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REMARKS ON THE MESSINIAN EVAPORITES OF ZAKYNTHOS ISLAND (IONIAN SEA, EASTERN MEDITERRANEAN)

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Abstract

Detailed mapping of the Neogene deposits on Zakynthos Island shows that the Messinian primary evaporite basins, formed over Ionian basement, are delimited by the westernmost outcrop of the Triassic evaporitic diapirs, located west of the Kalamaki-Argasi Messinian gypsum unit. The post-Miocene external Ionian thrust is emplaced west of the Triassic diapirs. Planktonic foraminifera biostratigraphy indicates that primary evaporite accumulation took place probably during the first stage of the Messinian salinity crisis (5.96-5.60 Ma), in shallower parts of a foreland basin, formed over the Pre-Apulian and the Ionian zone basement. Establishment of these depositional environments, before the Ionian thrust emplacement, was probably due to the particularities of the foreland basin, which extended from the external Ionian to the internal Pre-Apulian zone. Field observations, borehole data and an onshore seismic profile show that the Neogene sediments over the Pre-Apulian basement correspond to the foredeep through forebulge domain of the foreland basin, as it is documented from their spatial thickness distribution. In contrast, the Neogene sediments over the Ionian basement correspond to the wedge top of the foreland basin, which was less subsiding, as it is deduced by their reduced thickness. This lower subsidence rate was the result of the concurrent diapiric movements of the Ionian Triassic evaporites. In Agios Sostis area, located over Pre-Apulian basement, the Neogene sequence is intercalated by decametre-thick resedimented blocks consisting of shallow water selenite. To the southeast, this mass-wasting Messinian gypsum passes to mainly gypsum turbidite. In Kalamaki-Argasi area, located over Ionian basement, the shallow water environment led to the deposition of the observed primary gypsum. Erosion of the primary gypsum of both forebulge and wedge top supplied the foreland basin's depocenter with gypsum turbidites.
Key words: *gypsum, Messinian Salinity Crisis, Pre-Apulian zone, foreland basin.*

Περίληψη

Η λεπτομερής χαρτογράφηση των Νεογενών αποθέσεων της Ζακύνθου δείχνει ότι οι λεκάνες πρωτογενούς Μεσσήνιας εβαποριτικής απόθεσης, που σχηματίστηκαν πάνω

σε Ιόνιο υπόβαθρο, οριοθετούνται από τη δυτικότερη εμφάνιση των Τριαδικών εβαποριτικών διάπειρων (δυτικά της Μεσσήνιας ενότητας γύψου Καλαμάκι-Αργάσι). Η μετα-Μειοκαινική εξωτερική Ιόνια επώθηση τοποθετείται δυτικά αυτών των Τριαδικών διάπειρων. Βιοστρωματογραφική ανάλυση των συναθροίσεων πλαγκτονικών τρηματοφόρων στα Νεογενή ιζήματα δείχνει ότι η συσσώρευση πρωτογενούς εβαπορίτη έλαβε χώρα πιθανά κατά το πρώτο στάδιο της κρίσης αλμυρότητας του Μεσσηνίου (5.96-5.60 Εκατ.χρ.), στα αβαθέστερα τμήματα της λεκάνης προχώρας, η οποία σχηματίστηκε πάνω στο Προ-Απούλιο και Ιόνιο αλπικό υπόβαθρο. Ο σχηματισμός των περιβαλλόντων ιζηματογένεσης, πριν από την Ιόνια επώθηση, πιθανά οφείλεται στις ιδιαιτερότητες της λεκάνης προχώρας, η οποία εκείνο το διάστημα εκτείνονταν από την εξωτερική Ιόνια ως την εσωτερική Προ-Απούλια ζώνη. Νέα δεδομένα υπαίθρου, σε συνδυασμό με τη βιοστρωματογραφία, τα στοιχεία γεωτρήσεων και μία διαθέσιμη σεισμική τομή δείχνουν ότι τα Νεογενή ιζήματα πάνω στο Προ-Απούλιο υπόβαθρο αντιστοιχούν στον τμήμα της λεκάνης προχώρας, από το προβύθισμα (foredeep) ως την πρόσθια ανύψωση (forebulge), όπως αυτό διαπιστώνεται από την χωρική κατανομή του πάχους τους. Αντίθετα, τα Νεογενή ιζήματα πάνω στο Ιόνιο υπόβαθρο αντιστοιχούν στο τμήμα της λεκάνης προχώρας που βρίσκεται πάνω στο μετωπικό πρίσμα της ορογένεσης (wedge top), το οποίο βυθίζονταν λιγότερο όπως συνάγεται από το ελαττωμένο πάχος των ιζημάτων. Ο μικρότερος ρυθμός βύθισης οφείλεται στις διαπειρικές κινήσεις των Τριαδικών εβαποριτών. Στη Νεογενή ακολουθία, που βρίσκεται πάνω σε Προ-Απούλιο υπόβαθρο (περιοχή Άγιος Σώστης), παρεμβάλλονται επανιζηματοποιημένα μπλοκ δεκαμετρικού πάχους αποτελούμενα από σεληνίτη μικρού βάθους απόθεσης. Προς νότο, αυτή η βαρυτικά μεταφερόμενη μάζα της Μεσσήνιας γύψου μεταπίπτει κυρίως σε τουρβιδιτική γύψο. Στην περιοχή Καλαμάκι-Αργάσι που βρίσκεται πάνω σε Ιόνιο υπόβαθρο, το αβαθές περιβάλλον οδήγησε στην απόθεση της παρατηρούμενης πρωτογενούς γύψου. Η διάβρωση της πρωτογενούς γύψου τόσο της πρόσθιας ανύψωσης όσο και του μετωπικού πρίσματος επώθησης τροφοδότησαν το προβύθισμα της λεκάνης προχώρας με τουρβιδίτες γύψου.
Λέξεις κλειδιά: *γύψος, κρίση αλμυρότητας, Προ-Απούλια ζώνη, λεκάνη προχώρας.*

1. Introduction

Several analytical studies of the Messinian marine and evaporite deposits have been conducted across the Mediterranean realm over the past decades (Butler et al., 1995; Riding et al., 1998; Krijgsman et al., 1999**;** Iaccarino et al., 1999; Roveri et al., 2001; Krijgsman et al., 2002; Gargani et al., 2008; CIESM, 2008; El Euch-el Koundi et al., 2009; Mertz-Kraus et al., 2009; Lugli et al., 2010; Roveri et al., 2014). Few references and scarce analytical studies however exist on the Hellenic realm. This work presents the first results of a large study to investigate the Messinian salinity crisis in this area. In particular, the evaporite sequences in the Zakynthos Island are herein described. These consist of both primary shallow water gypsum, deposited into the shallower part of a basin, and gypsum turbidites deposited to its deeper part. It is determined that the tectonics of the foreland basins in front of the Ionian overthrust was the driving mechanism to the differentiation of the depositional environments.

2. Geological setting

The Island of Zakynthos is based on Alpine rocks belonging mainly to the Pre-Apulian (Paxos) and partly to the Ionian zone (Fig. 1). These two zones are separated by the Ionian thrust, whose emplacement took place in the Early Pliocene (BP, 1971; Sorel, 1976; Nikolaou, 1986; Underhill, 1989; Karakitsios, 2013). The Pre-Apulian zone of Zakynthos comprises upper Cretaceous to Pleistocene sediments, while the Ionian zone is represented by Triassic breccias and gypsum (corresponding to the lower stratigraphic unit of this zone); Cretaceous-Oligocene carbonates outcrop only in the Marathonisi Islet (2.5 km east of Keri, Fig. 1) and probably represent a lateral transitional facies between Ionian and Pre-Apulian zone (Nikolaou, 1986). These sediments are followed by similar Neogene and Quaternary deposits as those of the Pre-Apulian zone, which are however less thick and characterized by unconformities.

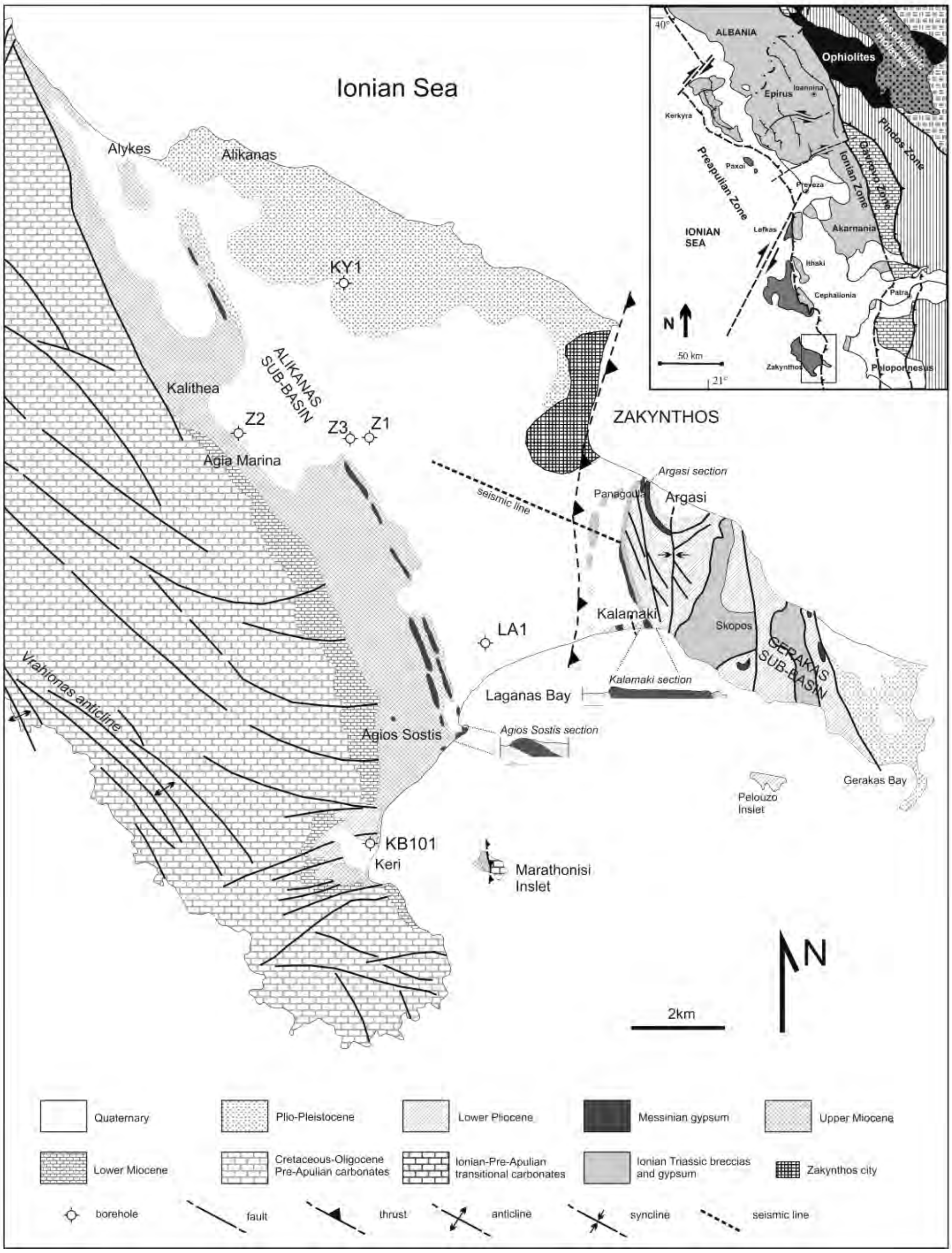

Figure 1 - Geological map of Zakynthos Island. The regional location is indicated in the inset map.

Significant shortening is seen in numerous NW-SE oriented reverse faults cutting through the Pre-Apulian Cretaceous-Oligocene sequence and within the late Miocene interbedded sandstone and marl sequences exposed in costal sections between Agios Sostis and Keri (Fig. 1). There, numerous post Miocene folds and reverse folds occur, indicating a post-Miocene age for the Ionian thrust emplacement (Underhill, 1989; Karakitsios, 2013). The Zakynthos Neogene and Quaternary deposits have been studied in several localities, mainly along the southeastern part of the island (Dermitzakis, 1977; Nikolaou, 1986; Triantaphyllou, 1996; Kontopoulos et al. 1997; Zelilidis et al. 1998; Duermeijer et al. 1999; Pierre et al., 2006; Agiadi et al. 2010). Based on these studies, the Lower Miocene Basin of Zakynthos Island was filled in the west by mainly clastic, flysch-type sediments, which eastward passed to shelf deposits. These deposits were followed by late Messinian marls and shales of 30-100 meters thickness, intercalated by Messinian gypsum beds. These evaporites have been interpreted as littoral to sabkha deposits (Dermitzakis, 1977; Nikolaou, 1986) or concentrated brines into shallow basins of less than 500m depth (Fabricius et al. 1978) or even as gypsum turbidites which were accumulated in water depths of less than a few hundred meters (Kontopoulos et al. 1997). The early Pliocene deposits on the Island comprise calcareous marls with pelagic fauna ("trubi" limestone) and sandstone intercalations. Middle Pliocene-Pleistocene corresponds to a transgressive sequence consisting of marls, clays, mudstones and sandstones in its lower part, while in the upper part it passes to an alternation of marls and marly limestones (Dermitzakis, 1977; Nikolaou, 1986).

3. Methodology

New field observations were made on the Argasi-Kalamaki and Agios Sostis areas, which were combined with detailed sampling. The field observations refer to the sedimentological and tectonic attributes of the Miocene to early Pliocene deposits in the study areas. In particular, field stratigraphic and sedimentological observations of the evaporite outcrops were carried out in order to distinguish the Triassic gypsum diapirs from the Messinian gypsum deposits in the southeastern part of Zakynthos Island (in the area between Kalamaki and Argasi), where both types crop out. Tectonic observations in conjunction with the available seismic profiles, allowed to precise the cartographic trace position of the Ionian thrust. Furthermore, the different types of evaporites were distinguished and cyclic deposition was also investigated in the evaporite sequence, as well as in the overlying "trubi" formation and the overlying lower Pliocene deposits. The work was focused in particular on the biostratigraphy and sedimentology of the lower and upper boundary transition of the Messinian evaporites. Overall, the palaeogeographic distribution of the Messinian gypsum deposits was determined by the integration of field and borehole data.

High-resolution sampling was carried out in order to perform integrated stratigraphy based on micro- and macropaleontological analyses (planktonic and benthic foraminifera, calcareous nannoplankton, ostracods, invertebrates and fish) and biogeochemical analyses (TOC content, stable isotope and organic biomarkers). Furthermore, core samples were obtained for magnetostratigraphic measurements, which are still under process.

The presented biostratigraphic analysis is based on the planktonic foraminifera assemblages. Planktonic foraminifera biostratigraphy of the Kalamaki section is based on the stratigraphic distribution of several late Miocene marker species supplemented by the coiling ratios of *Neogloboquadrina acostaensis*. The biostratigraphic analyses were carried out on 65 samples from the stratigraphic intervals below and above the gypsum *s.s.* deposits (samples Kal1-139 and Tr1-3).

4. Field observations

4.1 Kalamaki–Argasi Area

The Neogene sequence of the Kalamaki-Argasi area has been deposited over the Ionian zone basement. This section (Fig. 2) begins with a 15 meter-thick succession of alternating massive and laminated marls with rare calcareous marls and calcarenite intercalations. In the middle part of the succession bivalves, *Discospirina*, pteropods and molluscs have been observed. This succession is followed by 10 meters of slumped and folded sediments of the same lithology, partially covered by Quaternary debris, in turn overlain by the 98 meter-thick evaporitic unit. Six cycles of depositional gypsum types are identified within the evaporite unit, corresponding to massive, massive stratified, banded and branching selenite facies (Lugli et al., 2010); in the upper third of the succession also thin gypsrudites and gypsarenites intercalations are present. These deposits can be ascribed to the Primary Lower Gypsum unit (PLG; Roveri et al., 2008) deposited during the 1st stage of the Messinian salinity crisis (5.971-5.60; CIESM, 2008; Manzi et al., 2013). The last 8 meters of the gypsum unit are clastic sediments, comprising laminated greenish marls, intercalated (after the first meter of the succession) by a decimetric gypsarenite bed. Overlying the gypsum unit, with a low-angle angular unconformity (Messinian Erosional Surface; MES; CIESM, 2008; Roveri et al., 2014), are approximately 4 meters of an irregular alternation of greenish marls and discontinuous calcareous marl beds belonging to the 'LagoMare' facies. In stratigraphic continuity over the latter, follows the "trubi" carbonate formation. The "trubi" formation begins with 3 meters of massive marly limestones which are overlain by an alternation of decimetric carbonate and laminated marl beds.

In Argasi area (Fig. 1) a gypsum unit is recorded, which is very similar to that of Kalamaki. Here, eight lithological gypsum beds have been recognized. However, in this area it is not possible to observe the stratigraphic transition of the gypsum unit to the overlying and the underlying formations, due to the tectonics and the Quaternary debris that cache them. To the south-easternmost Skopos area some minor outcrops of Messinian gypsum are present consisting of reworked gypsum and sporadic gypsum turbidites.

4.2 Agios Sostis Area

The Neogene sequence of Agios Sostis area has been deposited over the Pre-Apulian zone basement. In this section (Fig. 2), the first 10 meters consist of decimetre-thick shale-sandstone alternations showing an upward decrease of clastic input. They are followed by 3 meters of thin sandstone beds and marl alternations, which further pass to a 3 meters alternation of laminated green shales and marls. An erosional surface (MES) separates this lower unit from the overlying gypsum unit. The unit is about 15 meters thick, consisting of many alternations of primary (cumulate) and clastic (gypsrudite, gypsarenite and gypsiltite) gypsum. This evaporitic unit, largely characterized by clastic deposits and lacking the typical shallow-water bottom-grown evaporitic facies described in the Kalamaki–Argasi area, can be ascribed to the Resedimented Lower Gypsum unit (RLG, Roveri et al., 2008). This unit that derives from the dismantlement and resedimentation of the PLG deposits has been deposited during the 2nd stage of the Messinian salinity crisis (5.60-5.55; CIESM, 2008; Roveri et al., 2008). The whole sequence presents an upward increase of the siliclastic component and may be divided into four cycles, each topped by a centimetric marly bed. Some 2 meters of hybrid sandstone beds follow, which, after 1.5 meters of observation gap, pass to a 18-meters-thick succession comprising graded sandstone and marl alternations. This succession exhibits an upward decrease of clastic input. Two meters of whitish marls finish the section. North of the section's end, at a distance of 60 meters, the rocky elevation of the Agios Sostis port consists exclusively of "trubi" carbonates.

Following a NNW direction (Fig. 1), starting from a point about 800 meters WNW of the Agios Sostis section, the Neogene sequence is intercalated by decametre-thick resedimented blocks consisting of shallow water selenite. They linearly crop out for a distance of approximately 3 kilometres. To the southeast, this mass-wasting Messinian gypsum outcrops passes to mainly gypsum turbidites as the ones observed in Agios Sostis section. These gypsum turbidites also present a second linear and more extensive outcrop, which is parallel to the shallow water selenite outcrops (Fig, 1). It becomes clear that the second linear outcrops correspond to gypsum turbidites derived from the first one, and located basinward along the Messinian paleoslope.

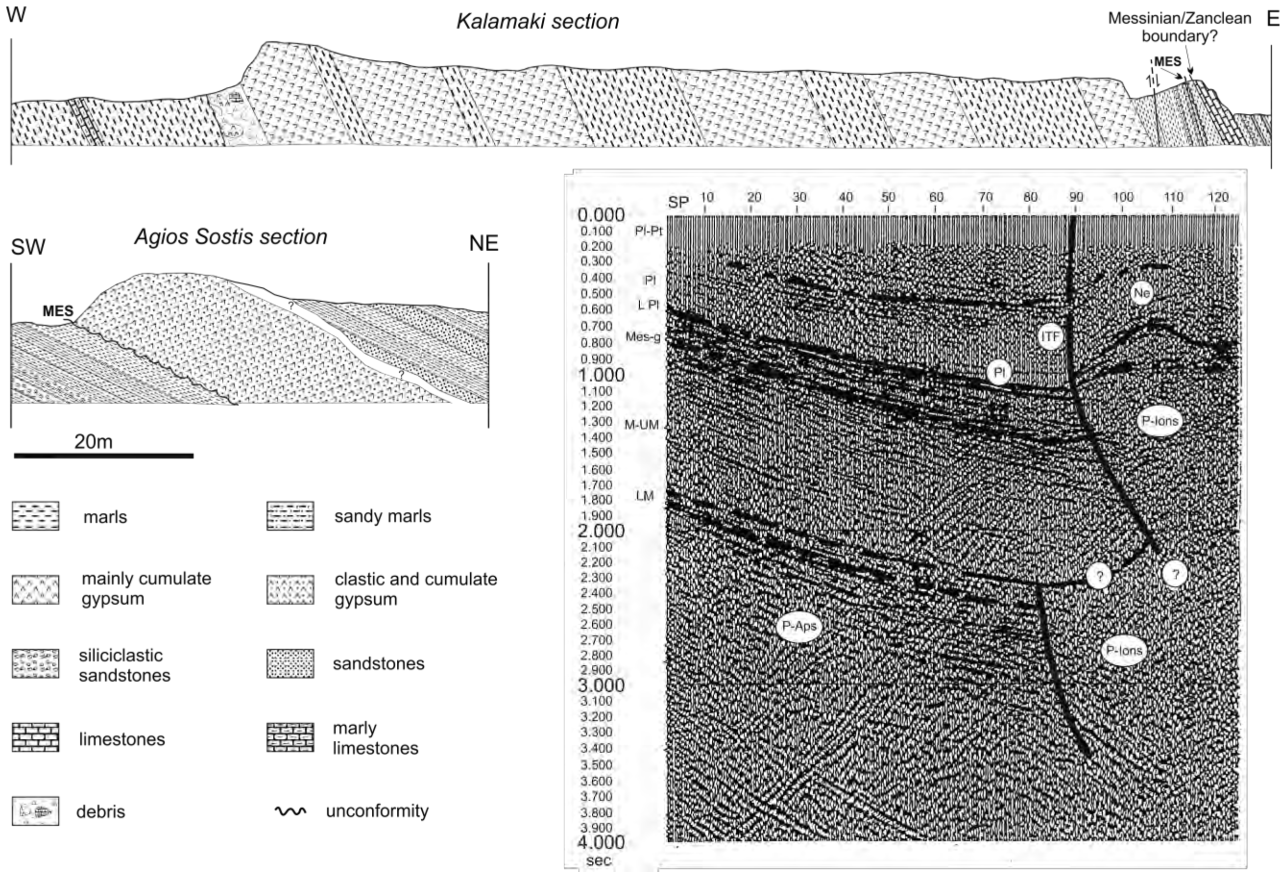

Figure 2 - Kalamaki and Agios Sostis sections. MES: Messinian Erosional Surface.
Seismic profile of the Fig. 1 seismic line (modified from the initial interpretation by Marinescu; in Nikolaou 1986): Pl-Pt: Pliocene-Pleistocene, Pl: Pliocene, LPl: Lower Pliocene, Mes-g: Messinian Gypsum, M-UM: Middle-Upper Miocene, LM: Lower Miocene, P-Aps: Pre-Neogene sequence of Pre-Apulian zone, P-Ions: Pre-Neogene sequence of Ionian zone–Triassic evaporites, ITF: Ionian Thrust Front, Ne: Undifferentiated Neogene, SP: Shot point, sec: Time in seconds.

5. Biostratigraphy

In the Kalamaki section, the stratigraphic interval below gypsum unit *s.s.* (samples 1 to 91) is attributed to the Late Messinian based on the distribution range of *Turborotalita multiloba*. Planktonic foraminiferal assemblages are characterized mainly by *Turborotalita quinqueloba* and *Turborotalita multiloba*, whereas *Globigerinoides obliquus*, rare specimens of *Globigerinoides quadrilobatus*, *Globigerina bulloides*, *Orbulina* spp., *Globigerinita glutinata, Neoquoboquadrina acostaensis* and rare specimens of *Globoturborotalita decoraperta* are also present in several samples. *Turborotalita multiloba* as well as *N. acostaensis* dextral coiling specimens occur in the assemblages from the base of the studied section. According to Krijgsman et al (1999), Sierro et al. (2001), Blanc-Valleron et al. (2002) and Drinia et al. (2007, 2008), *T. multiloba* shows its first influx at 6.42 Ma, predating the *N. acostaensis* sinistral to dextral coiling change at 6.36 Ma. Sinistral coiled specimens of the latter species are very rare in our assemblages indicating that the studied interval may be placed within the MMi 13c *Turborotalita multiloba* interval Zone, dated above the age of 6.36 Ma.

The stratigraphic interval overlying the gypsum and below the 'trubi' carbonates records the presence of planktonic foraminifers in a few levels. In samples 113 to 117 rare planktonic and benthic foraminifers occurs in the scarce residues. The assemblage is characterized by the presence *N. acostaensis* dextral coiled specimens, *Globoturborotalita nepenthes*, *Sphaeroidinellopsis* spp. *G. obliquus*, *Orbulina* spp. *G. glutinata* and *G. bulloides.*

The base of 'trubi' carbonates (sample Tr 1) is characterized by rare specimens of *G. bulloides, G. obliquus, N. acostaensis* dextral coiling, very similar to the ones at the lowermost part of MPl 1 biozone. The acme zone of *Sphaeroidinellopsis* spp. is determined at the second meter of the "trubi" formation (sample Tr 2). The assemblage is well preserved and diversified and mainly consists of *Sphaeroidinellopsis* spp. Other species such as *O. universa, G. bulloides, N. acostaensis, G. obliquus extremus, G. apertura, T. quinqueloba, G. trilobus* are very abundant. *Globorotalia scitula* dextral coiled specimens exist in the fourth meter of the "trubi" formation (sample Tr 3). Specimens of *G. margaritae* were not recognized.

6. Discussion on the Neogene Basin's Palaeogeographic and Structural Evolution

Field observations indicate that the Neogene sediments, in the main part of Zakynthos Island, have been deposited over the Pre-Apulian zone formations, whereas those in the southeastern part have been deposited over the Ionian zone. The correlation of field data with the available boreholes and seismic sections (Fig. 2 and 3) demonstrates that the Neogene Pre-Apulian formations, east of the Vrahionas anticline (Fig. 1), form a monocline dipping approximately 30º ESE. Borehole stratigraphies (Fig. 1) show that Neogene deposits (Messinian gypsum included) increase their thickness toward the dipping monocline. Indeed, the Neogene sediments are 800 m thick in the west, and 1350 m thick in the east (Fig. 3). It is also noted that in the largest depocentral area (Agios Sostis area) the western-most gypsum outcrops consist of eradicated blocks of Primary Lower Gypsum whereas the eastern ones consist of gypsum turbidites and cumulates (e.g. Agios Sostis). This means that erosion of the PLG deposits accumulated in a shallow basin located in the western part of the Zakynthos Island (now completely eroded) provided the clastic material which was deposited toward the depocenter of the Neogene basin. On the other hand, Neogene formations over the Ionian zone, in the southeasternmost part of the Island, present a much lower thickness (between 200-300m). Gypsum deposits very close to the Ionian thrust correspond to primary gypsum (PLG unit), but going to the east (Skopos area) only some rare minor gypsum outcrops may be observed, mainly reworked gypsum and occasionally gypsum turbidites. These differences show that the Zakynthos Neogene basin was not uniform, but subsidence in the monocline area (over

Pre-Apulian basement) was more rapid, providing greater sea depths compared to the eastern area (over Ionian basement).

The above observations may be explained by a simple model of continental foreland-directed migration of the Hellenide (Alpine) thrusting, during the late Neogene and Pliocene. The foreland basin in front of the Ionian thrust was compared integrated to the foreland basin systems of DeCelles & Giles (1996), although it is necessary to take into consideration the particular role that the Ionian Triassic evaporites movements may have played. In this foreland basin system, the Neogene formations over the Pre-Apulian zone corresponded to the foredeep and the flank between foredeep and forebulge, whereas those overlying Ionian zone rocks corresponded to the wedge top. The intense subsidence characterizing the foredeep and flank to forebulge areas was reflected in the great thickness of the clastic Neogene formations over Pre-Apulian zone (between 800-1350m) which partially derived from the eroded Pre-Apulian forebulge. Simultaneously, the diapiric movement of the Ionian Triassic evaporites prevented substantial subsistence to occur. As a result, the eastern part of the Neogene basin, over the Ionian zone basement, corresponded to a land-subsiding wedge top. This is reflected in the observed thin clastic Neogene formations derived from the Ionian orogen erosion.

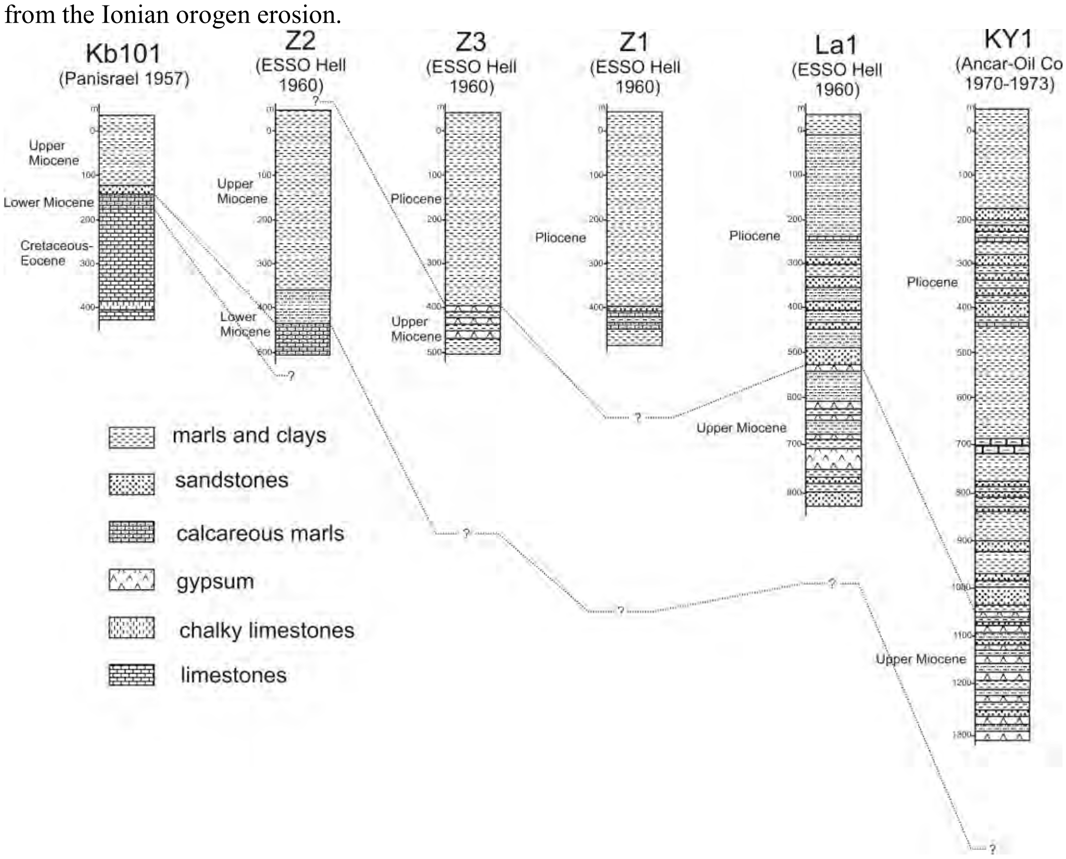

Figure 3 - Available borehole logs and correlations. Well operators are indicated.

The progressive filling of the foreland's basin Pre-Apulian part, during the Messinian, led the basin's area near to its forebulge to shallower depths. These depths together with the Upper Messinian overall negative hydrological balance (Mertz-Kraus et al., 2009) led to the deposition of the Primary Lower Gypsum unit. The subsequent erosion of PLG produced clastic gypsum that was deposited through gravity flows in the basin depocenter. At the same time, the wedge-top basin was characterized by shallower depths due mainly to the uplift of Triassic gypsum. Thus, the area close to the Ionian thrust received the observed primary gypsum deposits. Eroded gypsum material from these primary deposits supplied additional material to the foreland's basin foredeep (to the west). In contrast, in the eastern areas (e.g. Skopos) the observed gypsum deposits are represented only by some relics of reworked gypsum and sporadic gypsum turbidites.

7. Conclusions

Detailed mapping of the Messinian deposits on Zakynthos Island shows that the primary evaporite basins, formed over Ionian basement, are delimited by the westernmost outcrop of the Triassic diapirs, located west of the Kalamaki-Argasi Messinian gypsum unit. The post-Miocene external Ionian thrust is emplaced west of the Triassic diapirs.

In Kalamaki-Argasi area, located over Ionian basement, the deposition of primary gypsum indicates a shallow water environment. Based on facies analysis these deposits have been ascribed to the Primary Lower Gypsum unit (PLG; Roveri et al., 2008; 2014; Lugli et al., 2010)

Planktonic foraminifera biostratigraphy of the Zakynthos Messinian outcrops indicates that primary evaporite accumulation took place, probably during the 1st stage of the Messinian salinity crisis (5.971-5.60 Ma), within shallower parts of a foreland basin, which was formed over the Pre-Apulian and the Ionian Alpine basement.

In Agios Sostis area, located over Pre-Apulian basement, the Neogene sequence is intercalated by decametre-thick resedimented blocks consisting of shallow water selenite. To the southeast, this mass-wasting Messinian gypsum passes to mainly gypsum turbidites, indicating a deeper environment. These deposits deriving from the dismantlement and resedimentation of the PLG unit can be ascribed at the 2nd stage of the MSC (5.60-5.55 Ma)

The development and distribution of the depositional environments before the activation of the Ionian thrust was probably due to the particularities of the foreland basin, which, at that time, extended from the external Ionian to the internal Pre-Apulian zone (Karakitsios & Rigakis, 2007). Field observations, borehole data and the available onshore seismic profile show that the Neogene sediments over the Pre-Apulian basement increase their thickness toward the E-SE direction, following the dipping of Alikanas monocline (the sediments thickness ranges between 800m in the west and 1350m in the east). In contrast, the Neogene sediments over the Ionian basement present reduced thickness (between 200-300m). Thus, subsidence rates were higher in the Pre-Apulian domain than in the Ionian domain. This is consistent with halokinetic movements of the Ionian Triassic evaporites (Karakitsios, 1995).

The above data may be integrated to the following foreland basin's scheme. In this basin, the Neogene formations over the Pre-Apulian zone corresponded to the foredeep and the flank between foredeep and forebulge, whereas those overlying Ionian zone rocks corresponded to the wedge top, which is consistent with the diapiric movements of the Ionian Triassic evaporites. Erosion of the primary gypsum of both forebulge and wedge top supplied the foreland basin's depocenter with gypsum turbidites.

8. Acknowledgments

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