

## Hardground development and drowning of a Miocene carbonate ramp (Latium-Abruzzi): from tectonic to paleoclimate

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**ABSTRACT** - Three Upper Miocene hardgrounds have been analysed in this study, outcropping in the Latium-Abruzzi Apennines (Italy). The central Apennine hardgrounds all lie on top of the Latium-Abruzzi carbonate ramp succession and in each case are overlain by hemipelagic *Orbulina* marls; these marls are linked to plate flexure-related drowning and coeval input of terrigenous sediments. The hardground age ranges from Tortonian to Early Messinian.

Phosphate precipitation in the investigated hardgrounds was confined to a thin layer (up to 15 cm) close to the sediment-water interface. Here oxic to suboxic conditions prevailed, resulting in early-diagenetic iron cycling and subsequent phosphogenesis in oxygenated bottom-waters. Glaucony only occurs in the planktonic-rich marls that overlie and infill the phosphatized hardground level in the Latium-Abruzzi succession.

An upwelling flux triggered phosphogenesis, promoting the early lithification of the sea floor on the platforms. After upwelling event neritic carbonate production could not be re-established on the Latium-Abruzzi platform because of the persisting eutrophic conditions and the high rates of tectonic subsidence and terrigenous input linked to Apennine orogenesis.

The Latium-Abruzzi phosphorites are coeval with the Tortonian phosphogenic phase reported in the Mediterranean. Despite being a global event, regional and local factors played a major role in the hardground deposition at each site.

**KEY WORDS:** hardground, phosphate, glaucony, trophism, Miocene

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### INTRODUCTION

The Miocene carbonate platform successions of the Mediterranean area are characterized by phosphate and carbonate hardgrounds (Zalaffi, 1963; Carannante, 1982; Pedley and Bennett, 1985; Carbone et al., 1987; Corda 1990; Mutti and Bernoulli, 2003; Föllmi et al., 2008). These hardgrounds offer excellent insight into the environmental and oceanographic evolution of the western Mediterranean realm during the Miocene. Hardgrounds are interpreted as representing from non- or low-sedimentation conditions and condensed sedimentation on the shelf and deeper areas (Purser, 1969; Wilson, 1975; Mutti and Bernoulli, 2003). Due to their genetic relationship with reduced sedimentation rates, hardgrounds are commonly related to sea level rise (Loutit et al. 1988; Mutti and Bernoulli, 2003). However, not all reduced sedimentation events result in the formation of marine hardgrounds and, locally, favourable marine environmental conditions in subtidal to intertidal environments may promote selective early lithification of the sea floor (Nicolaidis, 1995; Mutti and Bernoulli, 2003). Mutti and Bernoulli (2003) showed that hardground formation in the Lower Miocene succession of the Maiella ramp is linked to upwelling flux, which may be triggered by regional

changes in water circulation and modulated by sea level changes and increased biological production. Recently, Föllmi et al. (2008) show that the phases of phosphogenesis in the Lower Miocene carbonates of Malta (Globigerina Limestone Formation) correlate well with other important phases of phosphogenesis outside of the Mediterranean area. Maxima in overall phosphorus burial rates in the oceanic domain indicate that the palaeo-oceanographic evolution of the Mediterranean water masses was in phase with that of other ocean basins.

In this work we analyse three locations related to a single Upper Miocene hardground development located in the Latium-Abruzzi succession (central Apennines, Italy). These occur in the Carseolani Mountains (Pietrasecca), Sirente Mountain and Marsica (Gioia Vecchio) areas. The central Apennine hardground lies on top of the Latium-Abruzzi carbonate ramp succession and subsequent Miocene carbonate deposition was terminated by plate flexure-related drowning and coeval input of the terrigenous *Orbulina* marls.

The aim of this paper is to analyse the role of global factors versus regional factors in the development of Latium-Abruzzi hardground and the relationship between hardground development and the end of neritic carbonate sedimentation and drowning of carbonate ramp.

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**GEOLOGICAL SETTING**

The Latium Abruzzi succession outcrops in the central Apennines (Fig. 1). The Apennines represent a fold-and-thrust belt derived from Neogene deformation of the Tethys passive margin. The evolution of the Apennine chain is related to the west-directed subduction of the Adriatic plate

under the European plate (e.g. Doglioni, 1991). The Neogene to Recent evolution of the north-central Apennines is characterised by east-north-eastward migration of deformation fronts and related foredeeps (Ricci Lucchi, 1986; Patacca and Scandone, 1989). The passive margin sediments of the Latium-Abruzzi platform (Fig. 1) mainly consist of Upper Triassic-Upper Miocene shallow-water carbonate

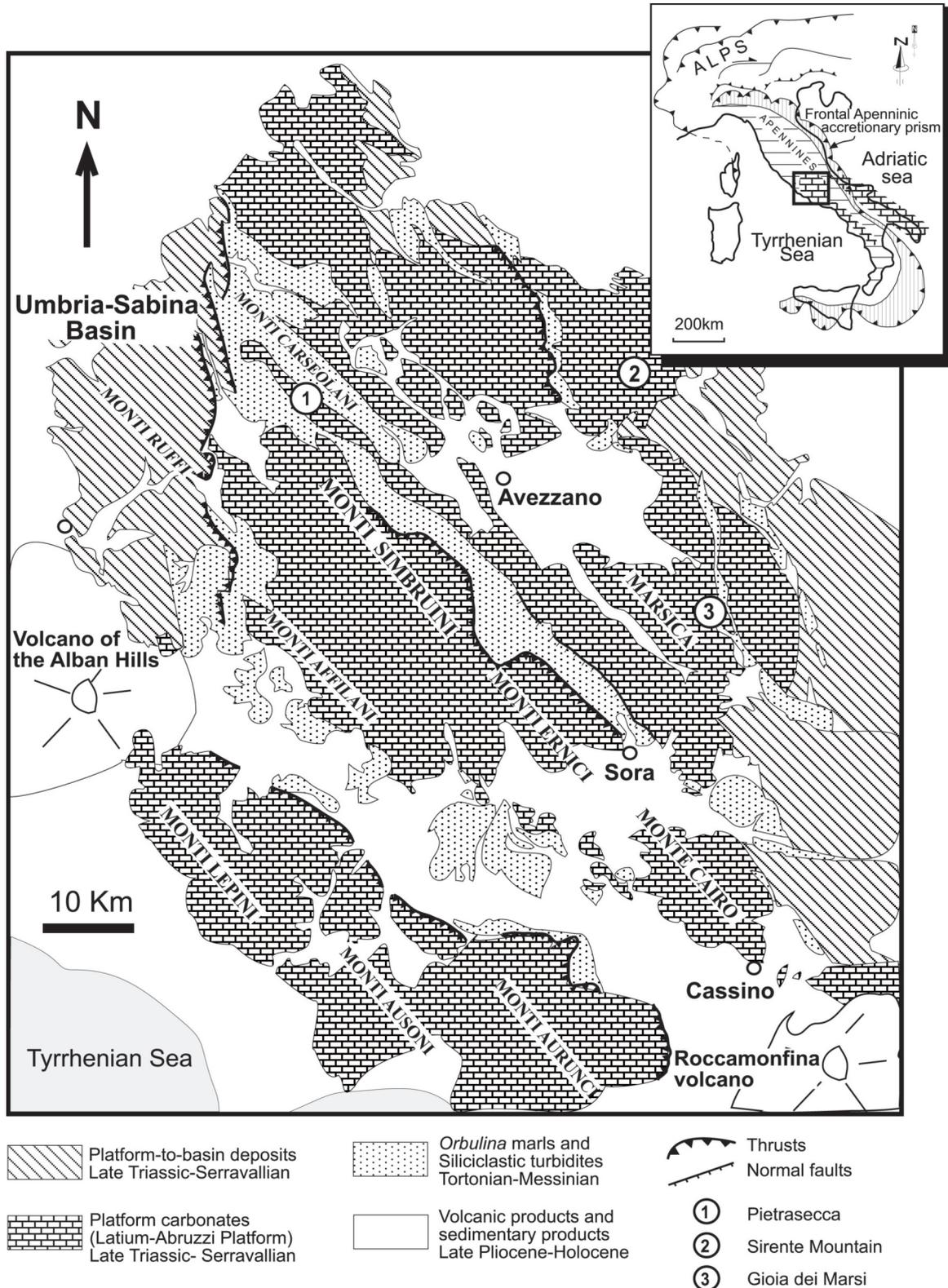


Fig. 1 - Geological map of the Latium-Abruzzi area showing the examined and sampled localities (modified from Brandano, 2001).

deposits. The Cretaceous platform limestones are unconformably overlain by Miocene carbonates, which in turn were terminated by plate flexure-related drowning and coeval input of terrigenous sediments.

The Miocene carbonates of the Latium-Abruzzi carbonate platform domain are known as the "Calcari a Briozoi e Litotamni" (Late Aquitanian to Tortonian). These carbonates were deposited on a low-angle, homoclinal ramp during a diachronous marine transgression induced by tectonic subsidence (Brandano, 2001; Brandano and Corda, 2002).

The inner ramp of the Latium-Abruzzi carbonate succession was characterised by a high-energy littoral environment which, passing down-dip, evolved into a shallow-water euphotic zone represented by facies colonized by seagrass-meadow interbedded with free-living, branching red algae facies ("Mäerl" facies). Small and scattered coral mounds mark the transition to the middle

ramp environment where rhodolitic and larger benthic foraminifera dominated carbonate production occurred below the wave base. The outer ramp environment is developed basinwards, beyond the middle ramp, in the aphotic zone. Bryozoans, bivalves and echinoids are the main sediment-producing biota. In the external outer-ramp belt, siliceous sponge spicules, echinoid fragments, and planktonic foraminifera are the main sediment components.

The investigated hardgrounds developed on top of the Miocene carbonate ramp succession and mark the end of the shallow-water deposition (Fig. 2). The hardgrounds are overlaid by hemipelagic clayey marlstone (*Orbulina* marls) and turbiditic siliciclastic deposits. The end of the carbonate sedimentation as well as the age of the terrigenous deposits are progressively younger moving north-eastward as result of the late Miocene evolution of the thrust-belt-foredeep system (Cipollari and Cosentino, 1995).

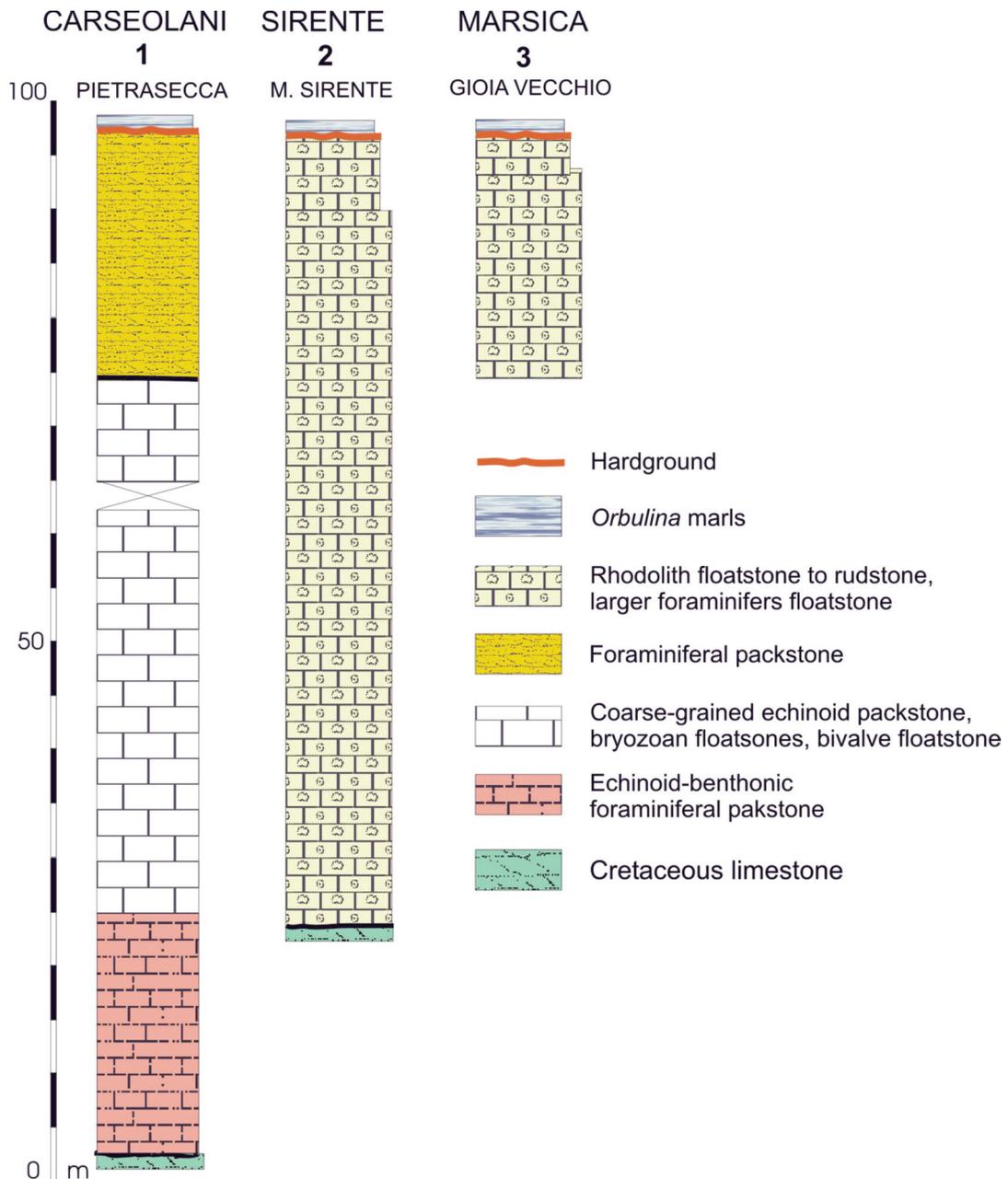


Fig. 2 - Measured stratigraphic sections. See Fig. 1 for locations.

In the Carseolani Mountains the marls immediately overlying the hardground have been dated by Pampaloni et al. (1994) and Cosentino et al. (1997) as belonging to the CN8 Nannofossil zone (9-9.5 Ma, Late Tortonian). In the Sirente Mountain and Marsica areas the top of carbonate succession has been dated Late Tortonian - Early Messinian (Brandano, 2001; Carminati et al., 2007).

## METHODS

Over 50 outcrop samples were collected in the Carseolani Mountains, Sirente Mountain and Marsica (Central Appennines) (Fig. 1). Compositional and mineralogical characterisation was based on petrographic examination of 80 thin sections. Mineralogical analyses were performed by both the X-ray powder diffraction (XRPD) and the electron microprobe analysis (EMPA) methods. Ten selected thin sections, polished and carbon-coated, were utilised for EMPA micro-analytical investigation (CAMECA instrument - IGAG-CNR, University of Roma "La Sapienza").

Red algae associations and test shape variation of the large benthic foraminifera (LBF) *Amphistegina* was used to constrain bathymetry of the depositional setting, according to the model proposed by Mateu-Vicens et al. (2009). Changes in *Amphistegina* test shape are related to the photic gradient along depth and may be documented by the thickness to diameter ratio (T/D) (Hallock, 1979). Based on water transparency, this relationship can be expressed as

$Z_0 = 2.592 T/D^{-2.293}$  in oligotrophic conditions,  $Z_m = 1.037 T/D^{-2.293}$  in mesotrophic situations and  $Z_{om} = 2.046 T/D^{-2.293}$  in oligo-mesotrophic environments (Mateu-Vicens et al., 2009), where Z corresponds to depth estimates.

## RESULTS

### Field characteristics

The studied hardgrounds show very similar field characteristics. The hardgrounds mark a major lithofacies change, from bioclastic packstone to planktonic-rich marls (wackestone) (Fig. 3A-D).

The hardground layer is 5 to 30 cm thick. The upper surface ranges from smooth to undulated, most of it is covered by iron-oxide crust, it cuts across grains, and it is often penetrated by borings. The main macroscopic features of this unit are nodules and polygonal structures (Fig. 3A). The texture and composition of the nodules are analogous to those of the surrounding sediment. The nodules range in size from 2 to 8 cm; borings and intra-nodules spaces are infilled by the planktonic-rich sediments of the overlying *Orbulina* marls.

At a larger scale the nodules are part of the polygonal structures mentioned above, which range in size between 20 cm and 1 m and have a surrounding raised edge. The cracks between the adjacent structures are infilled by overlying marls that are rich in planktonic foraminifera.

The faunal assemblage of the mineralized horizon is

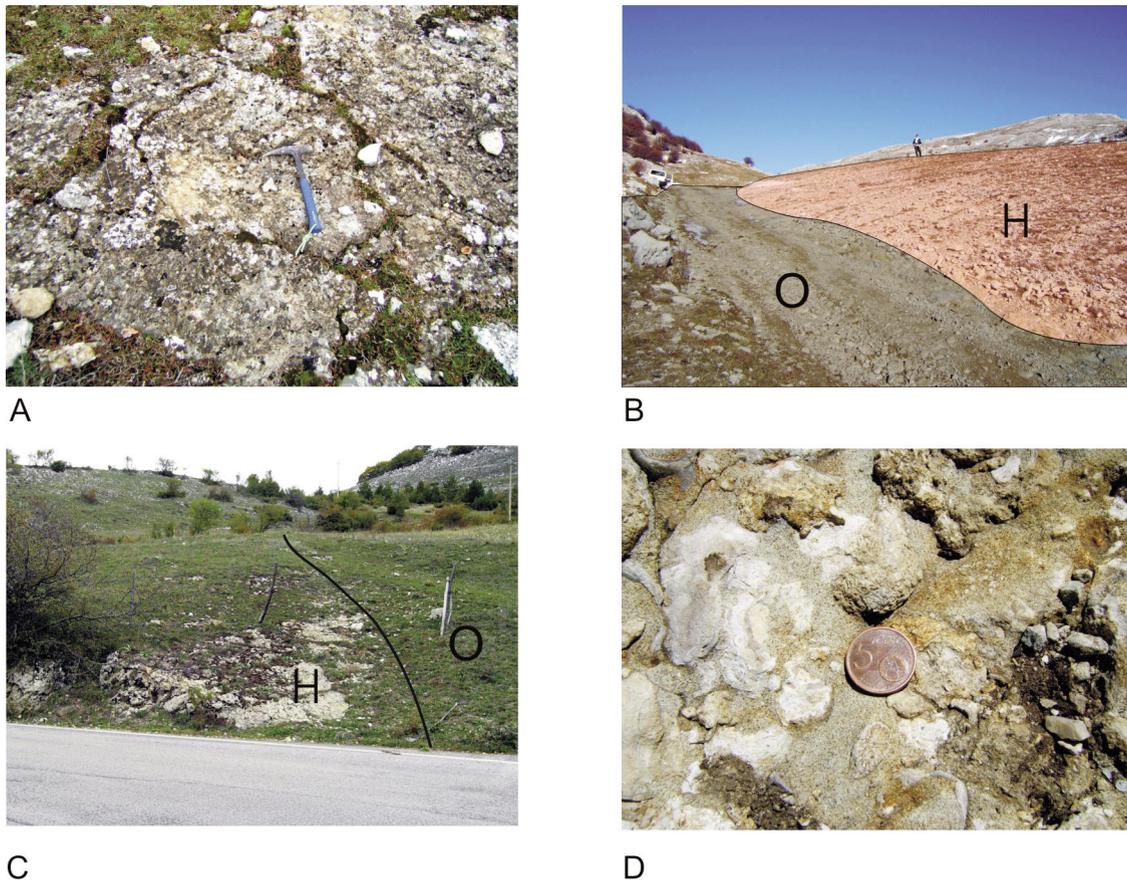


Fig. 3 - Outcrop photographs of investigated hardgrounds: A) nodules are part of the polygonal structures, cracks between the adjacent structures are infilled by overlying planktonic rich marls, (Pietrasecca); B) the investigated hardgrounds (H) developed on the top of carbonate ramp succession and are overlaid by *Orbulina* marls (O), (Sirente); C) (Gioia Vecchio); D) coarse nodular phosphate layer, some nodules are constituted by rhodolith (Sirente).

dominated by bivalves, gastropods, solitary corals, echinoid remains, bryozoans and brachiopods (Fig. 3D). Shark teeth are common.

In the Sirente hardground many of the nodules originated as rhodoliths (Fig. 3D). Rhodoliths show ellipsoidal shape. Major axis varies from 5 cm to 4 cm, medium axis from 5 cm to 3 cm and short axis from 3 cm to 2 cm. Their structure varies from columnar/branching to laminar-columnar. The nuclei are mostly made by bioclast fragments and/or bryozoan colonies. The rhodoliths are dispersed in a coarse bioclastic packstone with a skeletal assemblage dominated by echinoid and mollusc remains, bryozoan colonies, larger benthic foraminifera (*Amphistegina*, nummulitids) and red algae debris.

### Microfacies

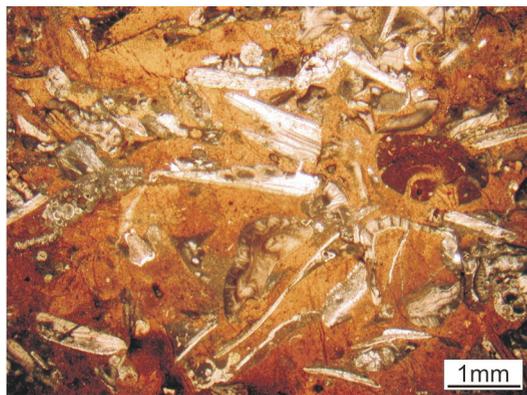
The sediment texture of investigated hardgrounds ranges from wackestone to packstone. Bioclasts mostly consist of benthic foraminifera (rotalids-*Cibicides*, textulariids, *Amphistegina*), fragments of bivalves (pectinids), balanids and echinoids (Fig. 4A). In the Marsica and Sirente hardgrounds coralline algae thalli and nummulitids (*Operculina* and *Heterostegina*) are present. Planktonic foraminifera (globigerinids and *Orbulina*) and sponge spicules are rare. The matrix consists of a calcisiltite whereas calcite cement types surrounding the largest bioclasts have bladed and fibrous patterns (Fig. 4B). Echinoid plates are overgrown by epitaxial cement (Fig. 4C). Intragranular cavities are infilled by blocky

calcite cement. The sediments of the overlying marls infill borings, spaces between nodules, and cracks, forming a planktonic packstone (Fig. 4D). The main components, besides the planktonic foraminifera, are ostracods, fragments of echinoids, brachiopods and *Chlamys*, and rare benthic foraminifera such as rotalids and *Lenticulina*.

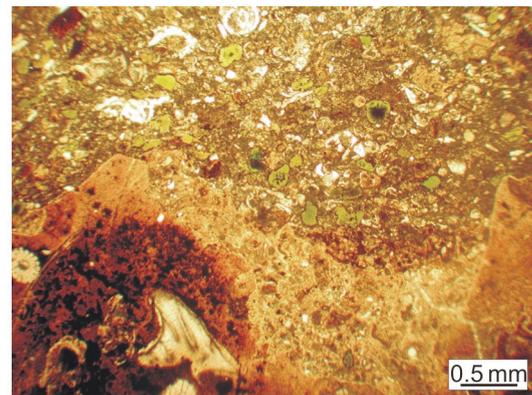
Paleobathymetry for the hardground has been inferred from *Amphistegina* tests measurements (i.e. thickness to diameter ratios -T/D-) in the wackestone to packstone microfacies. The *Amphistegina* T/D ratio ranges from 0.3 to 0.4, inferring paleodepth ranges from 15 to 30 m. *Amphistegina* tests are intact or very well preserved, and thus this bathymetric reconstruction is consistent with this balanid-rich skeletal assemblage.

### Mineralogical data

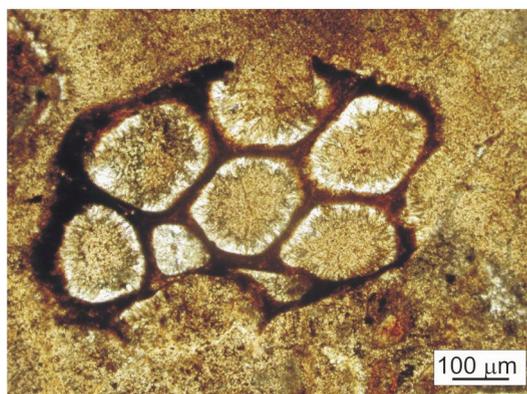
EMPA and XRPD analyses define three main mineral groups in the studied hardgrounds: phosphates (fluorine), glaucony and iron hydroxides (Fig. 5, Tab. 1). Through the XRPD patterns was possible to prevalently highlight fluorapatite and calcite, but not glaucony and iron hydroxides were detected with this method, probably due to their minor presence in the bulk samples. Representative chemical analyses of the three defined main mineral groups are reported in Table 1, which shows a mixed analysis for the iron hydroxides. In fact, a light quantity of phosphate is also present in the iron hydroxide composition (high P and Ca contents). The mineral micro-granular morphologies not



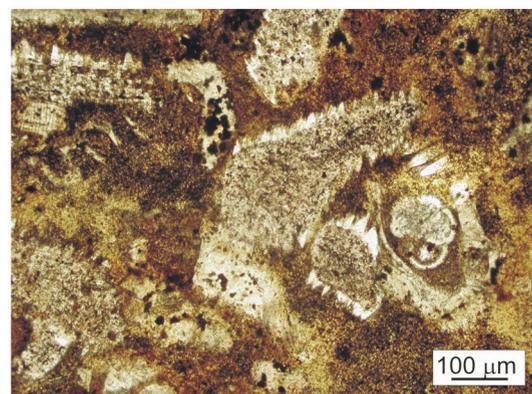
A



B



C



D

Fig. 4 - Photomicrographs of the investigated hardgrounds. A) lithology hosting the hardground, fragments of balanids and bivalves are abundant (Carseoani Mountains hardground); B) fibrous and bladed prismatic cement infilling bryozoan zoezia; C) epitaxial rim on echinoid remains; D) sandy-glauconitic marls infilling borings of phosphatized hardground (Carseoani Mountains hardground).

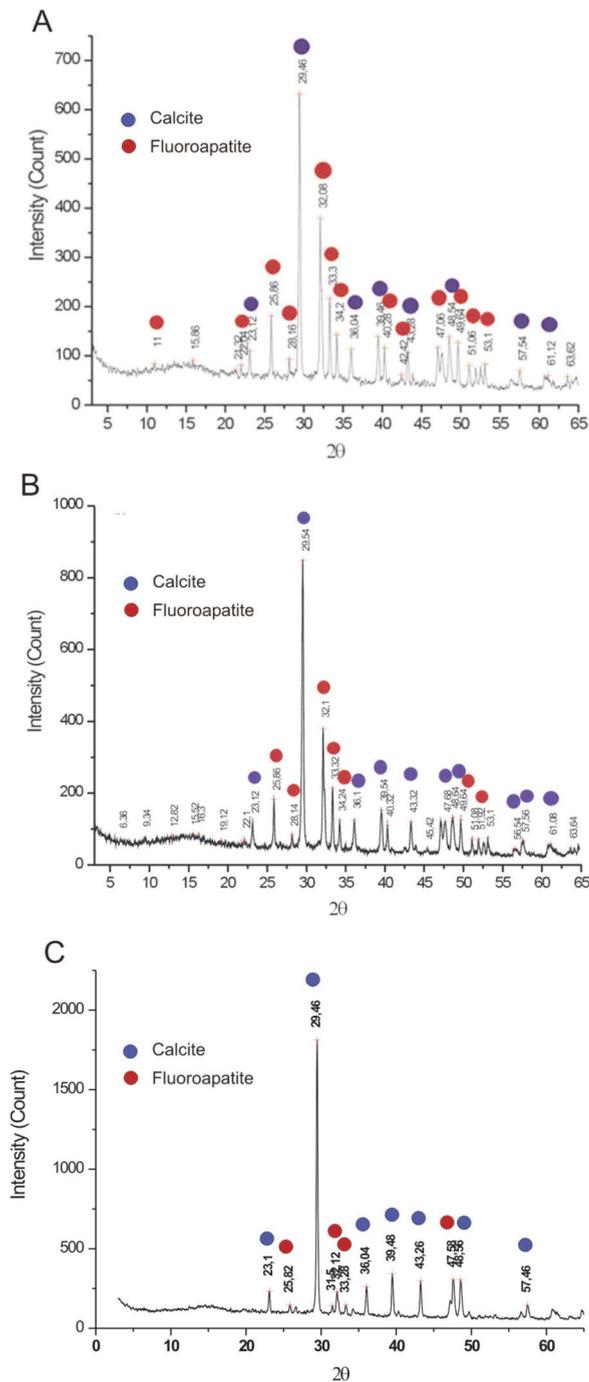


Fig. 5 - X-ray diffractogram of hardground sample, A Pietrasecca, B Sirente, C Gioia Vecchio.

allow to define a single specific composition for these mixed mineral phases.

The phosphate has been identified in thin sections as disseminated and laminar authigenic phosphate (sensu Carson and Crowley, 1993). Under plain polarised light, disseminated phosphate appears light to muddy brown and is characterised by a granular, isotropic appearance under crossed nicols. Phosphatisation is more intense towards the hardground surface and decreases (becomes more intermingled) with increasing distance from the top. The disseminated phosphate appears to have evolved locally into laminar phosphate, with each lamina ranging from 10

$\mu\text{m}$  to 50  $\mu\text{m}$  in thickness, that shows the same isotropic extinction. Dark black phosphatised pellets are present with surrounding brown haloes. Locally, reworked phosphatic bioclasts occur in the overlying *Orbulina* marls.

Glaucyony is abundant in the planktonic packstone that infills the borings, cavities and cracks of the hardground. Two main forms have been recognized: *granular glaucyony* (sensu Odin and Matter, 1981) and *infill of microfossil porosity* (sensu Carson and Crowley, 1993). In the granular glaucyony, grain shape ranges from rounded to subrounded and the grains are concentrated on the hardground surface (Fig. 4B). Well rounded grains probably replace faecal pellets that constitute an ideal substrate for glaucyony formation (Odin and Matter, 1981). The granules appear pale to yellow green under plain polarised light, with a characteristic dark green, granular appearance under crossed nicols (cf. Carson and Crowley, 1993). The glaucyony that infills planktonic foraminifera and, less frequently, the zoecia of bryozoans, presents a very similar optical behaviour to the granular glaucyony.

Finally the iron hydroxides (goethite?) are concentrated in the uppermost 10 cm of the hardground. Iron hydroxy can occur as clusters of microspherules (5-20  $\mu\text{m}$  diameter) embedded in the calcisiltite.

## DISCUSSION

According to many authors (Föllmi, 1996 and references therein), phosphogenesis results from the early diagenetic precipitation of carbonate fluorapatite in sub-oxic, organic-rich sediments. Thus, phosphate precipitation is usually restricted to the uppermost part of the sediment due to the increase of carbonate alkalinity with depth that inhibits further formation of apatite (Jahnke et al., 1983; Glenn and Arthur, 1988; Schenau et al., 2000; Mutti and Bernoulli, 2003). Moreover, carbonate fluorapatite formation requires the diffusion of fluoride from the overlying bottom water (Froelich et al., 1983).

In the present case studies, phosphate mineralization only occurs in the uppermost 10 to 15 cm, indicating that phosphate precipitation was confined to a thin layer close to the sediment-water interface. The co-occurrence of iron oxides and fluorapatite indicates redox conditions that oscillated between oxic and suboxic. These chemical conditions have been related to early-diagenetic iron cycling that promoted phosphogenesis in oxygenated bottom-waters (Sundby et al., 1992; Schenau et al., 2000).

The other authigenic mineral recognized in the analyzed hardgrounds is glaucyony, almost exclusively from the planktonic-rich marls overlying and infilling the phosphatised hardground level in the Latium-Abruzzi succession. Glaucyony occurs as condensed levels within fine-grained marine shelf and slope deposits, between 50 and 500 m water depth (Odin and Matter, 1981). Glaucyonic mineral formation takes place in micropores (5-10  $\mu\text{m}$  in diameter) and it is accompanied by dissolution and replacement of the host mineral. The most abundant form is the glaucyonic faecal pellets and infilled planktonic chambers (Odin and Matter, 1981; Chafetz and Reid, 2000).

The association of glaucyony and phosphate is characteristic of many hardgrounds (Pedley and Bennett, 1985; Loutit et al., 1988; Simone and Carannante, 1988; Amorosi, 1997; Carson and Crowley, 1993; Föllmi et al., 2008). Nevertheless, in the Latium-Abruzzi example glaucyony is not associated with phosphate. The latter occurs in the hardground whereas the

	phosphate		glaucyony			mix ph+hydr
	LA SM1A2	LA SM1A5	LA SM1A3	LA SM1A4	LA SM1A3.1	LA SM1A1
SO <sub>3</sub>	1,88	1,64	0,05		0,06	0,29
P <sub>2</sub> O <sub>5</sub>	27,13	28,87	0,05	0,06	0,06	5,51
SiO <sub>2</sub>	1,75	4,07	52,51	53,56	52,57	4,09
TiO <sub>2</sub>		0,01	0,08	0,11	0,07	
Al <sub>2</sub> O <sub>3</sub>	0,43	0,07	8,18	10,61	6,83	1,34
MgO	0,60	0,82	6,10	6,05	6,07	0,87
CaO	48,66	47,23	0,27	0,38	0,26	8,41
MnO	0,05	0,05	0,02		0,03	0,02
FeO	2,27	1,89	17,92	15,53	18,57	59,53
BaO	0,07	0,03	0,28	0,05	0,05	
Na <sub>2</sub> O	1,05	1,06	0,11	0,25	0,13	0,33
K <sub>2</sub> O	0,21	0,46	7,53	<b>6,83</b>	7,14	0,06
F	4,43	5,16	0,59	0,58	0,39	0,36
Cl	0,01	0,02			0,03	
	<b>88,54</b>	<b>91,38</b>	<b>93,69</b>	<b>94,01</b>	<b>92,26</b>	<b>80,81</b>
total	88,57	92,08	93,48	94,85	92,29	80,84

Tab. 1 - Geochemical data of selected samples from microprobe analysis on investigated hardground.

glaucyony is present in the overlying planktonic foraminifera-rich marls, as fecal pellets, and infilling the planktonic foraminifer chambers.

Hardgrounds are widely documented from Miocene successions in the circum-Mediterranean area, and are very frequently interpreted as being formed from the upwelling of nutrient-rich, deep waters (Carannante, 1982; Pedley and Bennett, 1985; Simone and Carannante, 1988; Corda, 1990; Mutti and Bernoulli, 2003; Föllmi et al., 2008). Coastal upwelling areas are known to have sediments with high authigenic phosphorus contents. Mutti and Bernoulli (2003) suggest a genetic model for a Burdigalian phosphatic hardground that occurs on the Majella ramp. According to these authors, an increase in current activity prevented sediment deposition, while the upwelling of cold, nutrient-rich water (warmed on the platform margin and stripped of some of its CO<sub>2</sub>) controlled early diagenetic processes. Continued upwelling and the consequent productivity increase in the surface water, along with the resulting rain of organic matter to the sea bottom, would have provided the phosphorous for the fluorapatite mineralization. A similar process may have driven the hardground formation in the Latium-Abruzzi. In these cases, bathymetric constraints (red algae associations and the *Amphistegina* T/D index) indicate that phosphatization took place in sediments deposited in water less than 25 m depth.

Following sedimentation in the Latium-Abruzzi platform, the sea floor was affected by intense tectonic activity related to the evolving foredeep system and related Apennine orogenesis (Carminati et al., 2007). According to many authors (Patacca and Scandone, 1989; Cipollari and Cosentino, 1997; Carminati et al., 2007) the Neogene evolution of the Central Apennines is characterised by east-north-eastward migration of deformation fronts and of the related foredeeps. According to Carminati et al. (2007) the

tectonic Miocene evolution of the Latium-Abruzzi platform is characterised by progressively north-eastward younging periods of uplift or stability (at 17.5-16 Ma in the Carseolani Mountains and at 11-9.5 Ma in the Northern Marsica region) followed by accelerations of subsidence rates (at 9.5 Ma to 7.6 Ma and after 8 Ma in the Northern Marsica region). Uplift stages in the foreland of accretionary prisms have been interpreted as the development of foreland flexural bulges in the subducting plate. The platform vertical motions fall in the general model for vertical motions expected to occur across the Apenninic subduction zone. In such a subduction setting, foreland subsidence is interrupted by a period of stability or slow uplift due to the development of protothrusts or to foreland propagation of compressive stresses related to Apennine. Soon after their formation, the protothrusts approach the foredeep basin and show increased subsidence related to the downflexure of the subducting plate.

The hemipelagic marls were deposited during the resulting sea-level rise, while at the same time glaucyony mineralization occurred in the planktonic-rich sediments overlying the hardground. It is important to note that the abundance of the planktonic fauna in the basal hemipelagic marls of the Latium-Abruzzi ramp may be related to an increase of organic productivity in sub-surface waters, caused by eutrophication induced by the upwelling currents.

The nodule structures in the Latium-Abruzzi platform may have an origin analogous to the early diagenetic processes described for nodular limestone by Purser (1969) and Bathurst (1971). Other possible controlling factors for the nodule formation include seawater saturation with respect to CaCO<sub>3</sub> (Bjorkum and Walderhaug, 1990) and surface reaction kinetics (Walderhaug and Bjorkum, 1992). The reworking and erosion of the unlithified sediment as a consequence of biogenic activity (bioturbation) and

erosional currents may contribute to enhance the nodular features. As cementation proceeds, the nodules may increase in size and coalesce, forming a continuously cemented hardground with a polygonal jointing pattern that represents the position of coalesced nodule boundaries (cf. Bjorkum and Walderhaug, 1990; Nicolaides and Wallace, 1997).

### Phosphogenesis and local vs. global correlation

Föllmi et al. (2008) report three main phosphogenic phases in the Mediterranean during the Oligo-Miocene:

25-18.9 Ma (Chattian to Aquitanian)

17-13.1 Ma (Langhian to Serravallian)

10-9.8 Ma (Tortonian)

Föllmi et al. (2008) relate the phosphogenic events to global warming and high sea-level episodes that would have promoted an increase of biogeochemical weathering and subsequent phosphate input into the oceans. The increased availability of phosphorous during these periods would have enhanced productivity, leading to eutrophic conditions. These phases of condensation and hiatuses are correlated with the occurrence of general hiatuses in oceanic sediments and are interpreted to be the consequence of increased bottom-water circulation due to climatic changes (Keller and Barron, 1983). Our case studies fit within the third phosphogenic phase reported by Föllmi et al. (2008). During this period predominant glaucony precipitation and minor phosphogenesis occurred on a global scale (Monterey Formation - Riggs and Sheldon, 1990). However, there are Miocene successions in the Mediterranean that lack phosphatic hardground horizons (i.e. Aquitanian to Serravallian from Sardinia, Martini et al., 1992; Vigorito et al., 2006 and Corsica, Ferrandini et al., 2002; 2003; Tortonian from southern Spain, Brachert et al., 1996; Betzler et al., 1997).

In the Latium-Abruzzi succession the hardground is limited to the northwestern sector, whereas in the southeastern part it is missing. In this sector of the ramp the "Calcari a briozoi e litotammi" Formation passes gradually into the overlying planktonic-rich marls (*Orbulina* marls).

As mentioned above, phosphatic hardground formation is closely tied to the occurrence of nutrient-rich, deep-water upwelling that is, in turn, controlled by various factors. In most cases, upwellings are driven by winds and topography (water depth and shape of the coastline) determines their effect on currents, stratification of the water column, and nutrient supply (Tomczak and Godfrey, 1994).

The investigated hardgrounds development occurred during Late Miocene which was warmer and wetter than present. Bohme et al. (2008) constructed two eight-million year long precipitation proxy records for Southwestern and Central to Eastern Europe in the Late Middle and Late Miocene. The records reveal two episodes of anomalously high precipitation. The first episode occurred 10.2 - 9.8 Ma, the second 9.0 - 8.5 Ma (Fig. 6). These episodes were coeval with global warm periods as indicated by marine and other continental climate proxy records. They refer to such climatic conditions in moderate latitudes as "washhouse" climate. This climate conditions might have induced changes in Mediterranean circulation pattern. Some authors proposed an estuarine circulation for the Mediterranean Sea during the Miocene humid climate phase (Gebhardt, 1999; Mutti and Bernoulli, 2003) and upwelling leading to hardground development (Mutti and Bernoulli, 2003).

The drowning of the Latium-Abruzzi platform seems to have been strongly influenced by environmental conditions predating the tectonic subsidence related to Apennines orogenesis. Intense phosphatisation, climate, deep-water upwelling, ocean - circulation pattern and the abundance of the planktonic fauna in the basal hemipelagic marls suggest an increase of organic productivity in sub-surface waters, caused by eutrophication processes that may have induced

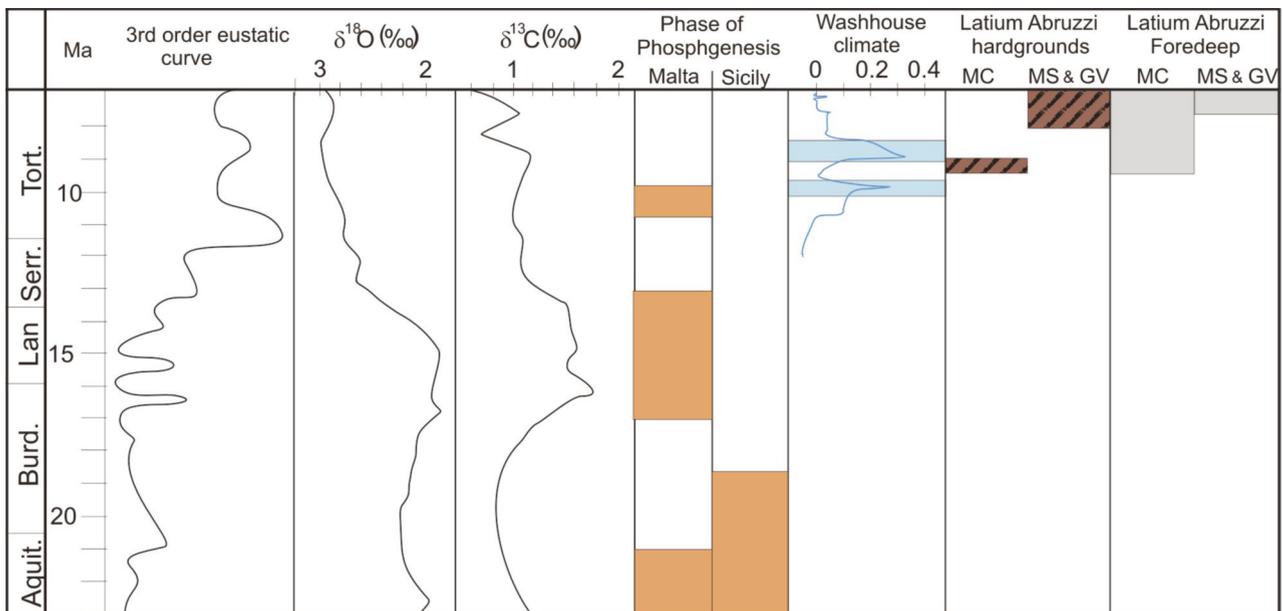


Fig. 6 - General trends in 3rd order eustatic sea-level change (Haq et al., 1987),  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotope records (Zachos et al., 2001), timing of the phases of phosphogenesis on Malta and Sicily (Föllmi et al., 2008), washhouse climate in Europe and estimated European freshwater runoff (Bohme et al., 2008), Latium-Abruzzi hardgrounds (MC – Carseolani Mountains, MS – Sirente Mountain, GV – Gioia Vecchio), timing of foredeep development in the investigated area (from Carminati et al., 2007).

a crisis in the carbonate production. The following tectonic subsidence definitively determined the drowning of the Latium-Abruzzi ramp. The resulting tectonically-driven sea-level rise promoted glaucony mineralization in the planktonic-rich sediments overlying the hardground.

Moreover, it is important to note that phosphatic hardgrounds developed in many, but not in all areas of the Latium-Abruzzi ramp. This non-uniform distribution may suggest that, in addition to phosphate input into the oceans related to the phosphogenic event topography, ocean circulation and winds may have played a significant role in controlling upwelling currents and hardground development.

## CONCLUSION

Phosphatisation in the investigated Upper Miocene hardgrounds only occurs in the uppermost 10 to 15 cm of the deposit, indicating that phosphate precipitation was confined to a thin, oxic to suboxic layer close to the sediment-water interface. This interval has been related to early-diagenetic iron cycling and subsequent phosphogenesis in oxygenated bottom-water. Glaucony mostly occurs in the planktonic-rich marls overlying and infilling the phosphatized hardground level in the Latium-Abruzzi succession.

The investigated hardgrounds are interpreted to be the result of upwelling of cold, nutrient-rich, deep water. Phosphatization took place within sediments deposited at less than 25 m depth.

During Late Miocene an anomalously humid and warm phase is suggested to have induced changes in the Mediterranean circulation and then to have controlled the upwelling currents.

The Latium-Abruzzi hardgrounds are coeval with the Tortonian phosphogenic phase reported in the Mediterranean. However, besides the globally recorded phosphate event, regional and local factors seem to have played a major role in the hardground distribution.

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