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PALEOBATHYMETRY OF A PLIOCENE VOUTES COAST (HERAKLION, CRETE)

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Abstract

The fish otolith assemblages identified in the Zanclean sediments of Voutes section (Heraklion, Crete) are analyzed in order to estimate the depth of deposition. The assemblages indicate that Voutes area was in fact a coast inhabited by a neritic fish fauna with significant mesopelagic component, mostly Myctophids. The benthic and benthopelagic group exhibits great diversity. In the late Zanclean, the study area corresponds to a deep neritic environment, which gradually uplifts. At the end of the Zanclean, Voutes area becomes a very shallow coast, as shown by the increased contribution to the assemblage by members of the Gobiid family, as well as the notable presence of Bothidae. Thereafter, the area deepens again, as the shallow benthic-benthopelagic component significantly decreases. This is consistent with the appearance of Pteropods and reaches a peak during the deposition of diatomites at maximum depth. At the upper part of the section, the sea bottom depth decreases again to allow for the deposition of marls with various molluscs remains, where Gadids and Gobiids again reappear. Finally, the upper diatomitic horizon is characterized by a rather poor fish fauna. These observations allow reconstructing the evolution of Voutes coastal area during the latest Zanclean until the Piacenzian.
Key words: *Fish, otoliths, Zanclean, Teleosts, Mediterranean.*

Περίληψη

Στην παρούσα εργασία παρουσιάζεται η παλαιοβαθυμετρική ανάλυση των συναθροίσεων ωτολίθων Ιχθύων, που προσδιορίστηκαν στα ιζήματα ηλικίας Ζαγκλίου στην τομή Βούτες (Ηράκλειο, Κρήτη). Η περιοχή Βούτες αποτελούσε μία ακτή με νηριτική Ιχθυοπανίδα, με υψηλή συμμετοχή μεσοπελαγικών ειδών, κυρίων Myctophidae. Τα βενθικά και βενθοπελαγικά ψάρια εμφανίζουν επίσης μεγάλη ποικιλότητα. Κατά το ανώτερο Ζάγκλιο, η περιοχή μελέτης αντιστοιχούσε σε βαθύ νηριτικό περιβάλλον. Σταδιακά η περιοχή ανυψώθηκε σε πολύ μικρά βάθη, όπως φαίνεται από την αυξημένη συμμετοχή στην πανίδα των Gobidae, αλλά και την παρουσία Bothidae. Στη συνέχεια, η περιοχή βάθυνε ξανά, καθώς παρατηρείται σημαντική μείωση της συμμετοχής των ρηχών βενθικών-βενθοπελαγικών ειδών. Το συμπέρασμα αυτό ενισχύεται από την παρουσία στο επίπεδο αυτό των Πτεροπόδων, αλλά και την απόθεση διατομιτών. Σε ανώτερο τμήμα της τομής, το βάθος της θάλασσας μειώνεται και πάλι, πριν τον ανώτερο διατομιτικό ορίζοντα, ο οποίος ωστόσο εμφανίζει ιδιαίτερα φτωχή συνάθροιση ωτολίθων.
Λέξεις κλειδιά: *Ιχθύες, ωτόλιθοι, Ζάγκλιο, Τελεόστεοι, Μεσόγειος.*

1. Introduction

Crete Island was created during the Late Miocene through the N-S and E-W extensional deformation of the south Aegean, resulting in the formation of multiple tectonic blocks and Late Miocene to Pleistocene sedimentary basins (Meulenkamp et al., 1988; van Hinsbergen and Meulenkamp, 2006). The Neogene sediments overlie a pile of alpine nappe substratum, which includes the metamorphic Plattenkalk and Phyllites - Quarzites Units followed by the Tripolis and Pindos-Ethia, as well as other minor units (Zachariasse et al., 2011).

The present emerged area of the Heraklion basin is a Pliocene graben structure located at the northern part of the central Crete Island, in the southern segment of the Hellenic Arc, between the mountains Psiloritis and Dicti. The alpine basement formations contain a rich melange of Triassic to Eocene sedimentary and metamorphic rocks, overlain by Neogene and Quaternary sedimentary deposits, recording a great diversity of environments and ecosystems (Symeonidis and Konstantinidis, 1967). The Pliocene Heraklion basin occurred in a region marked by a great number of successive paleogeographic Miocene frameworks, in the vicinity of the Messara basin. In the late Late Tortonian the activation of the eastern – western oriented Agia Varvara fault differentiated the two realms, which evolved separately since then (Delrieu et al., 1991).

The Pliocene deposits of the Heraklion basin are the most extensive on the Island. The marine sediments of the lowermost Pliocene generally overlie the late Messinian deposits (Delrieu et al., 1991; Meulenkamp et al., 1979), and consist of whitish marls and marly limestones of deep water origin, reflecting the Pliocene flooding which followed the lago-mare episode immediately after the Mediterranean Salinity Crisis.

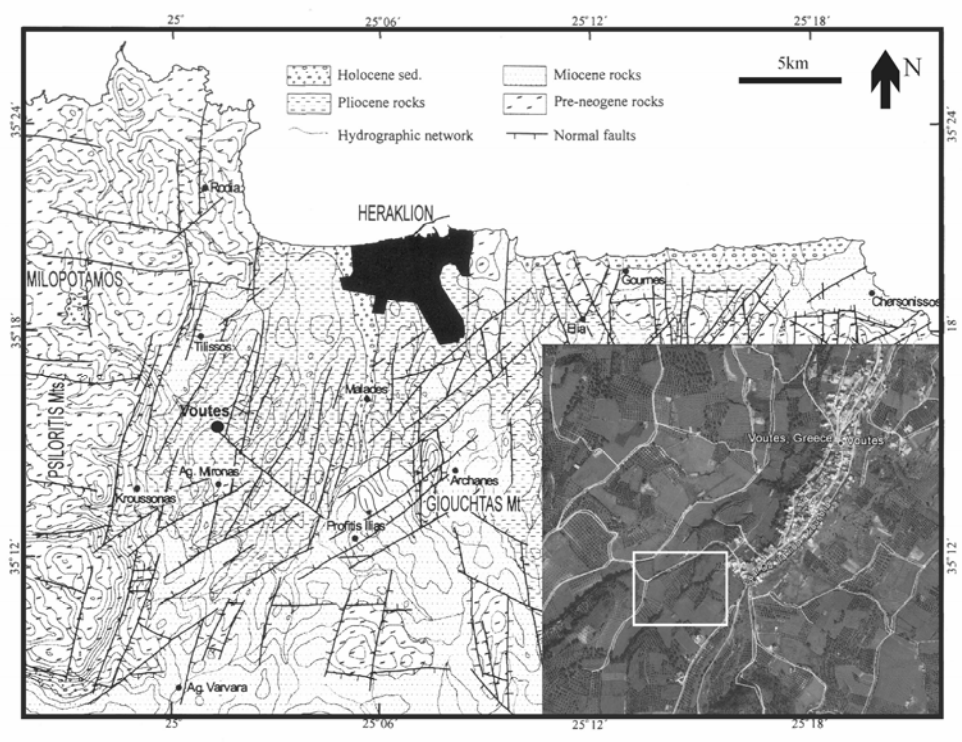

Figure 1. Heraklion area geological map (Fassoulas, 2001), indicating Voutes village.

Fish otoliths provide a unique tool in the investigation of the fish teleostean paleofaunas, due to their taxon – specific morphology, high frequency with which they are found in sediments of varying environments, and their generally good preservation (Nolf, 1985). In addition, they constitute very valuable paleoecological and paleobathymetrical indicators (Nolf and Brzhobohaty, 1994; Girone, 2000; Agiadi et al., 2010; et al., 2011). In the present study, fish otoliths from the Pliocene sediments of Voutes (Heraklion, Crete) are used as indicators in order to reconstruct the depositional depth.

2. Material and Methodology

The studied Voutes section is located southwest of the village Voutes in central Crete, south of Heraklion city. Geologically it is situated in the western section of the Heraklion basin (Figure 1). The section's sediments may be placed within the Finikia lithostratigaphic group (of Benda et al., 1974 and Meulenkamp et al., 1979) and include more than 60 meters of marls and sandy marls. Strong gravity flows have formed a series of sand lenses, on the lower part of the section, with distinctive sedimentologic attributes and characteristic fauna. The upper part of the section presents three diatomite horizons. On a total, nine (9) sediment samples were taken along Voutes section. Systematic identifications of the fish otoliths found within these samples are presented in Agiadi et al. (2013).

The relevant chronostratigraphic framework (Agiadi et al., 2013) for the evaluation of the results was provided through calcareous nannoplankton biostratigraphy, based on the biozonation scheme of Rio et al. (1990) as this has been incorporated in the magnetobiochronologic framework of Lourens et al. (2004) in Gradstein et al. (2004). The studied interval from Voutes section is assigned to the biozone MNN16, in particular above the highest occurrence of *R. pseudoumbilicus* and *Sphenolithus* spp. following the MNN14/15-MNN16 boundary (3.84 Ma, Lourens et al., 2004; Raffi et al., 2006) and just below the top of *D. pentaradiatus* paracme (3.61 Ma, Lourens et al., 2004), within the latest Zanclean.

The depth of deposition, through the analysis of the fish otolith assemblage, was estimated using the method of Nolf and Brzobohaty (1994) for bathyal and deep neritic assemblages with a significant mesopelagic component, as it was re-adjusted by Agiadi et al. (2010). According to this methodology, based on the modern depth ranges of all the taxa in each sample (Table 1), the number of possible presences for each 50-meter depth interval is calculated and expressed as a percentage of the total number of taxa involved in the analysis. The depth of deposition for each sediment sample is estimated as the maximum percentage in these plots.

The only requirement for the application of this method is that the systematic position of the fossil taxa has a close affinity to their modern analogues. The presence/absence data used includes only those taxa for which present-day bathymetric information is available. This means that higher order identified otolith specimens were completely excluded from analysis. Out of the 43 taxa present in Voutes sediments, only eight are extinct today, *Diaphus cavallonis*, *Myctophum fitchi*, *Scopelopsis pliocenicus*, *Pseudophichthys escavaratierensis*, *Rhynchoconger pantanelli*, *Parascombrops mutinensis*, *Gadiculus labiatus* and *Arnoglossus kokeni*. The present-day distributions assigned to these species were those of their most close living relative. To this end, genus level affinity was used, in conjunction with the corresponding present record in the Aegean Sea. These analogies are presented in Table 1. In particular, *Scopelopsis pliocenicus* has only one living species with a genus-level affinity, *Scopelopsis multipunctatus* (Hulley, 1990), to which it was assigned. At present, *P. splendens* is the only *Pseudophichthys* species occupying the Mediterranean Sea (Bañon et al., 2011). Consequently, *P. escavaratierensis* was also assigned to *P. splendens*. *Rhynchoconger* currently includes seven species, occupying either the Indo-Pacific or the western Atlantic coasts at various depths (Whitehead et al., 1986). In addition, congrids in the present Mediterranean include three species *Ariosoma balearicum*, *Conger conger* and *Gnathophis mystax* (Whitehead et al., 1986).

Table 1 - Present-day bathymetric distribution of the fish taxa identified in Voutes outcrop sediments or their modern equivalent. The data has been acquired from FishBase (Froese and Pauly, 2012).

Taxonomic placement		Bathymetric range (m)	References
Family	**Genus/Species**		
PELAGIC TAXA			
Sternoptychidae	*Maurolicus muelleri*	50->1524	Okiyama 1971
Phosichthyidae	*Vinciguerria poweriae*	50-1000	Yang et al 1996
Myctophidae	*Ceratoscopelus maderensis*	51-1082	Mytilineou et al 2005
	Diaphus adenomus	180-600	Hulley 1990
	Diaphus holti	40-777	Mytilineou et al 2005
	Diaphus metopoclampus (equiv. *D.cavallonis*)	90-1085	Mytilineou et al 2005
	Diaphus rafinesquii	40-1200	Bogutskaya 2007
	Diaphus splendidus	40-750	Hulley 1990
	Diaphus taaningi	40-475	Hulley 1990
	Hygophum benoiti	51-700	Hulley 1990
	Hygophum hygomii	0-800	Hulley 1990
	Myctophum punctatum (equiv. *M.fitchi*)	0-1000	Muus and Nielsen 1999
	Lobianchia dofleini	20-750	Hulley 1990
	Notoscopelus resplendens	0-2000	Hulley 1990
	Scopelopsis multipunctatus (equiv. *S.pliocenicus*)	3-2000	Hulley 1990
Bregmacerotidae	*Bregmaceros* spp.	?-1260m	Castellanos-Galindo et al 2006
BENTHIC AND BENTHOPELAGIC TAXA			
Congridae	*Pseudophichthys splendens* (equiv. *P.escavaratierensis*)	37-1647	Bañon et al 2011
	Modern Mediterranean Congrids (equiv. *R.pantanelli*)	0-700	Whitehead et al 1986
Chlorophthalmidae	*Chlorophthalmus agassizi*	50-1000	Whitehead et al 1986
Moridae	*Laemonema* spp.	200-1200	Whitehead et al 1986
Gadidae	*Gadiculus argenteus* (equiv. *G. labiatus*)	100-1000	Muus and Nielsen 1999
Bythitidae	*Grammonus ater*	reef-associated	Whitehead et al 1986
Carapidae	*Echiodon dentatus*	120-3250	OBIS 2006
Atherinidae	*Atherina boyeri*	coastal, very euryhaline	Maugé 1990
Apogonidae	*Apogon* spp.	reef-associated	Whitehead et al 1986
Epigonidae	*Epigonus denticulatus* (equiv. *Epigonus* sp.)	300-600	Whitehead et al 1986
Acropomatidae	*Synagrops spinosus* (equiv. *P.mutinensis*)	87-544	Mochiuzuki and Gultneh 1989
Sparidae	*Oblada melanura*	?-30	Bauchot and Hureau 1990
	Pagellus erythrinus (equiv. *Pagellus* sp.)	20-200	Bauchot and Hureau 1990
Cepolidae	*Cepola macrophthalma*	15-400	Whitehead et al 1986
Gobiidae	*Aphia minuta*	0-97	Iglesias and Morales-Nin 2001
	Deltentosteus quadrimaculatus	?-333	Mytilineou et al 2005
	Gobius niger	1-75	Whitehead et al 1986
	Gobius paganellus	?-15	Azevedo and Simas 2000
	Lesueurigobius friesii	10-130	Miller 1990
	Lesueurigobius sanzi	47-117	Miller 1990
	Lesueurigobius suerii (equiv. *Lesueurigobius* sp.)	?-337	Mytilineou et al 2005
Citharidae	*Citharus linguatula*	?-200	Nielsen 1981
Bothidae	*Arnoglossus* spp.	15-300	Whitehead et al 1986

All three species exhibit great depth distribution, from a few tens to more than 700 meters, which was thus used as a generalized assessment of the depth distribution of *R. pantanelli*. There is no living species placed within the genus *Parascombrops*, nor is there an Acropomatidae representative occupying the Mediterranean Sea at present. From the comparative morphological similarities between the North Atlantic species *Synagrops spinosus* (Campana, 2004) and the *P. mutinensis* otoliths of this and previous studies (Agiadi et al., 2011; Agiadi et al., 2013), it may be considered that this is an appropriate modern analogue to the fossil species. The only *Gadiculus* Mediterranean inhabitant today is *G. argenteus* (Muus and Nielsen, 1999), which was accepted here as the modern equivalent of *G. labiatus*. Finally, *Arnoglossus* spp. depth values encompass the distribution of all six extant *Arnoglossus* Mediterranean species (Whitehead et al., 1986).

An initial inspection of the depth distribution of the identified taxa in the samples indicated that the paleodepths did not surpass 1000 meters. Consequently, the analyses were conducted until that depth. In addition, *Maurolicus muelleri*, *Vinciguerria poweriae*, *Ceratoscopelus maderensis*, *Diaphus metopoclampus*, *Diaphus rafinesquii*, *Myctophum punctatum*, *Notoscopelus resplendens*, *Bregmaceros* sp., *Gadiculus argenteus*, *Scopelopsis multipunctatus* and *Pseudophthichthys splendens* were excluded from the analyses because their modern depth distribution range is great and encompasses almost entirely the 0-1000 meter interval. Their presence were considered only to clarify ambivalent depth estimates.

3. Paleobathymetric analysis

The paleodepth analysis and estimates are presented in Figures 2 and 3. In sample Voutes b, only three species may be considered, which provided a paleobathymetric estimate between 10-130 meters, *Cepola macrophthalma*, *Deltentosteus* aff. *quadrimaculatus* and *Lesueurigobius friesii*. In Voutes 3 the analysis delivered an estimate of 50-350 meters. However, this range is affected by the 50-meter intervals used in the analysis. After closer examination, it may be observed that the actual paleodepth estimate ought to be that where both *Aphia minuta* and *Diaphus adenomus* could coexist, and that is between 87-100 meters depth. The presence of *D. holti*, *H. hygomii* and *Laemonema* sp. in Voutes 4 leads to a paleodepth estimate between 200-800 meters, with no greater accuracy available for this level. The fish taxa identified in sample Voutes 1 did not allow for any paleobathymetric estimation. In particular, in this sample the following taxa have been identified (Agiadi et al., 2013): Myctophidae indeterminable (ind.), *Bregmaceros* sp., *Laemonema* sp., *Gadiculus labiatus*, Sparidae ind. and Perciformes ind. The great abundance of *Bregmaceros* sp., in conjunction with the presence of Myctophids and deep-water benthopelagic taxa such as *Laemonema* sp., *Gadiculus labiatus* and Perciformes, may indicate a rather deep marine environment, generally exceeding 200 meters.

A mixed fauna is revealed through the paleobathymetric analysis in sample Voutes c. Initially, the graphical results provide an estimate between 300-337 meters, delimited by the maximum depth distribution of *L. suerii*. However, the presence of *Oblada melanura* is problematic. This benthopelagic fish today inhabits rocky bottom of depths up to 30 meters, in the coasts of the eastern Atlantic and the Mediterranean Sea (Bauchot and Hureau, 1990). In addition, reef-associated taxa *Grammonus ater* and *Apogon* sp. (Whitehead et al., 1986) also also present in sample Voutes c. Two faunal units may thus be separated in this level, a deeper neritic unit from an environment reaching depths around 300-337 meters, and a shallow unit from depths between 0-30 meters.

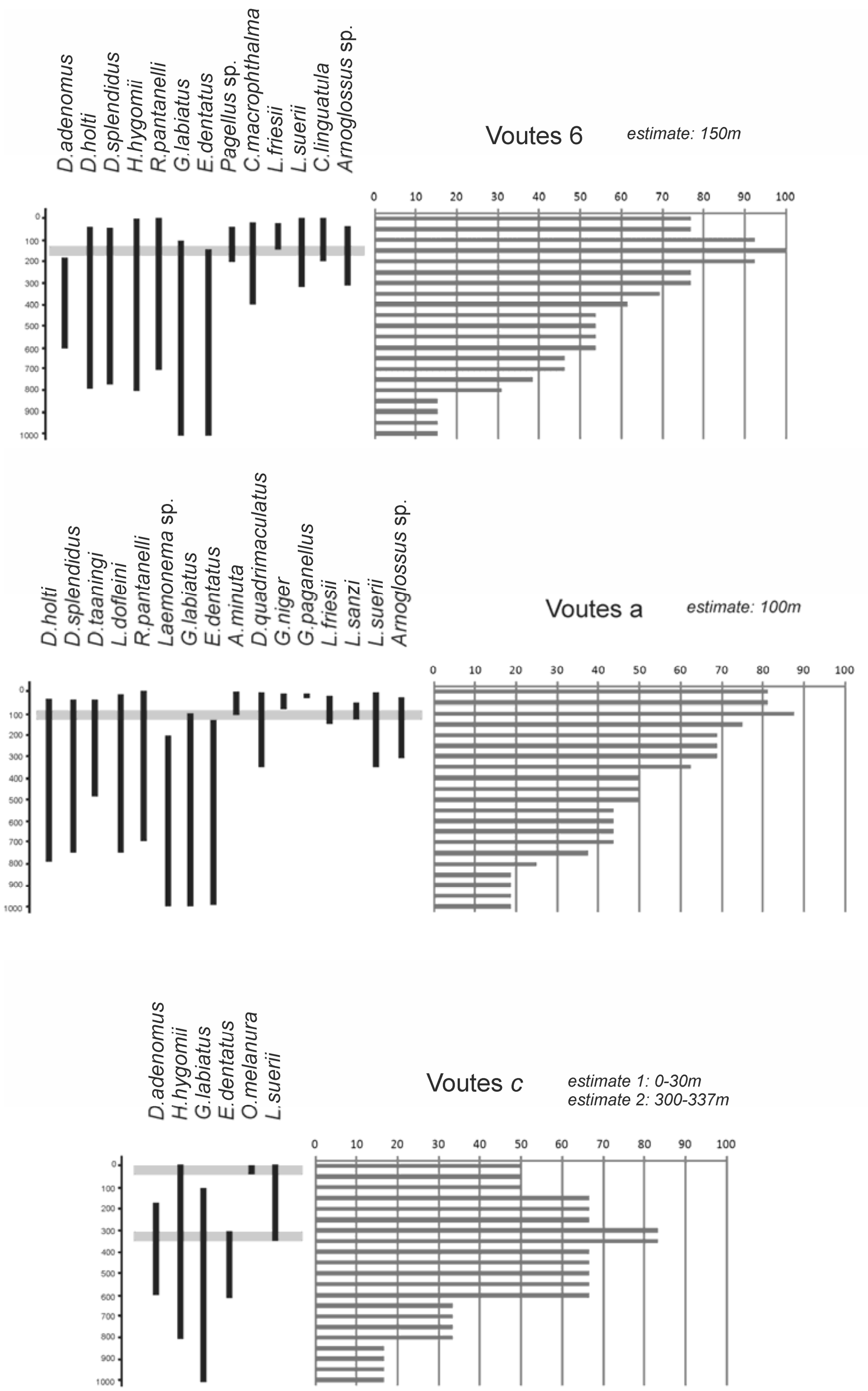

Figure 2. Paleobathymetric analysis and estimates.

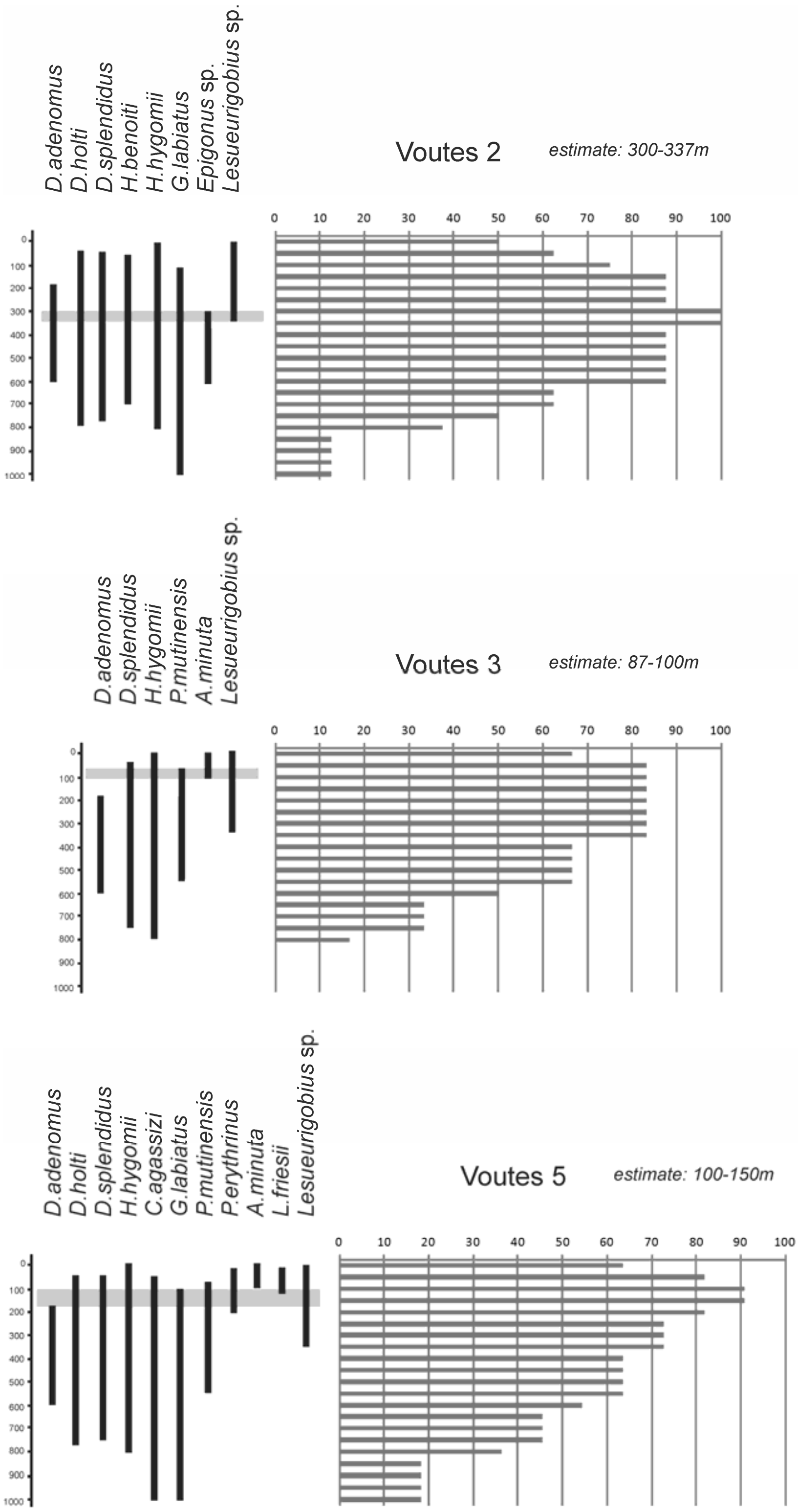

Figure 3. Paleobathymetric analysis and estimates (continuation).

4. Discussion and Conclusions

The paleobathymetric curve created from the analysis of the fish otolith fauna uncovered in the Voutes outcrop sediments present an interesting input in the paleogeographic evolution of the Central Crete area, namely the Heraklion basin (Figure 4).

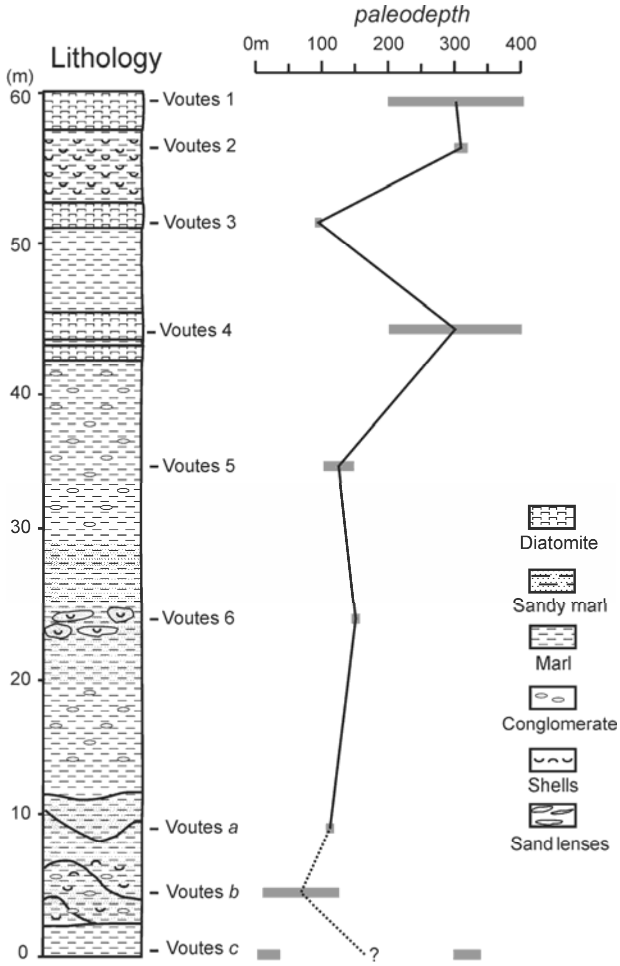

Figure 4. Voutes section lithology and paleobathymetric curve.

Generally, depths throughout this interval do not exceed 350 meters, although the lower part of the section (Figure 2) exhibits much shallower estimates, up to 150 meters. The deeper environments are found on the upper part of the section (Figure 3). However, no specific trend may be safely concluded from the estimated values. Rather several depth variations are visualized (Figure 4). In addition, the lower part of the Voutes outcrop reveals a mixture of the fish faunas from two realms, a deep water probably autochthonous faunal component, and a shallow allochthonous fauna. This is in accordance with the gravity flows observed at the lower part of the section, which seem to have incurred this mixing. Overall, during the late Zanclean, Voutes area was a coast, habitat for a rich shallow neritic Ichthyofauna. The results presented here offer new input on the tectonic – eustatic coupling effect on the paleogeography of central Crete, between 3.84 and 3.61Ma.

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