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POST- ALPINE LATE PLIOCENE – MIDDLE PLEISTOCENE UPLIFTED MARINE SEQUENCES IN ZAKYNTHOS ISLAND

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Abstract

Post-orogenic marine sequences crop out in two areas of Zakynthos Island: a) In Gerakas peninsula at the southeastern edge of the island and b) Along the coastal zone of central northern Zakynthos from Alikanas in the west to Zakynthos town in the east.

Detailed stratigraphic analysis of Gerakas area has shown the existence of three formations separated by two unconformities: 1) Gerakas Fm Q_1 comprising marls of Late Pliocene–Early Pleistocene age (2.8 – 0.9 Ma). 2) Kalogeras Fm Q_2 comprising littoral sandstones at the base (Q_{2a}), alternations of sandstones and marls in the middle (Q_{2b}) and marls (e.g. Porto Roma) in the upper part (Q_{2c}). The age of this formation is middle Pleistocene (0,8 – 0,5 Ma). 3) Agios Nikolaos Fm Q_3 comprising littoral sandstones.

Stratigraphic correlations between the two aforementioned areas have been made and equivalent stratigraphic formations, slightly differentiated in the central northern Zakynthos, have been identified. The upper unconformity is well pronounced in the area of Cape Gaidaros whereas the lower unconformity is often masked by debris accumulated along the base of the cliffs produced by the compact sandstones of Q_{2a} above the soft marls of the underlying Q_1. A remarkable increase in the thickness of the middle member Q_{2b} is observed in the northern part with respect to the equivalent Kalogeras Fm in Gerakas area. In contrast, the thickness of the upper member (Q_{2c}) is highly reduced in the limited northern outcrops compared to those of the southeastern exposure.

The Plio-Quaternary post-orogenic marine deposits in both regions represent the creation of the accommodation space formed by the westernmost extensional structure of the Hellenic arc. The two unconformities reflect sea-level changes during the Quaternary within an overall tectonic uplift of Zakynthos Island at the front of the Hellenic arc and trench system, while the entire post-orogenic sequence reflects the intense palaeoclimatic fluctuations of the Quaternary.

Key words: *stratigraphy, Quaternary, stratigraphic correlations, biostratigraphy, palaeoclimate.*

1. Introduction

Zakynthos Island is located at the front of the present-day Hellenic arc and trench system, which is

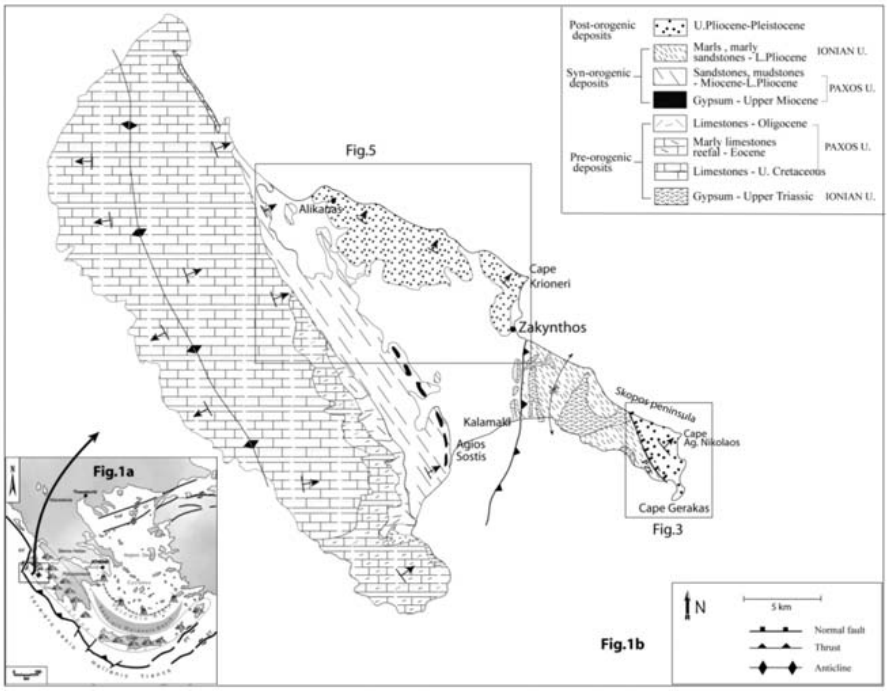

Fig. 1: a) Location of Zakynthos Island within the schematic representation of the Hellenic arc system, b) Geological map of Zakynthos island, modified after Underhill (1989).

formed along the convergent zone of the plate boundaries between the subducting African plate and the overriding Eurasian plate (Fig. 1a). The direction of slip and tectonic transport is trending northeast–southwest as this is deduced from tectonic data both onshore and offshore, from seismotectonic and geodetic data (e.g. McKenzie, 1972; Le Pichon and Angelier, 1979; McClusky *et al*., 2000; Reilinger *et al*., 2006). The Hellenic arc shows the characteristics of a thrust and fold belt which has evolved since early Tertiary by migration of the tectonic front from the inner part of the arc in the Aegean area to the more external part in the Ionian Sea. Tectonic units resulting from the different mechanical properties of the stratigraphic successions developed within the palaeogeography of the Hellenides have created nappes with westward tectonic emplacement bringing the more internal tectonic units over the more external (Aubouin et al, 1976). Thus, starting from the Hellenic trench in the west, which occupies depths around 4-5 km, we first observe the tectonic foreland of the Hellenic orogenic system which is known as Paxos unit. This unit is exposed only in the Ionian Islands of Zakynthos, Kephalonia, Lefkada and Paxos. The stratigraphic column comprises Jurassic–Oligocene carbonate rocks of platform and slope facies, followed by Miocene clastic sequences topped by the Messinian evaporites. The tectonism of the Paxos unit occurred during the Messinian–Early Pliocene when the Ionian nappe was emplaced on top of the Messinian evaporites (e.g. Skopos mountain in eastern Zakynthos) (Mercier *et al*., 1972; Underhill, 1989).

The next eastward tectonic unit is the Ionian nappe, which is observed on top of the Paxos unit in the eastern Zakynthos, eastern Kephalonia and eastern Lefkada. This unit comprises a stratigraphic column of Triassic evaporites, Late Triassic–Early Jurassic shallow-water carbonates, Middle Jurassic–Oligocene pelagic limestones with cherts and Oligocene-Miocene flysch. The sole Ionian formation exposed in Zakynthos, at the southeast part of the island, is the Triassic evaporites.

The geological structure of Zakynhos is rather simple, comprising a geometric anticline affecting all the stratigraphic formations of the Paxos unit in the west and a complex structure of the thrusted Ionian Triassic formations in the east (Fig. 1b). The anticlinal axis of Paxos unit in Western Zakynthos is observed within the Late Cretaceous limestones. The western limp of the fold lies below sea-level towards the deep trench whereas the eastern limp forms the central zone of Zakynthos with a monoclinal structure of an average dip of 40° to the east observed through the Tertiary sequence from the Eocene to the Early Pliocene. The Miocene sedimentary sequence rests unconformably (e.g. Mirkou, 1974; Dermitzakis, 1978) on the underlying platform carbonates along the lower slopes of the Zakynthos anticline with pre-Miocene uplift and erosion of the Eocene and Oligocene formations. The main deformation occurred within the late Miocene – early Pliocene as this is shown by the similar dip of the strata (30° – 45°) both below and above the unconformity. The Ionian thrust has affected the top of the Paxos sequence in the Messinian – Early Pliocene and the syntectonic early Pliocene sediments, at the northern part of the Skopos peninsula, trailed by the Triassic allochthonous formations. The presence of the Triassic evaporites has contributed to the overall complexity with disharmonic deformation (Nikolaou, 1986; Underhill, 1988).

The post-orogenic sediments of Zakynthos are exposed in two areas: (i) In southeastern Zakynthos at the area of Vassilikos, from Cape Gerakas at the south to Cape Agios Nikolaos at the north, at low altitudes below 60 m, and (ii) Along the northern coastal zone from Alikanas in the west to Zakynthos town in the east, where the uplifted marine Plio-Pleistocene sediments form successive hills up to 200 m of elevation.

2. Materials and Methods

During this work the authors carried out geological mapping of the central-northern part of Zakynthos island (Fig. 1) and produced the nannofossil biozonation of ten samples collected from the uppermost beds of the Q_2 Fm marls (Figs 1, 5) (right below the Q_2/Q_3 unconformity) at Cape Gaidaros and Ag. Charalambos sections, probably the only locations where the upper unconformity of the post-orogenic sequence outcrops in the northern part of the island. The nannofossil study was performed on the counts of 300 placoliths using an optical polarizing light microscope and the biozonation was based on the analysis of the biostratigraphically important taxa such as *Pseudoemiliania lacunosa*, *Reticulofenestra asanoi*, *Gephyrocapsa* sp.3, *Gephyrocapsa* spp.>4 etc. Biozones were determined according to the biozonal scheme of Rio et al. (1990). The biostratigraphic analysis allowed lithostratigraphic correlation of the upper unconformity (essentially the topmost marls of the Q_2 Fm) to the equivalent southern post-orogenic outcrops in the Vassilikos area whose extensive published (Triantaphyllou, 1996; Papanikolaou, 2008) biostratigraphic (97 analysed stratigraphic levels) and magnetostratigraphic data (76 analysed stratigraphic levels) render it as a good reference composite sequence, almost 500-metres thick, for the post-orogenic Quaternary deposits of the island.

3. The Quaternary deposits in southeast Zakynthos

The marine Quaternary deposits at the southeast part (Vassilikos area) of the island and the rather conspicuous unconformity separating pelagic marls from the overlying coastal sandstones and calcarenites, e.g. at Gerakas beach, have been known quite a long time ago (e.g. Keraudren, 1970). However, detailed geological mapping by Dermitzakis et al. (1977) proved the existence of two similar unconformities within the Quaternary succession with the distinction of three formations (Figs 2, 3). Later studies (Triantaphyllou, 1993; Triantaphyllou et al., 1997; Duermeijer et al., 1999; Broadley et al., 2006; Papanikolaou, 2008) have better constrained the age of the above stratigraphic succession within the Quaternary and, with the support of biostratigraphy and magnetostratigraphy, have determined with accuracy the chronostratigraphic extension of each formation (Papanikolaou, 2008) (Fig. 4).

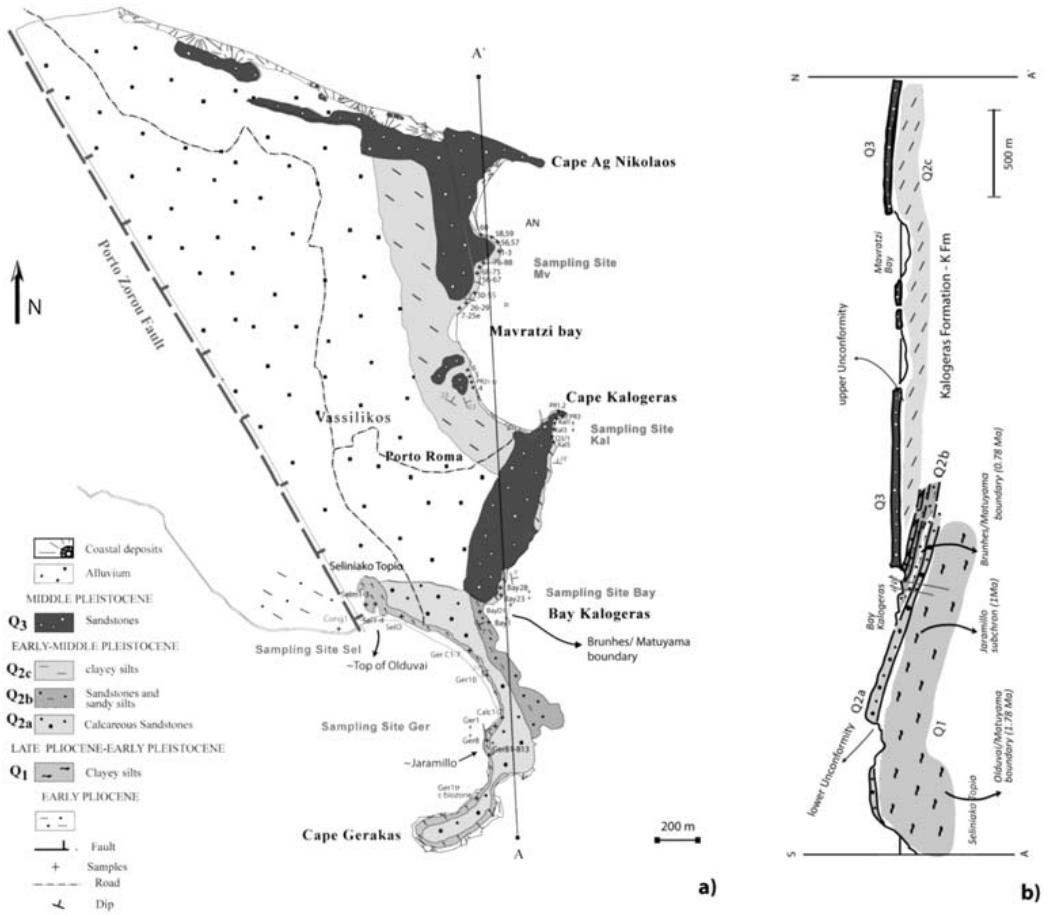

Fig. 2: a) Detailed geological map of southeast Zakynthos peninsula. b) geological section trending N-S (`A-A on the geological map) showing the succession of the three Quaternary post-orogenic formations Q_1, Q_2 and Q_3 and the approximate positions of the magnetostratigraphic events (Papanikolaou, 2008).

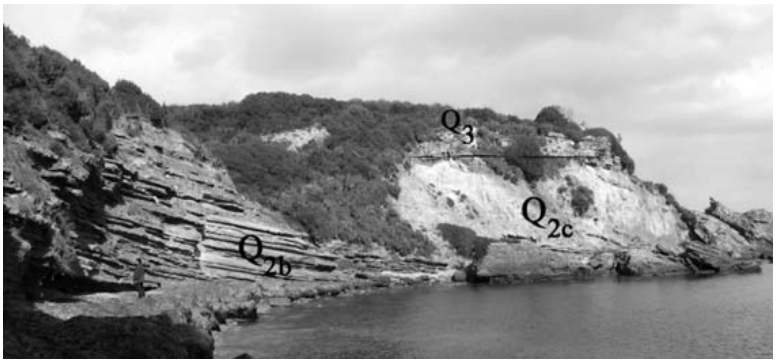

Fig. 3: Photo from Bay Kalogeras location showing the two members of Q_2 Formation, that is the alternations of sandstones and silts of Q_{2b} overlain by the silts of Q_{2c}, both unconformably overlain by the calcareous sandstones of Q_3 Formation.

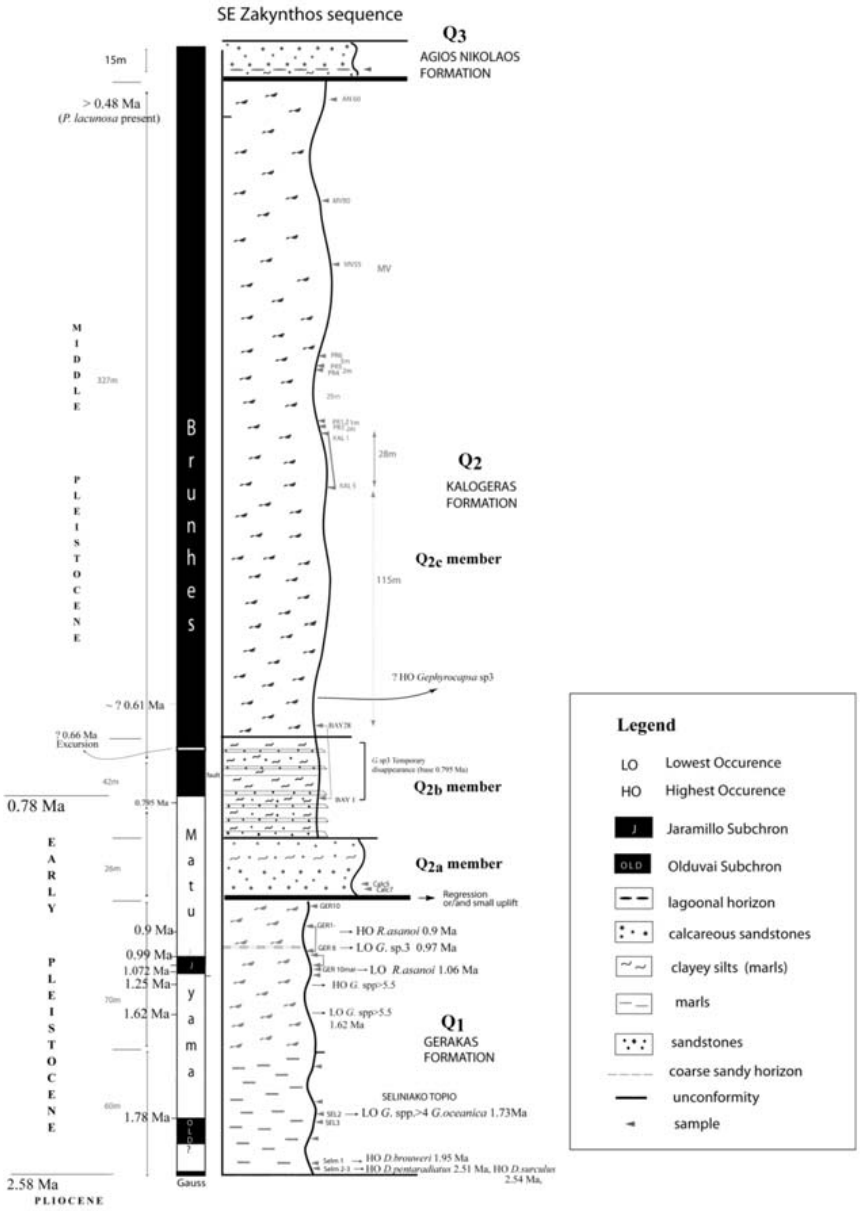

Fig. 4: Composite stratigraphic profile for the southeast peninsula formations. The palaeomagneto-biostratigraphical events are annotated (Papanikolaou, 2008).

In particular, from the bio- and chrono- stratigraphic point of view the southeast Zakynthos provides a composite section (~ 480-metres thick) (Fig.4) starting with Q_1 (Gerakas) Formation exposed at Seliniako Topio and along Gerakas beach at the south comprising 130-metres thick blue marls and clayey silts with the older exposed deposits assigned to nannofossil biozone MNN 16-17, therefore latemost Pliocene in age (~ 2.8 Ma) (Papanikolaou, 2008). The top of the Olduvai Subchron (1.8 Ma) was identified at the middle part of Q_1 Fm while a couple of metres higher the MNN19a/19b nannofossil biozones boundary was recognised.

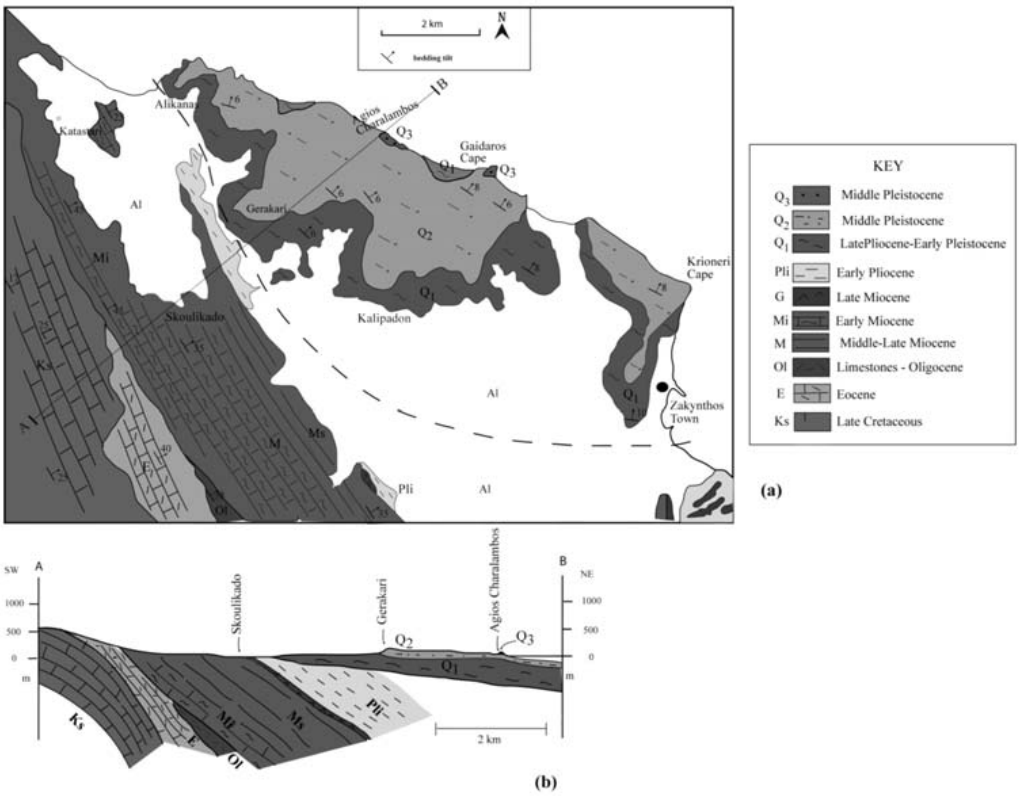

Fig. 5: a) geological map of the central-northern part of Zakynthos and b) geological section SW-NE trending (A-B on the geological map) showing the unconformably overlying post-orogenic deposits of Q_1, Q_2, Q_3 over the carbonate and clastic sequence of Paxos Unit.

The Jaramillo Subchron (1.07-0.99 Ma) was identified at the uppermost part of the formation and the top of the Q_1 Formation has an estimated age of around 0.85 Ma.

The composite section continues northward with Q_2 (Kalogeras) Formation which is initiated at the verge of the latemost Early Pleistocene (~0,8 Ma) and terminates in the Middle Pleistocene (~ 0,5 Ma). This formation consists of three members: a) $Q_{2a,}$ is 40-metres thick and consists of calcareous sandstones and calcarenites, b) Q_{2b} is 25-metres thick and comprises alternations of sandstones and silts, and c) Q_{2c} is around 320-metres thick and consists of silts and intercalations of sandy silts (Fig.3). The Matuyama/Brunhes boundary (0.78 Ma) was identified at the lower beds of the Q_{2b} member and the uppermost beds of the Q_{2c} member, slightly north of Porto Roma, were estimated to be within the nannofossil biozone MNN19f as *P. lacunosa* is present and therefore these beds are older than 0.48 Ma.

The onset of the overlying unconformable Q_3 (Agios Nikolaos) Fm more likely corresponds to the biozone MNN20, thus in the Middle Pleistocene (~ 0,45 Ma), yet its top remains chronologically undetermined (Papanikolaou, 2008).

The entire post-orogenic sequence in SE Zakynthos is bounded by the Porto Zorou fault in the west against the Early Pliocene and Triassic formations of the Skopos mountain, and thus the basal sediments of the post-orogenic series are intangible. On the other hand, the top of the Agios Nikolaos Fm dips under the present-day sea-level to the north extending to the present–day continental shelf of the

island. Thus, the uplifted Middle Pleistocene marine terrace represented by the Agios Nikolaos Fm may be stratigraphically followed by shelf sediments related to the Late Pleistocene and Holocene sea-level changes. This association can only be determined through combined onshore/offshore studies.

4. The Plio-Quaternary deposits of central - northern Zakynthos

The post-orogenic deposits of central-northern Zakynthos are shown in the map of Fig.5 produced during this work. The landscape behind Zakynthos town is a distinctive slightly inclined sedimentary sequence to the north with blue marls at the base capped by brown-reddish sandstones, which form a pronounced marine terrace with steep cliffs and the old castle on top. Biostratigraphic and magnetostratigraphic studies on the popular Citadelle section at Zakynthos town, have shown that it incorporates the Gelasian/Calabrian boundary (until recently Plio/Pleistocene boundary) (Bizon and Müller, 1977; Mirkou, 1987) and the latest Pliocene (Triantaphyllou 1993, 1997; Duermeijer et al., 1999; Suballyova et al., 1999).

In particular, the Citadelle section (Q_1) is more than 200-m thick, while younger beds of the sequence are extended to the north, at the Akrotirio Kryoneri, where the deposition of Q_1 marls persists, at least up to the nannofossil biozone MNN19d (well within the Early Pleistocene) (Triantaphyllou, 1993). The section had been previously studied and was assigned an age of the nannofossil biozone NN19 (Blanc-Vernet and Keraudren, 1969; Kowalcyk et al. 1977). The lower Pleistocene marls are unconformably overlain by around 12-metres thick calcareous sandstones with sandy-marly intercalations (Q_{2a}) which represent the lower unconformity of Gerakas sequence. This unconformity is morphologically apparent all along the southern slopes of the central-northern post-orogenic outcrop, from Zakynthos town in the east to Gerakari and Alikanas in the west, formed by the superposition of the Q_{2a} sandstones upon the Q_1 marls. Thus, the morphology is rather characteristic with the top of the hills being approximately 200 m high, and the geometrical surfaces of the overlying strata of the sandstones dipping with 6°– 8° to the north. The most characteristic area occurs near the two settlements of Gerakari village, where the Lower Gerakari is built on the blue marls and the Upper Gerakari on the overlying sandstones (Fig.5). The slightly inclined post-orogenic sedimentary sequence contrasts the structure of the underlying Late Cretaceous to Early Pliocene sedimentary formations which dip 30°– 45° to the northeast, as shown in the SW–NE geological section starting from the eastern slopes of the Zakynthos anticline in the southwest to the coastal zone in the northeast (Fig. 5b). The contact between the marls and the sandstones is rarely discernible because it is masked by large blocks and debris fallen from the sandstone cliffs on the underlying soft marls. The change of facies is very abrupt and it may be related to a small disconformity with a minor stratigraphic hiatus.

The upper unconformity (Q_2/Q_3) has been detected during this study in two small outcrops along the coastal zone in the areas of Cape Gaidaros (Fig. 6) and Agios Charalambos. At Cape Gaidaros the upper sandstones (Q_3) overlie, with a small angular unconformity, the alternations of sandstones and marls (Q_{2b}) (Fig.6a). More than 2 meters of marls (Q_{2c}) are missing below the unconformity due to erosion during the chronostratigraphic hiatus between the base of the upper sequence (Q_3) and the top of the middle sequence (Q_{2b-c}). Agios Charalambos section is exposed north of Zakynthos town, at the eastern coast, where the uppermost beds of the exposed 3 metres of marls (Q_{2c}) are correlated with the nannofossil biozone MNN19f (presence of *P.lacunosa*, absence of *Gephyrocapsa* sp. 3) (Middle Pleistocene), and are unconformably overlain by calcarenitic sandstones (Q_3).

The superposition of all three post-orogenic stratigraphic formations in the central-northern Zakynthos can be seen in a few coastal sections as is the case at the western cliffs at Cape Gaidaros where

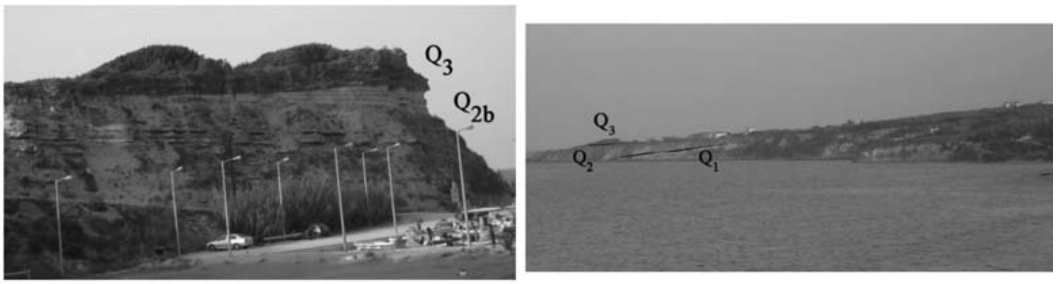

Fig. 6: a) photo showing the sandstones (Q_3) sitting unconformbaly on top of the alternations of marls and sandstones (Q_{2b}) at Cape Gaidaros area. b) photo showing the succession of all three post-orogenic formations at the north coasts of Zakynthos island. The marls of Q_1 Fm are underlain by the alternations of sandstones and marls of Q_2 Fm and the sandstones of Q_3 Fm are clearly overlain on top with an angular unconformity.

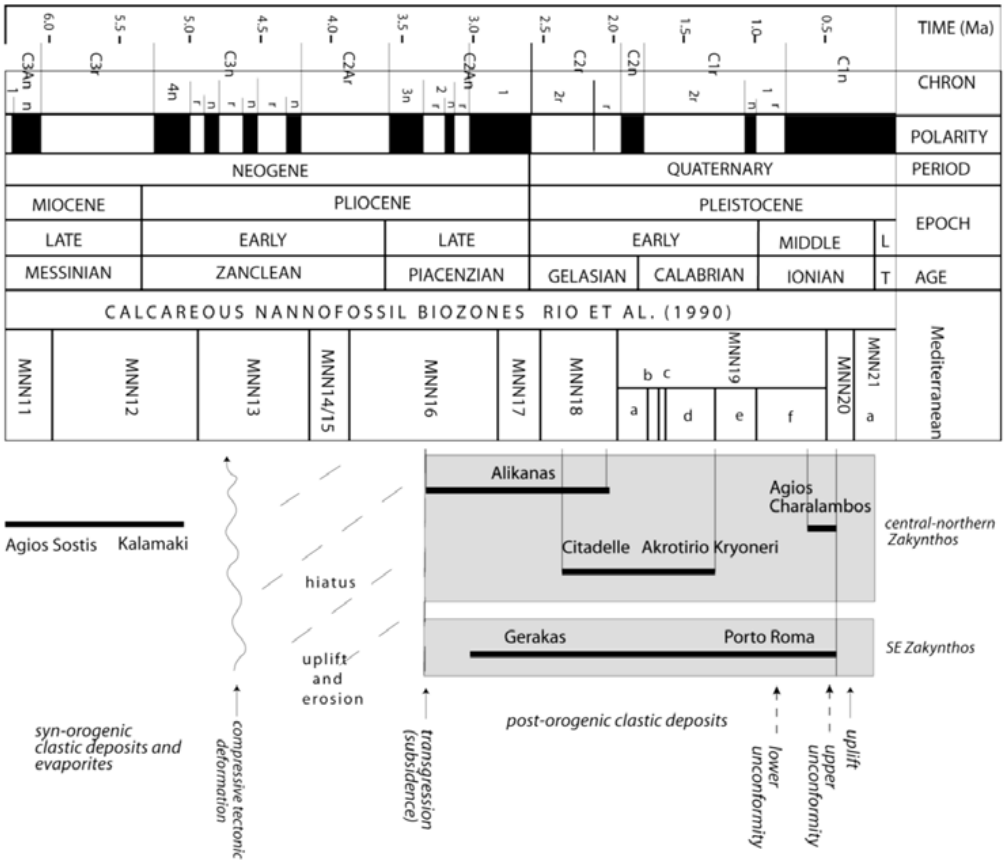

Fig. 7: Stratigraphic table-chart showing the stratigraphic ranges of selected (composite) sections. The chronostratigraphic chart is according to the newly ratified geological time scale (Gibbard et al., 2009).

the blue marls of Q_1 underlie the sandstones and alternations of sandstones and marls of Q_2 as well as some relics of the upper sandstones of Q_3 over Q_2 (Fig. 6b).

5. Discussion and Conclusions

Correlation of the post-orogenic formations of the central-northern part of the island with those of the southeastern part shows a general similarity with only small differences shown on the stratigraphic table-chart of Fig.7. Thus, both unconformities are present with similar characteristics, such as involving dramatic facies changes, except that the lower unconformity is a disconformity, whereas the upper unconformity clearly is an angular unconformity. Both unconformities form marine terraces with contrasting facies below and above.

The main difference between the two post-orogenic outcrop-groups (the south and the north) is the highly reduced thickness in the silts of the Q_{2c} member of only a few metres thick in the central-northern Zakynthos, as opposed to the hundred metres-thick marls in the SE Zakynthos, as seen in the area of Porto Roma. Inversely, the next difference between the two areas refers to the increased thickness of the middle member, $Q_{2b,}$ of the alternations of sandstones and silts, which is almost double in central-northern Zakynthos than that in the southeast. The recorded thickness of Agios Nikolaos Formation is only a few metres in central-northern Zakynthos whereas it exceeds 20 metres in the Agios Nikolaos Cape at southeast Zakynthos.

The compilation of single and composite sections shown in Fig.7 infers that the latest synorogenic deposits in Paxos unit, those of Agios Sostis and Kalamaki sections (Fig.1), are of latest Miocene–earliest Pliocene age (Dermitzakis, 1978; Duermeijer et al., 1999). In particular, these deposits display the Messinian transition from the clastic sequence into evaporitic beds (laminated gypsum, gypsum arenites, balatino, gypsum conglomerates), which are overlain by "trubi" limestones and calcareous marls. Consecutively, compressive deformation and tectonism occurs in the Early Pliocene as a result of the overthrusting Ionian nappe.

The marls sitting on top of the Ionian Triassic evaporites in Skopos peninsula are of Pliocene age, possibly Middle–Late Pliocene (Zellilidis et al., 1998), and are deformed by the evaporitic diapirism (Underhill, 1988). The lack of firm chronologies of these marls, which in this study are characterised as synorogenic deposits during the overthrust of the Ionian nappe, points to the need of further chronostratigraphical study.

The post-orogenic deposits in Zakynthos island are initiated as early as Late Pliocene with the marly deposits at northern Alikanas section being somewhat older (biozone MNN16a according to Triantaphyllou, 1993) than those of Gerakas (Seliniako Topio) (MNN 16-17, latemost Pliocene, Papanikolaou, 2008).

The unconformities of Zakynthos island, at least those at the southeast part of it, seem to reflect eustatic sea-level changes. So, the two unconformities more likely correlate with the sea-level fall of two severe northern hemisphere glaciations, namely the lower unconformity correlates with the cold Marine Isotope Stage (MIS) 22 while the upper unconformity with MIS 12 (Papanikolaou 2008). These eustatic sea-level changes are superimposed on a series of tectonic phases characteristic for this part of the Hellenic arc. Therefore, subsidence during the Late Pliocene-Early Pleistocene and uplift during the Middle Pleistocene is witnessed not only in the Zakynthos sequence but also in the coastal zone of Kyparissiakos Gulf where formations of `Calabrian` marls are unconformably overlain by Pleistocene sandstones. This infers that an extensional depositional centre along the Zakynthos channel and Kyparssiakos Gulf developed during the Late Pliocene–Middle Pleistocene and was

subsequently followed (in the Middle Pleistocene) by stronger uplift of the marine deposits in Western Peloponnesus (Papanikolaou et al., 2007) and weaker in eastern Zakynthos.

6. Acknowledgments

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