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**ICNOLOGIA  
DE LES CONQUES MARINES PLIOCENES DEL MARGE  
NORD-OCCIDENTAL DE LA MEDITERRÀNIA**

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## 5. CONCLUSIONS





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### 5.1. Conclusions sistemàtiques

#### 5.1.1. Bioturbació

- S'han reconegut 26 icnospècies en les conques del Pliocè de la Mediterrània nord-occidental, de les quals 11 han estat classificades a nivell icnospecífic, 8 ho han estat a nivell icnogenèric i les set restants han estat deixades en nomenclatura oberta.

- Es descriu un nou icnogènere, nova icnoespècie, *Sinusichnus sinuosus* al Baix Ebre, Baix Llobregat i Var, que correspon a sistemes de galeries sinuoses atribuïbles a crustacis decàpodes.

- Tots els icnofòssils estudiats corresponen a l'activitat d'organismes invertebrats (anèl·lids, crustacis i equinoderms especialment) excepte els rastres de tetràpodes del Baix Llobregat, atribuïbles a mamífers.

- Els icnogèneres més abundants i més àmpliament distribuïts són *Skollithos*, *Thalassinoides*, *Palaeophycus*, *Scalarituba*, *Teichichnus*, *Phycosiphon*, *Planolites* i *Sinusichnus*.

#### 5.1.2. Bioerosió

- S'han reconegut 13 icnogèneres corresponents a estructures de bioerosió.

- Els icnofòssils més abundants són *Gastrochaenolites* i *Entobia* en relació a paleopenyasegats i dipòsits conglomeràtics, i *Entobia*, *Oichnus* i estructures de duròfags en relació a substrats esquelètics. *Teredolites* és l'únic icnogènere reconegut en substrats llenyosos (fusta).

### 5.2. Conclusions parcials

#### 5.2.1. Baix Ebre

- Els dipòsits pliocens del Baix Ebre s'han estudiat a l'aflorament de Sant Onofre i corresponen al reompliment d'una badia soma amb certes influències d'aigües salobres.

- Els dipòsits transgressius inclouen:
  - Petits esculls de rodòfícies, vermètids i serpúl·lids amb un seguit de fàcies associades i en relació a un paleopenyasegat amb *Gastrochaenolites* i *Entobia*.
  - Fàcies de platja conglomeràtiques i sorrenques. Els conglomerats representen el *foreshore* i inclouen còdols perforats amb *Gastrochaenolites* i *Entobia*. Les sorres corresponen al *shoreface* i presenten una icnofàbrica motejada amb *Skolithos* com a única estructura biogènica important.
  - Fàcies de badia soma alternants lutí·fíco-sorrenques amb poca bioturbació dominant els caus en J.
- Les margues blaves es troben per sobre de les unitats transgressives i presenten una fàbrica totalment homogeneïtzada per bioturbació amb *Thalassinoides* reomplerts per conques per l'acció de febles turbulències.
- L'única unitat clarament regressiva està constituïda per alternances d'argiles i sorres depositades en un context de badia i que inclouen diferents icnofàbriques:
  - Icnofàbrica de *Skolithos* amb laminació primària corresponent a dipòsits de barra sorrenca.
  - Icnofàbriques de *Sinusichnus* i de *Teichichnus*-*Fuglichnia* desenvolupades en relació a dipòsits turbidí·fícs sorrencs intercalats entre argiles.
  - Icnofàbrica monoespecífica de *Teichichnus* que representa un ambient molt som i de baixa salinitat.

### 5.2.2. Baix Llobregat

- L'àrea del Baix Llobregat inclou diversos afloraments amb dipòsits marins pliocens que permeten reconstruir la conca com una ria soma i elongada.
- La transgressió pliocena va donar lloc a superfícies de bioerosió i incrustació amb una associació de traces fòssils típicament litoral composta fonamentalment composta per *Gastrochaenolites* i *Entobia*.
- El reompliment de la conca va ser fonamentalment argilós (margues blaves) amb major influència continental en forma de sorres a les zones més proximals i en el període final del reompliment (unitat lutí·fíco-sorrenca superior).
- La unitat de margues blaves es presenta totalment bioturbada però sense estructures definides degut al caràcter originalment semiflúid del sediment. Això és

coherent amb un medi som, ric, amb elevada taxa de sedimentació i de bioturbació. Localment devia ser molt som com indica la presència de rastres de tetràpodes.

- La unitat lutítico-sorrenca es troba poc bioturbada però amb diversitat de traces fòssils. Hi ha una variació important en les associacions icnològiques, amb quatre icnofàbriques fonamentals que de N a S són: *Ophiomorpha*, *Phycosiphon-Skolithos*, *Phycosiphon-Sinusichnus* i *Scalarituba-Laminites*.

- Les icnofàbriques reconegudes a la unitat lutítico-sorrenca (excepte la d'*Ophiomorpha*) mostren abundància de traces de sedimentívors vàgils que es troben en relació als nivells de sorres com a colonitzadors postdeposicionals. Els conjunts icnològics predeposicionals són menys diversos i constituïts fonamentalment per caus d'habitació.

- La distribució de traces fòssils i icnoassociacions en direcció proximal-distal permet reconèixer el caràcter cada cop menys energètic del medi amb canals sorrenca amb *Ophiomorpha* al Nord, una zona intermèdia amb abundants *Skolithos* en fàcies argiloso-sorrenques i una zona distal amb fàcies similars però sense *Skolithos*.

- La distribució de traces fòssils i icnoassociacions permet també, en relació a altres dades paleontològiques, establir una zonació de la ria en funció de la salinitat amb un sector proximal salobre (amb fauna indicativa d'aquestes condicions), un sector central amb salinitats intermèdies i un sector distal totalment marí (amb presència d'estructures d'equínids).

### 5.2.3. Alt Empordà

- Els dipòsits marins pliocens de l'Alt Empordà corresponen a la sedimentació en un paleogolf som.

- El registre icnològic de l'Alt Empordà és especialment important pel que fa a la bioerosió. Són freqüents els paleopenyasegats relacionats amb la transgressió zancleana que presenten una associació icnològica constituïda per *Gastrochaenolites*, *Entobia* i en alguns casos cubetes d'equínids regulars. En una localitat aquestes estructures s'han reconegut formant horitzons ben definits el que permet situar el màxim transgressiu per la conca.

- El reompliment sedimentari està constituït per margues blaves, sorres i conglomerats.

- Les margues blaves presenten una icnofàbrica homogènia amb conspicus *Thalassinoides* reomplerts per restes esquelètiques introduïdes per l'acció de febles turbulències.

- Les sorres presenten una única estructura de bioturbació, *Skolithos*.

- Els conglomerats poden presentar abundants perforacions de l'associació *Gastrochaenolites-Entobia*. En un cas s'ha reconegut una superfície d'enduriment en relació als conglomerats indicada per l'existència de dos conjunts de traces fòssils.

#### 5.2.4. Rosselló

- El Rosselló és una conca relativament soma amb reompliment marí i continental. Els afloraments més interessants des del punt de vista icnològic es troben a la vall de la Valmagna.

- La majoria de les evidències icnològiques s'han reconegut en les margues blaves que mostren una icnofàbrica molt bioturbada dominada per *Planolites* amb *Teichichnus*, *Thalassinoides* i *Laminites*. Associats a aquesta icnofàbrica apareixen petits nivells de sorres amb *Ophiomorpha*. Correspon a un medi d'*offshore-shoreface* en condicions marines normals com indica la presència de traces d'equínids (*Laminites*).

#### 5.2.5. Orb

- La conca pliocena de l'Orb és una ria en la que els únics bons afloraments de Pliocè marí es troben en el sector més proximal.

- Localment es coneixen paleopenyasegats amb *Gastrochaenolites* i ostreïds que enregistren la transgressió zancleana.

- La secció de Cessenon, que es troba en posició molt proximal, està constituïda per margues blaves molt bioturbades amb una única icnospècie *Phycosiphon incertum*. Puntualment s'ha reconegut la presència d'incipients *firmgrounds*. Aquests dipòsits corresponen a condicions molt somes i de salinitats baixes.

#### 5.2.6. Rhône

- La conca del Rhône és una ria de grans dimensions en la que només s'ha estudiat una secció a Pichegu on es pot reconèixer una clara seqüència deltaica amb margues blaves de prodelta i sorres de front deltaic.



- Les margues blaves es troben totalment bioturbades amb excavacions vermiformes pobrament preservades.

- En el front deltaic la bioturbació és escassa o absent en les sorres. En un tram argilós interpretat com una badia interdistributària molt soma i amb baixa salinitat es pot reconèixer una icnofàbrica monospecífica de *Scalarituba* associada a petits nivells carbonàtics que apareixen en relació a *Psilonichnus*.

### 5.2.7. Var

- La conca de Var és una ria relativament profunda amb reompliment constituït fonamentalment per margues blaves i conglomerats.

- Alguns penyasegats, relacionats amb la transgressió zancleana, amb *Gastrochaenolites* han estat identificats.

- L'aflorament més complet del reompliment sedimentari de la conca es troba a Saint Isidore on es poden reconèixer tres icnofàbriques diferents, cada una d'elles en relació a una determinada fàcies sedimentària.

- Les margues blaves presenten una icnofàbrica amb *Diplocraterion* i estructures amb envans. L'icnofàbrica suggereix unes condicions de sedimentació tranquil·les en un medi clarament d'*offshore* amb esporàdics i impredecibles fenòmens erosius.

- En relació a fàcies de llims sorrencs resultat de sedimentació turbidítica, es reconeix l'icnofàbrica de *Phycosiphon-Planolites* intensament bioturbada i amb diversitat important. Indica condicions marines relativament profundes amb sedimentació discontinua.

- En els dipòsits conglomeràtics, només alguns canals sorrencs presenten esporàdics *Phycosiphon*.

## 5.3. Conclusions generals

### 5.3.1. Bioturbació

- La majoria de les traces corresponen a organismes sedimentívors i detritívors. Això és coherent amb conques marginals, amb gran producció de matèria orgànica, amb sedimentació fonamentalment argilosa i generalment somes.

- Malgrat que la majoria de les traces fòssils presenten una dispersió geogràfica important dins de l'àrea estudiada, les associacions reconegudes varien molt i generalment són molt locals. Aquesta variabilitat està relacionada amb la variabilitat



que es dona en aquestes conques marginals susceptibles de ser afectades per molts canvis paleoambientals.

- S'han descrit 17 icnofàbriques que presenten diferents associacions icnològiques, índexs de bioturbació i icnodiversitat.

- En funció de l'icnodiversitat i l'índex de bioturbació s'han separat tres grups principals d'icnofàbriques:

- Icnofàbriques monospècífiques de sedimentívors amb elevat índex de bioturbació. Inclou tres icnofàbriques, totes corresponents a medis molt somers i salinitats baixes.

- Icnofàbriques amb icnodiversitat baixa a moderada i índex de bioturbació baix en argiles i sorres. Corresponen a dipòsits de badia soma del Baix Ebre i Baix Llobregat.

- Icnofàbriques amb icnodiversitat baixa i molt poca bioturbació en sorres corresponents a fàcies d'alta energia.

- Les icnofàbriques amb major diversitat, i en algun cas índex de bioturbació més alt, dins de cada tipus de sediment corresponen sempre a la conca de Var, indicant les condicions més profundes i clarament marines.

- Els principals factors que van controlar la distribució de les traces fòssils i les icnofàbriques són la salinitat, l'energia hidrodinàmica, la batimetria i l'estil de sedimentació.

### 5.3.2. Bioerosió

- La bioerosió apareix fonamentalment en paleopenyasegats, dipòsits conglomeràtics, conquilles i, localment, superfícies d'enduriment.

- Els paleopenyasegats reconeguts mostren una associació icnològica molt característica formada principalment per *Gastrochaenolites* i *Entobia* que es troba associada a fauna incrustant. Aquest conjunt d'evidències paleontològiques constitueix el registre de la transgressió zancleana.

- Els dipòsits conglomeràtics presenten la mateixa associació que els paleopenyasegats. La bioerosió és més intensa en conglomerats de *foreshore* que en conglomerats fandeltaics degut al menor període de residència dels clastes en el segon cas.

- Les associacions de traces fòssils de bioerosió són molt recurrents en totes les conques a diferència de les de bioturbació que són molt variables. Això es degut a que la bioerosió es troba limitada a contextos molt concrets en que hi ha disponibilitat de substrats durs.



**RESUM EN ANGLÈS**





## **Ichnology of the marine Pliocene basins in the northwestern Mediterranean margin**

### **0. Presentation**

The Pliocene basins of Catalonia (Baix Ebre, Baix Llobregat and Alt Empordà) and South-East France (Rosselló, Orb, Rhône and Var) have been well documented over the last century. During the last 20 years, many publications on their geology, stratigraphy, paleontology and paleogeography have been carried out. In this thesis, the ichnological study has been developed in order to complete the work previously undertaken on bioerosion and to begin the study of bioturbation.

### **1. Ichnology. Concepts and applications**

Ichnological studies in Spanish languages are rather scarce. Hence, an extensive introduction to ichnological problems has been carried out in chapter 1. This chapter is an up-to-date revision of the ichnological theoretical framework. A special emphasis is given to biology, taphonomy and ecological implications of fossil and recent traces. The chapter is completed with a complete terminological glossary in Catalan.

### **2. Geology of the northwestern Mediterranean**

The main tectonic units in the northwestern Mediterranean are, from South to North, the Iberian Range, the Pyrenees and the Alps. All three are compressive belts. The Alps are the most important and belong to the Himalayan-Alpine Range which extends from Gibraltar to Eastern Asia. The Pyrenees form the boundary between the European plate and the Iberian microplate. Finally, the Iberian Range (including the Iberian Range s.s. and the Catalan Coastal Ranges) is a minor range formed inside the Iberian microplate. In relation to these three compressive belts, two areas with little or no deformation are the Ebro Basin (a Tertiary foreland basin bounded by the Pyrennes and the Iberian Range) and the French Central Massif (a cratonic area formed mainly by Paleozoic rocks). In the Mediterranean margin these structures were overprinted by Neogene extensional faulting which was responsible for the opening of the Valencia Through and the migration of the Corso-Sardinian Block.

The Late Neogene geological history of the Mediterranean was strongly controlled by a late Miocene event known as the "Messinian crisis". In the latest Messinian the Mediterranean basin was isolated from the Atlantic Ocean, resulting in a very important sea-level fall. As a consequence, deep fluvial valleys were eroded in the margins of the Mediterranean. Later, in the earliest Zanclean (early Pliocene) a transgression reestablished the connections between the Mediterranean and the Atlantic.

flooding the messinian valleys and giving rise to several marginal marine basins (rias and bays) along the Mediterranean coast.

### 3. Ichnology of the northwestern Mediterranean Pliocene basins

#### • Baix Ebre

The Baix Ebre basin is in the Southern part of Catalonia near the town of Tortosa (Tarragona province). The main outcrop is located near the old hermitage of Sant Onofre. The stratigraphic sequence is constituted by seven lithostratigraphic units, from bottom to top: Rodophytes unit, Gravels and sands unit, Lower sandy clay unit, Blue clay unit, Upper sandy clay unit, Sant Onofre carbonatic unit and Roca Corba conglomeratic unit. The two last units are continental.

The Gravels and sands unit corresponds to a retrograding beach formed by a conglomeratic foreshore with bored pebbles which includes *Gastrochaenolites* and *Entobia*, and a sandy shoreface hosting a mottling-*Skolithos* ichnofabric.

The Rodophytes unit includes small rhodophyte-vermetid-serpulid buildups associated with bioclastic packstones, bioerosion surfaces (with *Gastrochaenolites*, *Entobia* and encrusting oysters and pectinids) and carbonatic microconglomerates. These facies are associated with a small pre-Pliocene paleorelief. The buildups and the packstones occur on top of it, meanwhile the bored and encrusted surfaces and the microconglomerates are on the slope. All body fossils and trace fossils assemblage indicates a littoral, very shallow environment.

The Lower sandy clay unit consists of alternating sands and clays. The sand beds are thin and mainly tabular. The degree of bioturbation is low. The only abundant trace fossils are J-burrows that sometimes can occur very crowded under sand beds. Some escapement structures and rare epigenic trails complete the ichnological assemblage. The unit is interpreted as bay deposits with turbiditic supply of sands in a rather restricted environment as indicated by poor ichnofaunal and microfaunal assemblages.

The blue clays correspond to the maximum of the Zanclean transgression in the Baix Ebre. This unit is very rich in fauna, especially molluscs. The ichnofabric is rather homogeneous with only one clearly distinct ichnofossil, *Thalassinoides*, filled by shells and shell fragments. The sedimentation of the unit took place in a shallow quiet environment with some brackish influences (as indicated by the fauna) and some weak turbulent events that were strong enough to introduce the local shelly material in decapod burrows but not to supply coarser sediment from more littoral areas.

The Upper sandy clay unit is similar to the lower one but includes a more diverse and more abundant trace fossil record. Four different ichnofabrics or ichnoassemblages can be recognized. The first is associated with planar-laminated to rippled sand beds interlayered in clays. The degree of bioturbation is low and the main ichnofossil is *Sinusichnus sinuosus* associated with *Teichichnus rectus* and scarce *Scalartuba missouriensis*, *Scolicia* and simple trails. The second ichnofabric also occurs in interlayered sands and clays. In this case, the sands show hummocky lamination and host *Teichichnus* and escapement structures. A thick (3 m) cross-bedded sand bed has been recognized in the upper part of the unit. It includes an ichnofabric dominated by primary lamination with scarce *Skolithos* and escapement structures. The last ichnofabric corresponds to a monospecific association of *Teichichnus* restricted to thin and thoroughly bioturbated layers in the uppermost part of the unit. The unit is interpreted as having been deposited in a bay environment with frequent sand supply and a low degree of bioturbation. The thick sand bed with *Skolithos* corresponds to a sand bar prograding under energetic conditions and the monospecific concentrations of *Teichichnus* to a restricted, brackish but organic-rich environment colonized by an opportunistic deposit-feeder.

The sedimentary fill of the Baix Ebre basin includes transgressive and regressive periods. During the transgressive period, buildups and bioerosion surfaces were developed on the most isolated areas of the paleorelief with low or no terrigenous sedimentation. Other nearshore areas were occupied by pebbly-sandy beaches including typically littoral trace fossils (*Gastrochaenolites*, *Entobia*, *Skolithos*) which change laterally to shallow bay sands and clays deposited in a rather restricted paleoenvironment with low bioturbation dominated by J-burrows. The blue clays represent outer bay deposits which corresponds to the maximum of the transgression. During the regression, the marine deposits were sands and clays including different facies and ichnoassemblages which correspond to bay deposits, sand bars and restricted proximal environments. The continental units, lacustrine and alluvial, culminate the regressive sequence.

#### • Baix Llobregat

The Baix Llobregat basin corresponds to a small elongated paleoria located near the city of Barcelona. It is bounded by the Collserola and Garraf massifs which belong to the Catalan Coastal Ranges. The Pliocene outcrops are located along the basin. Most of the outcrops show a very similar stratigraphic section.

The Pliocene sediments cover a previous paleorelief and the boundary surface is extensively bored (*Gastrochaenolites* and *Entobia*) and encrusted (oysters and



pectinids). The presence of a conglomeratic lag which includes bored pebbles is commonly associated with the boundary. In some outcrops, this lag is replaced by a thicker conglomeratic deposit that corresponds to a retrograding fan-delta. Over these transgressive deposits, the blue clays and the Upper sandy clay unit constitute the regressive part of the sedimentary sequence. At one locality, the Pliocene is culminated by a conglomeratic fan-deltaic unit. The northernmost outcrop shows a very different succession that includes a fluvial conglomeratic unit overlain by a sandy clay unit with brackish fauna.

The blue clays show an homogeneous fabric with neither sedimentary nor biogenic structures. The homogeneous character suggests total bioturbation but without formation of distinct trace fossils. This indicates the soupy character of the substrate and also the absence of deep-tier structures affecting deep buried, more consistent sediments. This situation is consistent with a shallow marginal environment with a high rate of sedimentation. In one locality tetrapod trackways have been found, inferring a locally very shallow water depth.

The Upper sandy clay unit has provided several assemblages of trace fossils. The distribution of ichnofossils and ichnoassemblages is strongly related with the proximal, intermediate or distal position of the outcrops. El Papiol, the most proximal outcrop of this unit, includes thick sand bodies that correspond to distributary channels. The fabric is mainly dominated by physical features but some *Ophiomorpha* and scarce *Macaronichnus* beds occur. In the other outcrops, channels are absent and the unit is more clayey with trace fossils occurring in relation with thin sand layers. Three different assemblages have been recognized, each including a poor domichnia-dominated predepositional suite and a two-tiered sediment-feeders-dominated postdepositional suite. The distribution of these assemblages and the ichnofossils suggests an important hydrodynamic longitudinal gradient as indicated by the abundance of *Skolithos* in the proximal sector and its absence in the distal part. The importance of salinity changes is also obvious due to the presence of echinoid burrows only in the more distal, near open sea, sectors.

#### • Alt Empordà

The Alt Empordà basin is located in the Eastern Catalan Pyrenees around the city of Figueres (Girona province). The Pliocene includes both continental and marine sediments. The marine sequence includes from the bottom to the top: a bored and encrusted surface recording the Zanclean transgression, and a regressive sequence consisting of blue clays overlain by sandy and conglomeratic deposits.

The record of the transgression is very good in these basins with different paleocliffs recognized with borings and encrusting organisms. The borings are mainly *Gastrochaenolites*, *Entobia* and, more locally, echinoid bowls. In one of the outcrops it is possible to recognize a vertical arrangement in the distribution of trace fossils with three well-defined horizons: echinoid bowls, *Gastrochaenolites* and *Entobia* from the top to the bottom. This zonation is due to a stopping in the transgression and corresponds to the transgressive maximum.

The blue clays are very shelly and include shelly-filled *Thalassinoides* as the only distinct trace fossil in an homogeneous background. The presence of these *Thalassinoides* indicates the existence of weak storms or turbulences.

The sandy facies only include some *Skolithos* and the conglomeratic facies sometimes show bored pebbles (with *Gastrochaenolites* and *Entobia*), more abundant in foreshore facies than in fan-deltaic facies. In one outcrop an intraformational hardground has been recognized by the presence of two ichnosuites, one consisting of *Gastrochaenolites* and *Entobia* which affect the pebbles, and the other formed by *Gastrochaenolites*, affecting indistinctly the pebbles and the matrix. This hardground was related to a minor sea-level change in a littoral area.

#### • Rosselló

The Rosselló basin is located in the eastern French Pyrennees, around the city of Perpignan. The main marine Pliocene outcrops are placed along the Tech and Têt valleys. They correspond to sandy blue clays that include abundant fauna, especially molluscs. The ichnofabric of these blue clays is fully bioturbated with very abundant *Planolites* and frequent *Thalassinoides*, *Teichichnus* and *Laminites*. Despite the high degree of bioturbation, the ichnological diversity is low and the trace fossils are not highly complex. The blue clays are sandy but only a few sand layers were not destroyed by bioturbation. These layers include *Ophiomorpha* as the main ichnofossil. *Teredolites* is sometimes present in wood fragments. The ichnological assemblage, the mollusc fauna and the sedimentological data indicate a shallow upper offshore environment in open fully marine waters (as indicated by the presence of *Laminites*, an echinoid burrow).

#### • Orb

The Orb basin is located in the Hérault in the surroundings of the city of Béziers. The outcrops are rather scarce and poor. The most complete section is situated in the locality of Cessenon, corresponding to the inner part of the ria.

The Zanclean transgression is recorded in some outcrops by *Gastrochaenolites* borings and encrusting oysters, representing a palaeocliff developed on the Messinian tuff.

The Cessenon section consists of blue-grey clays overlain by black, lignitiferous sands and clays. The blue-grey clays show a high degree of bioturbation consisting of only one ichnospecies, *Phycosiphon incertum*. Some black horizon have sharp-bounded burrows, indicating a possible incipient firmground. The clays contain no macrofauna and a poor microfauna composed of restricted-environment forms. All data (paleogeographical, sedimentological, ichnological and paleontological) suggest a brackish and very shallow environment, situated in an organic-rich proximal area of the ria and supporting an opportunistic deposit-feeder infauna.

#### • Rhône

The Rhône basin is the largest of all the studied basins. It extends from the Mediterranean Sea in the Camargue region to the city of Lyon. Only one outcrop has been studied in detail, the quarry of Pichegu, near the town of Saint Gilles (Bouches-du-Rhône). In this locality there is a good exposure of the fossil-rich blue clays overlain by a yellow sandy unit. The section corresponds to a well-developed deltaic sequence with prodelta clays at the base and delta front sands above.

The blue clays contain abundant fossil fauna, dominated by molluscs, and show a highly bioturbated ichnofabric with very abundant poorly preserved worm-like burrows attributable to deposit-feeders.

The sandy facies of the delta front display very scarce trace fossils which are only present in the bottom of the unit (*Rhizocorallium*, *Teichichnus*, *Skolithos*). However, the sandy unit contains a muddy interval, interpreted as an interdistributary bay, where the ichnological record is more important. In this interval some thin carbonatic layers display a monospecific fully-bioturbated ichnofabric constituted by *Scalartuba missouriensis*. Associated to these layers long *Psilonichnus tubiformis* have been recognized. The sedimentary setting and the presence of *Psilonichnus* indicate a very shallow paleoenvironment with opportunistic occurrences of infaunal deposit-feeders (*Scalartuba* producers) giving rise to highly bioturbated layers.

#### • Var

The Var basin is situated in the surroundings of Nice (Alpes-Maritimes). The sedimentary fill of this basin is formed by two main units: blue clays and conglomerates. The depositional system has been interpreted as a medium-deep fan.

In some outcrops, where the marine deposits onlap the calcareous Mesozoic basement, paleocliffs which include boring structures (*Gastrochaenolites*, *Maeandropolydora* and *Trypanites*) and encrusted shells (oysters and pectinids) have been recognized. These fossil rocky shores were developed during the Zanclean transgression.

The best section to study the marine Pliocene in the Var basin is situated at Saint Isidore in the NW part of the city of Nice. In this outcrop three facies associations (blue clays, sandy silts and sands and conglomerates) have been recognized and each one hosts a particular ichnofabric.

The blue clays correspond to normal offshore sedimentation and contain a very rich faunal assemblage, dominated by molluscs. The ichnofabric is wholly bioturbated with abundant spreiten structures (*Asterosoma*, *Rhizocorallium* and *Teichichnus*), some *Phycosiphon* and *Palaeophycus*, and frequent *Diplocraterion*. The *Diplocraterion* burrows are made very distinct by ferrugination and show long vertical and narrow U-burrows with rather poor development of retrusive spreiten. Despite the bioturbated background indicates a quiet, rather deep environment, the presence of long *Diplocraterion* usually is related with energetic unstable environments. Their presence needs to be explained as the result of a very particular sedimentary setting. The blue clays actually correspond to a quiet deep setting, but unpredictable and very rare but very important erosion processes also took place, as is indicated by the presence of conglomeratic bodies, deposited by gravity flows, intercalated in the blue clays. This peculiar situation can explain the whole ichnofabric.

The sandy silts show a very bioturbated ichnofabric with remains of primary lamination only in some sand beds. These deposits correspond to small turbiditic lobes usually produced after conglomeratic slumping as a result of a greater instability in the fan front. The ichnofabric is dominated by very abundant *Phycosiphon*, abundant *Teichichnus* and *Palaeophycus*, and other traces which include *Scalarituba*, *Thalassinoides*, *Skolithos*, *Sinusichnus*, *Diplocraterion*, *Scolicia* and cf. *Rosselia*. *Phycosiphon* and *Scalarituba* often occur gregariously on the top of sand layers as produced by opportunistic colonists. The high degree of bioturbation and the high diversity suggest a fully marine, relatively deep environment. The greater simplicity of the traces and the substitution of spreiten feeding burrows by small grazing burrows in comparison with the blue clays assemblage is due to the greater degree of instability in this setting.

The conglomeratic intervals only include scarce trace fossils in sand beds. These trace fossils are rare *Phycosiphon*, and very rare *Scolicia* and *Laminites*. Sand bodies



are sometimes recognizable as channels. In this kind of energetic environment bioturbation could only be scarce.

The high diversity and degree of bioturbation of the two main ichnofabrics and the abundance of spreiten feeding structures in the blue clays is consistent with an open, relatively deep (more than 100 m for some authors) sedimentary setting for the Var basin in Saint Isidore.

#### • Bioturbation. General discussion and conclusions

The trace fossil taxa show a wide distribution in the studied area. Most of them are present in three or more basins. *Skolithos* and *Thalassinoides*, present in five basins, are the most abundant and extensive ichnotaxa. *Palaeophycus*, *Scalarituba*, *Teichichnus*, *Phycosiphon*, *Planolites* and *Sinusichnus* are also very common ichnogenera. The majority of the traces corresponds to deposit and detritus-feeders with high environmental tolerance. This situation is consistent with marginal, organic-rich settings with a high sedimentation rate and changing paleoenvironmental parameters.

Despite the similarity of the taxa present in each basin, significant differences are revealed following an ichnofabric approach. Seventeen ichnofabrics are well-defined in the Pliocene of the NW Mediterranean:

#### BLUE CLAYS ICHNOFABRICS

- Ichnofabric 1. Monospecific *Phycosiphon* ichnofabric.

Occurrence: Cessenon (Orb)

B.I.: 4-5

Constituents\*: *Phycosiphon* (M).

Interpretation: Very shallow, restricted and brackish environment in a proximal ria.

- Ichnofabric 2. Shelly-filled *Thalassinoides* ichnofabric.

Occurrences: Ciurana (Alt Empordà) and Sant Onofre (Baix Ebre)

B.I.: 6

Constituents: *Thalassinoides* (M), worm-like burrows (A).

Interpretation: Shallow and quiet bay environment affected by occasional weak turbulences.

- Ichnofabric 3. *Planolites* with *Thalassinoides* and *Teichichnus* ichnofabric.

Occurrence: Valmagna (Rosselló)

B.I.: 5-6

Constituents: *Planolites* (M), *Thalassinoides* (S), *Teichichnus* (S), *Laminites* (S).

Interpretation: Upper offshore fully marine environment.

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\* M. Main constituents, S. Secondary constituents, A. Accessory constituents.

- Ichnofabric 4. *Diplocraterion*-spreiten structures ichnofabric.

Occurrence: Saint Isidore (Var)

B.I.: 4-5

Constituents: *Diplocraterion* (M), *Teichichnus* (M), *Asretosoma* (M), *Rhizocorallium* (M), *Phycosiphon* (S), *Palaeophycus* (A).

Interpretation: Fully marine offshore environment under quiet conditions with unpredictable and very rare erosional events.

## SANDY UNITS ICHNOFABRICS

### In clays:

- Ichnofabric 5. Monospecific *Teichichnus* ichnofabric.

Occurrence: Sant Onofre (Baix Ebre)

B.I.: 6

Constituents: *Teichichnus* (M)

Interpretation: Very shallow brackish environment hosting a low-diversity deposit-feeding infauna.

- Ichnofabric 6. Monospecific *Scalarituba* ichnofabric

Occurrence: Pichegu (Rhône)

B.I.: 6

Constituents: *Scalarituba* (M)

Interpretation: Very shallow and brackish interdistributary bay.

### In alternating sands and clays:

- Ichnofabric 7. J-burrows ichnofabric

Occurrence: Sant Onofre (Baix Ebre)

B.I.: 1-2

Constituents: J-burrows (M), escapement structures (S), single trails (S), bilobated trails (A).

Interpretation: Shallow bay, rather restricted environment with discontinuous sandy turbiditic discharges.

- Ichnofabric 8. *Sinusichnus* ichnofabric.

Occurrence: Sant Onofre (Baix Ebre)

B.I.: 2

Constituents: *Sinusichnus* (M), *Teichichnus* (S), *Scalarituba* (A), *Scolicia* (A), single trails (A).

Interpretation: Shallow bay with discontinuous sandy turbiditic discharges.

- Ichnofabric 9. *Teichichnus*-Fugichnia ichnofabric

Occurrence: Sant Onofre (Baix Ebre)

B.I.: 2

Constituents: *Teichichnus* (M), escapement traces (M), J-burrows (S).

Interpretation: Shallow bay environment with storm supply of sands.

- Ichnofabric 10. *Phycosiphon-Skolithos* ichnofabric.  
 Occurrences: El Papiol and Pic d'en Valls (Baix Llobregat) B.I.: 2  
 Constituents: *Phycosiphon* (M), *Skolithos* (M), *Thalassinoides* (S), *Palaeophycus* (S), *Planolites* (S).  
 Interpretation: Shallow ria with occasional supply of sands. Sand deposition controlled the existence of a predepositional ichnosuite and a two-tiered postdepositional ichnosuite.
- Ichnofabric 11. *Phycosiphon-Sinusichnus* ichnofabric.  
 Occurrences: El Tarc (Baix Llobregat) B.I.: 1-2  
 Constituents: *Phycosiphon* (M), *Sinusichnus* (S), tiny J and Y-burrows (S), *Thalassinoides* (A).  
 Interpretation: Shallow ria with occasional supply of sands. Sand deposition controlled the existence of a predepositional ichnosuite and a two-tiered postdepositional ichnosuite.
- Ichnofabric 12. *Scalarituba-Laminites* ichnofabric  
 Occurrences: Can Albareda and Torrent del Terme (Baix Llobregat) B.I.: 2  
 Constituents: *Scalarituba* (M), *Laminites* (M), *Phycosiphon* (S), *Cardioichnus* (S), single trails (A), horizontal undifferentiated burrows (A).  
 Interpretation: Shallow fully marine ria with occasional supply of sands. Sand deposition controlled the existence of a predepositional ichnosuite and a two-tiered postdepositional ichnosuite.
- Ichnofabric 13. *Phycosiphon-Palaeophycus* ichnofabric.  
 Occurrences: Saint Isidore (Var) B.I.: 4-5  
 Constituents: *Phycosiphon* (M), *Palaeophycus* (M), *Teichichnus* (M), *Scalarituba* (S), *Diplocraterion* (S), *Skolithos* (A), *Thalassinoides* (A), *Sinusichnus* (A), *Scolicia* (A), cf. *Rosselia* (A).  
 Interpretation: Relatively deep and fully marine environment in an unstable fan slope with dominant turbiditic deposition.

In sands:

- Ichnofabric 14. *Skolithos*-primary lamination ichnofabric  
 Occurrences: Sant Onofre (Baix Ebre) B.I.: 1-2  
 Constituents: *Skolithos* (M), escapement traces (S).  
 Interpretation: Prograding sand bar.
- Ichnofabric 15. *Skolithos*-mottling ichnofabric  
 Occurrence: St. Onofre (Baix Ebre), St. Miquel-St. Mori (Alt Empordà) B.I.: 4-5  
 Constituents: *Skolithos* (M), mottling (M), *Palaeophycus* (A).  
 Interpretation: Moderately energetic shoreface.

- Ichnofabric 16. *Ophiomorpha* ichnofabric.

Occurrence: El Papiol (Baix Llobregat)

B.I.: 2

Constituents: *Ophiomorpha* (M), *Macaronichnus* (S), *Skolithos* (A) in a background dominated by sedimentary structures.

Interpretation: High energy sandy channels in a proximal ria.

- Ichnofabric 17. *Phycosiphon*-primary lamination ichnofabric.

Occurrence: Saint Isidore (Var).

B.I.: 1-2

Constituents: *Phycosiphon* (M), *Planolites* (A), *Laminites* (A), *Scolicia* (A).

Interpretation: Medium-deep fan channel.

These ichnofabrics have been plotted in an Ichnodiversity-Bioturbation Index diagram. Three main groups of ichnofabrics are recognized from this diagram:

Group I: Highly-bioturbated monospecific clay ichnofabrics including ichnofabrics 1, 5 and 6. All correspond to brackish and very shallow environments where highly-tolerant sediment-feeders could thrive successfully. The other clay ichnofabrics (2, 3 and 4) are also highly bioturbated but with variable diversity.

Group II: Low-bioturbated, low-to-moderate diversity ichnofabrics in alternating sandy and clayey sediments. This group includes ichnofabrics 7, 8, 9, 10, 11 and 12. Rather simple deposit- and detritus-feeding structures and dwelling traces are dominant. All these ichnofabrics correspond to shallow bay settings with normal clay deposition and eventic sand sedimentation. These ichnofabrics characterize the sandy clay units of the Baix Ebre and Baix Llobregat basins. The only sandy-clayey ichnofabric not included in this group is ichnofabric 13 from the sandy silts of Var that hosts a higher-diversity fully-bioturbated fabric as a result of deeper, more open marine conditions.

Group III: Very-low-bioturbated low-diversity ichnofabrics in sands, including ichnofabrics 14, 16 and 17. All three show a fabric dominated by primary lamination with few and scarce trace fossils. They correspond to high energy settings: sand bars (14), shallow submarine channels (16) and medium-deep fan channels (17). The other sandy ichnofabric (15) is out of this group because of the higher bioturbation rate resulting from lower energy conditions.

The analysis of trace fossils and ichnofabrics points out the similarity between the Baix Ebre and Baix Llobregat and the shallow water character of most of the basins. The Var basin ichnofabrics show the highest diversity, and sometimes also the highest bioturbation grade, in comparison with other ichnofabrics hosted in similar lithological settings. This is a direct consequence of the greater depth of this basin.



#### • Bioerosion. General discussion and conclusions

Bioerosion structures occur in four different substrates: paleocliffs, conglomeratic deposits, hardgrounds and shells.

The record of paleocliffs is very extensive in most of the basins. They are related to the Zanclean transgression and are recorded by the presence of borings and encrusting shells. The trace fossil assemblage is typically littoral and very recurrent in the whole study area, dominated by *Gastrochaenolites* and *Entobia* associated with other borings (*Maeandropolydora*, *Caulostrepsis*, *Trypanites*, echinid bowls).

Bioerosion in conglomerates, and also in the only recognized hardground (Els Olivets, Alt Empordà) shows an identical assemblage to that in rocky shores. Foreshore conglomerates host more abundant borings than fan deltaic conglomerates.

#### 4. Systematic ichnology

Twenty six ichnospecies have been recognized in the studied Pliocene basins, eleven of which have been classified to species level, eight to ichnogenus level and the other seven have been left in open nomenclature.

The most abundant, peculiar or well-preserved ichnotaxa have been described. In the description, trace fossils have been grouped into five classes:

- Epigenic trails and trackways. Include single and bilobate trails and tetrapod trackways.
- Simple dwelling structures. Include *Skolithos linearis*, *Palaeophycus*, J-burrows, tiny J and Y-burrows and *Psilonichnus tubiformis*.
- Branching systems. Include *Thalassinoides suevicus*, *Thalassinoides* isp., *Ophiomorpha nodosa* and the new ichnogenus, new ichnospecies *Sinusichnus sinuosus*.
- Spreiten structures. Include *Diplocraterion*, *Teichichnus rectus*, *Asterosoma* and *Rhizocorallium*.
- Winding burrows. Include *Planolites montanus*, *Phycosiphon incertum*, *Scalarituba missouriensis*, *Scalarituba biserialis* and the trace fossils of the *Scolicia* group (*Scolicia*, *Laminites* and *Cardioichnus planus*).

The only new ichnotaxon is *Sinusichnus sinuosus* n. igen., n. isp., corresponding to sinuous, spreiten branching burrows which exhibit a high regularity in the shape of its elements. It is interpreted as a trace fossil very similar to *Thalassinoides*, with a similar ethological significance and produced by a detritus feeding decapoda as well.

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