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Sequence stratigraphy of a Mesozoic carbonate platform-to-basin system in western Sicily

Research Article

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Abstract: Sequence stratigraphic studies of the Triassic through Paleogene carbonate successions of platform, slope and basin in western Sicily (Palermo and Termini Imerese Mountains) have identified a sedimentary cyclicity mostly caused by relative oscillations of sea level. The stratigraphic successions of the Imerese and Panormide palaeogeographic domains of the southern Tethyan continental margin were studied with physical-stratigraphy and facies analysis to reconstruct the sedimentary evolution of this platform-to-basin system.
The Imerese Basin is characterized by a carbonate and siliceous-calcareous succession, 1200-1400 m thick, Late Triassic to Eocene in age. The strata display a typical example of a carbonate platform margin, characterized by resedimented facies with progradational stacking patterns. The Panormide Carbonate Platform is characterized by a carbonate succession, 1000-1200 m thick, Late Triassic to Late Eocene, mostly consisting of shallow-water facies with periodic subaerial exposure.
The cyclic arrangement has been obtained by the study of the stratigraphic signatures (unconformities, facies sequences, erosional surfaces and stratal geometries) found in the slope successions. The recognized pattern has been compared with coeval facies of the shelf. This correlation provided evidence of sedimentary evolution, influenced by progradation and backstepping of the shelf deposits.
The stratigraphic architecture of the platform-to-basin system is characterized by four major transgressive/regressive cycles during the late Triassic to late Eocene.
These cycles, framed in a chronostratigraphic chart, allows the correlation of the investigated shelf-to-basin system with the geological evolution of the African continental margin during the Mesozoic, showing tectono-eustatic cycles. The first cycle, encompassing the late Triassic to early Jurassic, appears to be related to the late syn-rift stage of the continental margin evolution. The following three cycles, spanning from the Jurassic to Eocene, can be related to the post-rift evolution and to thermal subsidence changes.

Keywords: shelf-to-basin system sedimentology • transgressive/regressive cycles • tectono-eustatic cycles • mesozoic western Sicily

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1. Introduction

Sequence stratigraphy is crucial to the study of the stratigraphic evolution of carbonate platforms [1–9]. Relatively few studies apply sequence stratigraphy to outcrops of ancient carbonate slope and base-of-slope successions [10–16].

A slope-margin depositional area of a basin is believed to be the best place where sea-level oscillations can be recognized, and where clastic carbonates and siliciclastic deposits show a similar response to transport and sedimentation by waves and currents. The shedding of clastic carbonate sediments to the basin during periods of relative sea-level fall, as predicted by standard sequence stratigraphic models, is one of the most controversial aspects of the application of sequence stratigraphic concepts to carbonate systems (e.g. [8, 14, 17–19]). It has been suggested that the major volumetric components of a carbonate lowstand wedge may be megabreccias and associated debris generated by platform-margin collapse [14, 20].

The accurate correlation of sediments that have been synchronously deposited at the margin of carbonate platforms in shallow and deep-water environments is required in order to reconstruct ancient oceanic environmental conditions and sea level changes [8, 12, 16, 20, 21]. Unfortunately, accurate correlation between these types of sedimentary units is often difficult for several reasons, including: (1) physical destruction of the rocks during post-depositional tectonism and associated differential erosion; (2) differences in the quality and resolution of the biostratigraphic records preserved in basinal and platform limestones [22, 23].

The lack of a well-preserved physical continuity between Sicilian platform and basinal facies domains has been described in other studied margins (for example the Maiella section [24, 25]; the Vercors Mountains [13, 20, 26]; the Cantabrian Mountains [27]; the Great Bahama Bank [12]). This lack of continuity means that the shelf and basin successions should be study separately. Correlation between isolated basin and platform stratigraphic sections can be accomplished using changes in sedimentological composition [13, 21, 28–30].

The main aim of the present study is the analysis of the Mesozoic carbonate basin-slope Imerese successions and comparison with the coeval carbonate shelf and shelf margin of the Panormide successions. In addition, the original geometry and facies distributions of the Mesozoic platform-to-basin system will be reconstructed. Comparison of the results of the studies made on the shelf and basin successions, using physical-stratigraphy, facies and geometric trend analyses, and biostratigraphic dating of unconformity surfaces, has permitted the recognition of sedimentary cyclicity mostly caused by relative oscillation of sea-level.

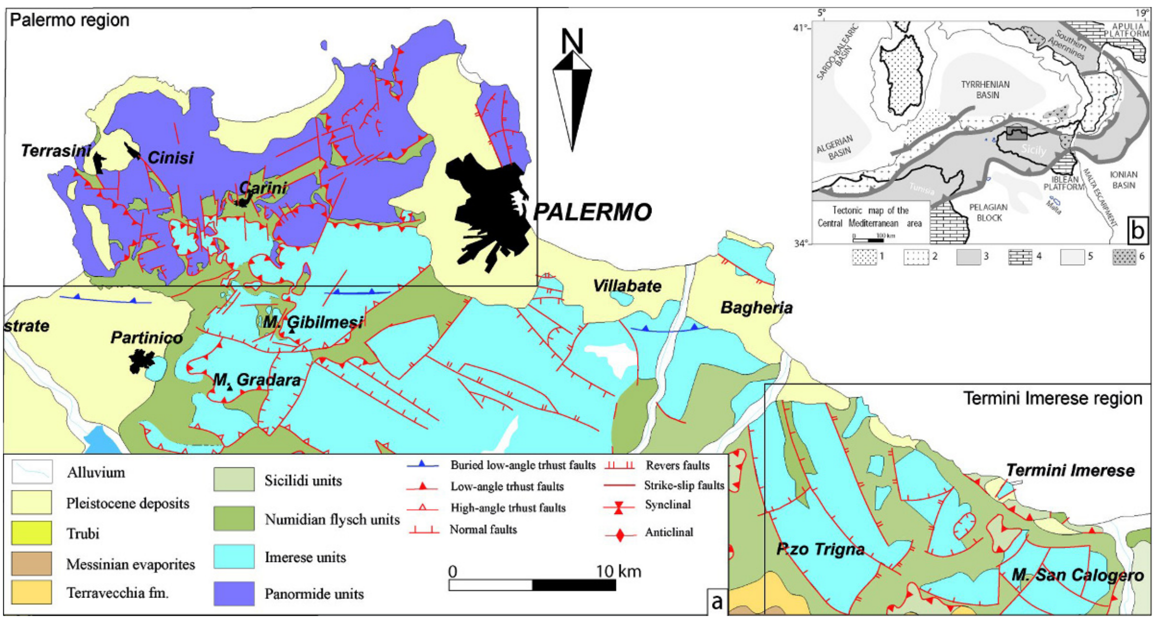

Figure 1. a) Geological map of north-western Sicily (modified after [33]) and location of the study areas. b) Tectonic map of the central Mediterranean (modified after [34]). Legend: 1) Corsica-Sardinia; 2) Calabrian Arc, Kabylian and "Internal" Flysch succession, ophiolites; 3) Maghrebian-Sicilian-Southern Apennine nappes and defomed foreland; 4) Foreland (Tunisia, Iblean Plateau, Apulia); 5) Areas with superimposed extension; 6) Plio-Quaternary volcanoes.

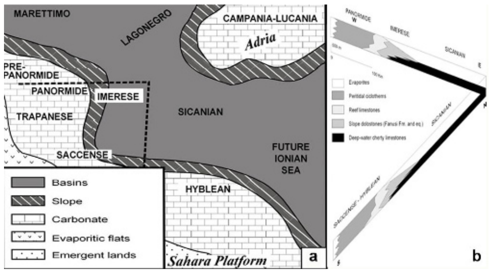

Figure 2. Palaeogeographic reconstruction during the Late Triassic of the southern Tethyan margin (a). In (b) palinspastic sections across the platform-basin system of Sicily in the late Triassic (dashed line in a) (modified after [34]).

2. Geological setting and palaeogeography

In western Sicily the carbonate successions of the Mesozoic-Cenozoic platform and basin facies were studied in two main regions (Figure 1a). In the Termini Imerese region widespread Late Triassic-Eocene pelagic carbonates, radiolarite mudstones with resedimented shallow-water facies outcrop. These deposits pertain to the locally known Imerese Basin. In the Palermo Mountains region, Mesozoic, mainly shallow-water carbonate successions (shelf environment), with thick, deeper water facies intercalations are exposed. They are locally known as the Panormide Carbonate Platform domain.

The investigated successions are incorporated into the Sicilian fold and thrust belt (Figure 1b) that originated from the deformation of the Mesozoic-Cenozoic sedimentary cover of the Sicilian area of the African continental margin. The resulting tectonic units were stacked during the Miocene-Pliocene, with southwards and southeastwards vergence, [31–33] and reference therein.

A restoration of the Mesozoic palaeogeography allows a platform-to-basin system to be reconstructed (Figure 2). Although it is not known whether the location of the Imerese Basin is internal or external with respect to the Panormide Carbonate Platform, there is general agreement about an original adjacent location of the two paleodomains [32–38].

Previous studies have highlighted Mesozoic tectonic influences on the sedimentary evolution of the African continental margin outcropping in Sicily, since the infra-Liassic strike-slip tectonics [39].

The present fragmentation of the whole platform-to-basin margin by Tertiary thrust tectonics, is believed to be the result of the reactivation of the Mesozoic fault systems which controlled the original morphology of the ancient Sicilian margin [40].

Palaeoenviromental reconstruction refers the deposits of the Panormide Carbonate Platform succession to a Bahamian-type carbonate platform [41] with rimmed shelf-margin (Late Triassic and Late Jurassic) and open-platform with ramp geometries (Late Cretaceous and Late Eocene). Common fossils include corals, sponges, hydrozoans, rudists and benthic macroforaminifera.

There have been few paleoenvironmental studies on the Imerese basin succession. These studies have focused on the lithostratigraphic units, their age and on the resedimented facies [35, 42–48].

3. Methods and procedure

Excellent exposure of the slope successions, which are exposed for several kilometres in the Termini Imerese Mountains, has permitted the examination of large-scale (basinal) geometries. Panoramic photomosaics were analyzed like seismic sections and the sediments were subdivided into unconformity-bound sequences according to the procedure described by [49, 50] and references therein and [51]. Sections measured in the field provide the sedimentologic and stratigraphic information necessary for sequence analysis. Facies analyses, age-dating (calibrated by biostratigraphy), sequence-stratigraphic methods [52, 53] and transgressive/regressive sequence analysis [49–51, 54, 55], have been used to obtain the main results.

Some stratigraphic sections within the studied areas were measured and sampled. The collected stratigraphic data have been synthetised in two columnar sections representing, respectively, the upper Triassic to upper Eocene slope-to-basin Imerese composite succession and the coeval Panormide carbonate platform composite succession.

4. Lithostratigraphy and facies analyses

4.1. Imerese slope succession

The Imerese Basin is characterized by a carbonate and siliceous-calcareous succession 1200-1400 metres thick, Late Triassic to Late Eocene in age. The Imerese pelagic succession is dominated by spectacular gravity-flow deposits which include: a) breccias, megabreccias and megaconglomerates, b) bioclastic turbidites, c) laminated fine-grained limestones (dilute turbidites).

The strata display a typical example of a carbonate platform margin, characterized by resedimented facies with progradational stacking patterns.

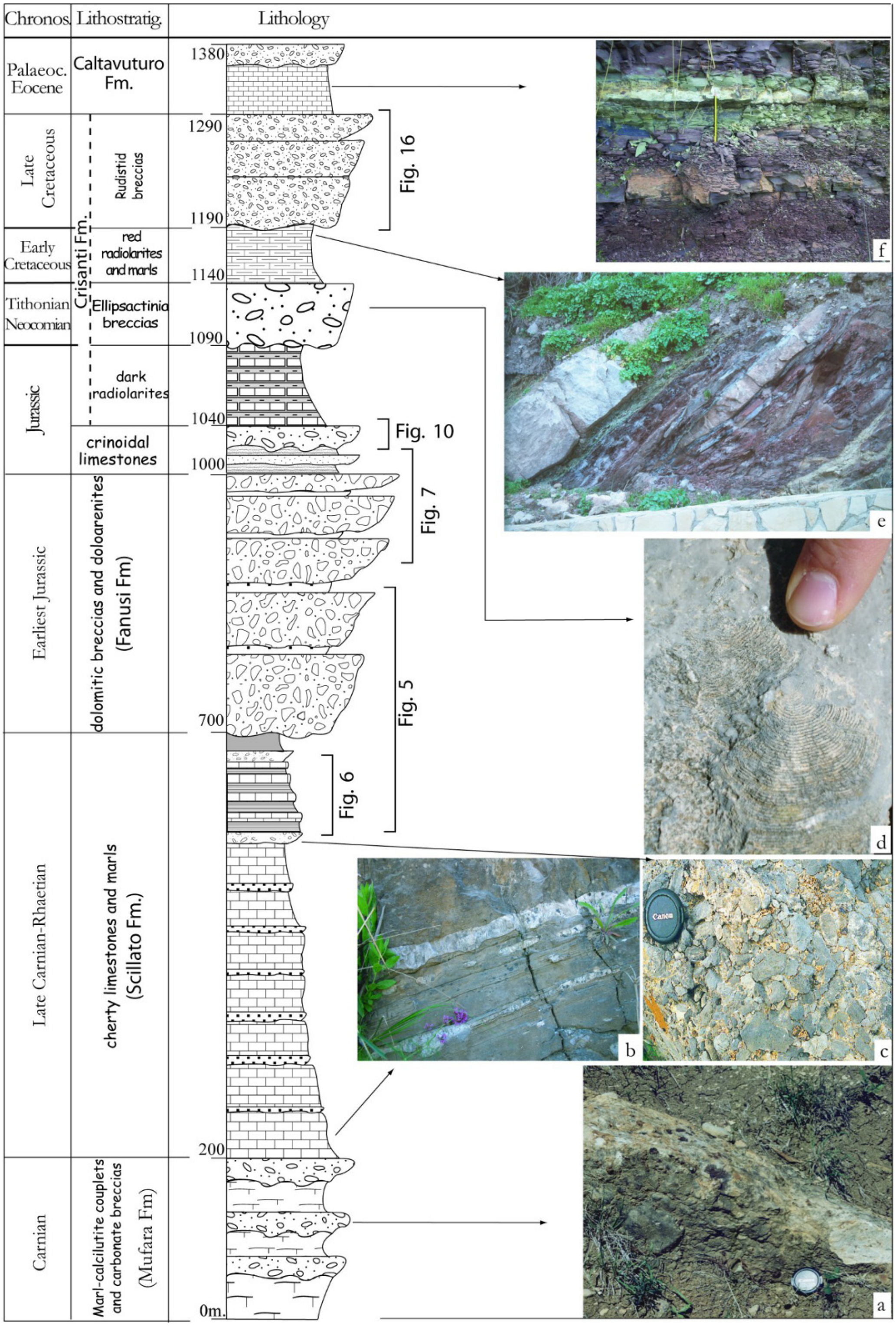

Figure 3. Imerese composite stratigraphic succession. a) graded breccia intercalations in the brown marls of the Mufara Formation, b) laminated thin-bedded cherty limestones (Scillato Formation), c) pebbly conglomerates lie at the top of the aggrading cherty limestone sequence of the Scillato Formation, d) breccias with *Ellipsactinia* sp. fragments, e) grainstone with lenticular geometry interbedded in the red radiolarites and marls Member of the Crisanti Formation, f) red mudstone and marls of the Caltavuturo Formation.

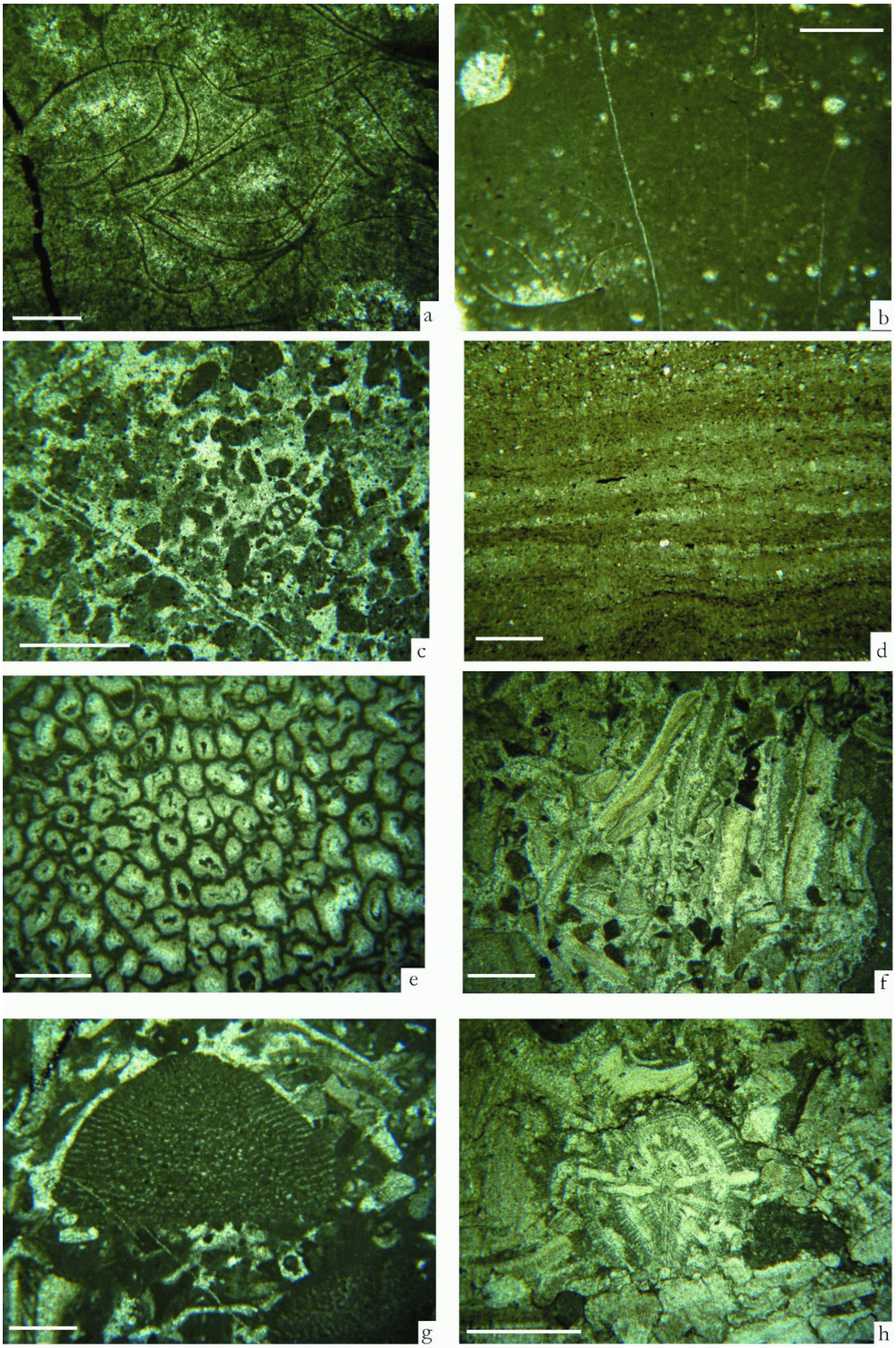

Figure 4. Microfacies of the Mesozoic Imerese succession deposits. a) wackestone with pelagic bivalves (PPL, scale bar 1 mm, Mufara Formation), b) radiolarians and pelagic bivalve-bearing wackestone (PPL, scale bar 1 mm, Scillato Formation), c) grainstone with benthic foraminifera (PPL, scale bar 1 mm, crinoidal limestones unit), d) dark laminated radiolarian bearing wackestone (PPL, scale bar 1 mm, radiolarite Member of the Crisanti Formation), e) Ellipsactinia fragments (PPL, scale bar 1 mm, Ellipsactinia breccias Member of the Crisanti Formation), f) grainstone with rudist fragments (PPL, scale bar 1 mm, rudistid breccias Member of the Crisanti Formation), g) grainstone with benthic macroforaminifera (PPL, scale bar 1 mm, rudistid breccias Member of the Crisanti Formation), m) grainstone with Orbitoides spp. (PPL, scale bar 1 mm, upper portion of the upper Member of the Crisanti Formation).

The succession (Figure 3), from the bottom, consists of:

- Yellow to brown laminated mudstone-wackestone (a in Figure 4), regularly alternating with yellow marls, 30-250 m thick, with radiolarians, sponge spicules, bivalves (*Halobia* sp.) and ammonoids (*Trachiceras aon* Münster). Coarse carbonate breccia (1-5 m thick), with erosional lower boundaries (a in Figure 3) are cyclically interlayered with incomplete turbidite sequences. They display shallow-water derived fragments, consisting of graded rudstone-floatstone with coral, algae, sponge (*Tubiphytes* sp.), and crinoidal fragments, and laminated grainstone-to-packstone. The lower boundary does not outcrop. These deposits, locally known as the Mufara Formation., on the grounds of the regional stratigraphy from several sections in central and western Sicily, are assigned to the Julian-Early Tuvalian time interval [56–59].

- Grey thinly-bedded cherty limestones (b in Figure 3), 300-500 m thick, consisting of monotonous laminated mudstone-wackestone/marl couplets in a aggrading succession (Figure 5), locally known as the Scillato Formation. In certain places these deposits are capped by a few metres of laminated grainstone and pebbly conglomerates (c in Figure 3), associated with ferromanganese crusts (hardgrounds, [58, 60]); several metres of red-to-green clay and packstone-wackestone alternations, with progradational geometries and regressive facies units (Figure 6), follow upwards. Biocalcarenites and breccias, consisting of both deep-water and shallow-water derived-fragments with corals, algae and sponges, follow above. The fossil content, consisting of radiolarians, sponge spicules, conodonts, ostracods and rare bivalves (*Halobia styriaca* Mojsisovics, *Halobia norica* Mojsisovics) dates these beds to the Late Carnian-Rhaetian time interval [58, 61–63].

- White massive dolomites (Fanusi Formation), coarse-grained decametric dolomite breccia beds and thin graded and laminated doloarenites, 250-300 m thick, with erosion and downlap surfaces (Figure 5), unconformably overlie the limestones. Pervasive dolomitization has obliterated fossils and organic traces, and an Early Jurassic age is commonly indicated on the basis of its stratigraphic position encompassed between Rhaetian cherty limestones and Lower Jurassic crinoidal limestones. The several coarsening and thickening upwards facies units (Figures 7, 8), showing intraformational erosional surfaces (Figures 9, 10), channel filling geometries, and progradational geometries, are cyclically repeated.

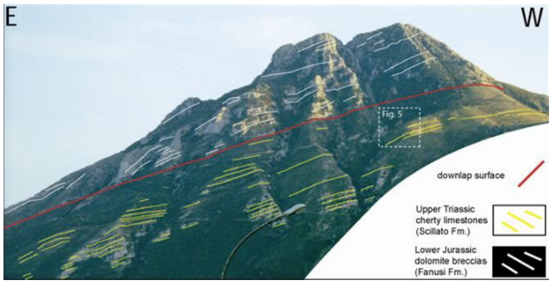

Figure 5. Downlap relationships between the megabeds of the lowermost Jurassic dolomite breccias (Fanusi Formation) and upper Triassic cherty limestones (Scillato Formation). San Calogero Mountain (Termini Imerese Mountains.).

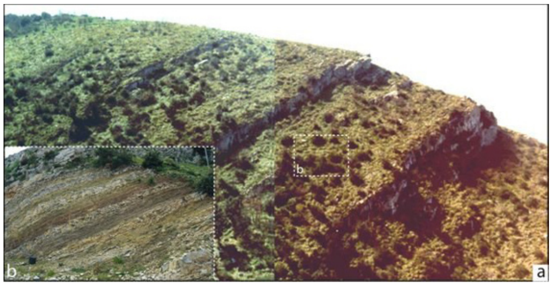

Figure 6. Prograding parasequence cycles in the upper portion of the upper Triassic Scillato Formation limestones (a), several simple cycles represented by regular alternations of mudstone-wackestone and varicoloured clays (b), northern side of San Calogero Mountain (Termini Imerese Mountains).

- Bioclastic and oolitic packstone-to-grainstone, with crinoids and benthic foraminifera (c in Figure 4), alternating with red and green marls (informally named crinoidal limestones), sit unconformably, with onlap onto the underlying strata (Figure 7). Calcareous breccias, with reef-derived elements, are commonly interlayered. The latter, consisting of several metres thick rudstone-floatstone with Triassic sponge fragments, corals, algae and crinoids, shows lenticular and channelized geometries (Figure 11), with lower erosional surfaces. Brachiopods and nannofossils date these beds to the Plienbachian-Toarcian time interval [64, 65].

- Pelagites (radiolarites, siliceous mudstone, marls, clays) and redeposited carbonate facies (calcareous breccias, conglomerates and turbiditic lithoclastic to bioclastic grainstone-packstone), 250-300 m thick, unconformably follow (Figures 7-10, 12). The unit, locally known as the Crisanti Forma-

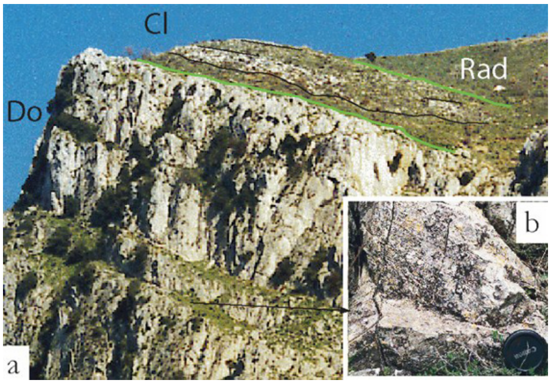

Figure 7. Panoramic view of the lower Jurassic Imerese succession (a) at S. Calogero Mountain (Termini Imerese Mountains). Legend: Do, dolomite breccias (Fanusi Formation), Cl), crinoidal limestones unit, Rad), dark radiolarites Member of the Crisanti Formation. The green lines are the transgressive surfaces with onlap terminations. The dolomite breccia consists of alternations of megabeds of breccias and thin bedded dolomite, characterized by cross- and oblique-laminated doloarenites (b).

Figure 8. Panoramic view of the Jurassic-Cretaceous succession outcropping at Monte Stingi (Termini Imerese Mountains). The Jurassic radiolarites (Rad) onlap the lower Jurassic dolomite breccias (Do, Fanusi Formation), as inclined beds, followed by an erosional unconformity, then the subhorizontal beds of the *Ellipsactinia* breccias (Ell). Lc are the lower Cretaceous red radiolarites and marls and Rud are the Cenomanian rudistid breccias of the Crisanti Formation. Green lines are onlap surfaces and red one the lower erosional surfaces of the breccia deposits.

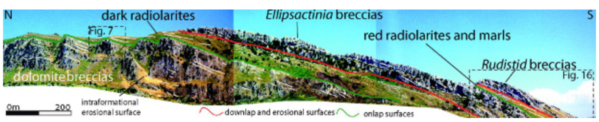

Figure 9. Physical-stratigraphic relationships of the Jurassic-Cretaceous Imerese succession viewed in a panoramic photomosaic of the western flank of Rocca di Mezzogiorno (S. Calogero Mountain, Termini Imerese Mountains). It is possible to see the onlap and downlap surfaces of the major T/R facies cycles.

Figure 10. Upper Triassic-Cretaceous Imerese succession, panoramic photomosaic of the eastern flank of Rocca di Sclafani (Madonie Mountains). Onlap and downlap surfaces are depicted. The *Ellipsactinia* breccias downlap, above an erosional surface, upon the older Jurassic dark radiolarite Member of the Crisanti Formation.

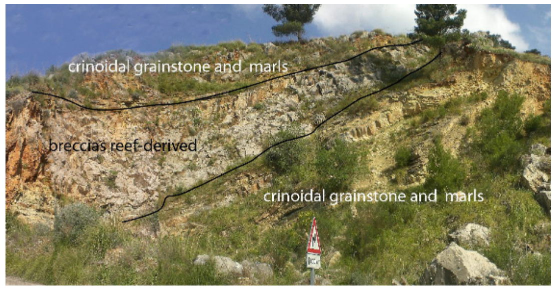

Figure 11. Lenticular geometry of the calcareous breccias with reef-derived elements interbedded with lower Jurassic crinoidal limestones (southern Palermo Mountains).

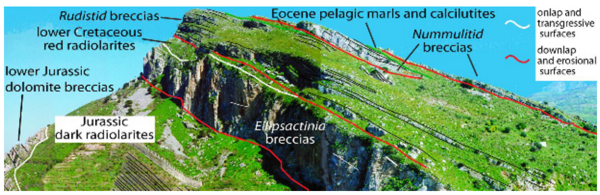

Figure 12. Panoramic view of the western side of Cozzo Famo (Termini Imerese Mountains), where the geometric relationships of the Jurassic-Eocene units of the Imerese slope succession are visible. The lower Cretaceous red radiolarites and marls Member of the Crisanti Formation is here 5 metres thick and, laterally, disappear.

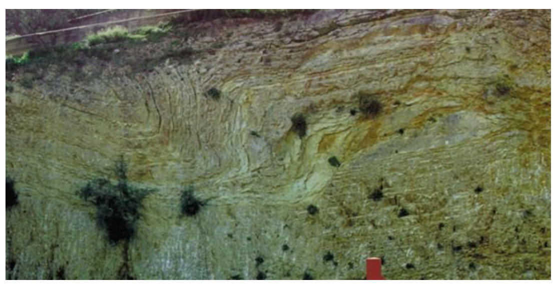

Figure 13. Megaslump structures in the Jurassic radiolarites of the lowermost Member of Crisanti Formation (Trabia village).

tion, consists of: a) thin black radiolarites, bedded cherts and clays with parallel lamination (d in Figure 4), burrows destroying lamination, and slump and megaslump structures (Figure 13). The lower boundary is a transgressive surface (Figures 7-10, 12), which onlaps the crinoidal limestone unit and the Lower Jurassic dolomites of Fanusi Formation. A Middle-Late Jurassic age is generally indicated [45, 64]; b) calcareous breccias, packstone-to-grainstone and oolitic grainstone, (*Ellipsactinia* breccia Member), 50-60 m thick, with erosion and downlap (Figures 8-10, 12, 14). The breccia elements consist of reef margin-derived fragments with hydrozoans (*Ellipsactinia* sp., d in Figure 3 and e in Figure 4), corals, gastropods (*Nerinea* sp.), algae and microproblematica. A Tithonian-Neocomian age is indicated on the basis of the reworked fossil content [42, 45], and on the *Calpionella elliptica* (Cadisch), found in the matrix. The resedimented body shows decametric thick coarse rudstone and dm thick bioclastic grainstone and laminated packstone, regularly alternating in two coarsening and thickening-upwards units (Figure 9); c) bedded cherts, mudstone and red marl alternations (red radiolarite and marl Member), 50 m thick, with sponge spicules, radiolarians, benthic (*Dorothia gradata* (Berthelin), *D. filiformis* (Reuss), *Marginulina planiscula* (Reuss)) and planktonic foraminifera (*Ticinella primula*), Lower Cretaceous in age. They lie above a transgression surface (Figures 8, 9, 12) with onlap terminations (Figure 15). Packstone-grainstone with benthic foraminifera (*Orbitolina paronai* (Prever), *O. conoidea* (Gras)) and rudistid fragments, are interbedded in the upper portion of the succession (e in Figure 3); d) rudstone and grainstone-packstone, 80-100 m thick, with rudistid fragments (f in Figure 4) and benthic foraminifera (*Orbitolina texana* (Renz), *Orbitoides media* (D'Archiach), *Siderolites* cf. *calcitrapoides* Lamarck, g and h in Figure 4) of Late Cretaceous age (Rudistid breccias Member), with erosion and downlap (Figures 11, 13). The resedimented graded and laminated beds, with lower erosional surfaces, are organized in several coarsening-upwards facies units, showing progradational geometries (Figure 16).

- Reddish, white and greenish wackestone-mudstone and marls (Caltavuturo Formation, f in Figure 3) 20-200 m thick; slump structures, parallel lamination and bioclastic grainstone-packstone intercalations are common. The fossil content consists of planktonic foraminifera (*Morozovella velascoensis,*

Figure 14. Erosional contact between the *Ellipsactinia* breccia Member of the Crisanti Formation and the Jurassic black radiolarites Member of the Crisanti Formation (Cozzo Petroso, Trabia Mountains).

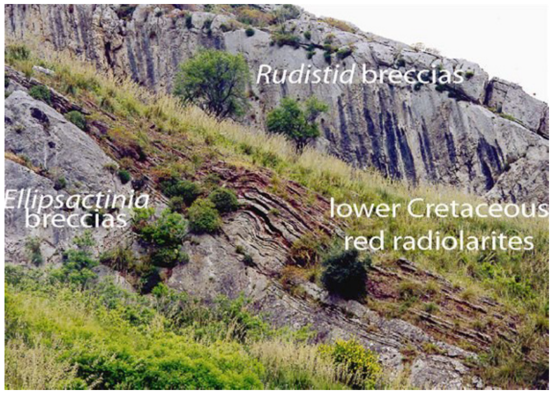

Figure 15. Onlap relationships between the Lower cretaceous red radiolarites and marls Member (Lc) with the *Ellipsactinia* breccia Mb. of the Crisanti Formation. Rud is the upper rudistid breccias Member.

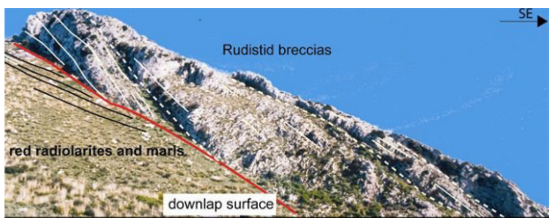

Figure 16. Panoramic view of the southern side of Rocca di Mezzogiorno. An erosional unconformity at the base of the breccias and turbidites (Cenomanian Rudistid breccias Member of the Crisanti Formation), highlighted by downlap geometry; truncation of the older strata (Lower Cretaceous red radiolarites and marls Member of the Crisanti Formation) is, also, present. The white dashed lines are the sequence boundaries of the third order cycles.

M. subbotinae, M. aragonensis, Turborotalia cerroazulensis s.l. biozones) and calcareous nannofossils (NP10 to NP22 biozones), that indicate a Paleocene-Eocene time interval. The lower boundary is a transgressive surface, which onlaps onto the Crisanti Formation.

- Rudstone and grainstone-packstone with benthic macroforaminifera (*Nummulites partschi* De La Harpe, *Nummulites prelucasi* Douville), colonial corals fragments, bryozoans, etc., 20-30 m thick (Nummulitid breccias, Late Eocene) along an erosional surface with downlap (Figure 11).

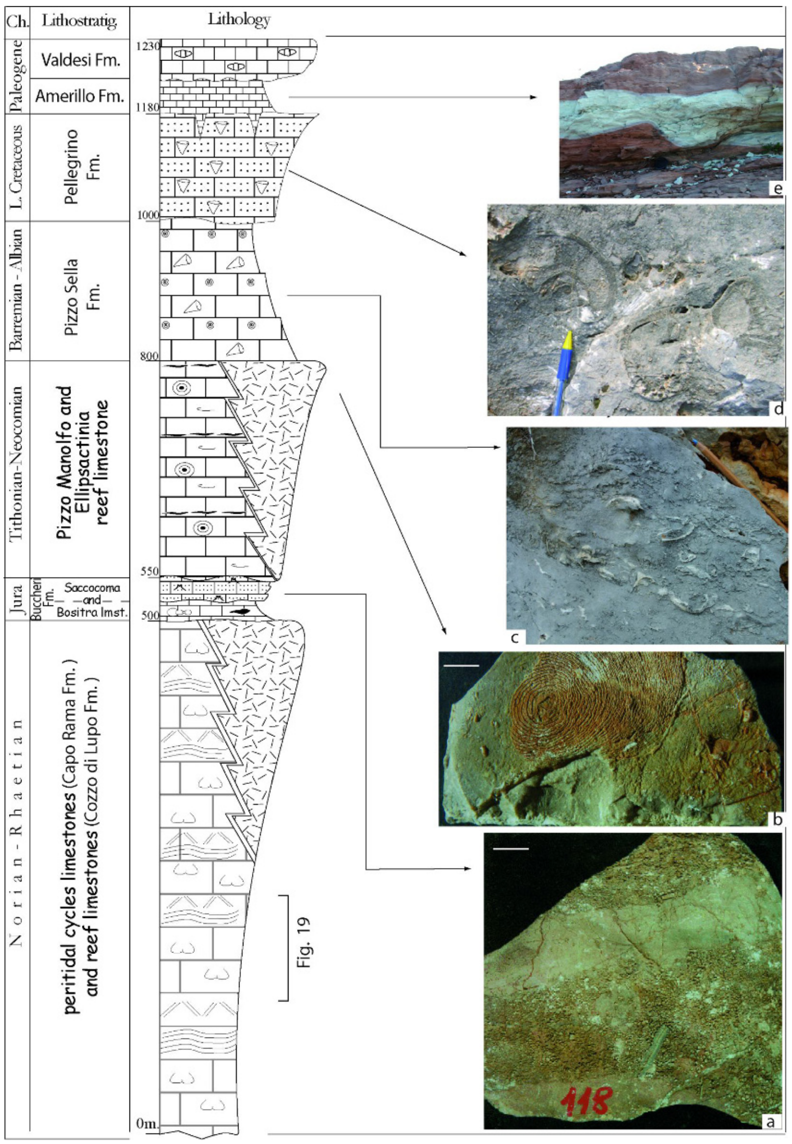

Figure 17. Panormide composite stratigraphic succession. a) grainstone with pelagic crinoids interbedded with pink ammonite wackestone (*Saccocoma* limestones, scale bar 2 mm); b) boundstone with *Ellipsactinia* sp. and corals (*Ellipsactinia* reef limestones, scale bar 1 mm); c) Requienid floatstone and algae wackestone alternations (Pizzo Sella Formation); d) Caprinid and rudistid boundstone (Pellegrino Formation); e) pelagic limestones with slumping structures (Amerillo Formation).

Figure 18. Upper Triassic white peritidal limestones (a) outcropping in the Capo Rama type-area (Palermo Mountains). The thick-bedded succession consists of wackestone with large megalodontid shells (b), wackestone with large oncoids (c) intercalations of stromatolitic dolomites (d) loferitic breccias with tepee structures (arrows).

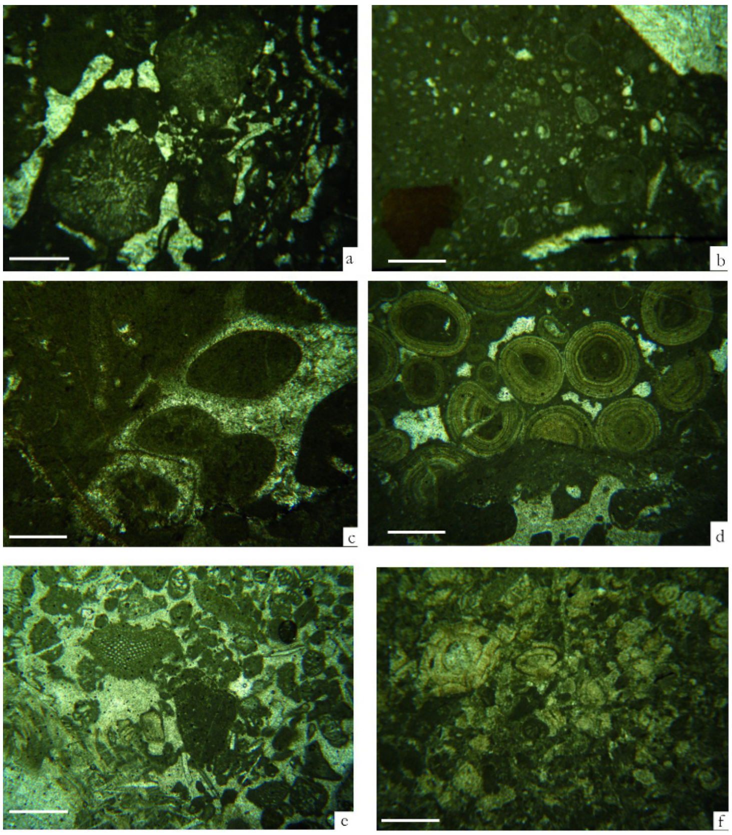

Figure 19. Microfacies of the Mesozoic Panormide succession deposits. a) wackestone-packstone with algae and bioclasts (PPL, scale bar 1 mm, Capo Rama Formation); b) intra-bioclastic wackestone with coated grains (PPL, scale bar 1 mm, Capo Rama Formation); c) wackestone with nerineids (PPL, scale bar 1 mm, Pizzo Manolfo limestones); d) oolite packstone with broken grains (PPL, scale bar 1 mm, Pizzo Sella Formation); e) grainstone-packstone with benthic foraminifera and rudistid fragments (PPL, scale bar 1 mm, Pellegrino Formation); f) packstone with benthic macroforaminifera (PPL, scale bar 1 mm, Valdesi Formation).

4.2. Panormide shelf succession

The Panormide carbonate platform succession consists of a 900-1200 m thick body of Late Triassic to Late Eocene age, mostly characterized by shelf facies (inner-platform to reef margin environments), with periodic subaerial exposure and pelagic sedimentation episodes. Several detailed studies have described the stratigraphy, lithofacies associations, depositional and diagenetic characters, fossil assemblages, high frequency cycle arrangement and palaeogeographic evolution [41, 66–77]. The present paper deals with the sedimentologic and physical-stratigraphic features. Lithofacies correlations, angular unconformity surfaces, geometric patterns and major facies sequences have been recognized, described and correlated to obtain the most complete succession.
The reconstructed succession (Figure 17), from the bottom, consists of:

- White and grey fine-grained shallow water limestones, consisting of a wackestone with mollusca (megalodontids, ammonoids, gastropods) and oncoids (a-b in Figure 18), dasycladacean algae (a in Figure 19), hydrozoans, benthic foraminifera, intraclasts (b in Figure 19), alternating with stromatolitic dolomites and loferitic breccias (Capo Rama Formation, Figure 18), organized in shallowing upward sequences (peritidal cycles). The unit, about 500 m thick, on the basis of the fossil content has been assigned to the Late Triassic-Early Jurassic time period [41, 78]. Laterally this unit changes to a boundstone, 300-500 m thick, with calcareous sponges, corals, algae, benthic foraminifera and microproblematica of Norian-Rhaetian age [69, 71, 72], alternating with bioclastic packstone-grainstone and breccias with reef-derived fragments (Cozzo di Lupo Fm.). Locally, the upper boundary is an angular unconformity erosional surface, capped by red Jurassic bauxite clays (Figure 20).

- Crinoidal packstone-grainstone, mudstone-wackestone with brachiopods (*Rinchonellina*? *renevieri* (Haas), *Phimatothyris carasulum* (Zittel)) of Pliensbachian-Toarcian age [79–81], a few metres thick, unconformable.

- Reddish nodular mudstone-wackestone with ammonites, belemnites, pelagic bivalves and radiolarians, locally known as the Buccheri Formation of Toarcian-Tithonian age, with onlap surfaces. It consists of condensed beds with iron-manganese crusts (*Bositra* limestones) and crinoidal packstone-to-grainstone *Saccocoma* limestones (a in Figure 17).

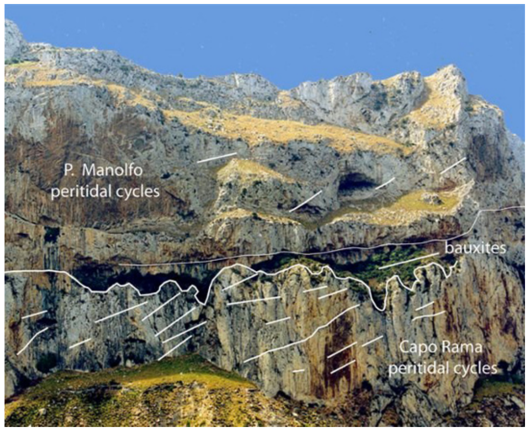

Figure 20. Angular unconformity between Upper Triassic Capo Rama Formation, peritidal limestones and the Upper Jurassic Pizzo Manolfo peritidal limestones. On the irregular erosional and karstic unconformity surface, bauxite deposits are present (northern side of Monte Gallo, Palermo Mountains).

- Fine-grained wackestone with bivalves, gastropods (*Nerinea* sp., c in Figure 19), benthic foraminifera and calcareous algae, stromatolites and loferitic layers organized into shallowing upward cycles (Pizzo Manolfo limestones). 200-300 m thick, they pass laterally into grey boundstone, consisting of encrusting hydrozoans (*Ellipsactinia* sp., b in Figure 17), corals, algae and gastropods, alternating with oolitic grainstone and breccias with reef-derived elements of Late Tithonian-Neocomian age (*Ellipsactinia* reef limestones). The reef limestones, approximately 300 m thick, have clinoforms, progradational geometries and downlap relationships with the underlying upper Jurassic *Saccocoma* limestones (Figure 21). The upper boundary is often an erosional surface affected by palaeokarst dissolution.

- Wackestone-packstone with requienids (Pizzo Sella Formation., c in Figure 17), oolitic grainstone (d in Figure 19), stromatolites and bioclastic wackestone, with nerineids, algae, benthic foraminifera (*Palorbitolina lenticularis praecursor* (Montanari), *Rectodyctioconus giganteus* Schroeder) of Barremian-Aptian interval [82, 83], with an onlap geometry.

- Grey packstone-grainstone with *Orbitolina* spp. and bioclasts (e in Figure 19), rudistid and Caprinid boundstone (d in Figure 17), stromatolites and loferitic limestones (Cenomanian), radiolitid grainstone-to-packstone with *Orbitoides me-*

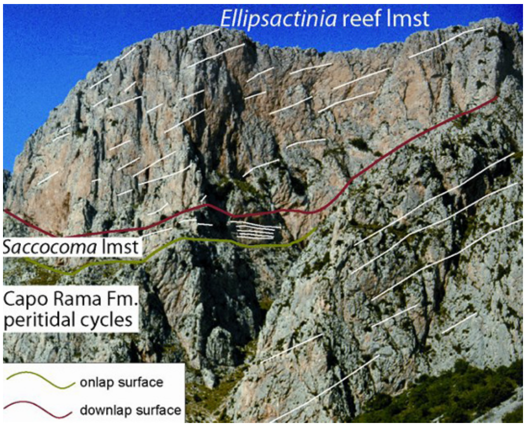

Figure 21. Downlap relationships between the Tithonian *Ellipsactinia* reef limestones and the Upper Jurassic *Saccocoma* limestones; the latter onlap onto the tilted and eroded beds of the Upper Triassic Capo Rama Formation peritidal limestones (Monte Pecoraro, Palermo Mountains).

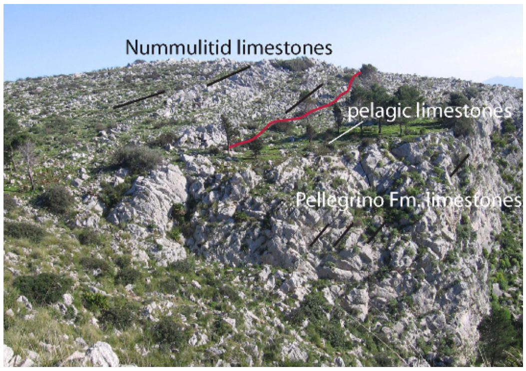

Figure 22. Downlap and erosional relationships (red line) between the Late Eocene Nummulitid limestones (Valdesi Formation) and the Late Cretaceous pelagic limestones of the Amerillo Formation and the rudistid limestones of the Pellegrino Formation (Monte Gallo, Palermo Mountains).

dia (D'Archiach) of Campanian-Maastrichtian age (Pellegrino Formation, 100-200 m thick). The lower boundary is a submarine erosional surface, showing downlap terminations with the Pizzo Sella Formation limestones. The upper boundary is an irregular erosional surface, often characterized by neptunian dykes filled by Paleogene planktonic foraminifera-bearing mudstone.

- White, grey and reddish marls and planktonic foraminifera-bearing mudstone, bioclastic packstone intercalations, with bryozoan and calcareous algal fragments (Amerillo Fm.), 50-70 m thick, onlap the Pellegrino Formation limestones or the *Ellipsactinia* reef limestones. A Late Cretaceous-Late Eocene age is indicated on the basis of the planktonic foraminifera biozones [66]. Slumps, megaslumps and fine-grained turbidites are common (e in Figure 17).

- White and grey calcarenites with large benthic foraminifera (Nummulitids, Alveolinids, f in Figure 19), hermatypic coral fragments (Valdesi Formation), 10-25 m thick, of Late Eocene age [83], downlap along an erosional surface the older pelagic deposits (Figure 22). Parallel, cross laminations and graded bedding are present in these deposits.

5. Discussion

The comparison and correlation between the unconformity surfaces, facies and geometric stacking patterns, recognized both in the shelf and basin successions, permit a reconstruction of the stratigraphic architecture of the Mesozoic shelf-to-basin system. This study has revealed a close relation between sedimentary evolution and cyclicity.

The tectono-stratigraphic features recognized (e.g. tilted fault block of the Triassic shallow-water limestones, subaerial erosion, see Figure 20), point out a tectonic influence in the sedimentary evolution of the Panormide/Imerese platform-to-basin system. The tectonic control on sedimentation has been related to the syn-rift and post-rift phases that involved the Tethyan continental margins during the Mesozoic [2, 39, 84–95].

5.1. Cyclicity

Different orders of cyclicity have been distinguished for the Triassic through Paleogene Sicilian shelf and slope successions [96–98]. These cycles are ranked by their temporal, spatial (vertical and horizontal arrangement) and depositional architecture [49, 50, 99, 100]. This hierarchical subdivision is not always visible in this study, probably due to: 1; the incomplete resolution of the data (lack of statistical and quantitative data, poor biostratigraphic resolution, etc.), and 2; the tectonic control on the cycles. Four Late Triassic through Palaeogene major transgressive/regressive cycles have been recognized and can be compared to platform-to-basin systems (Figures 23, 24). Subaerial erosional unconformities and correlative maximum regression surfaces, corresponding to basin-scale onlap surfaces, are useful in defining the sequence units [49, 50, 101]. These surfaces, separating transgressive from regressive deposits, are the cycle boundaries. A basin-scale submarine erosional surface, characterized by downlap terminations, separating regressive from transgressive deposits, is considered the maximum flooding surface of the T-R cycles [49–51, 101].

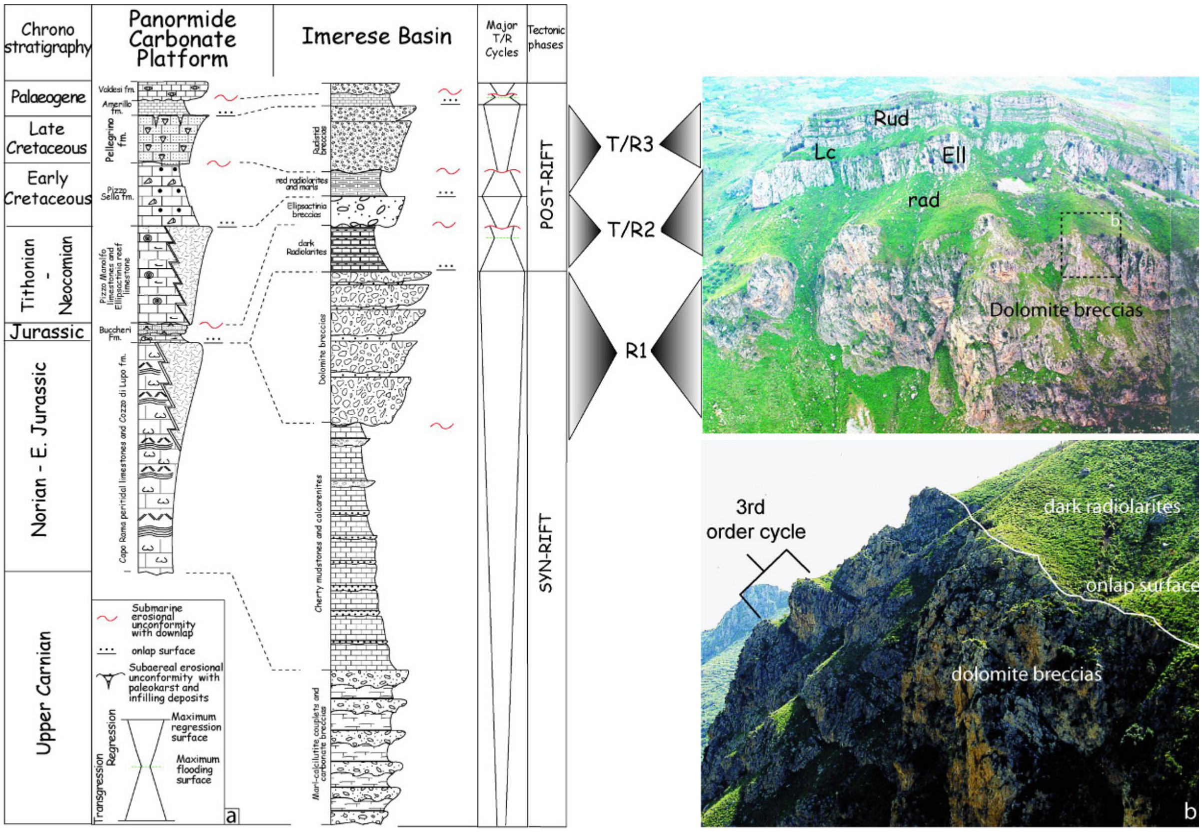

Figure 23. a) Cyclic organization of the Imerese succession, viewed on the northern side of Cozzo Famo (Termini Imerese Mountains.) and correlation with the Panormide carbonate platform succession. Legend: dolomite breccias of the Fanusi Formation, rad: dark radiolarites Member, Ell: *Ellipsactinia* breccias Member, Lc: red radiolarites and marls Member, Rud: Rudistid breccias Member of the Crisanti Formation; b) third order cycles of the lower Jurassic dolomite breccias of the Fanusi Formation.

Second and third-order T-R cycles and parasequence cycles have been defined along the studied isolated sections (see Figures 6–8, 18, 23b). These minor cycles have a good fit to the framework of first order T-R cycles; and they are highlighted in particular along the regressive phase of the slope successions [97].

1st major T-R cycle

Main characteristics

The first cycle (T-R1) is an incomplete cycle, consisting only of the upper Triassic-lower Jurassic deposits included in a regressive phase (Figures 23, 24). The cycle has a duration, at least, of 30 My although the related transgressive phase is absent. The occurrence of erosional surfaces, karst features, neptunian dykes, hiatuses, uplifted strata of the upper Triassic shelf-margin and proximal slope deposits, shows that the upper cycle boundary is a major tectonically-enhanced erosional unconformity (Figure 20). The correlatable boundary in the basin succession is the maximum regression surface, occurring at the top of the lower Jurassic dolomite breccias (Fanusi Formation, Figures 7-10, 23a, b).

Regressive phase

The regressive phase includes the Upper Triassic-Lower Jurassic Capo Rama peritidal limestone, the Cozzo di Lupo reef limestone, the basinal Carnian marly calcilutites (Mufara Formation), the upper Carnian-Rhaetian cherty limestones (Scillato Formation) and the Lower Jurassic dolomite breccias (Fanusi Formation).

The pelagic and hemipelagic sedimentation of the Carnian Mufara Formation was repeatedly interrupted by debris flows and turbidity currents, carrying shallow-water carbonate debris onto the slope and base-of-slope site. Five third order depositional sequences, highlighted by the resedimented intercalations, have been recognized. The reef-derived carbonate breccias in the basin succession are generally related to sea-level fall and shelf margin collapse [14, 20]. These prograding units have similar geometries and facies sequences of the "forestepping depositional sequences" described by [102], representing the building blocks of major order cycles [103].

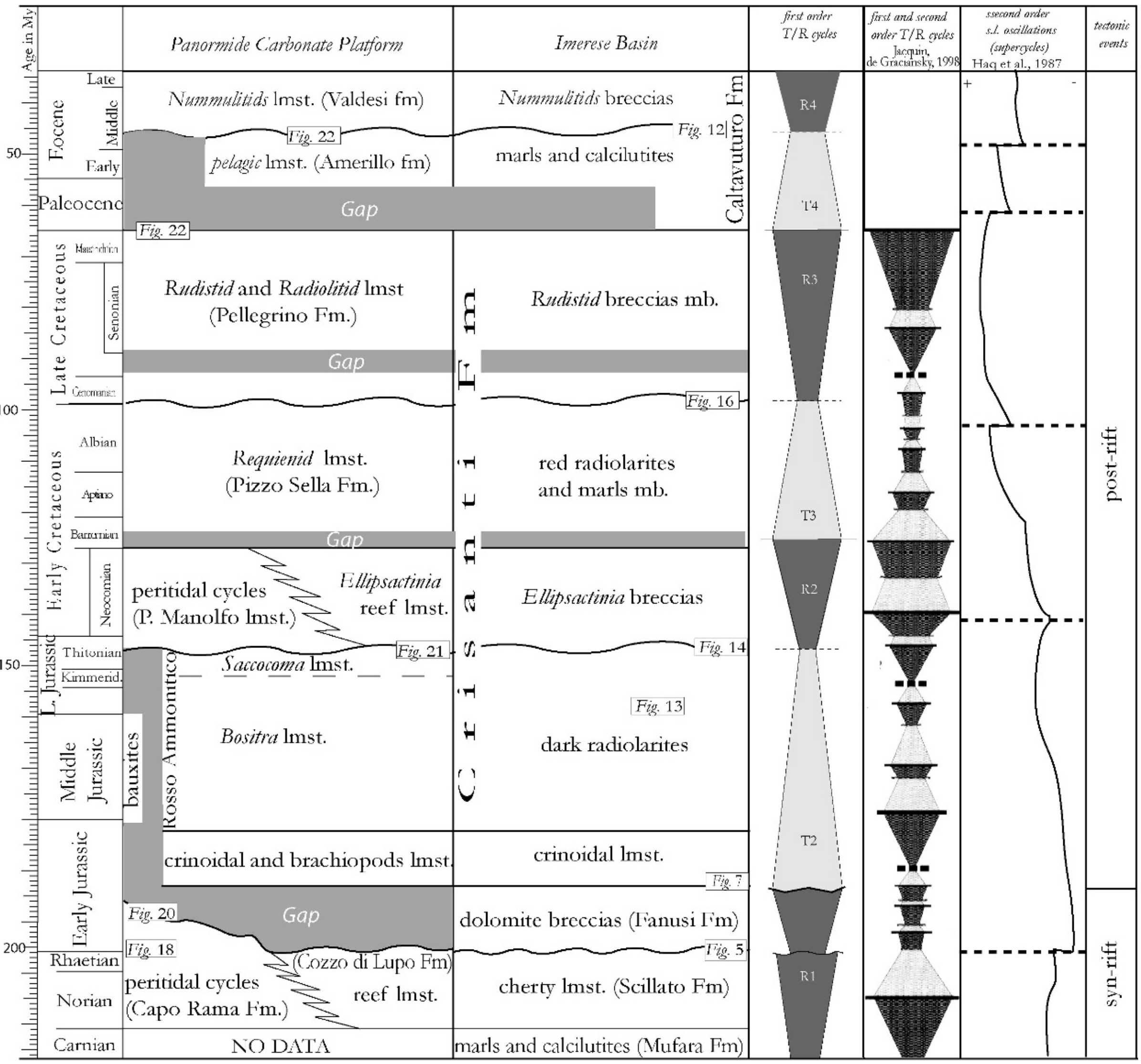

Figure 24. Chronostratigraphic scheme of the Panormide and Imerese lithostratigraphic units and their correlation with identified T-R cycles. On the right is a comparison with the T-R cycles of [101] and with the supercycles of [108]. These have some similarities in terms of timing of the cycles and their evolution in relation to the tectonic phases of the southern Tethyan continental margin.

During this major regressive phase, hundreds of metres of the Norian-Lower Jurassic shelf deposits (Capo Rama

Formation., Figure 18a), and coeval deep-water deposits (Scillato Formation.), developed with an aggradational-to-progradational geometric pattern (Figures 5, 6), interpreted as a second order transgression/regression cycle. The Fe-Mn crust, lying at the top of the Norian aggrading cherty limestones (Scillato Formation), can be compared with the maximum flooding surface of this second order cycle; the forestepping parasequences, at the top of the Scillato Formation (Figure 6) and the Lower Jurassic dolomite breccias (Fanusi Formation), represent the products of this second order regressive phase.

The Fanusi Formation deposits are organized in several third order forestepping depositional sequences (Figure 23b). Each cycle consists of thick poorly rounded lowstand dolomite breccias with an erosional lower boundary and thin transgressive/highstand laminated and fine-graded doloarenites (Figure 7b). These cycles appear to be the building blocks of the thick regressive phases of the major order cycles. The dolomite breccias of the Fanusi Formation are envisaged as the resedimentation products of the shallow-water limestones eroded from the adjacent Panormide platform, that during the Early Jurassic was subjected to tectonic fragmentation and subaerial exposure [39]. In this relatively lowstand sea-level time, the resedimented materials of the Fanusi Formation were deposited in the basin as a lowstand prograding complex systems tract (*sensu* [49, 99]).

2nd major T-R cycle

Main characteristics

The 60 My long second major transgressive/regressive cycle includes lower Jurassic to lower Cretaceous sediments (Figures 7-15, 20, 21, 23, 24). The lower boundary is a drowning unconformity, developed by tectonic movement. It is loccated above the subsiding and faulted upper Triassic-lower Jurassic platform, and it is distinguished by the onlap of the younger pelagic deposits (Buccheri Formation.). The correlative surface in the basin has been recognized due to the occurrence of onlapping Jurassic pelagic deposits, progressively younger, above the regressive Fanusi Formation For the shallow-water and reef-margin successions (Pizzo Manolfo and *Ellipsactinia* reef limestones), the upper boundary is an erosional surface, slightly tectonically enhanced, associated with fractures and neptunian dykes. This erosional boundary becomes a maximum regression surface on the top of the Neocomian *Ellipsactinia* breccia Member of the Crisanti Formation.

Transgressive phase

The transgressive phase consists of Jurassic deposits (crinoidal, condensed *Bositra* and *Saccocoma* limestones of the Buccheri Formation.), developed on a carbonate pelagic plateau setting. In the basin aggradational dark radiolarites (from the lower member of the Crisanti Formation) onlap the older dolomite breccias (Figures 7, 8, 23a, b).

The resolution of the Jurassic cyclicity is poor in view of the imprinting of the first order relative sea-level rise, which masks minor and higher frequency cycles. The discontinuous pelagic platform sedimentation and the poor biostratigraphic data of the radiolarites into the basin do not help to recognize the presence of minor order cycles.

Regressive phase

A correlative platform-to-basin submarine erosional surface, separating transgressive from regressive deposits, represents the maximum flooding surface of this cycle. A Tithonian-Neocomian aggrading-to-prograding carbonate platform with rimmed shelf-margin (Pizzo Manolfo peritidal and *Ellipsactinia* reef limestones) developed during the regressive phase (Figures 23, 24). The *Ellipsactinia* reef limestones downlap the *Saccocoma* limestones that pertain to the older transgressive deposits (Figure 21). The lateral growth towards the basin of the carbonate shelf deposits, mostly along by-pass margins, has produced a large volume of reef-derived debris (*Ellipsactinia* breccias Member), which downlap onto the older dark radiolarites (Figure 14). Clinoforms and erosional channel geometries (Figures 8, 10, 12) suggest the effects of debris flows along submarine canyons. Several carbonate turbiditic-fans along the basin margin were developed.

The lithofacies of the *Ellipsactinia* breccias are characterized by a chaotic texture, gradation and lamination structures. The entire succession is arranged in two coarsening and thickening-upwards sequence cycles. They are interpreted as two second order transgressive/regressive cycles (Figure 9), governed by long-term sea-level change; their forestepping sequence characters fit well within the frame of the first order regressive phase.

3rd major T-R cycle

Main characteristics

The third major T-R cycle (T-R3) comprises lower to upper Cretaceous successions for a duration of approximately 65 My (Figures 23, 24). The lower boundary corresponds to the erosional (subaerial?) surface carved into the Neocomian shelf-margin deposits. This surface can evolve either into a drowning surface with neptunian dykes filled by upper Cretaceous pelagic limestone (Amerillo Formation), or, along the inner platform succession, into an onlapping unconformity surface covered by Barremian-Aptian shallow water deposits (Pizzo Sella Formation). A transgressive surface (Figures 9, 12), with onlap terminations (Figure 15), between lower Cretaceous radiolarian pelagic deposits (red radiolarites and marls Member of the Crisanti Formation) and the regressive *Ellipsactinia* breccias Member marks the lower boundary in the basin. The upper boundary of the cycle is a tectonically-enhanced erosional unconformity, as evidencing by the presence of several dykes, cutting the top of the Upper Cretaceous platform deposits; the correlative surface in the basin is a maximum regression surface on the top of the Upper Cretaceous Rudistid breccias (Figure 12).

Transgressive phase

During the transgressive phase a Late Barremian-Early Aptian open carbonate shelf developed in the Panormide domain. The Pizzo Sella Formation limestones are characterized by overall aggradational geometries. The Imerese Basin is characterised at this time by a low angle slope depositional setting, with aggradational deep-water facies (red radiolarites and marls Member of the Crisanti Formation).

Regressive phase

A major downlap surface, associated with submarine erosion and hiatus observed both in platform and slope settings (Figure 16) separates regressive from transgressive deposits.

The regressive phase, that encompasses the upper Cretaceous successions, consists of progradational rudistid open carbonate shelf deposits (Pellegrino Formation), which downlap onto the older aggrading shelf facies (Pizzo Sella Formation); skeletal turbidites and breccias (Rudistid breccias Member), which were deposited along the slope at the foot of the escarpment, form a regressive turbiditic fan system. The latter consists, at least, of three third order forestepping depositional sequences (Figure 16), that fit in with the major regressive phase.

4th major T-R cycle

Main characteristics

The overlying major transgressive/regressive cycle (T-R4) encompass the uppermost Cretaceous-upper Eocene deposits and has a duration of about 30 My. A drowning unconformity, overprinting the Maastrichtian erosional surface, is characterized by hiatuses, palaeokarst features and neptunian dykes filled with upper Cretaceous and/or Eocene planktonic foraminifera-bearing mudstone (Amerillo Formation.), is the lower boundary of the cycle in the shelf. This surface, in the basin, is marked upwards by an overall facies change to the pelagic Caltavuturo Formation deposits.

Transgressive phase

In the shelf system an upper Cretaceous-Eocene deep-water succession developed. The aggradational pelagic strata of the Amerillo Formation onlap the older Pellegrino Formation limestones. The basin has been dominated by aggradational pelagic and hemipelagic sedimentation (Caltavuturo Formation), onlapping the underlying regressive Rudistid breccias Member of the Crisanti Formation.

Regressive phase

The regressive phase includes the Upper Eocene deposits. An open shelf "foramol-type" facies (*sensu* [104]), consisting of Nummulitid coarse-grained deposits (Valdesi Formation), developed along the basin margin and the carbonate turbiditic fans (Nummulitid breccias of the Caltavuturo Formation), along the depositional slope. These deposits, within both carbonate shelf and basin systems, are characterized by regressive facies sequences and progradational geometries.

The lower boundary, separating regressive from transgressive deposits, is an overall downlap surface onto the underlying pelagic limestones of the Caltavuturo and Amerillo Formations (Figures 12, 22). The upper boundary of the cycle in the shelf successions is not exposed; in the basin it is marked by an overall facies change to clay and siliciclastic deposits related to synorogenic Numidian flysch sedimentation.

5.2. Origin of the cycles

In order to understand the main factors that have influenced the evolution of the Panormide-Imerese carbonate platform-to-basin system, tectonics, subsidence and aggradation of the platform have been studied, to determine the history of relative sea-level oscillations and possible eustatic influence.

Vail et al. [105] and Posamentier et al. [106] referred the formation of the depositional sequences and unconformity boundaries to eustatic sea-level oscillations, interpreted from global sequence correlation [107, 108]. This original concept has been progressively modified on the basis of interaction with other factors. For example, tectonic causes [101, 109–115] or depositional factors such as sediment supply and growth of carbonate sedimentary systems [8, 116, 117], have been proposed.

The cycles described here have been defined on the basis of long-term transgressive/regressive phases [48]. The cycle boundaries, which are the result of a major downward shift of coastal onlap, are often associated with significant time gaps, usually with subaerial exposure (more evident in the shelf succession) and also faulted, folded or uplifted beds are commonly linked. These events are related to the major tectonic phases that developed during the evolution of the ancient continental margin [36, 39, 87, 95] (Figure 24). These tectonic pulses, producing the major unconformities, are commonly related to late syn-rift and post-rift phases of the evolution of the southern Tethyan continental margin [36, 39, 85–87, 89–95, 118], as seen in other passive margins [101, 112, 113].

Subsidence is of particular importance because it controls the long-term aggradation of the platform and basin. Although there aren't specific studies on the subsidence of the Sicilian Mesozoic passive margin, its history may be similar to that of the other platform-basin systems that formed in the same passive margin. Where the subsidence history of this margin can be established, it shows an exponentially decaying thermal subsidence following initial rifting subsidence [118–120].

During the late Triassic-Jurassic the strong thicknesses of the Sicilian platform and basin successions suggest high rates of tectonic subsidence related to late syn-rift phase of the continental margin [36, 39, 86, 87, 95]. Total subsidence rates decreased approximately exponentially with time during the late Jurassic and Cretaceous, indicating that thermally induced post-rift subsidence of the continental margin was the main controlling factor [121]. Since the Mesozoic, the Mediterranean area has experienced a tectonic change from divergent to convergent movements between Pery-Tethyan plates [122–124]. These movements might reflect crustal deformation due to intraplate stresses [110, 111]. In the Sicilian margin the long phase of erosion or possibly non deposition during the Paleocene, as well as an Eocene pulse of aggradation, suggest tectonic enhancement of the sea-level signal due to intraplate stresses. The Late Eocene and Early Oligocene regressive trends may be related to high rates of sedimentary supply [117], with lateral growth (progradation) of shallow-water deposits into the basinal areas.

Each recognized cycle has a duration of more than 60 My except for the last cycle, which was probably interrupted by the Tertiary orogenic phase. When the Sicilian cycles are compared with the curves of global sea-level oscillations [108] and the transgressive-regressive cycles recognized in the European basins [101] (Figure 24), there are some similarities in terms of timing of the cycles and genesis of the sequence boundaries. This comparison confirms the tectono-eustatic mode of the cycles

Minor orders of cyclicity are recognized, mostly in the slope succession. These second order cycles reflect minor events of relative sea-level change, created by modulation within the long-term thermal basin subsidence of the major order cycles [25, 49, 50, 101–103]. The third order depositional cycles are the building blocks of the second order T-R facies cycles, according to [20]. The forestepping sequence cycles [102] with infilling patterns that developed during the regressive phases of major order sea-level oscillations, can easily be recognized within the Imerese slope succession (Figures 15, 21b). Similarly, the parasequences and parasequence sets recognized (Figures 6, 17) have a stratigraphic architecture related to the transgressive or regressive phases of the sequence cycles of second and third order, such as suggested by [99, 106], and have been related to high-frequency sea-level oscillations [6, 7, 41, 67, 68, 73, 74, 77, 125, 126].

6. Conclusions

Sequence stratigraphic studies of the Triassic through Paleogene carbonate successions of platform, slope and basin in western Sicily (Palermo and Termini Imerese Mountains) have identified a sedimentary cyclicity mostly caused by relative sea-level oscillation (tectono-eustatic cycles). Physical stratigraphy and facies analysis are powerful tools to reconstruct the stratigraphic architecture and the sedimentary evolution of the Sicilian Mesozoic-Paleogene carbonate shelf-to-basin deposits.

The studied stratigraphic successions from the Imerese and Panormide palaeogeographic domains of the southern Tethyan continental margin, are now incorporated in the complex Sicilian Chain. Good correlations were obtained between shelf and basin in spite of their isolated stratigraphic successions and their physical characters, notwithstanding the lacking of field continuity.

The correlative strata from shelf to basin are organized in four major transgressive/regressive cycles which span from the late Triassic to Eocene. These cycles are characterized, both in platform and basin setting, by transgressive deposits that onlap older regressive deposits. The latter, characterized by progradational geometries, downlap the older transgressive deposits.

The first transgressive/regressive cycle (T-R1) is an incomplete cycle since it consists only of the upper Triassic-lower Jurassic deposits included in a regressive phase. T-R2 includes Jurassic to early Cretaceous successions; T-R3 comprises early to late Cretaceous successions. T-R4 encompasses Paleocene-Eocene carbonate deposits.

Different depositional motifs are recognizable within the carbonate shelf and slope successions, and they are closely related to the transgressive/regressive cyclicity.

The platform-to-basin system's original physiographic profile was interrupted by scarp-margins and discontinuities, produced during the major tectonic events.

The whole slope succession consists of more than 50% of shallow water (mostly reef) derived debris. Sedimentary evolution, of the slope-to-basin depositional systems, was partially guided by vertical and lateral growth and retreat of the carbonate platform margins. Different stages of carbonate platform growth have been distinguished and related to the different phases of the first order cycles. The sedimentary evolution of the carbonate platform was controlled by long-term relative sea-level change (tectonic subsidence and eustasy).

During the major regressive phases, when the shelf facies prograded outwards into the basin, frequent by-pass, debris flow, and turbidity current processes occurred. In these sedimentary settings prograding geometries were frequent. During major transgressive phases the slope was characterized by widespread gravity structures, such as slides, slumps and megaslumps along low angle slope depositional settings, where the geometries show the most aggradational patterns.

The timing of the main tectonic events (obtained by biostratigraphy and interpretation of stratigraphic relationships) is often contemporaneous to the time of the sequence boundary of the major T-R Sicilian cycles.

The Sicilian platform-to-basin system sediments reflect changes that relate to the opening of the Mesozoic Tethyan sea. Particularly, the Upper Triassic-Lower Jurassic deposits, represented by vast thickness resulting from a consistent subsidence, appear to be related to the late syn-rift phase of the continental margin. The upper boundary of this cycle is a tectonically-enhanced unconformity, related to the regional tectonic movements and to global sea-level fall events. The last three cycles, spanning from Jurassic to Eocene, can be related to the post-rift evolution, characterized by thermal subsidence changes and intraplate movements.

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