The Late Miocene Reef Complex, Mallorca

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REGIONAL SETTING

THE MEDITERRANEAN

(from Carminati E. & Doglioni C., 2004: Mediterranean tectonics.
In *Encyclopedia of Geology*, Elsevier, pp. 135-146.)

For papers related to the evolution of the Western Mediterranean visit C. Doglioni web page:
(http://tetide.geo.uniroma1.it/sciterra/sezioni/doglioni/Doglioni_home.html)

It is commonly accepted that Mediterranean geology has been shaped by the interplay between the African and European plates, and smaller intervening microplates. The Mediterranean was mainly affected by rifting during the Mesozoic, and oceanic Tethys areas and passive continental margins developed. During the late Mesozoic, the extensional regime inverted and the Mediterranean area became dominated by subduction zones (Cimmerian, Dinarides, and Alps–Betics). The previously formed Tethyan oceanic lithosphere and the adjacent continental margins were consumed. The composition (oceanic or continental), density, and thickness of the lithosphere inherited from the Mesozoic rift controlled the location, distribution, and evolution of the subduction zones. Closely related to the Mediterranean geodynamics are the Carpathian subduction and the Pyrenees (**Fig. 1**).

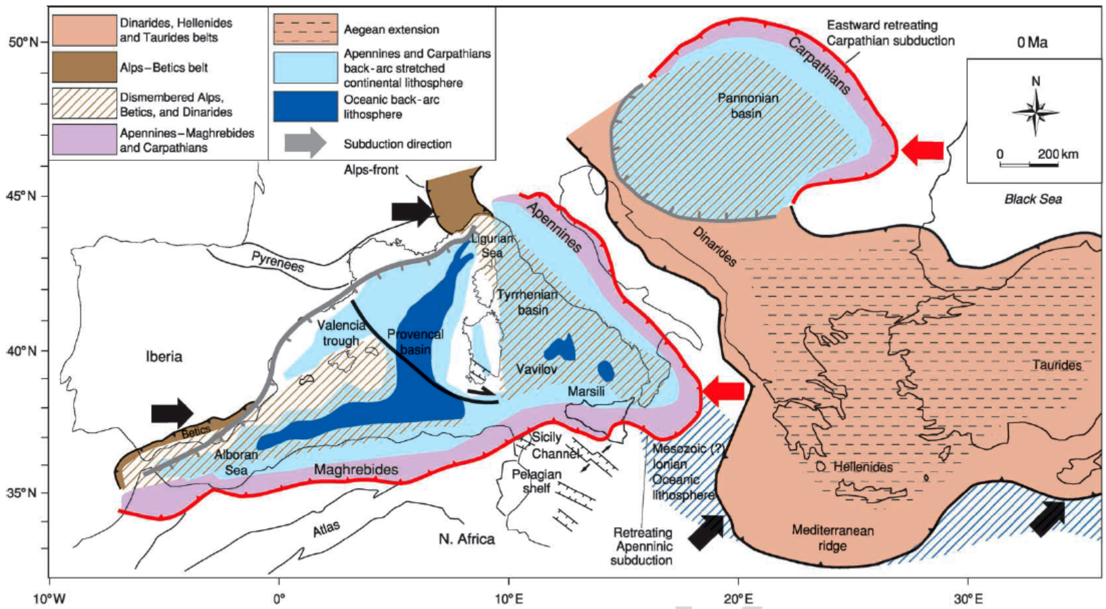


Figure 1- Present geodynamic framework of the Mediterranean areas. There are four subduction zones with variable active rates: Apennines–Maghrebides (westwards), Carpathians (westwards), Dinarides–Hellenides–Taurides (north-eastwards), and Alps (south-eastwards). The Apennines–Maghrebides subduction-related back-arc basin of the western Mediterranean stretched and scattered into segmented basins most of the products of the Alps–Betics orogen (from Carminati & Doglioni, 2004).

The Mediterranean orogens have two distinct signatures:
- **a)** High morphological and structural elevations, double vergence, thick crust, involvement of deep crustal rocks, and shallow foredeeps characterize eastwards or north-eastwards-directed subduction zones (Alps–Betics and Dinarides–Hellenides–Taurides).
- **b)** Conversely, low morphological and structural elevations, single vergence, thin crust, invol-vement of shallow rocks, deep foredeeps, and a widely developed back-arc basin characterize the westwards-directed subduction zones of the Apennines and Carpathians. This asymmetry can be ascribed to the 'westward' drift of the lithosphere relative to the mantle, at rates of about 49 mm/year as computed from the hotspots reference frame.

All Mediterranean orogens show typical thrust-belt geometries with imbricate-fan and antiformal-stack associations of thrusts. The main factor that varies between orogens and within single belts is the depth of the basal décollement. The deeper it is, the higher is the structural and morphological elevation of the related orogen.

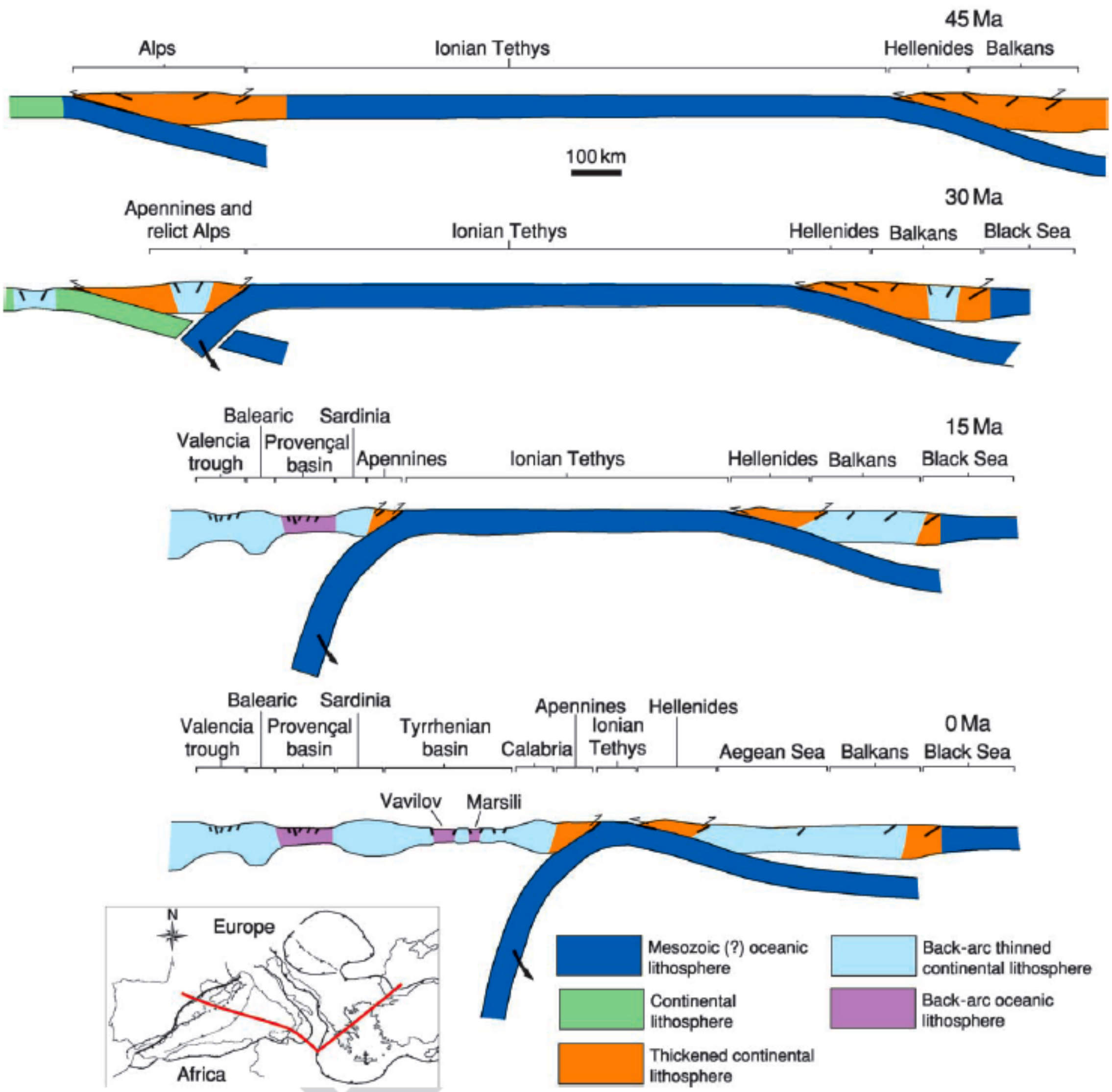


Figure 2- During the last 45 Ma, the evolution of the Mediterranean, along the trace shown on the map (inset), is the result of three main subduction zones: the early eastwards-directed Alpine subduction, the Apennines subduction switch along the Alps retrobelt, and the Dinarides–Hellenides subduction. The last two slabs retreated at the expense of the inherited Tethyan Mesozoic oceanic or thinned continental lithosphere. In their hanging walls, a few rifts formed as back-arc basins, which are progressively younger towards the subduction hinges. (From Carminati & Doglioni, 2004).

Extensional basins are superimposed on these orogenic belts: on the western side are the Valencia, Provençal, Alboran, Algerian, and Tyrrhenian basins, A characteristic feature of the western Mediterranean is the large variation in lithospheric and crustal thickness (**Fig. 2**). The lithosphere has been thinned to less than 60km in the basins (50–60km in the Valencia trough, 40 km in the eastern Alboran Sea, and 20–25km in the Tyrrhenian Sea), while it is 65–80km thick below the continental swells (Corsica–Sardinia and the Balearic promontory). The crust mimics these differences, with a thickness of 8–15km in the basins (Valencia trough, Alboran Sea, Ligurian Sea, and Tyrrhenian Sea) and 20–30km underneath the swells (Balearic promontory and Corsica–Sardinia), as inferred by seismic and gravity data.

These lateral variations in thickness and composition are related to the rifting process that affected the western Mediterranean, which is a coherent system of interrelated irregular troughs, mainly V-shaped, that began to develop in the Late Oligocene–Early Miocene in the westernmost parts (Alboran, Valencia, Provençal basins), becoming progressively younger eastwards (eastern Balearic and Algerian basins), culminating in the presently active east–west extension in the Tyrrhenian Sea (**Figs. 1, 2, 3 & 4**).

In western Mediterranean, the westwards-directed Apennines–Maghrebides subduction started along the Alps–Betics retrobelt (**Figs. 2 & 4**), where oceanic and thinned continental lithosphere occurred in the foreland to the east. Subduction underneath the Apennines–Maghrebides consumed inherited Tethyan domains (**Figs. 2 & 3**). In contrast to the 'eastwards'-migrating extensional basins and following the 'eastwards' retreat of the Apennines subduction zone, the Betics–Balearic thrust front was migrating 'westwards', producing interference or inversion structures (**Fig. 2**). The part of the Alps–Betics orogen that was located in the area of the Apennines–Maghrebides back-arc basin (**Figure 1**) has been disarticulated and spread out into the western Mediterranean (forming the metamorphic slices of Kabylie in northern Algeria and Calabria in southern Italy).

Paradoxically, the extension that determined most of the western Mediterranean developed in the context of relative convergence between Africa and Europe. Therefore, the eastwards migration of the Apennines–Maghrebides arc is not a consequence of the north–south relative convergence between Africa and Europe but is instead a consequence of the Apennines–Maghrebides subduction rollback, which was generated either by slab pull or by the 'eastwards' flow of the mantle relative to the lithosphere deduced from the hotspot reference frame.

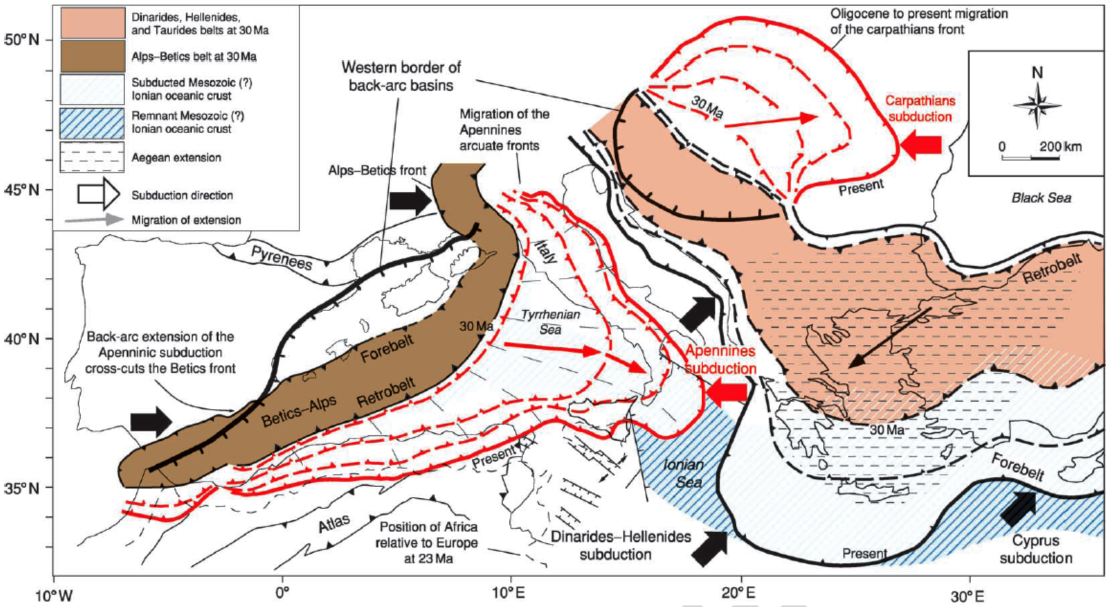
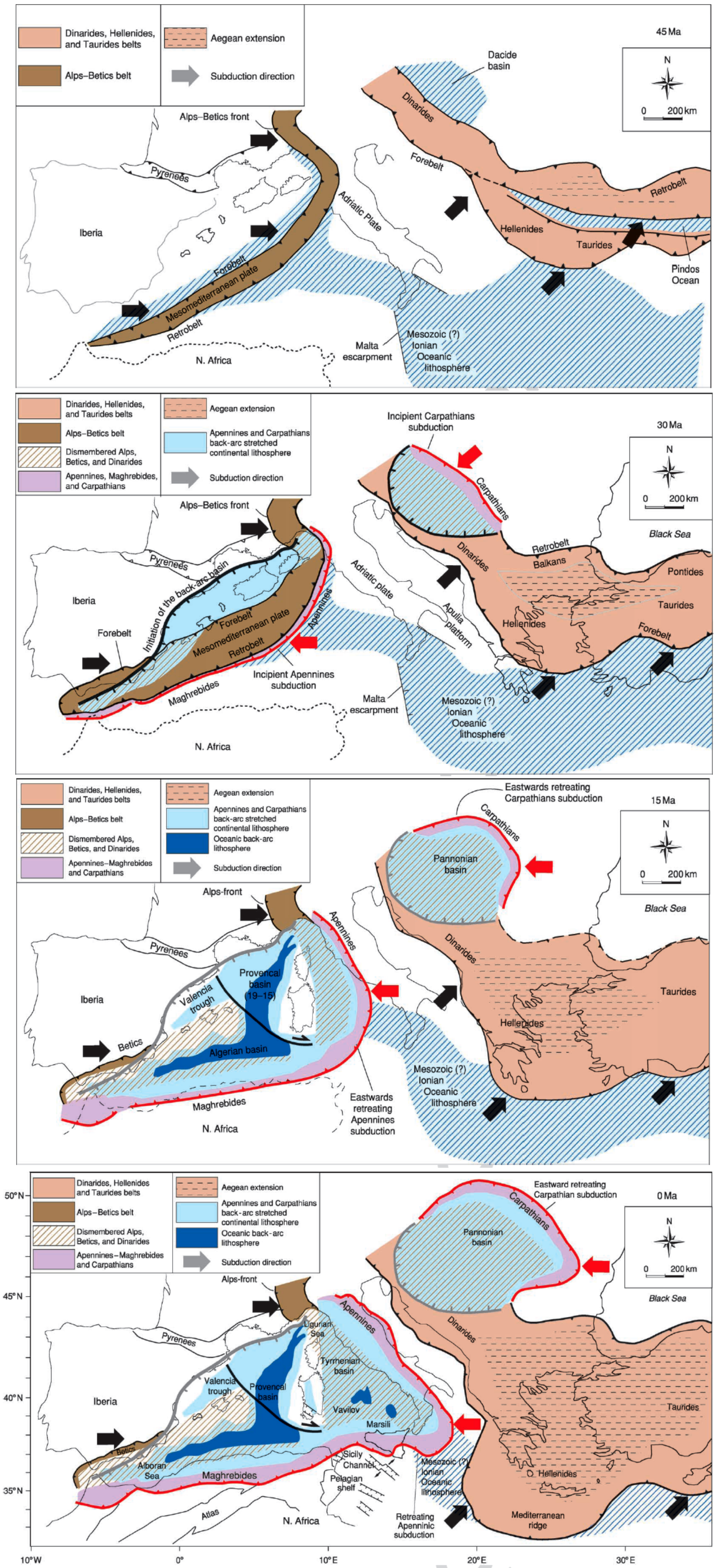


Figure 3- The Mediterranean realm has been shaped during the last 45Ma by the evolution of several subduction zones and related belts:

- **the single eastwards-vergent Apennines–Maghrebides and the related western Mediterranean back-arc basin;**
- **the double-vergent Pyrenees,**
- **the double-vergent Alps–Betics;**
- **the double-vergent Dinarides–Hellenides–Taurides and related Aegean extension, and**
- **the single eastwards-vergent Carpathians and the related Pannonian back-arc basin. (From Carminati & Doglioni, 2004).**



The Alps were continuous with the Betics to Gibraltar, consuming an ocean located to the west.

The locations of the subduction zones were controlled by the Mesozoic palaeogeography. The Alps–Betics formed along the southeastwards- dipping subduction of Europe and Iberia underneath the Adriatic and Meso-Mediterranean plates.

The Valencia trough, the Liguro-Provençal basin, and the North Algerian basin were almost completely opened at 10 Ma. Note the 'eastward' vergence of both the Apennines–Maghrebides trench and the back-arc extensional wave

Present geodynamic context.

Figure 4- Palaeogeodynamic reconstructions of the Mediterranean-Carpatians during the Cenozoic (from Carminati & Doglioni, 2004)

THE BALEARIC ISLANDS

The Balearic archipelago is the emergent part of the "Balearic Promontory", which extends into the Western Mediterranean as the north-eastward part of the Betic Range External Zones **(Figs. 5 & 6**). The Balearic Islands are characterized by ranges of folded and thrusted Mesozoic, Paleogene, and Middle Miocene rocks that are flanked by areas covered with only slightly deformed Late Miocene to Pleistocene sedimentary rocks (**Fig. 7**).

During the Mesozoic, the Balearic Promontory experienced extension and thinning related to the break up of Pangea and the opening of the Tethys. The onset of the Alpine orogeny produced a lithosferic flexure of this continental-crust segment during Paleogene times. The major compressional events occurred during mid Miocene, the same as in southeastern Spain (Betic Range) and northern Africa (Maghrebides Ranges). The ranges are northeast trending and the dominant structural style is that of stacked thrust sheets which were placed toward the northwest during the Middle Miocene. The Upper Miocene rocks are fairly flat-lying, having undergone only slight tilting and flexure associated with normal and strike-slip faulting during the late Neogene to middle Pleistocene time.

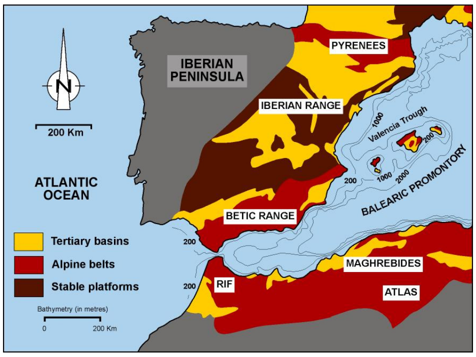


Figure 5-Tectonic provinces of Spain, the Balearic Islands and North Africa (from Pomar et al., 1996)

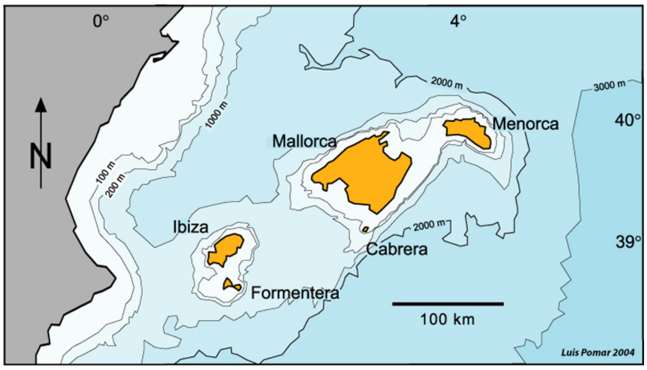


Figure 6–The Balearic Promontory in Western Mediterranean (Pomar)

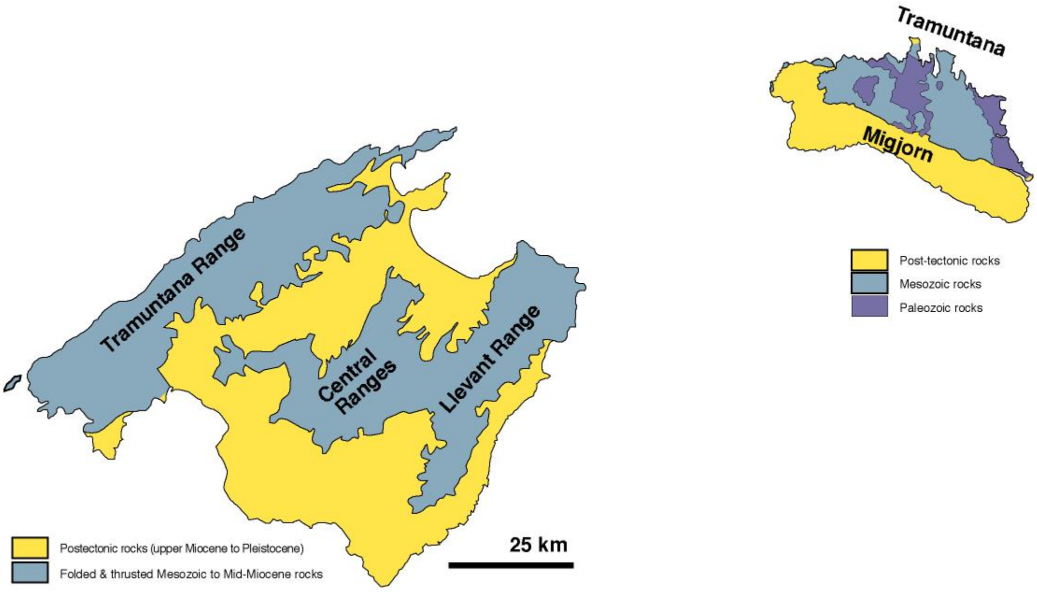


Figure 7: geological sketch of Mallorca and Menorca (L. Pomar)

Mallorca Island is characterized by basin-and-range topographical configuration that resulted from Late Miocene to Early Pleistocene faulting. The mountain ranges are horst-blocks of the Alpine fold belt. Late Miocene, Pliocene and Pleistocene deposits onlap the folded Mesozoic to Middle Miocene rocks, constructing near-horizontal platforms around the ranges and filling down-dropped areas. Two regions compose Menorca Island. The Tramuntana region in the north is also a horst-block of the Alpine fold belt, and the Migjorn region in the south is composed by Upper Miocene platforms (**Fig. 7**).

STRATIGRAPHY

Miocene rocks comprise two broad groups of units relative to Middle Miocene tectonics. The lower group (Lower and Middle Miocene) is pre- and synorogenic (**Fig. 8**). It onlaps the Paleogene and Mesozoic rocks and is folded and thrusted (except on Menorca Island). The Upper Miocene rocks are post-orogenic and overlie the lower group and the deformed Mesozoic and Paleogene rocks on all of the Balearic Islands.

LOWER AND MIDDLE MIOCENE

Mallorca – Sant Elm Calcarenitic Formation:

It consists of a tens-of-meters thick unit that mainly crops out on Mallorca, but also on Menorca and on the north of Ibiza. It unconformably overlies the Mesozoic and Paleogene substratum. Commonly, it is composed by carbonate lithoclastic and bioclastic calcarenites, on which coral patch reefs, red algae biostromes and seaweed deposits. Most facies associations correspond to shallow-water and littoral environments, but alluvial fan and lacustrine deposits also exist at some localities, as well as deeper (aphotic) shelf deposits characterized by the presence of sponges and planktonic foraminifera. Volcanic rocks from the N and NW of Mallorca representing on-shore pyroclastic accumulation of calc-alkaline rhyodacitic composition yielded (K-Ar dates) a Burdigalian age (18.6 to 19 Ma). Foraminifera data in these northerly localities suggest an Early Miocene (Aquitanian or Burdigalian) age whereas in southeastern localities a Late Oligocene age has been suggested.

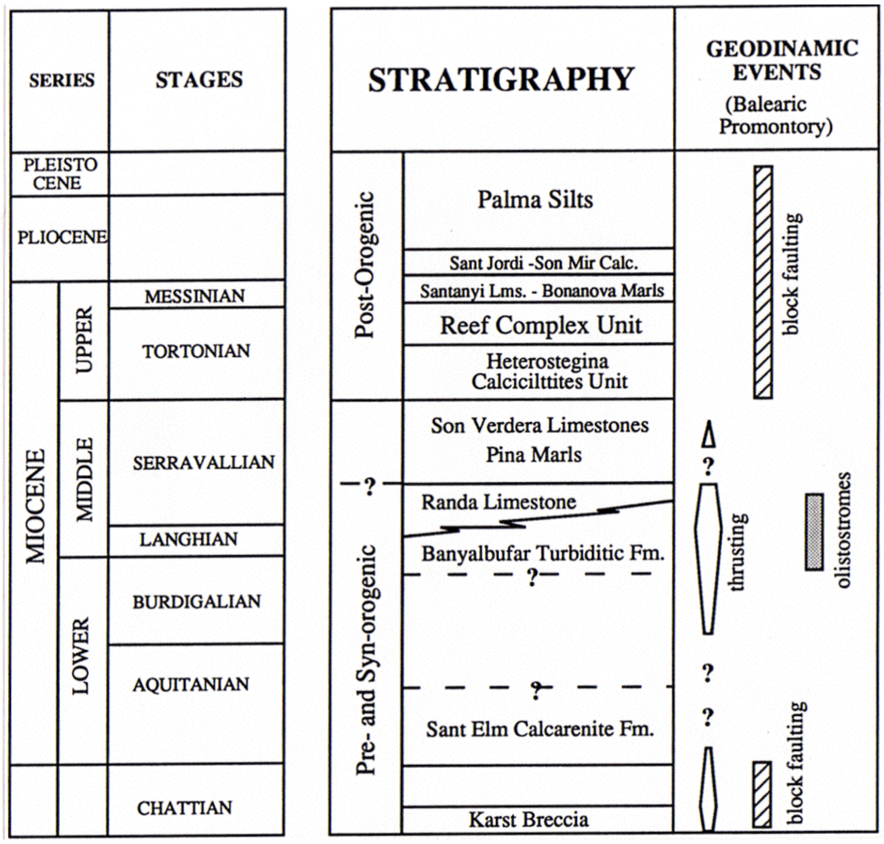


Figure 8– Mallorca Neogene units (Pomar, unpublished)

Mallorca – Banyalbufar Turbiditic Formation:

This unit is widespread on Mallorca and Ibiza outcrops. It unconformably onlaps both Mesozoic and older Tertiary rocks. The upper boundary is frequently a tectonic surface corresponding to the thrusts that cut the sequence. Thickness is very variable, but it reaches up to 450 m in the NW of Mallorca. Lithoclastic calcarenites and grey marls mostly compose this Formation, but minor breccia, conglomerates and silexite beds are present. Olistostromes are frequent. It corresponds to a transgressive turbiditic suite, infilling small foreland basins developed during emplacement of the thrust sheets. The turbidites show a deepening-upward trend, evolving from proximal deep-sea fan environments to basin plain. Planktonic foraminifera from the NW and central area of Mallorca suggest a Langhian age.

Mallorca – Randa Calcarenites:

The Randa Calcarenites Unit is a 130-m-thick limestone succession, which crops out on the Randa hills, in the Central Zone of Mallorca. It consists of bioclastic calcarenites, which prograded on the active margin of a piggyback basin. Its regressive sequence is interpreted to be consequence of basement uplift due to thrusts emplacement. The lower part of the Randa limestone succession is composed of thin beds of marly hemipelagites (the Banyalbufar turbidites) interlayered with coarse grained skeletal turbidites. The components of the hemipelagites illustrate an important planktonic contribution whilst components of the turbidites document the transport of skeletal sediment from a shallow water area (photic zone). They are overlain by a thick (150 m) limestone unit which consists of coarse-grained skeletal packstones containing fragments of red algae, bryozoans, larger foraminifera (*Amphistegina*, *Heterostegina*), bivalves and, locally, rhodoliths and lithoclasts. Planktonic foraminifera are rare. The Randa Limestone has a composition similar to the "large perforate foraminifera sands" of the Persian Gulf, but coralline-algae fragments are more abundant. Slivers of basement exposed to erosion by contemporaneous up-thrusting offer the best interpretation for the basement-derived pebbles, which are locally abundant in the Randa limestone.

Two different parts are recognized in this limestone succession. The lower part is 130-m thick and characterized by coalescence of relatively small lobes, built-up by amalgamated sigmoidal turbiditic beds. The absence of fine-grained sediments is interpreted as consequence of the depositional dip (avoiding deposition) as well as winnowing by bottom currents. Storm-triggered small-volume turbidites might be responsible for the bulk of this lithofacies.

The upper part of the sequence is 20-m thick, also characterized by amalgamated turbiditic packstones with similar skeletal constituents, but the texture is coarser and rhodoliths are more abundant. Sedimentary structures include hummocky cross-stratification at different scales, channel-like erosion surfaces, and convex-up beds with chaotic cores and parallel or cross-bedded laminated flanks. The channel-like erosion surfaces may result from density currents and be the feeders of the lobes. Depositional setting for this upper part may be the transition zone between the lobes and the channels in a deep-sea fan system. Different sized hummocky-like structures have been reported from modern deep-sea fans in the lobe-channel transition zone, but their characteristic features are only morphological, because of limitations on sampling. Additionally, rolling hummocky topographies, which appear to be the result of positive (constructional) features, as well as miscellaneous types of roughness that might correspond to small bedforms, have been also documented in modern systems. Moreover, sediment waves ranging from 0.25 to 2 km in wavelength and heights up to 40 m are developed on many of the large levees on the sides of the channel on modern fan over-bank deposits, but they do not appear to be common on small fan systems. Nevertheless, neither the relief of the sediment waves nor the levees themselves are likely to be recognizable in ancient turbidites

Mallorca – Pina Marls and Son Verdera Limestones:

The Pina Marls Unit is mainly composed of massive grey marls with gypsum and, locally, interbedded with sandy layers and centimeter-thick coal beds. They contain of scarce charophyta, ostracod and mammal remains mixed with resedimented Burdigalian foraminifera. Thickness varies from a few meters up to 500 m in the depocenters. The Pina Marls unit has been interpreted to represent deposition in evaporitic mud flats, swamps and brackish, shallow-water, lacustrine environments during Serravallian.

The Son Verdera Limestones Unit conformably overlies the Pina Marls. Thickness ranges from 10 to 70 m and it is composed of limestones and fine-grained terrigenous deposits, organized in two facies associations representing shallow brackish lacustrine environments.

a) Brownish limestones, with chert nodules, interbedded with grey marls and organic-matter bearing siltstones. They contain gastropods, ostracods and charophytes, fish otoliths and mammal remains.

b) Greenish marls with abundant carbonate- and iron-rich nodules, interbedded with thin stromatolitic layers. They contain plant debris and gastropod and mammal remains.

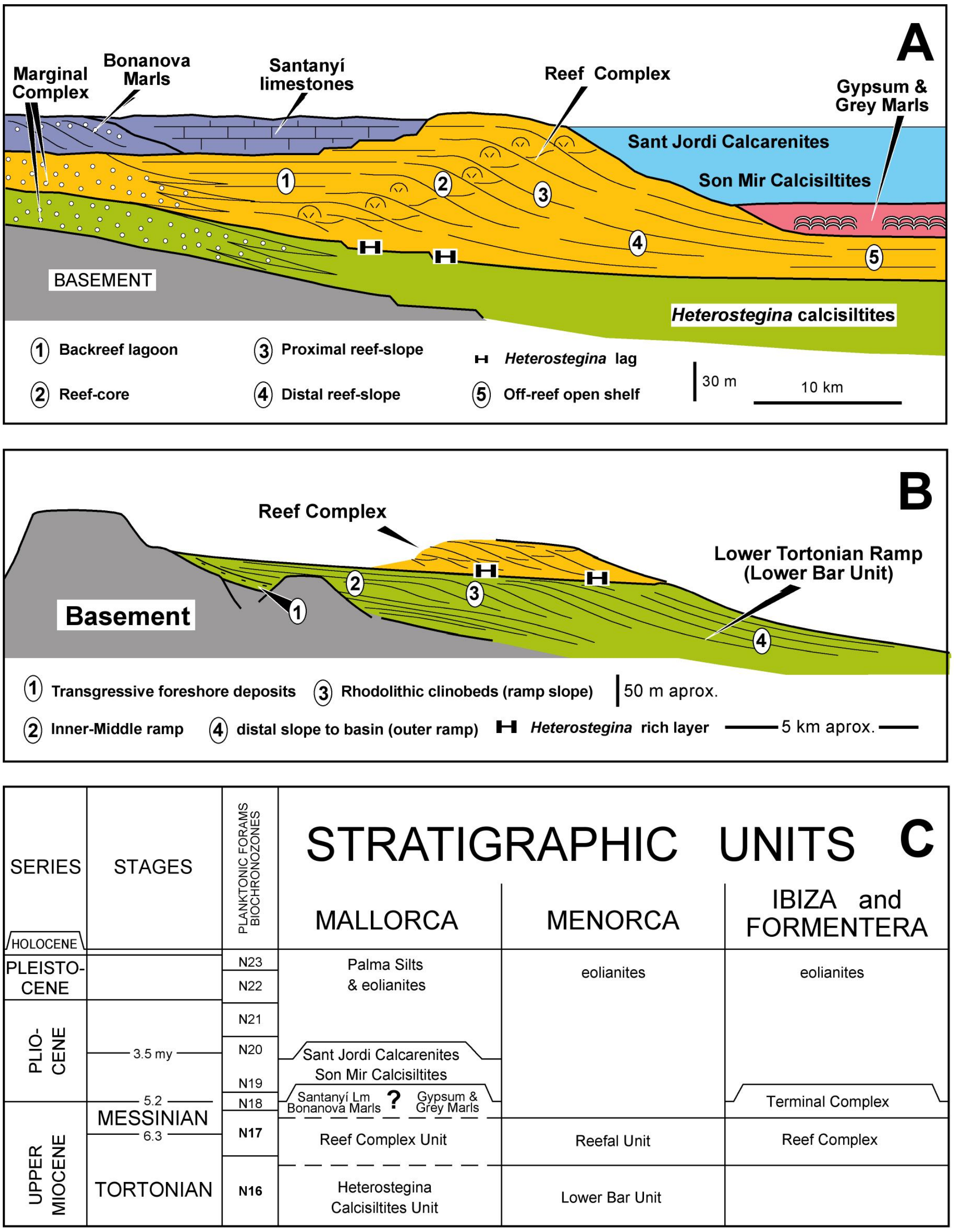


Figure 9– A: Mallorca upper Miocene and Pliocene stratigraphic architecture. B: Menorca Upper Miocene stratigraphic architecture. C: Balearic Islands upper Miocene units correlation. From Pomar et al. (1996).

UPPER MIOCENE

Post-orogenic Upper Miocene rocks are extensively exposed on the Balearic Islands and can be divided into three major sedimentary units (**Fig. 9**). The lower unit crops out on Mallorca (*Heterostegina* Calcisiltites Unit and Menorca (Lower Bar Unit). It includes extensive rhodalgal biostromes without coral reefs, and it is attributed to Early Tortonian time (N16). The middle unit contains well-developed progradational coral reefs on all the islands (Reef Complex), and it is attributed to Late Tortonian – Early Messinian times (N17). The upper unit, assigned to the Messinian, crops out on Mallorca and Ibiza. It consists of a variety of lithologies, including oolites and stromatolites (equivalent to the Terminal Complex of Esteban, 1996), evaporite, dolomite and marls, and fan-delta conglomerates and marls.

Mallorca Lower Tortonian – *Heterostegina* Calcisiltites:

This unit, which extends over the whole of the Palma Basin, is known in Mallorca principally from borehole data and from small outcrops. On outcrops, the lower boundary is represented by an angular unconformity over the deformed Mesozoic to Middle Miocene basement. It is 200-m thick and it is composed in areas situated towards the central part of the depositional system (platform) of pebbly sandstone at the base, evolving upwards to bioturbated bioclastic calcisiltites with *Heterostegina*, red algae, bryozoa, fish teeth, *Amphistegina*, miliolids, mollusks and echinoids. Towards the edges, it evolves into coarser sands and conglomerates. At the depocenter, the upper boundary is a surface overlain by 1-1.5 m thick layer rich in *Heterostegina*. The unit is characterized by the lack of coral reefs. Chronostratigraphically this unit is attributed to the N16 Blow zone (Early Tortonian). Depositional setting is interpreted to be a shallow carbonate platform on the margins of which fan deltas of the "**Marginal Complex**" were deposited by streams draining from the highlands of deformed Mesozoic and Paleogene rocks.

Menorca Lower Tortonian – Lower Bar Unit:

This unit is up to 500 m thick in the subsurface and is very well exposed on the sea cliffs. It is composed of two systems tracts. The transgressive systems tract is composed by large-scale cross-bedded pebbly sandstone units (foreshore) onlapping and backstepping onto Neogene and Mesozoic rocks. The highstand systems tract is the Lower Bar Unit (**Fig. 9**). It is composed of prograding and aggrading units deposited on a high-energy distally steepened ramp (*sensu* Read 1985). On such a ramp, the slope steepens at the transition between the middle and outer ramp (basinal). On this distally steepened ramp in the HST, fan-delta and pebbly beach deposits pass into gently seaward-dipping inner-ramp lithofacies, composed of burrowed foraminifer, lithoclast and mollusk dolopackstone. They grade seawards into medium- to coarse-grained cross-bedded dolopackstone-grainstone of the middle ramp, with red algae, mollusks, bryozoans, larger foraminifera (*Heterostegina* and *Amphistegina*) and some rhodoliths. The middle ramp itself passes seaward into a ramp slope facies with large-scale clinoforms dipping at 15°-20°. These are composed of rhodolithic grainstone interlayered with coarse- to medium-grained dolopackstone, rich in red algal fragments, echinoids, bryozoans and foraminifera. Basinward, the ramp slope interfingers with thinly bedded and gently undulating fine-grained dolopackstone/wackestone containing planktonic foraminifera (outer ramp). This unit is also attributed to the N16 Blow zone (Early Tortonian).

UPPER TORTONIAN-LOWER MESSINIAN

Reef Complex – both Mallorca and Menorca

The Upper Tortonian-Lower Messinian unit (**Fig. 9**) consists of progradational reef-rimmed platforms on all the Balearic Islands. The maximum thickness of this reefal unit is about 180 m. On **Menorca** it has been mostly removed by erosion but is known from several outcrops. On **Mallorca,** it is exquisitely exposed in sea-cliff outcrops and well known from numerous boreholes (Pomar and Ward 1995, 1999; Pomar et al. 1996). At the depocenter, it overlies conformably the *Heterostegina* calcisiltites and, on the margins, unconformably onlaps the folded basement. On the margins it is represented by the "Marginal Complex" (**Fig. 9**), rich in terrigenous sediments. The upper boundary is an erosion surface with karstic morphology, caves and paleocliffs.

It is composed of several facies associations: off-reef open-shelf lithofacies overlie the *Heterostegina*-rich bed and, in turn, are overlain by progradational forereef-slope and reef-core and, locally, by back-reef lagoon lithofacies. In this Reef Complex, both stratigraphic and diagenetic heterogeneities derive from the complex hierarchical stacking patterns of high-frequency (4th- to 7th-order) accretional units (Pomar and Ward, 1999). All these accretional units, which represent high-frequency depositional sequences (7th- to fourth-order, *sensu* Haq et al., 1987), have similar characteristics in stratal geometries, bounding surfaces, and facies architecture. Chronostratigraphical knowledge of this unit is poor; nevertheless, diverse regional considerations as well as foraminiferal assemblages from borehole samples allow its attribution to the Late Tortonian-Early Messinian (N17 Blow zone). K-Ar dates on well-preserved sanidine and biotite phenocrystals from a bentonite layer found in the back-reef lagoon deposits near Cap Blanc, Mallorca, are 7.0 ± 0.2 My for the biotite (7.4% K) and 6.0 ± 0.2 My for the sanidine (9.7% K). More recent Ar-Ar dates on the sanidines yielded a more reliable age of 6.230 My, and 6.457 My on the biotites, which indicates for these sediments an age of Early Messinian.

MESSINIAN

Bonanova Marls:

This 35-m thick unit is found only in the northwestern part of Palma Bay on Mallorca, it overlies unconformably the margins of the Reef Complex. Lithologically consists at the base of marls rich in scallops, oysters, gastropods and small corals, evolving vertically into conglomerates and red clays (alluvial fan). The Santanyí Limestones, or the Pleistocene eolianites overlies this unit

Gypsum and Grey Marls:

This relatively thin unit -its thickness seldom surpasses 10-m - is known from bore-holes and the sea cliffs of the Palma basin. It overlies conformably the slope and fore-slope (open-shelf deposits) of the Reef Complex. It is overlain by the Pliocene Son Mir Calcisiltites, which partially fill the depositional space (basin) in front of the former reefs. Some authors have considered this unit as the lateral equivalent of the evaporitic deposits, which characterize the Late Miocene (Messinian) age in the Mediterranean area. It is composed of dolomite layers and gypsiferous grey marls with shallow-water mollusks, stromatolites and fish debris.

Santanyí Limestones:

This unit is today limited in extension to the eastern part of Mallorca (Marina de Llevant), western side of the Palma basin, and to northern Ibiza. It has been considered as facies equivalent to the "Terminal Carbonate Complex" and attributed to the Messinian. It unconformably overlies the erosional surface formed at the top of the reef-core and lagoonal deposits of the Reef Complex and is overlain unconformably by the Palma Siltstones of Pleistocene age. This last erosional surface is thought to correspond to the base of the Pleistocene. From the 30-m-thick deposits several sub-facies associations have been described:

(1) **Miliolid packstone and grainstone** with vertical root moulds considered as indicative of near shore lagoons/mangrove swamps.
(2) **Stromatolitic bindstones and mudstones** deposited in a regressive succession, locally with spectacular thrombolites and stromatolites. These form giant domes (15 m long and 4 m high) interpreted as of subtidal origin at the base, are overlaid by small domes (1 m diameter, 30 cm high) of intertidal origin and finally at the top by planar stromatolites of supratidal origin.
(3) **Cross-bedded oolitic grainstone** with giant subtidal thrombolites and stromatolites (oolitic shoals).

Stratigraphic Correlation of the Bonanova Marls, the Gypsum and Grey Marls and the Santanyí Limestone units:

The Santanyí Limestone is generally assigned to the Messinian, equivalent to the Terminal Carbonate Complex of Esteban (1996). Nevertheless, the stratigraphic correlation between the Santanyí Limestones and the Reef Complex (Fig. 1B) is uncertain because of the lack of chronostratigraphic data. This is not just a regional problem as it is still controversial the stratigraphic record of climatic and paleoceanographic changes in the Mediterranean during the late Messinian (e.g.: Clauzon et al., 1996;

Keogh and Butler, 1999). Cornée et al. (2002) have shown that the onset of the Sorbas gypsum deposition (Southern Spain), considered as the marker of the Messinian Salinity Crisis onset, is contemporaneous with aggrading Porites reef building of the terminal carbonate complex of Melilla. Pomar et al. (1996) and Pomar and Ward (1999) have shown coral reefs to build a 20 km prograding platform that ended when a major fall in sea level allowed shallow-water dolostones and evaporites to accumulate in the previous basinal setting (Gypsum and Grey Marls Unit; **Figure 9**). Moreover, Pomar (2001) has shown the good match between the sea-level cycles inferred from the reef-crest line for the megasets of sigmoids with the oxygen-isotope curve built by Abreu and Haddad (1998) as a proxy of eustatic sea-level changes. According to this match, the reefal platform progradation ended with a major fall in sea level during Late Messinian Messinian.

In the southeastern coastal outcrops of Mallorca, the erosional surface on top of the Reef Complex and underlying the Santanyí Limestones represents erosion during a relative fall of sea level. In basin-margin settings, like near Palma, the regressive Bonanova Marls Unit may represent deposition during fall of sea level. If this fall of sea level had been time equivalent to a major lowstand of the Messinian sea level, then the shallow-platform carbonate rocks of the Santanyí Limestones above this surface probably would have been deposited after the time of extensive evaporite deposition in the western Mediterranean. However, deeper-platform- and basinal facies equivalents of the Santanyí Limestones are unrecognized on Mallorca, making this interpretation difficult to substantiate. Cornée et al. (2004) consider this unconformity to be related to major environmental–paleo-oceanographic changes in the Mediterranean, rather than to a major sea-level drop or to climatic change

POST MIOCENE ROCKS

Pliocene deposits are only known on Mallorca, where these units comprise a regressive succession with a maximum thickness of 370 m in the Palma Basin, overlying a major erosion surface on top of previously described units toward the margins. Environments of deposition range from shallow marine (Son Mir calcisiltites) at the base, to eolian (Sant Jordi calcarenites) at the top. Both units represent the latest infilling of the remaining basins rimmed by the Miocene reefs. The calcisiltites contain *Ammussium* and planktonic foraminifera. The foraminiferal assemblage dates this unit as Early Pliocene.

Pleistocene deposits include up to 200-m-thick conglomerates and red silts in the grabens of Mallorca. Eolian calcarenites interbedded with red silts (paleosoils) of Pleistocene and Holocene ages are common in all the Balearic Islands.

THE REEF COMPLEX

Development of coral reefs was a widespread feature in the western Mediterranean during Late Miocene, and the Balearic Islands (Mallorca, Menorca, Ibiza and Formentera) were near the northern limit of this reef growth **(Figure 10 A**). In the Balearic area, these reef complexes developed in shallow submerged areas around islands resulting from Alpine (Middle Miocene) orogeny. The most extensive progradational platforms are on the southern margins of the three largest islands (**Figure 10 B**).

The largest Upper Miocene prograding platform in Western Mediterranean is the Llucmajor platform on southern Mallorca, a 20-km wide belt of reefal limestone and dolomite (**Figures 10 B & 11**). Here, the "Reef Complex" crops out along 20 km of the high sea cliffs in the Cap Blanc area. These sea cliffs display in exquisite detail the facies architecture of part of the reef-rimmed carbonate shelf.

The platform is mainly flat-lying with only slight tilting associated with basins subsidence and strike-slip faulting during the Pliocene and early Pleistocene. The possible influence of gentle uplift on the depositional patterns cannot be ruled out. Nevertheless, the lack of terrigenous influx onto this flat-lying platform suggests that there was tectonic stability on Mallorca during the time of deposition of this platform. Loading subsidence probably has also not significant influenced on the lithification of these rocks as indicated by their low density (20-60% of porosity). This may well be due to the short time (on the order of 2 My) in which this sheet-like unit prograded across the shallow platform (Pomar and Ward, 1994). Additionally, the excellent preservation of large primary **(Figure 12)** and secondary pores is considered as indicative that the Llucmajor carbonate platform has been buried only a few tens of meters at most.

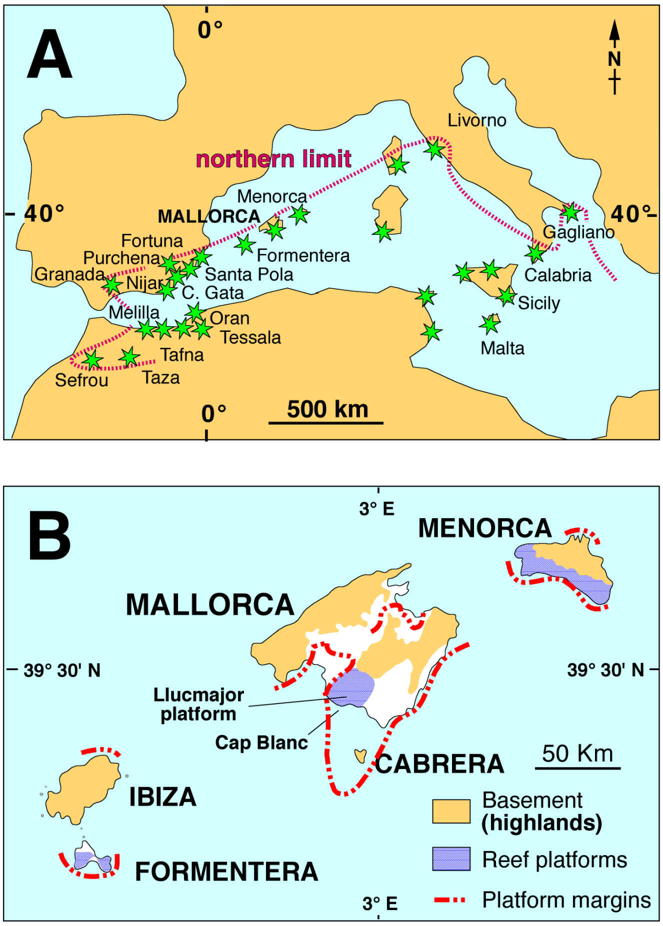


Figure 10. A: Upper Miocene reefs are abundant in Western Mediterranean; the "northern limit" marks the approximate northernmost position of Late Miocene reef growth. B: Late Miocene carbonate platforms around the Balearic Islands prograded preferentially to the south. (Pomar et a., 1996).

LITHOFACIES

The complete exposures in vertical sea-cliffs at Cap Blanc area allowed to establish a detailed facies model **(Figure 14)** and to create a high-resolution genetic model for the architecture for the progradational reef platform. The rocks are commonly partly- to completely dolomitized. Four main lithofacies can be distinguished in the Llucmajor Platform:

Figure 11. Eastward view of the Llucmajor platform.

Figure 12. Large-scale primary pore (framework porosity) within the reef core lithofacies, near Cap Blanc (Pomar et a., 1996)**.**

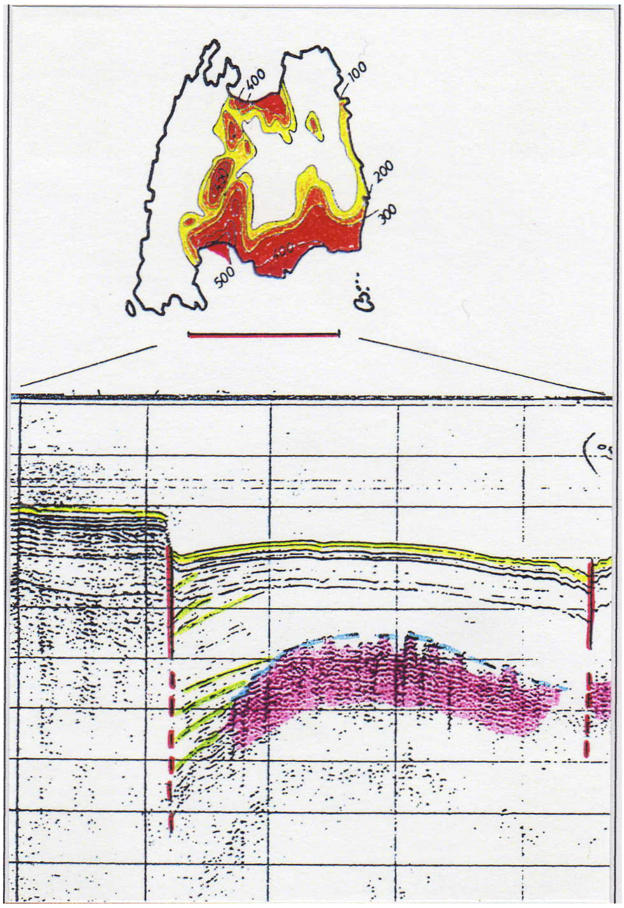


Figure 13. Seismic line offshore Mallorca. Upper Miocene rocks (pink) are flexured and onlapped by Pliocene deposits (yellow). The strike-slip faults affect the Pleistocene.

Lagoonal lithofacies:

The lagoonal lithofacies are characterized by horizontal beds, bounded by erosional surfaces. These lagoonal rocks can be differentiated broadly into "outer-lagoon", "middle lagoon" and "inner-lagoon" lithofacies.

Outer lagoon

Lagoonal rocks, behind the reef core (**Figures 14, 15 & 16**), are characterized by coral patch reefs and horizontal layers of skeletal grainstone and packstone with lenses of coral breccia. Patch reefs in older parts of the reef-lagoon complex (Cala Pi area) are composed of *Porites*, *Tarbellastraea* and minor amounts of *Siderastraea*, but in younger parts (near Cap Blanc) they are almost entirely *Porites*. Larger coral patches are about 5-10 m in diameter with inter-reef areas about the same width. Massive domal and columnar coral colonies, some as large as 2 m in diameter, characterize the outermost-lagoon lithofacies, while smaller hemispheroidal heads are typical farther inland. Most corals are encrusted and interlayered with red algae, and commonly they are intensely bored by pholads, sponges and worms. Outer-lagoon grainstone and packstone are composed (**Figure 16**) of abundant red algal fragments and rhodoliths, echinoids, benthic foraminifera and mollusks. Serpulid worm tubes, *Halimeda*, bryozoans, miliolids and peloids are common to rare constituents. Beds typically lack internal stratification. Erosional discontinuities or hard grounds are common, and many of these surfaces are perforated by mollusk and worm (?) borings. Some scalloped and pitted discontinuities separating outer-lagoon units in the Vallgornera area are probable microkarst surfaces. One such surface is encrusted with large oysters.

Middle lagoon

Middle lagoon lithofacies is built by 1-5 m thick horizontal layers lacking internal stratification and with some small coral heads. These layers are commonly composed of packstone/grainstone with red algae, echinoids, benthic foraminifera and mollusks (**Figure 16**). Bryozoan, Halimeda, and coral fragments can be present, as well as peloids and ceritid gastropods. Stratification of some thicker grainstone units grade upward from low-angle trough-crossbedded, to medium-scale trough-crossbedded to flat-laminated. This bedding and abundance of miliolids, peloids, mollusks and red algae in these grainstones indicate that sandy shoals and/or bars built to sea level in the interior parts of the lagoon.

Inner lagoon

Lithofacies are composed by thin- to medium-bedded grainstone, packstone, and mudstone layers. Miliolid foraminifera and mollusks are abundant throughout (**Figure 16**). Locally also other foraminifera like alveolinids, soritids, and trochamminids can be found. Some beds are mainly composed by pellets and peloids, while in others ceritid gastropods are dominant. Some ooids and ostracods may also be present, as well as red algae, oncolites, and oogonia of charophyta. This lithofacies also includes stromatolites and thrombolites, subaerial crusts, and paleosoils. Abundant vertical rhizocretions are preserved in mangrove-swamp lime mudstone. Other zones of root traces are associated with paleosoils and subaerial crusts. Intraclasts are common in some layers, and blackened lime-mudstone intraclasts occur just above some caliche crusts.

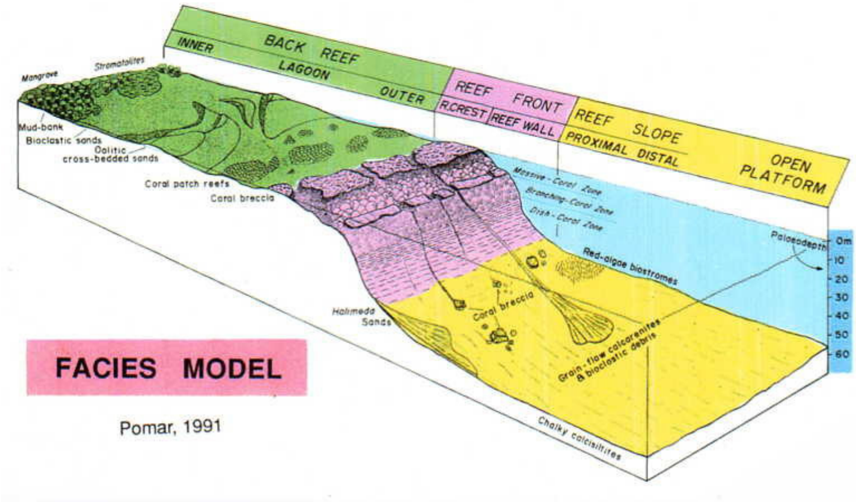


Figure 14. Facies model.

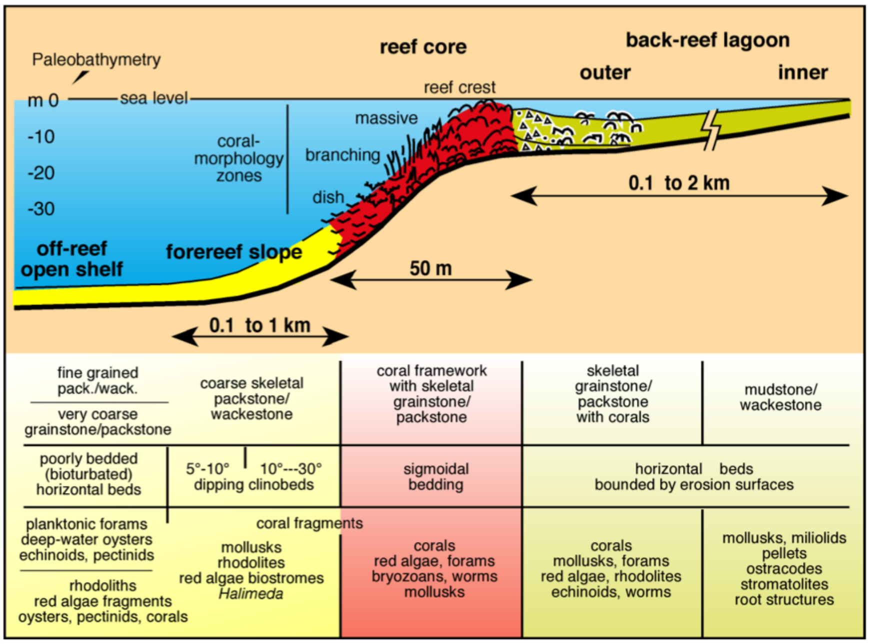


Figure 15 Textures, bedding and components of the reef complex lithofacies (Pomar et al., 1996)**.**

COSTITUENTS	OUTER LAGOON	MIDDLE LAGOON	INNER LAGOON	ROOT ZONE	STROMATOLITE	TRANSGRESSIVE GRAINSTONE	BEACH
worm tubes	r						
corals	r	r					
Halimeda	r	r					
bryozoans	r	r					
red algae	XXXXX	CCC	r			r	CCC
echinoids	XXXXX	CCC	r	r		r	r
bentic forams	CCC	CCC	r			r	r
molluscs	CCC	CCC	XXXXX		r	XXXXX	XXXXX
miliolids	r	CCC	XXXXX		r	CCC	CCC
peloids	r	r	CCC	XXXXX	CCC	XXXXX	XXXXX
pellets		r	XXXXX	XXXXX		XXXXX	XXXXX
ceritid gast.		r	CCC	r		CCC	
ooids			r				r
ostracodes			r				
calcisphere			r				

XXXXX: abundant > 25%

CCC: common 25% - 5%

r: rare < 5%

Figure 16 Components distribution in the lagoonal lithofacies (Pomar et al., 1996)**.**

Reef-Core lithofacies

Massive coral-reef limestone and dolostone, with a characteristic sigmoidal bedding (**Figure 15)** inter-finger landward with the lagoonal lithofacies and basinward with the fore reef-slope lithofacies. In most of the platform, the reef framework is constructed by only three genera (*Porites*, *Tarbellastraea* and minor amounts of *Siderastraea*), but at the Cap Blanc area, the only reef builder is *Porites*.

Secondary framework components are encrustations of red algae, foraminifera, bryozoans, worm tubes, and vermetid gastropods as well as microcrystalline rinds and crusts (cyanobacteria?). The excellent exposures of these reefs reveal a well-developed vertical zonation of the growth forms of *Porites*. Where the entire reef sequence is exposed, three zones of coral morphology can be distinguished (**Figures 15 & 17)**

- a lower zone of "dish corals",
- a middle zone of "branching corals", and
- an upper zone of "massive corals".

A section through the typical vertical zonation will be reviewed during our visit to outcrops on the Cap Blanc sea cliff.

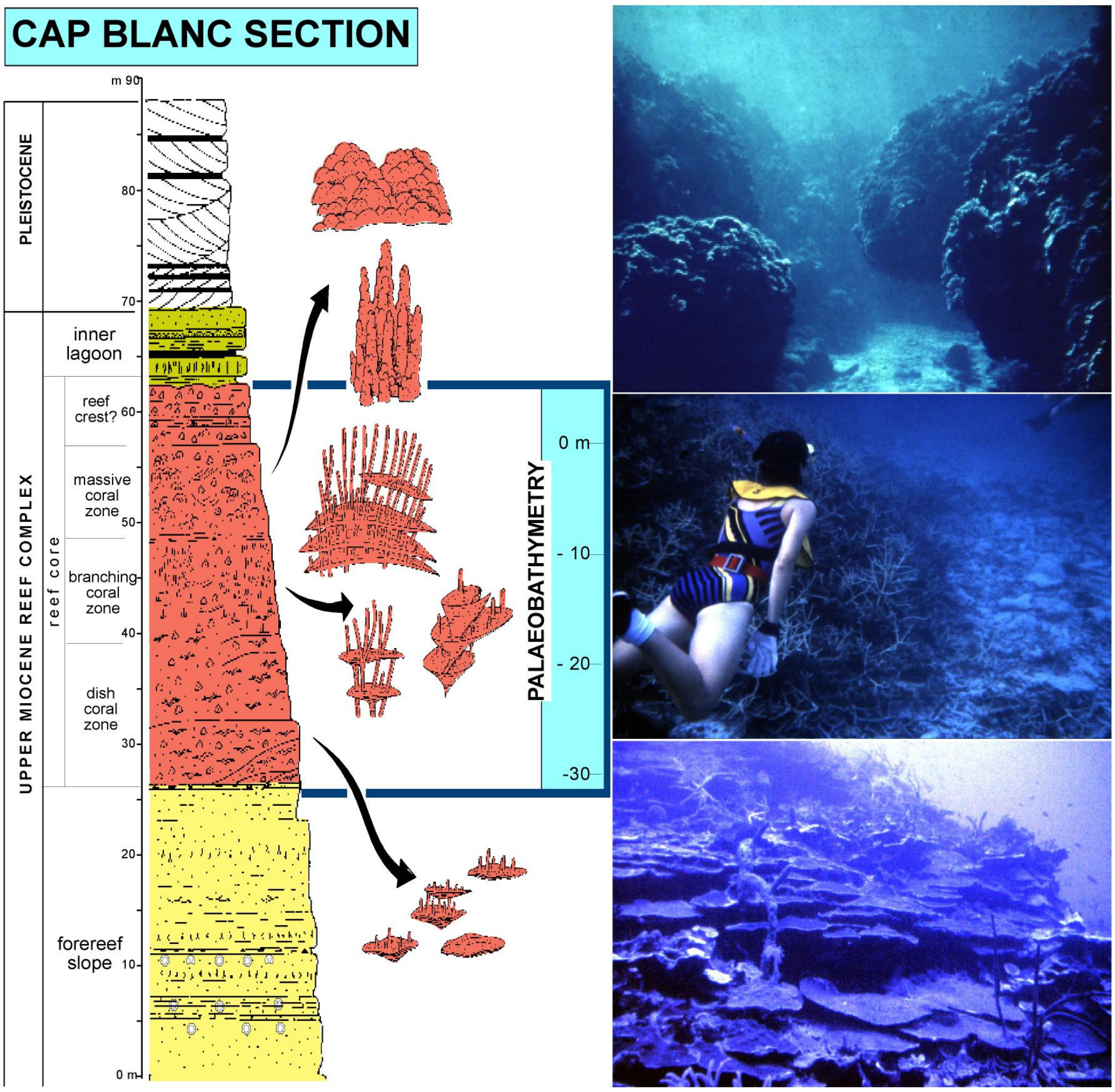


Figure 17 The Cap Blanc section; shape of the coral colonies and inferred paleobathymetry (Pomar et a., 1996)**.**
Modern corals with different growth form from the Caribbean Sea.

The dish-coral zone (**Figures 15 & 17**) at Cap Blanc is about 15-20 m thick and rests on a clearly recognizable downlap surface. At other localities, this lower zone conformably overlies reef-slope beds of coral rubble and skeletal dolograinstone/packstone. Characteristic coral growth form in the lower reef are wavy plates up to 30 cm in diameter. Platy forms with finger-like vertical protuberances become more abundant upward. Inter-coral spaces are filled with dolowackestone and dolopackstone containing fine detritus of echinoids, red algae, foraminifera, mollusks, and ostracods. Borings on the in-situ corals of this zone are scarce. This contrasts to the highly bored coral fragments in the underlying reef-slope deposits, which were derived from shallow-water corals. Coral rubble with interparticle porosity

The branching coral zone (**Figure 15 & 17**) is 7.5-m thick in Cap Blanc and is characterized by stick- to branch-shaped corals colonies. The largest branched *Porites* form thickets that are 2-3 m across and up to 4-m high. Between some of the branching-coral build-ups are channel deposits of coral dolorudstone and coarse skeletal dolograinstone with inter grown laminar corals. The constructional reefs and associated channels represent the "spurs and grooves" described from many modern reef fronts. Within the branching framework, layers of dolograinstone and dolopackstone alternate with laminar coral bridges; these layers of coral bridges and sediment are dipping toward the grooves. Allochemical components are red algae, corals, worm tubes, mollusks, and echinoids. Encrusting organisms within the coral framework in this zone are red algae, bryozoans, worms, foraminifera). Only small sponge borings are observed on the stick and branching corals.

In the lower part of the branching coral zone, large framework cavities are 2-25 cm across and several cm high, but cavities larger than 2 m wide and 1 m high have been found. One exceptionally large cavity near Cap Blanc is up to 6 m wide and 2 m high (**Figure 12**). These large cavities are partly filled with cones and fans of coarse skeletal dolograinstone filtered through the framework from above, indicating the presence of (large) primary megapores.

The massive coral zone (**Figure 15 & 17**) is characterized by diverse coral morphologies with abundant encrustations and borings. In Cap Blanc this zone is about 7.5 m thick and is constructed by mainly massive, head-like, *Porites*. Other corals like *Tarbellastraea* and *Siderastraea* are minor constituents.

Channels filled with dolograinstone and dolorudstone trend perpendicular to the reef tract, suggesting that the spur-and-groove system extended into this morphology zone. In the upper part of the reef, massive *Porites* colonies are thickly encrusted by red algae and riddled with pholad and sponge borings. Other encrusting organisms in this zone are foraminifera, worms, bryozoans, and vermetid gastropods. The reef crest is characterized by small massive and laminar *Porites* and a few spherical heads of *Siderastraea*. In-situ coral build-ups are inter layered with lenses of coral breccia and large rhodoliths. Several erosional discontinuities truncate both coral colonies and penecontemporaneously lithified sediment.

Reef Slope lithofacies

The reef-slope lithofacies (**Figures 14 & 15)** is represented by a succession of clinoform-beds tens to hundreds of meters long, consisting of dolomitized coarse-skeletal grainstone and packstone. Two different depositional realms can be differentiated within these deposits:

Distal-reef-slope

These deposits are gently dipping (less than 10°), and they consist of poorly stratified, extensively burrowed red algae-mollusk dolopackstone and dolograinstone. Characteristic components in these beds are sand- to pebble-sized rhodoliths, and megafossils like whole-shell bivalves, and large oysters. Locally bioherms formed by branching and encrusting red algae are found.

Proximal-reef-slope

These deposits are more steeply dipping (10° to 30°) and consisting of dolomitized skeletal and intraclastic grainstone, packstone, rudstone, and floatstone that inter finger landward with in situ coral reefs. Lenticular layers of coral rubble and skeletal dolograinstone are common. Blocks of reef rock up to 80 cm in diameter occur in the upper layers. Fossils of the proximal reef slope are red algae fragments and rhodoliths, coral fragments, bivalves (some whole), gastropods (including vermetids), echinoids, bryozoans, and the green alga *Halimeda*. Although *Halimeda* fragments occur throughout the fore reef and peri-reef deposits, this alga is a principal component only in the youngest part of the fore reef-slope, which is exposed 8-11 km Northwest of Cap Blanc.

Open-shelf Lithofacies

Open-shelf (shallow basin) lithofacies (**Figure 15)** is represented by flat lying, poorly bedded (bioturbated) and mostly dolomitized fine-grained skeletal packstone/wackestone. There are two main types of open-shelf lithofacies:

Red algal lithofacies.
It consists of coarse-grained, poorly sorted, red algae-rich grainstone/packstone to rudstone/floatstone with 1- to 15-cm rhodoliths. Clumps and layers of branching red algae are common in some intervals. Other skeletal constituents include large oysters, pectinids, the larger foraminifer *Heterostegina* and the coral *Tarbellastraea*.

Packstone-wackestone with planktonic foraminifers.
This lithofacies commonly overlies the red-algae-rich open-shelf deposits in cores and in outcrops along the western coast of the Llucmajor Platform, and it can be traced in those outcrops into distal-slope strata of the reef complex. It consists of fine-grained packstone and wackestone, rich in planktonic foraminifers, ostracodes and silt- to very-fine-sand-size detritus of oysters, other bivalves, echinoids and red algae. Characteristic megafossils are oysters (*Neopycnodonte navicularis*), large irregular echinoids, pectinid bivalves, small scaphopods and scarce sclerosponges.

Locally the open-shelf and distal-reef-slope units are cut by 1- to 8-cm-wide near-vertical fractures ("neptunian dikes") filled with laminated dolomudstone and dolowackestone.

REEF PLATFORM ARCHITECTURE AND RESERVOIR PREDICTION

As previously discussed ("The Reef Complex, Mallorca") tectonic movements are not thought to have a significant influence on the stratigraphical development of the Cap Blanc platform. Hence, its overall build-up as well as the above described lithofacies types and diagenetic overprint are attributed to sea-level changes which cyclicity can be interpreted based on sequence stratigraphical concepts.

Therefore, it is felt that a stratigraphical model based on the observations at Cap Blanc can be used as a predictive tool for the interpretation of sedimentary architecture and general reservoir characteristics of carbonate packages deposited on relatively stable platforms during time intervals of known sea-level cyclicity.

The Basic Building Block

The basic building block of the Llucmajor platform is a sigmoidal shaped depositional unit (called here a "SIGMOID" and considered as representing 7th order cyclicity *sensu* Haq et al., 1987/6th order *sensu* Abreu & Haddad, 1998). It is composed of (**Figures 15 & 18**):

-) a horizontal lagoonal bed passing basinward into
-) a sigmoidal shaped reef-core body, then into
-) a reef-slope clinoform and finally into
-) a horizontal open-shelf bed.

This accretional unit is bounded by an erosional surface in the upper part (lagoon and reef-core lithofacies) and by their correlative conformity in the lower part (lower portion of reef-core, slope and open-shelf lithofacies). Some of these basic accretional units are wedge-shaped as result of non-depositional or erosional truncation of its upper part (lagoon and upper portion of reef-core lithofacies), or both.

Completely preserved sigmoids often show an internal arrangement of the distribution of lithofacies:

In the upper portion of the reef-core facies, massive (shallow-water) corals encrusting the lower erosional surface pass upward into branching forms, indicating deepening upward conditions (increase of accommodation). In the lower portion, dish-shaped (deeper-water) coral colonies sharply and conformably overlie the proximal reef-slope deposits of the previous unit, and pass upward into coarse-grained reef-slope deposits. This also indicates deepening upward conditions (increase of accommodation). Nevertheless, in some sigmoids, coral-morphology is characterized by a shallowing-upwards zonation indicating sedimentary aggradation (decrease of accommodation). The vertical succession (**Figure 19**) within the reef-core reflect aggradation during sea-level rise, with the shallowing- or deepening-upward trends depending on the ratios between sea-level rise and carbonate production/sedimentation rates (accommodation vs. production). The erosional surface truncates the branching corals in the reef-core facies and, commonly, it is incrusted by shallow-water, massive corals. This shift of the coral-morphology zones (from relatively deeper to shallower) across the boundaries reflects the amount of sea-level fall. Boundaries between consecutive sigmoids that do not show a clear shift of the coral-morphology zones may also be explained as result of other processes. In general, the lack of sub aerial-exposure features at most of the sigmoid boundaries lead us to interpret them as the result of lowered wave base during a sea-level fall period, during which the platform remained submerged. However, this observation can also be interpreted as the result of marine erosion onto a subaerial exposure surface, followed by subsequent flooding and coral growth.

Figure 18. Sigmoids at Punta Negra.

ROCK UNITS	ESTIMATED PERIOD	AMPLITUDE of sea-level cycles	MAXIMUM PROGRADATION	Order of sea-level cycles	
				Haq et al (1987)	Abreu & Haddad (1998)
Llucmajor Platform	1.9 Ma	-	20 km	3rd order	
Megasets of sigmoids	400 ka ?	~ 100 m	7 km	4th order	3rd order
Cosets of sigmoids	100 ka	60-70 m	2 km	5th order	4th order
Sets of sigmoids	?	20-30 m	200 m	6th order	5th order
Sigmoids	?	< 15 m	20 m	7th order	6th order

Table 1

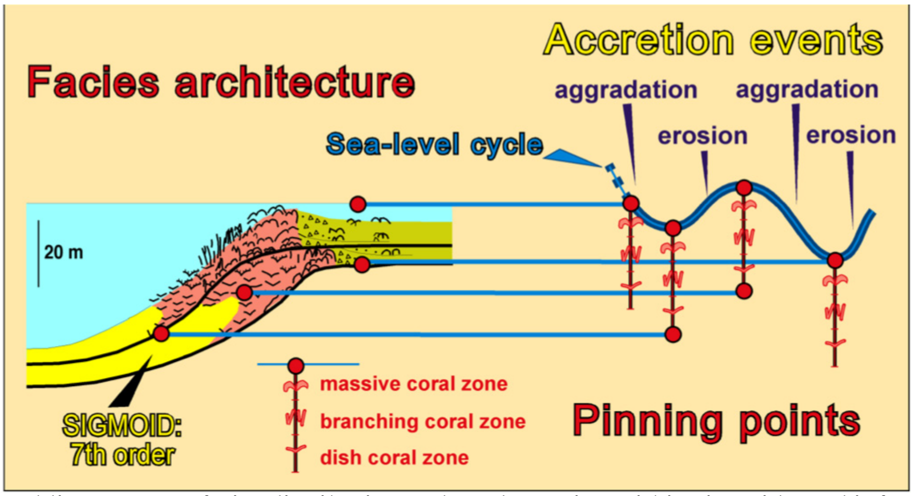


Figure 19. Bedding patterns, facies distribution and coral zonation within sigmoids, and inferred genetic relationship to the highest-frequency sea-level fluctuation (Pomar and Ward, 1995)**.**

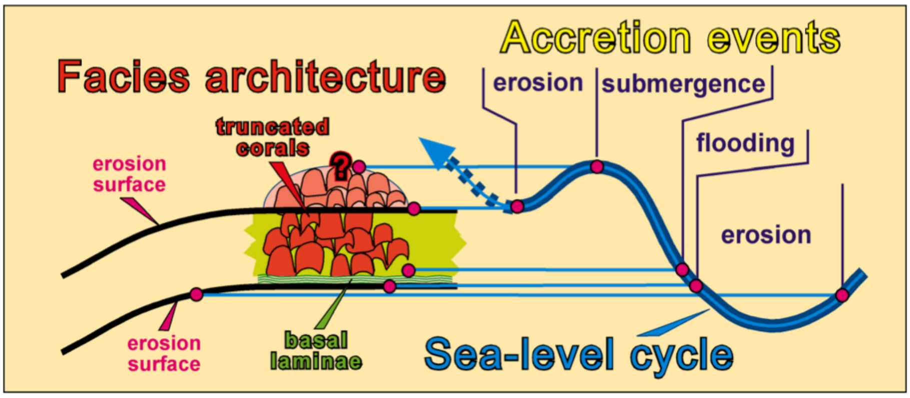


Figure 20. Internal organization of facies and bounding surfaces within a lagoonal bed, and its relationship to accretion/erosion processes induced by the high-frequency sea-level cyclicity (Pomar and Ward, 1995)**.**

In the lagoonal facies, thin laminites or gastropod-rich wackestone (restricted facies) resting on the erosional surface are overlain by packstone, wackestone, and grainstone with red algae, echinoids, mollusks, and benthic foraminifera (open lagoon) (**Figure 20**). In outer lagoonal facies, the basal laminites are overlain by both, coral-patch reefs and coarse skeletal grainstone (inter patch sediments). The upper erosional surface truncates everything, including the patch-reefs corals and the grainstone sediments of the outer-lagoon facies. Basal laminites record the flooding of the platform top while overlying coral patches record the submergence of the platform to the optimum production conditions. The correlation of the erosional surface from the lagoon to the reef core indicates that it is due to a sea level fall. Consequently, the erosional truncation on top of the coral patches indicates that the upper, shallowing-up, part of the cycle is missing, and can be related to the sea-level fall.

In the reef-slope and open-shelf settings, intense bioturbation can destroy the internal arrangement of the lithofacies and obscure the conformable nature of its boundary.

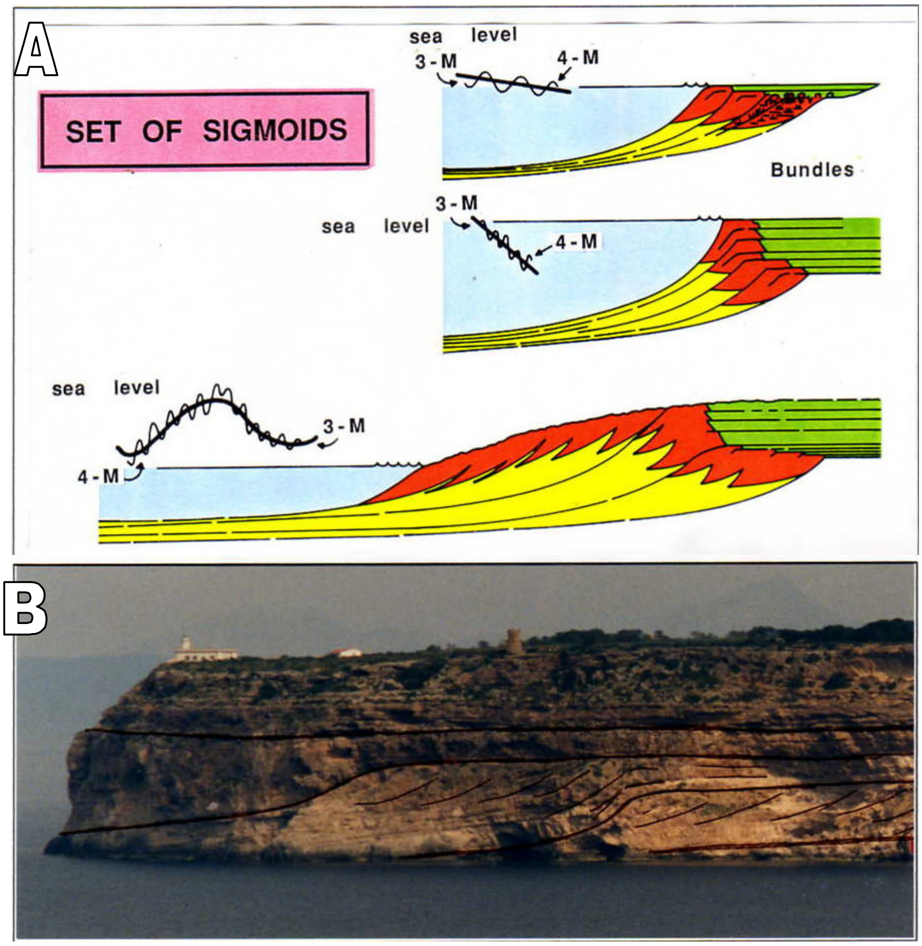


Figure 21 A: Progradational and aggradational bundles of sigmoids compose a Set (Pomar, 1993)**. B: Sets of sigmoids at Cap Banc.**

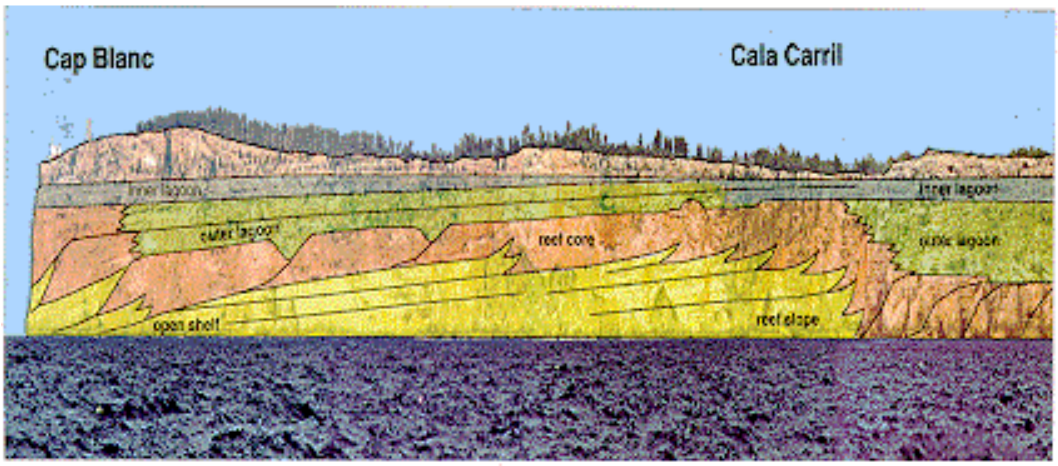


Figure 22: Sets stack in progradational, aggradational and offlapping bundles to form a coset of sigmoids. A coset of sigmoids can be seen on the sea cliffs between Cap Blanc and Cala Carril (horizontal: 2 km; sea cliff at Cap Blanc: 90 m).

Larger-Scale (lower order) Accretional Units

In the sea-cliff outcrops of the Cap Blanc area, the basic accretional units ("SIGMOIDS") are stacked forming different magnitudes of larger-scale accretional units (**Table 1**):

"SIGMOIDS" are stacked in a "**SET of sigmoids**" (**Figure 21**), and sigmoid-sets stacked in a "**COSET of sigmoids**" (**Figure 22**). Basin scale correlation of core data allows recognition of even lower-order accretional units: the "SETS of cosets", or "**MEGASETS**" (**Figure 23**), resulting from the stacking of the cosets of sigmoids. Finally the whole of the Llucmajor platform is considered to be representative for a 3rd order cycle. All of these accretional units (**Figure 23**) have similar characteristics in terms of facies distribution, boundaries and internal stacking of the higher-order units.

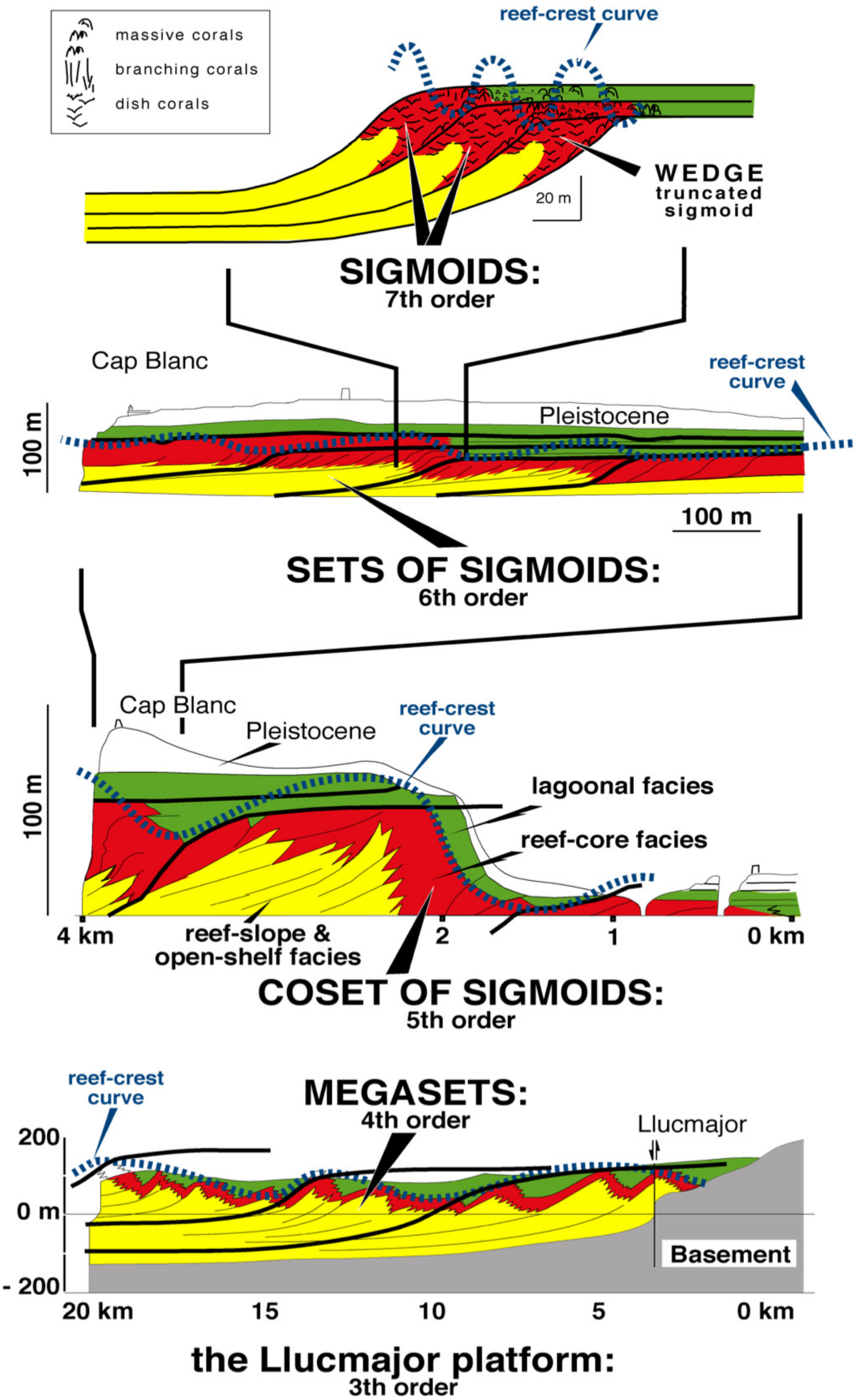


Figure 23. Hierarchical stacking of the accretional units in the Llucmajor Platform, Mallorca (Pomar and Ward, 1994**). Sigmoids, Sets and Cosets can be seen on the sea cliffs. Megasets are interpreted from borehole data. Orders are related to Haq et al. (1987) cycles. Megasets correspond to 3rd-order cycles in Abreu & Haddad (1998) cycles.**

Facies distribution in a set or in a coset of sigmoids (in a basinward direction) is as already described above:

- horizontal lagoonal beds,
- sigmoid-bedded reef-core with wavy configuration (upward and downward shifts of the general progradation), and
- gently inclined reef-slope to open-shelf lithofacies.

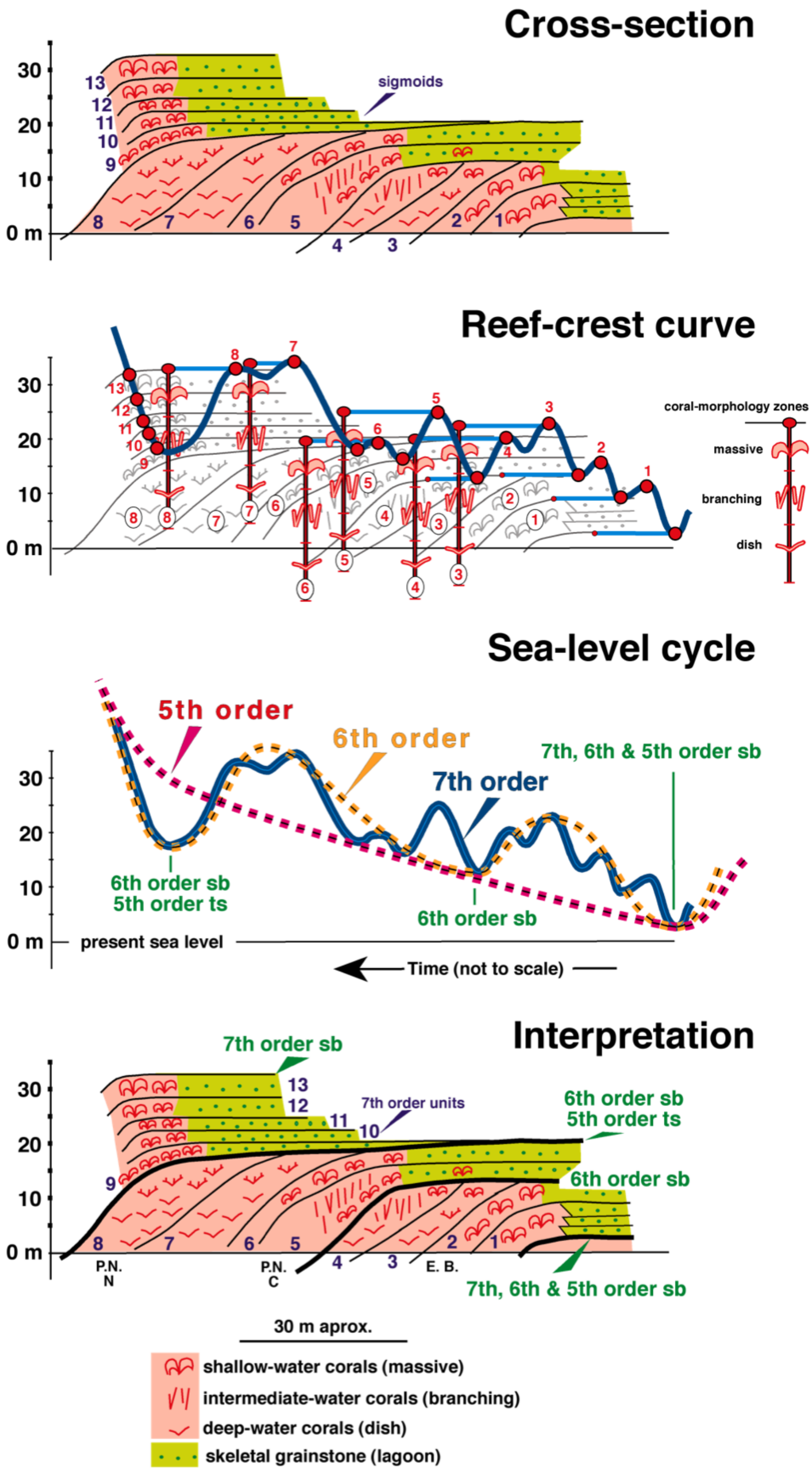


Figure 24. An accurate sea-level curve can be constructed from the changes of the coral-morphology zonation within the accretional units and across bounding surfaces and, subsequently, the hierarchy of the basic accretional units established (Pomar and Ward, 1995**).**

Unit boundaries in the landward part are major erosional surfaces, often marked by caliche or microkarst. Basinward, the unit boundaries are formed by the correlative conformities. The vertical distribution of coral morphologies within the reef facies, as well as subaerial surfaces within the lagoonal facies, show that most depositional cycles resulted from sea-level fluctuations rather than sedimentological (auto cyclical) influences. Moreover, sedimentological observations seem to indicate that the depositional packages were essentially unaffected by early compaction induced by either mechanical or chemical processes. For these reasons, the upward and downward shifts of the reef-core facies and the vertical shifts of coral morphologies within the reef-core facies can be assumed to be representative for the amplitudes of sea-level fluctuations. Thus, the **reef-crest curve** (Pomar, 1991) can be defined by the successive positions of the reef-crest (measured or inferred from the coral-zonation), reflecting the amplitude of relative sea-level fluctuation (**Figures 23 & 24**) and the extent of progradation in time. The amplitude of fluctuation for the megasets is on the order of 100's of meters, with 3 to 6 km of progradation. The cosets of sigmoids show an amplitude of 50-70 meters in 1 to 3 km of reef progradation, and the sets of sigmoids show an amplitude of 20-30 m in a reef progradation of 100s of meters.

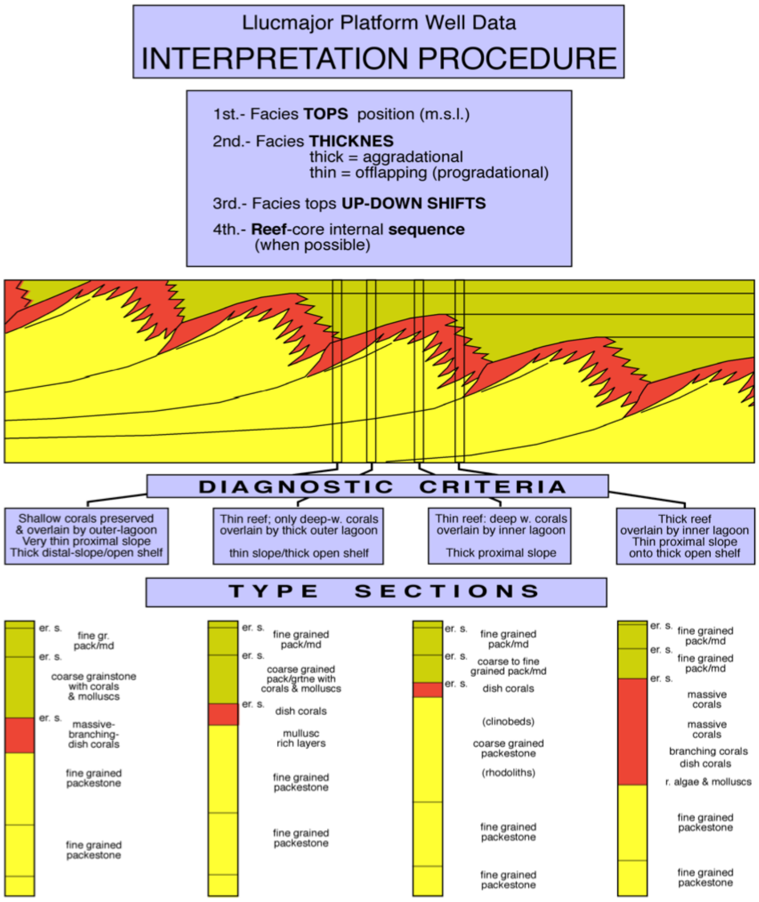


Figure 25. The interpretation procedure considers 4 steps in the analysis of the core data (Pomar and Ward, 1995**).**

Llucmajor platform 3-D architecture

The architectural analysis resulting from sections measured on the sea-cliffs outcrops allowed establishing the diagnostic criteria (**Figure 25**) used for the interpretation of borehole data. Detail logs from cores taken in 70 wells (**Figure 26**) allow to establish the distribution patterns of the reef complex (**Figure 27**), its paleogeography and to construct a three-dimensional model of the reefal platform's architecture. This model is based on interpretation of aggradation, progradation, or offlap patterns from combining several parameters (**Figure 25**):

1st, the relative elevation of the facies tops,

2nd, the reef-core thickness,
3rd, the upward or downward shifts of reef-cores and, when possible,
4th, the reef-core internal succession and the thickness of the coral-morphology zones.

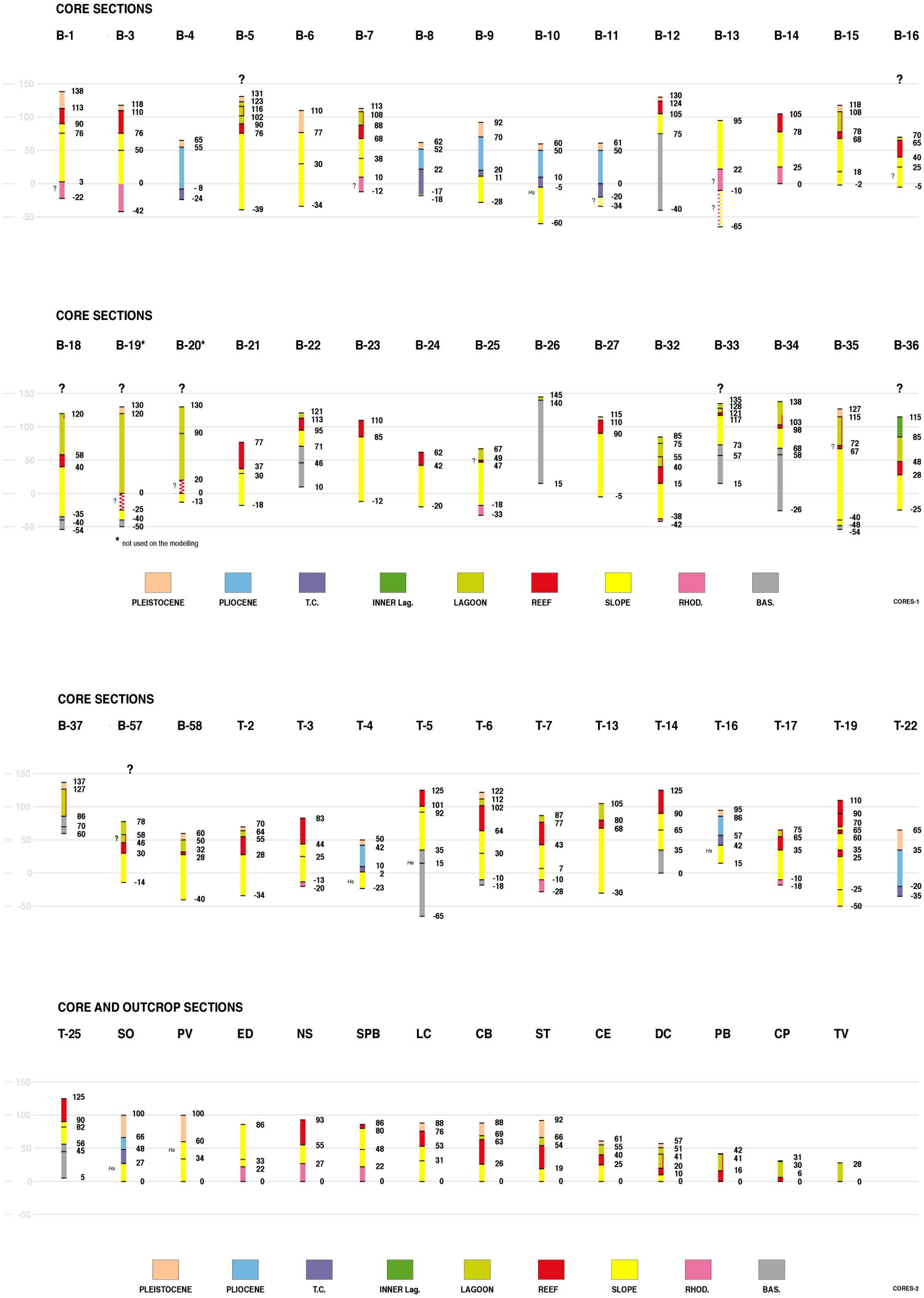


Figure 26. Core and outcrop database.

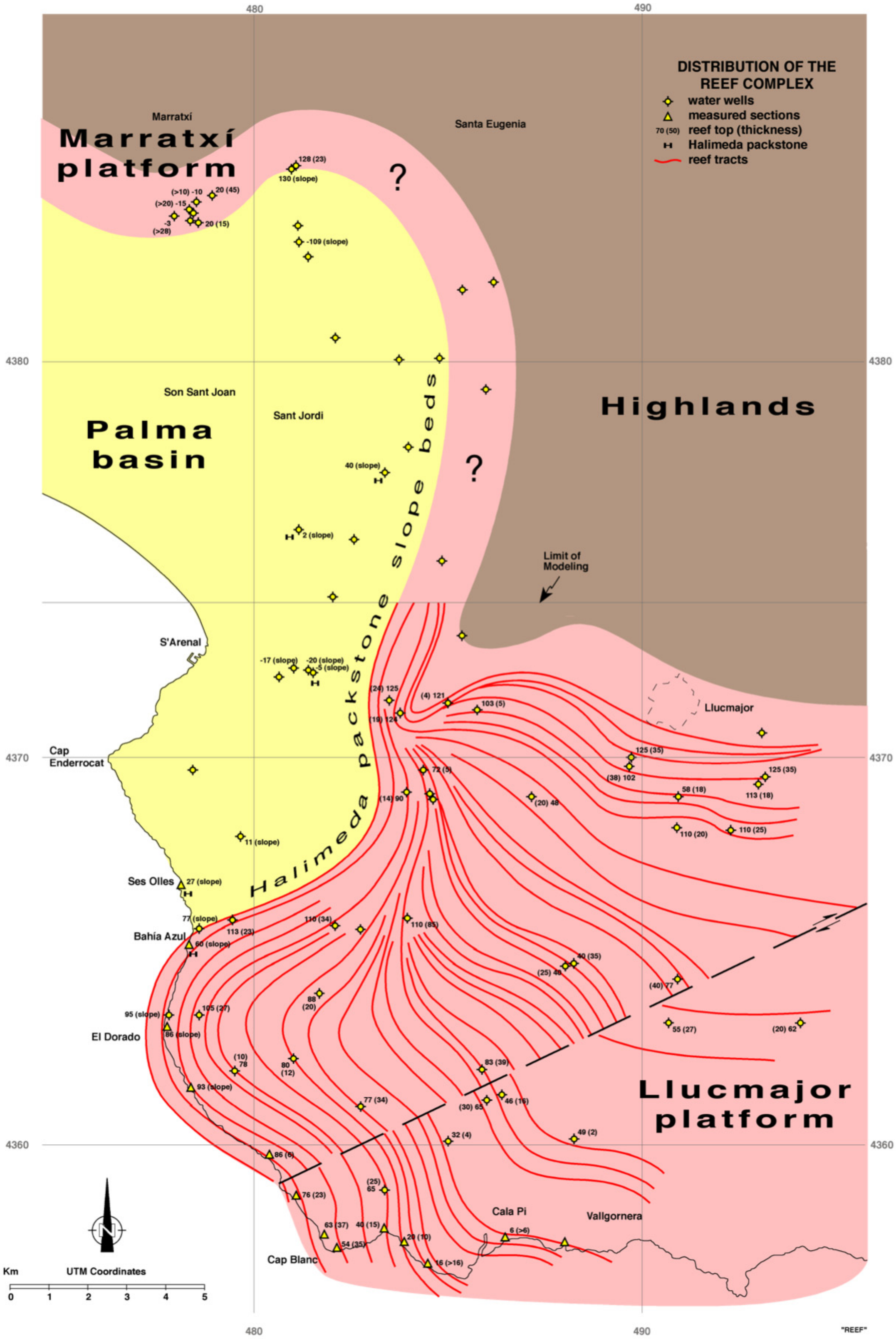


Figure 27. Distribution of the Llucmajor reefal platform and the Palma basin according to core data. A narrow reefal platform (Marratxí) rims the Palma basin to the north (Pomar and Ward, 1995**).**

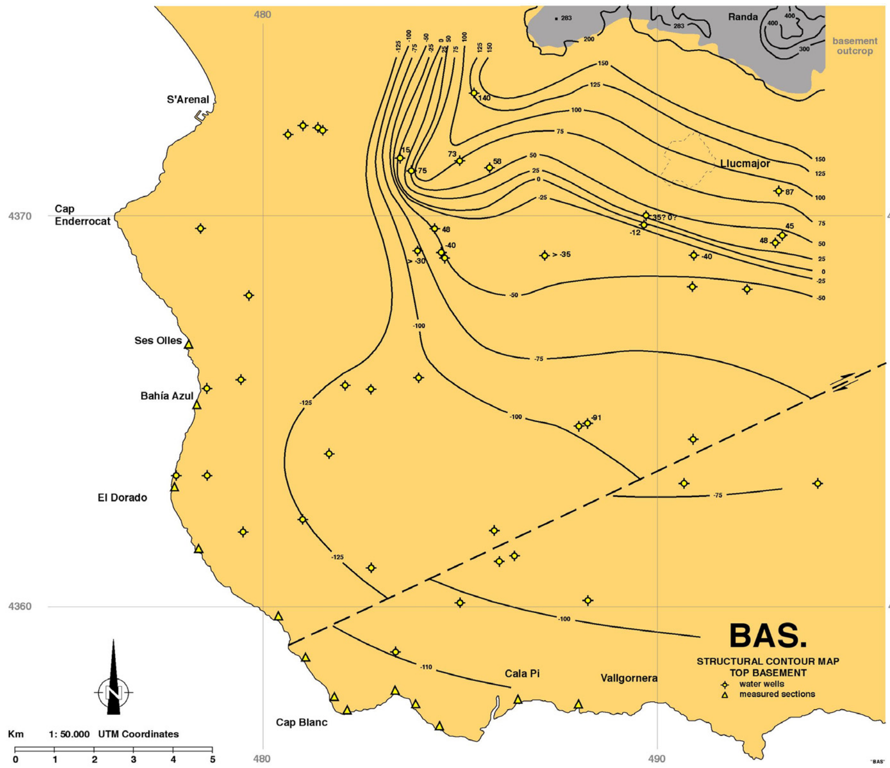


Figure 28. **Basement (pre-Reef-Complex unit) contour lines as traced (and inferred) from borehole data (**Pomar and Ward, 1995**).**

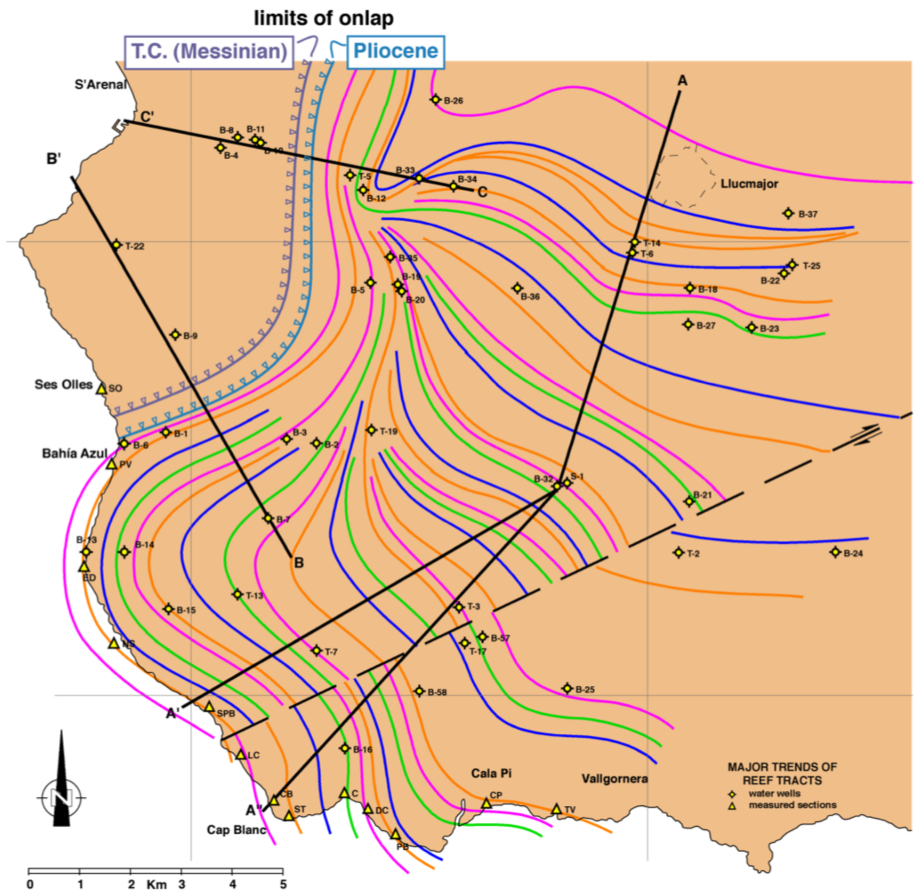


Figure 29. Three-dimensional platform architecture interpreted from integration of well data and measured sections on the sea cliffs. Color reef-tract lines represent the successive position of the progradational reefs (colors are just indicative to compare with figure 30 (Pomar and Ward, 1995**).**

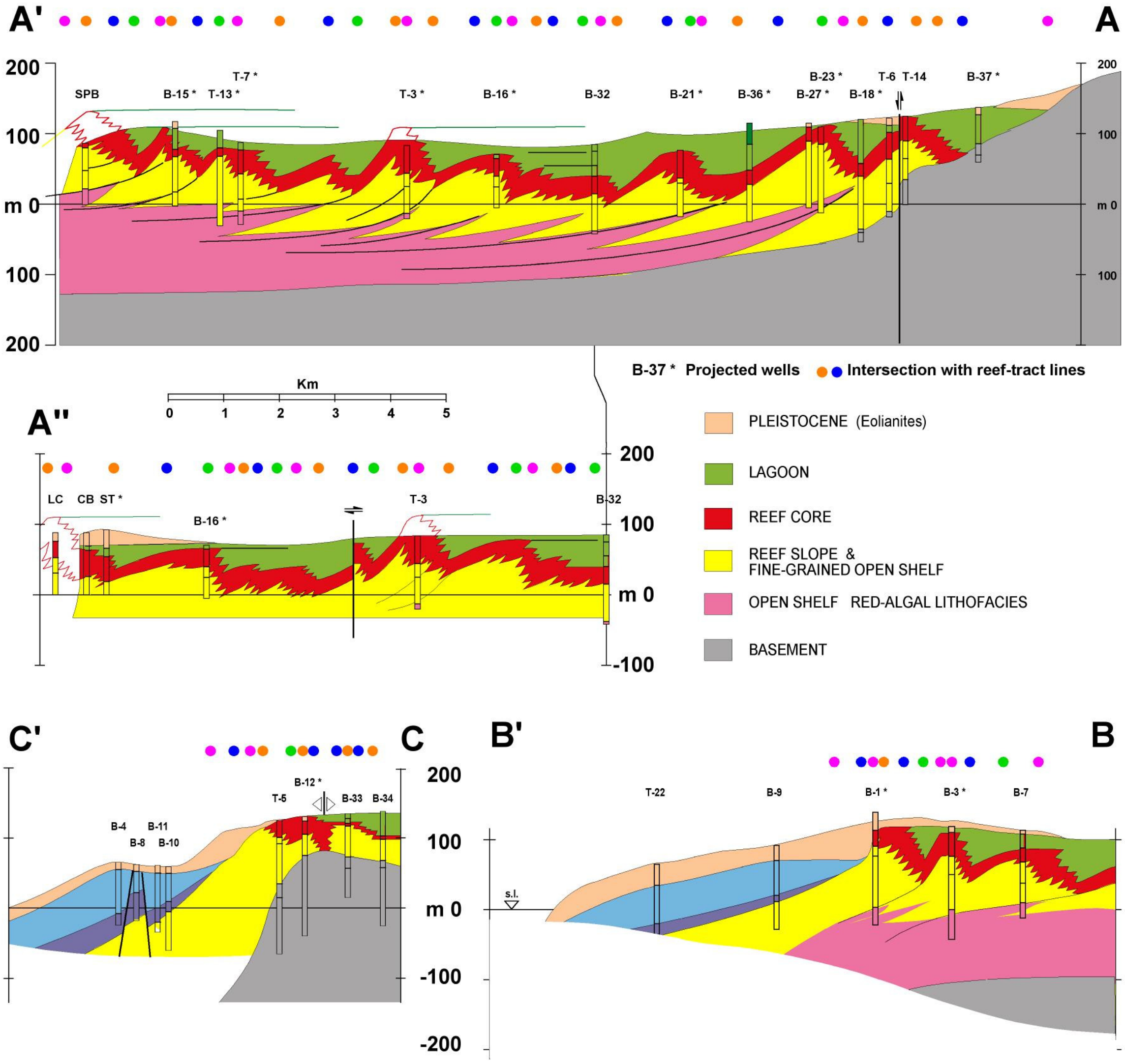


Figure 30. Cross-sections based on borehole data and sea-cliffs section-logs. Interpretation procedure as indicated in Figure 25 (Pomar and Ward, 1995)**.**

This interpretation procedure allows to trace the reef-tract lines (**Figure 29**) and to build cross-sections (**Figure 30**). The reef-tract lines represent the successive position of the reefs prograding over the Llucmajor platform. This interpretation visualizes important differences in the progradation rates, depending on the depositional gradients. Progradation (A-A' in **Figures 29 & 30**) is more important toward the South, where the basin was shallower, and it is dramatically reduced toward the West (C-C' **Figures 29 & 30**), within the margin of the relatively deeper Palma basin. These differences in the amount of progradation as controlled by the platform configuration resulted in the clockwise rotation of the successive reef tracts towards the Palma basin.

SEQUENCE STRATIGRAPHIC IMPLICATIONS

Sequence stratigraphic analysis carried out on the high-frequency accretional units within the Upper Miocene reef complex of the Cap Blanc area shows several differences in the stratigraphic architecture from that represented in the "standard" siliciclastic sequence-stratigraphic models. The Mallorca model, however, is compatible with dynamic models of sequence stratigraphy.

High-frequency Reefal Platform Depositional Sequences

The basic reefal accretional unit, the "sigmoid" has characteristics of a "small" depositional sequence. The arrangement of facies (within a sigmoid and across the erosional boundaries) reflects changes in accommodation, which result from higher-order sea-level fluctuations and they can be equated to the systems tracts. Larger-scale accretional units (sets, cosets and megasets of sigmoids) resulting from hierarchical stacking of sigmoids also have characteristics of depositional sequences. All of them are:

1) sigmoidal in shape,
2) bounded landward by erosional surfaces which pass basinward to correlative conformities,
3) composed of an inner belt of horizontal lagoonal beds, a middle belt of sigmoid-shaped reef-core lithofacies, and an outer belt of reef-slope and open-shelf lithofacies.
4) Changes in stacking patterns allow definition of four systems tracts in all hierarchical units of a category higher than "sigmoids": "low still stand" (LST), "aggrading" (AST), "high still stand" (HST), and "offlapping" (OST). The vertical shifts of the reef-core facies within each system tract are characteristic and therefore allow establishing an accurate relationship with each part of the sea-level cycles (**Figure 31**).

The "low still stand" systems tract (**Figure 31 B**), which forms during the initial sea-level rise after the lowest point of the sea-level cycle, is composed of a relatively thin prograding reef-core facies and poorly developed or absent lagoonal beds. The fore reef-slope and open-shelf facies thin basin wards.

The "aggrading" systems tract (**Figure 31 C**) is formed during the rise of sea level and is characterized by aggradation within all depositional systems (from the lagoon to the open shelf) and therefore it is volumetrically the most important. Lagoonal facies of the AST overlies the prior LST and onlaps onto the erosion surface. Thick reef-core facies shows mainly aggradation without backstepping. The fore reef-slope and the open-shelf facies are also thick and aggradational. This AST differs from transgressive systems tract by the absence of a condensed section above it and the absence of backstepping; only the lagoonal facies shows landward onlapping.

The "high still stand" systems tract (**Figure 31 D**), which forms during the high part of sea-level cycle, is composed of thin progradational reef-core facies, fore reef-slope facies wedging out basinward, and volumetrically condensed open-shelf facies. Commonly, lagoonal beds are absent (if deposited, they may have been eroded during the subsequent sea-level fall).

The "offlapping" systems tract (**Figure 31 E**), which forms during the falling sea level, is composed of thin prograding and downstepping reef-core facies, which downlaps onto the open-shelf facies (of the previous systems tract), without significant fore reef-slope facies. There is no lagoonal facies, and the open-shelf facies are volumetrically condensed. This OST was originally described as "offlapping reefs" by using the Swain's (1949) definition of offlap as "*the progressive offshore regression of the up dip terminations of the sedimentary units within a conformable sequence of rocks, in which each successively younger unit leaves exposed a portion of the older unit on which it lies*". The OST differs from the standard models, which do not envision deposition during sea-level fall. Recently, however, similar units in siliciclastic systems have been designated "stranded parasequences" on the "forced regressive wedge systems tract", "forced-regression" deposits of a lowstand prograding wedge. An erosional surface bounds the OST at the top while its base is formed by a downlap surface. The OST basinward correlates with a condensed interval in which sediments are volumetrically condensed (relatively condensed section).

These Mallorca sequences exhibit other two significant differences with the Exxon-type depositional sequence (**Figure 32**):

* Lowstand fans (LSF) have been not observed, and their temporal equivalent systems tract may be the downstepping reefs (OST) that formed during falling sea level.
* The "classical" backstepping of the transgressive systems tract (TST) is absent. It is because carbonate production on the Llucmajor platform was considerable during sea-level rise, and

the platform evolved from low-stand-progradational into aggradational geometries as sea level started rising.

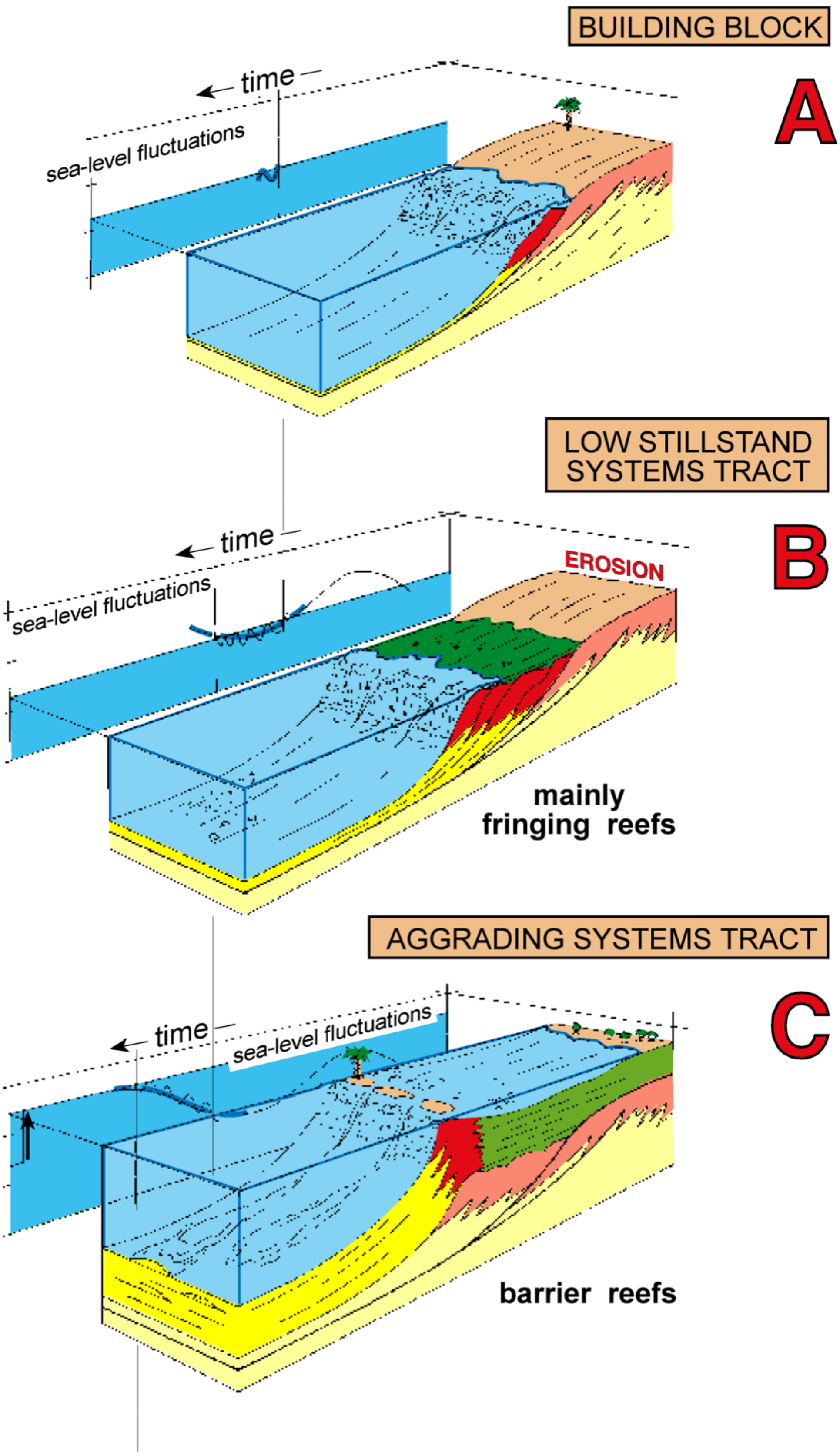


Figure 31 (Pomar and Ward, 1994)**.**

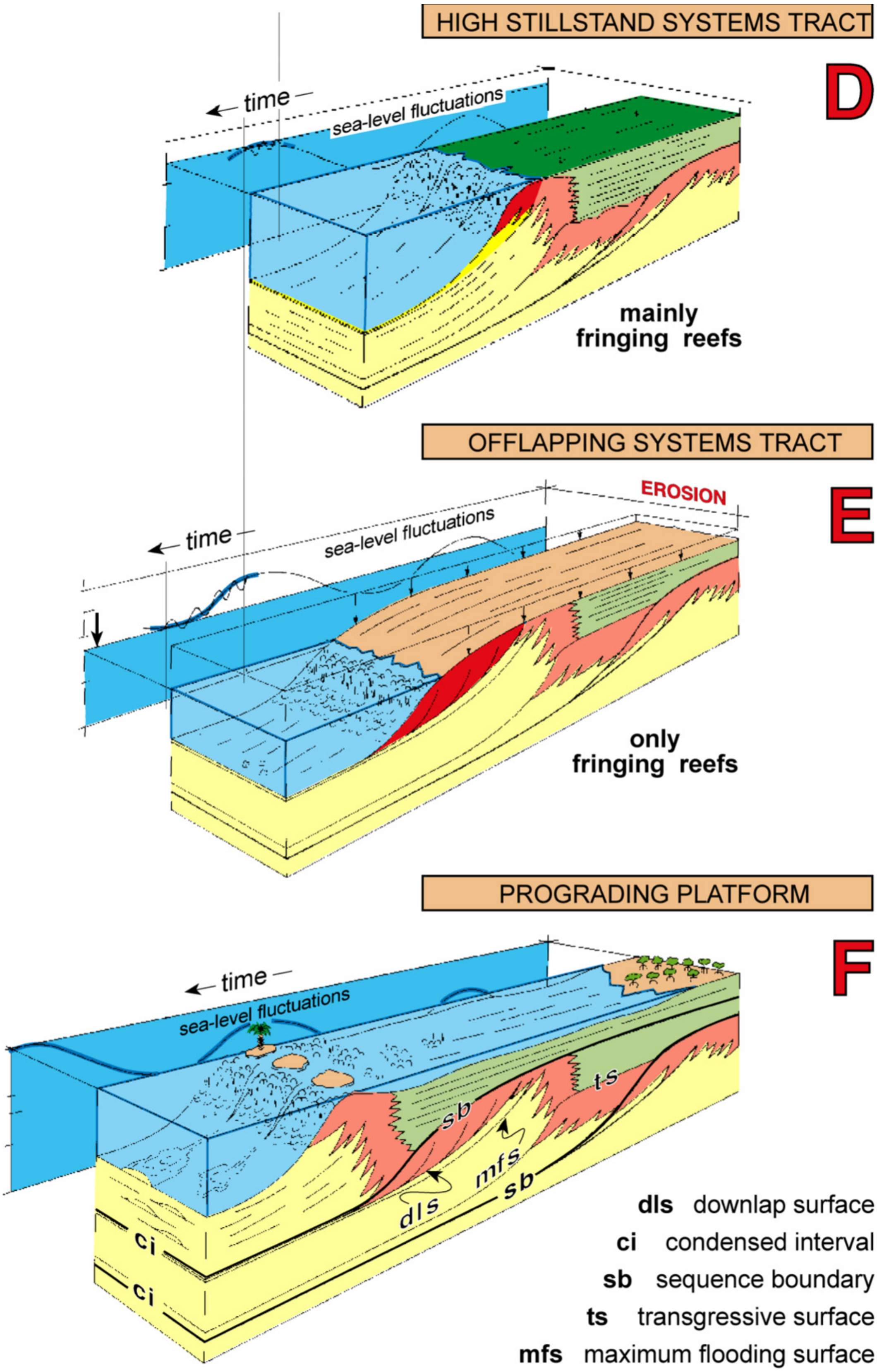


Figure 31 (continuation) (Pomar and Ward, 1994)**.**

Systems Tracts Boundaries

In this carbonate system there are only two relevant surfaces bounding the systems tracts: the erosional surface and the downlap surface basinward, both of which merge into the distally condensed interval (**Figures 31 F & 32**). These two surfaces were formed at the same time, during the period of sea-level fall. The transgressive surface (**ts**) and the maximum flooding surface (**mfs**) are not represented by significant changes in lithology, but they may be identified from the systems-tracts stacking patterns (there are yet no wireline-logs from this area).

The reef-slope and open-shelf as well as the reef-core to lagoon facies aggraded during sea-level rise without backstepping. There is, therefore, no deepening-upward sequence followed by a shallowing-upward sequence that would allow the characterization of the maximum flooding surface. The **mfs** merges basinward with the bottom of the distally condensed interval, and the **ts** merges with the top of this condensed interval. The **ts** and **mfs** merge with the erosional surface landward. The sequence boundary (**sb**), which represents the lowest point of sea level, is the erosion surface landward and basinward merges with the **ts** and the **mfs** within the condensed interval.

Without high-resolution data, only two accretional packages may be identified: an aggradational package related to sea-level rises and an offlapping (progradational) package related to the still stands (highs and lows) and falls of sea level.

At outcrop scale, there are no lithologic criteria for defining neither the boundaries of the systems tracts nor the level of hierarchy of the discontinuities and erosion surfaces. Only from stacking patterns in the dip direction can the sequence-stratigraphic framework be adequately defined. A single surface (See **Figure 24**) may represent the boundary of distinct systems tracts in the different order of units, as result of its fractal stacking. The entire prograding platform is built up mainly by stacking of aggrading systems tracts which formed during sea-level rises of various orders of magnitude. The HST, OST, and LST systems tracts are mainly represented on the reef-core facies, and correspond to the distally condensed intervals of the open-shelf facies and to the erosional surfaces of the lagoonal facies (**Figure 31 F**).

Accommodation versus Carbonate Production

One of the fundamental concepts derived from the architectural model of the Llucmajor progradational reef platform is the relationship between sea-level fluctuation and carbonate production. Sea-level change not only determines the accommodation space, but it also determines the efficiency of the carbonate factory and thus the amount of carbonate production and sedimentation. Major amounts of carbonate sediment were produced when the shallow platform was flooded during the rise of sea level (**Figure 31 C**). Intermittent sea-level rises following brief falls cause re-establishment of carbonate production in lagoons that have been filled by sedimentation during slowing or cessation of sea-level rise. The rate of carbonate production kept-up with the rate of creation of accommodation space and, consequently, instead of transgressive retrogradation, aggradation occurred in all depositional settings (lagoon, reef, slope and open-shelf).

During stillstand of sea level (low- or high-stand) (**Figure 31 B & D**), the shallow platform was obliterated or filled, causing reduction of carbonate production. The lack of increase in accommodation space, due to the absence of significant subsidence, resulted in progradation of the reef system onto thin slope deposits.

During sea-level fall, both the absence of productive shallow platforms and the destruction of accommodation space, resulted in the offlapping of the reef system onto the open shelf without significant reef-slope deposits and with erosional truncation of the upper part of the previous high-stand reef and lagoonal deposits (**Figure 31 E**).

Lagoonal deposits, as well as open-shelf deposits, correspond to stacked aggradational systems tracts. Only from the progradational patterns of the reef may the platform architecture be interpreted.

Another important characteristic of the stratal architecture is the relationship between accommodation space and the length and angle of the slope. In the lower-order accretional units (megasets), the low stillstand units display short and gently inclined clinobeds. By contrast, the clinobeds of aggradational and high-stillstand megasets are hundreds of meters long and steep (with up to 30° slopes). Large slope beds dipping up to 35°-45° have been described from Quaternary fore slopes as well as in ancient examples.

This relationship between carbonate production and relative sea-level observed in the Llucmajor Platform is similar to platform flooding and carbonate shedding documented elsewhere from Quaternary carbonates, as well as from the Late Miocene to Recent Great Bahaman Bank. Platform shedding during the Quaternary occurred when the platform top was flooded. Prograding clinoforms of carbonate sediments during long-term relative sea-level rise has been also documented.

The Cap Blanc model indicates that much of the carbonate shedding occurred while the sea level was rising and the platform top was continuously flooded, rather than during high stands.

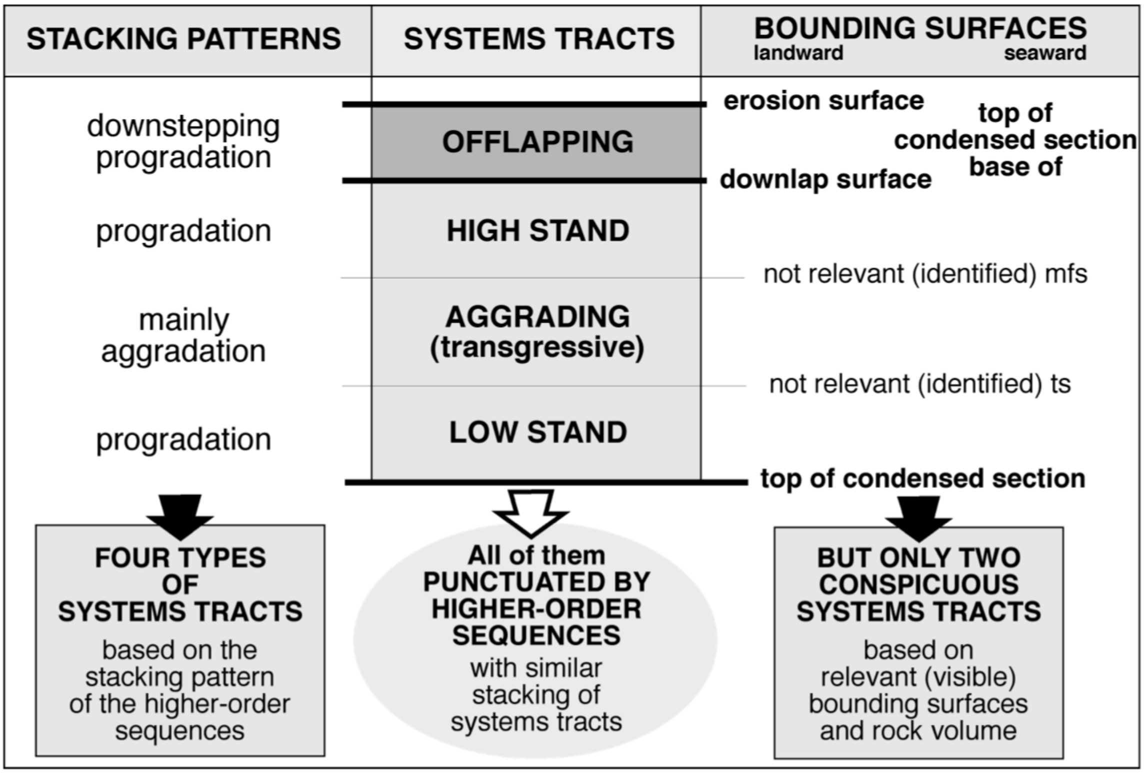


Figure 32

Basin Floor Topography versus Carbonate Production

The reconstruction of the three-dimensional model of the Llucmajor prograding platform illustrates the importance of pre-existing topography (depth and steepness) as a controlling factor on its architecture, i. e. overall morphology of the depositional profile (**Figures 27, 28, 29, 30 & 33**). Because this factor not only determines the accommodation space available but also controls the area and efficiency of the carbonate factory:

On a low gradient depositional profile (**Figure 30 A, 33 & 34**), sea level fall induced significant progradation of the offlapping reefs. During lowstands of sea level (**Figure 33 & 34**), carbonate production in shallow-basin settings was significant over a large area. Only coarse red-algae-rich sediment remained on the shallow open shelf, because wave action winnowed finer material and transported it to deeper parts of the basin. During the lowest stands of sea level, even patches of corals grew on the open shelf (shallow basin). The red-algal biostromes interfingered the fore-reef slope of the LST on the shallower part of the basin. When sea level rose, most of the production of sediment shifted to the shallower shelf, where extensive lagoons developed behind reefs. The red-algal deposits did not produce where the basin floor was too deep to allow light penetration. It is inferred from the stratigraphic architecture that during a rise of sea level, deposition on the open shelf was primarily the result of shedding of fine sediment from the shallow-shelf lagoons.

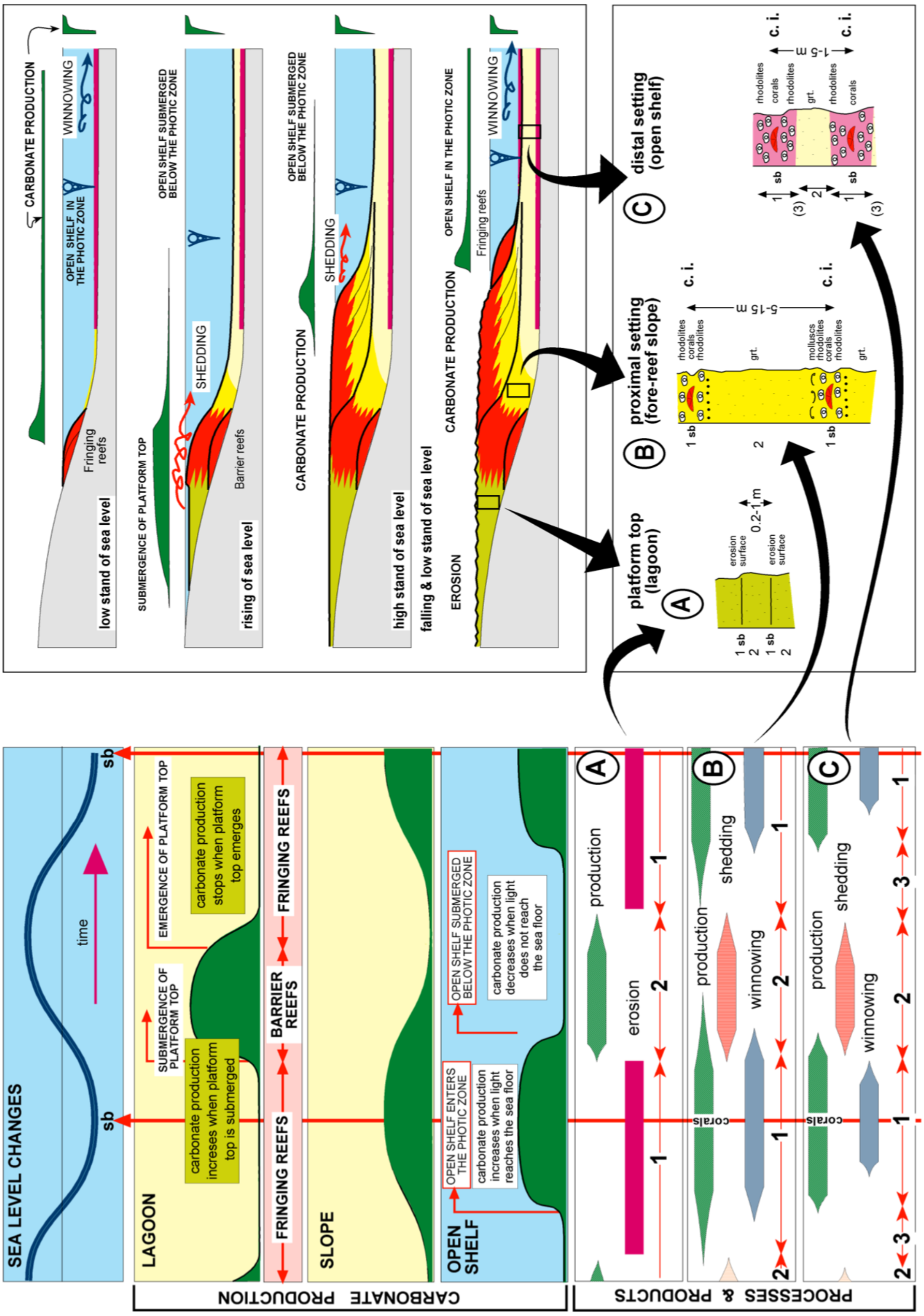


Figure 33. — Diagram showing relationships between sea-level fluctuations, carbonate production, and depositional processes on three parts of a reef-rimmed carbonate platform, and stratigraphic sections built up in lagoons, fore-reef slopes, and open shelves in response to the depositional processes during sea-level fluctuations (Pomar and Ward, 1999)**.**

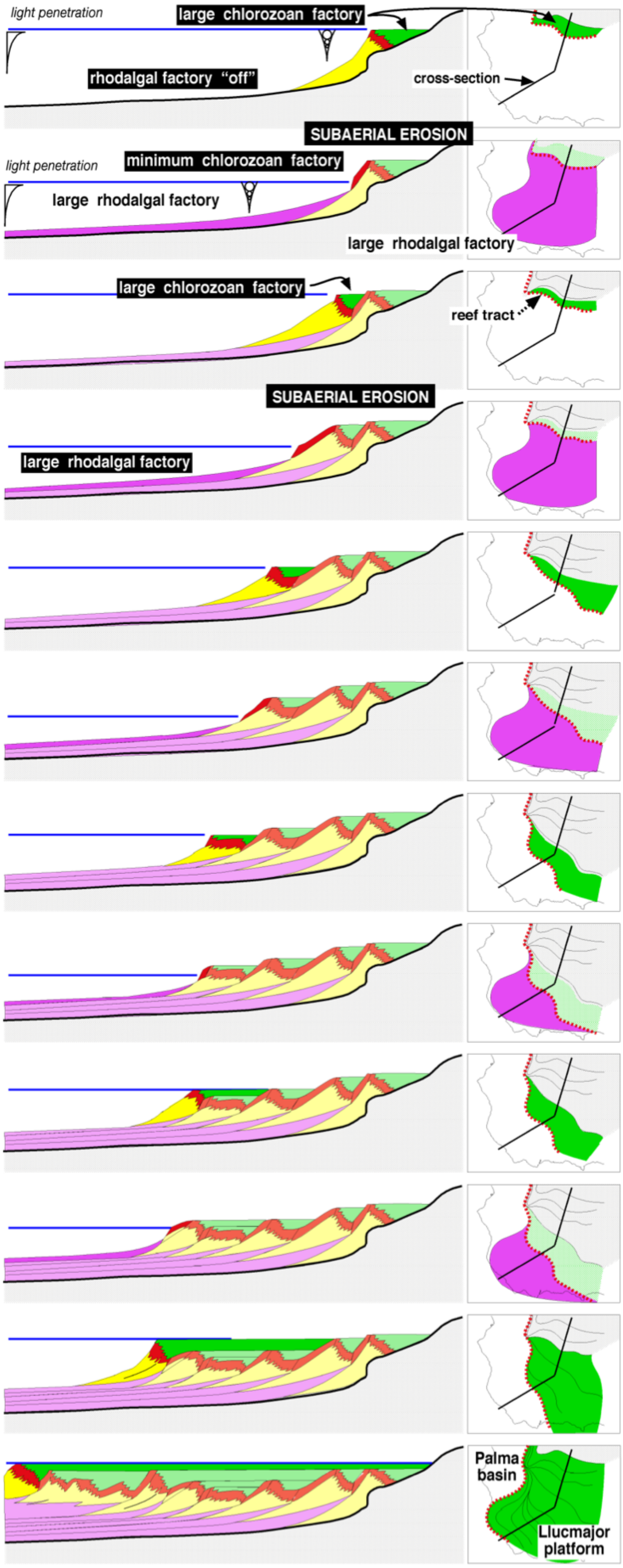


Figure 34. Reconstruction of the 20 km of reefal progradation to the S-SW, during a period of about 2 Ma, based on borehole and outcrop data. The relatively fast progradation is interpreted to be the result of two carbonate factories that alternated in phase with sea-level fluctuations on a gently dipping area

On the other hand, where the topographic gradient was steeper (**Figure 29 & 30: C-C'**), the amount of progradation of the offlapping reefs is minor. Platform flooding during sea-level rises produced only small lagoonal areas where carbonate production was not optimal and the down slope shedding was proportionally small. Similarly, the benthonic carbonate production during lowstands of sea level was also reduced onto the sea floor with a steeper bathymetric gradient because the available area for efficacious production was narrower. Thus, various depositional gradients produce dramatic differences in platform progradation.

In the Llucmajor platform the reefs prograded faster toward the southern margin of the shallow open shelf than toward the west, along the margin of the Palma basin. This resulted in greater production of carbonate on the southeastern part, where the lagoons were wider during sea-level rises, and also because oligophotic carbonate production (red algae) occurred throughout much of the shallow basin during lowstands of sea level. This increased production in the areas with low bathymetric gradient produced a seemingly clockwise rotation towards the Palma basin of the reef tracts of the successive progradational events (**Figure 29, 30 & 33**).

This illustrates the importance of sediment supply (carbonate production) in controlling the progradational architecture. The efficiency of the carbonate factory is controlled by the fluctuations of the sea level and the bathymetric gradient of the depositional profile.

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