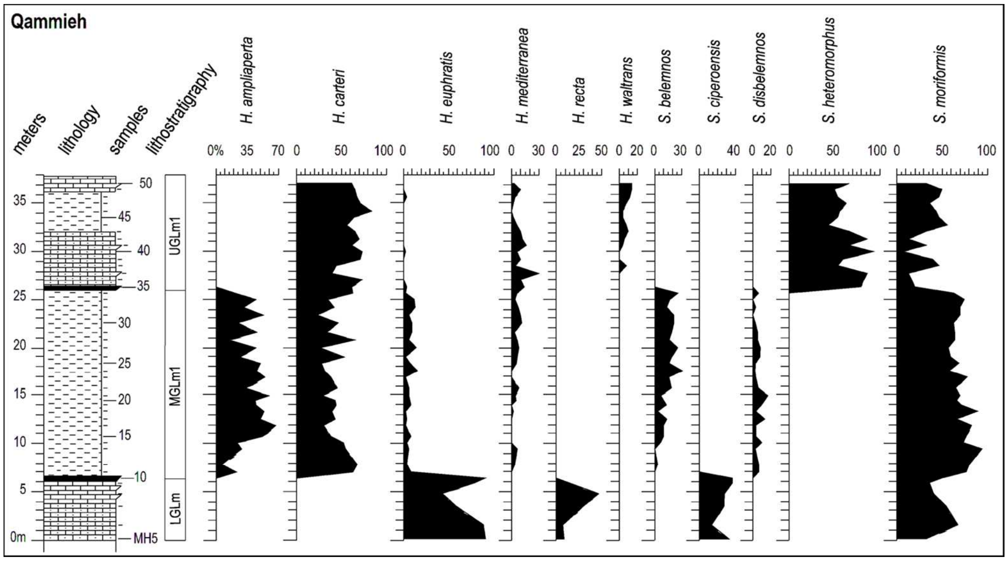
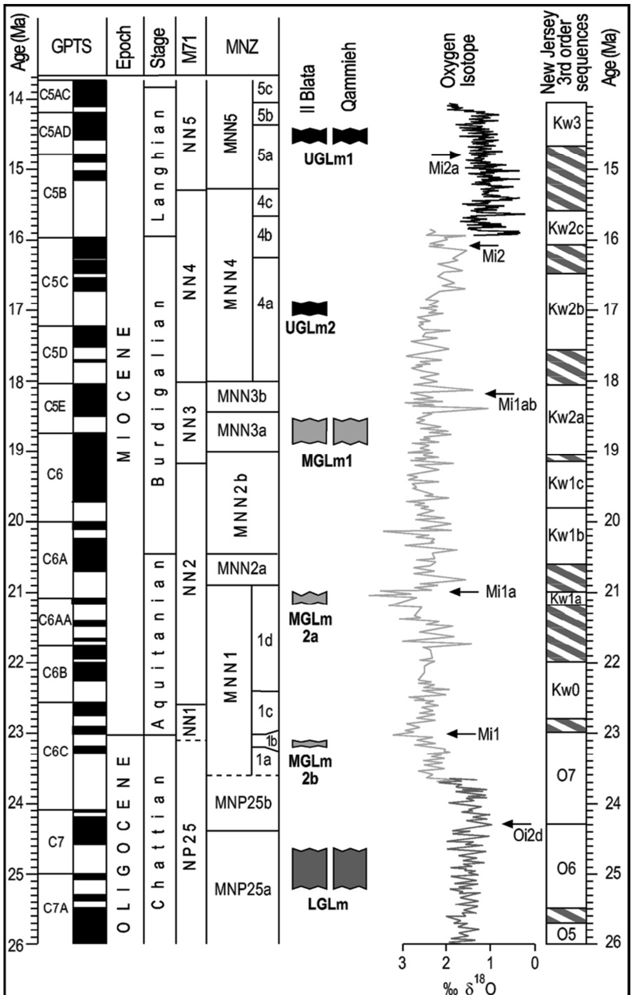


Fig. 5 – Quantitative distribution patterns of selected nannofossils of Helicosphaera and Sphenolithus genera from Il Blata section.
173x126mm (250 x 250 DPI)



Quantitative distribution patterns of selected nannofossils of Helicosphaera and Sphenolithus genera from Qammieh section.
172x95mm (250 x 250 DPI)



δ18O Event	δ18O Maximum Age	
Mi2a	14.8	BOULILA *et alii* (2011)
Mi2	16.1	
Mi1ab	18.2	
Mi1a	21.0	MILLER *et alii* unpublished, in BOULILA *et alii* (2011)
Mi1	23.1	
Oi2d	24.3	BOULILA *et alii* (2011)

Bio-chronostratigraphic framework adopted in the present study. The different depositional intervals recognised in the two areas are compared to the main Oligo-Miocene cooling events of MILLER et alii (1991) (light grey line: PEKAR & DECONTO, 2006; dark grey and black lines: BOULILA et alii, 2011) and to the New Jersey third-order sequences recalibrated by BOULILA et alii (2011). M71=MARTINI (1971); MNZ=Mediterranean Nannofossil Zonation includes FORNACIARI & RIO (1996) and DI STEFANO et alii (2008). Bioevents chronology from RAFFI et alii (2006), DI STEFANO et alii (2008), IACCARINO et alii (2011), BACKMAN et alii (2012) and FORESI et alii (2014).
90x172mm (250 x 250 DPI)

Lithostratigraphic Acronyms	
UCL	Upper Coralline Limestone
GS	Greensand
BC	Blue Clay
GL	Globigerina Limestone
UGLm	Upper Globigerina Limestone member
MGLm	Middle Globigerina Limestone member
LGLm	Lower Globigerina Limestone member member
LCL	Lower Coralline Limestone
XCB1	Xwieni Conglomerate Bed 1
UGLHg	Upper Globigerina Limestone Hardground
XCB	Xwieni Conglomerate Bed
TMGLOg	Terminal Lower Globigerina Limestone Omissionground
QCB1	Qammieh Conglomerate Bed 1
FiRLHg	Fomm-ir-Rih Local Hardground
ES1	Erosional Surface 1
QCB	Qammieh Conglomerate Bed
TLGLHg	Terminal Lower Globigerina Limestone Hardground
ES	Erosional Surface
BGLPB	Basal Globigerina Limestone Phosphatic Bed
Biostratigraphic Acronyms	
FO	First Occurrence
FCO	First Common Occurrence
LO	Last Occurrence
LCO	Last Common Occurrence
PB	Paracme Beginning
PE	Paracme End
AE	Acme End

Lithostratigraphic and biostratigraphic acronyms adopted in the present paper.
90x113mm (200 x 200 DPI)

basal Marker		Biozone	Author	Age (Ma)	Author (Age)
FCO	*H. walbersdorfensis*	MNN5c	2	14,05	2
LCO	*H. waltrans*	MNN5b	2	14,35	2
PE	*S. heteromorphus*	MNN5a	2	15,26	6
PB	*S. heteromorphus*	MNN4c	2	15,64	6
LCO	*H. ampliaperta*	MNN4b	2	16,05	6
FCO	*S. heteromorphus*	MNN4a	2	17,99	5
LCO	*S. belemnos*	MNN3b	1	18,43	5
FO	*S. belemnos*	MNN3a	1	19,01	4
FO	*H. ampliaperta*	MNN2b	1	20,43	4
AE	*H. euphratis*	MNN2a	1	20,89	4
FO	*S. disbelemnos*	MMN1d	1	22,41	4
LO	*S. delphix*	MNN1c	1	23,06	4
FO	*S. delphix*	MNN1b	1	23,38	4
LCO	*D. bisectus*	MNN1a	1	no data	
LO	*S. ciperoensis*	MNP25b	1	24,40	3

Bioevents and relative age and references considered in the present study. 1=FORNACIARI & RIO (1996), 2=DI STEFANO et alii (2008), 3=RAFFI et alii (2006), 4=BACKMAN et alii (2012), 5=FORESI et alii (submitted), 6=IACCARINO et alii (2011).
90x60mm (200 x 200 DPI)