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M. DERMITZAKIS, V. KARAKITSIOS and E. LAGIOS

RESULTS OF GRAVIMETRIC MEASUREMENTS OF THE LAST 7 YEARS IN CRETE (GREECE) AND THEIR CONTRIBUTION TO THE UNDERSTANDING OF THE RECENT-ACTIVE DEFORMATION OF THE REGION

Μ. ΔΕΡΜΙΤΖΑΚΗΣ, Β. ΚΑΡΑΚΙΤΣΙΟΣ και Ε. ΛΑΓΙΟΣ

ΑΠΟΤΕΛΕΣΜΑΤΑ ΒΑΡΥΤΟΜΕΤΡΙΚΩΝ ΜΕΤΡΗΣΕΩΝ ΤΩΝ ΤΕΛΕΥΤΑΙΩΝ 7 ΧΡΟΝΩΝ ΣΤΗΝ ΚΡΗΤΗ (ΕΛΛΑΔΑ) ΚΑΙ ΣΥΜΒΟΛΗ ΤΟΥΣ ΣΤΗΝ ΚΑΤΑΝΟΗΣΗ ΤΗΣ ΠΡΟΣΦΑΤΗΣ ΕΝΕΡΓΟΥ ΠΑΡΑΜΟΡΦΩΣΗΣ ΤΗΣ ΠΕΡΙΟΧΗΣ

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by

M. DERMITZAKIS, V. KARAKITSIOS** & E. LAGIOS****

1. GENERAL INTRODUCTION

The Mediterranean is tectonically an especially active area and thus the geodynamic factors should always be taken seriously in mind.

The present situation was resulted from a long geological history. The Alpic mountain ranges have been gradually formed during the last 180 million years, since the closure of the Tethys ocean which broadened eastwards.

Since the opening of the Atlantic, Europe and Africa have comprised two separate plates with relative movements.

The most recent phase, which began 50 My ago is characterized by slow rotation of Africa northwards, around an axis placed in the Gibraltar area. The relative convergence speed remains minor, less than one centimeter per year. This may mean that the drift is hindered by collision between the two continents. At present this collision is pushing Turkey towards the West, where apparently the last remains of ocean crust still exist.

All these movements indicate the existence of high energies in the lithosphere.

The Mediterranean, therefore, is characterized by a dense-pattern (only 10% of the area of its basins is situated at a distance more than 100 km from the coastaline). This fact caused a rapid sedimentation in these basis (approximately 0,3 mm/year in the last 5 million years). As a consequence, the crust has been buried under a layer of sediments about 10 km thick at least.

Because of the weight of these sedimentary beds, the Western Mediterranean basins subsided for at least 7 km while those of Eastern Mediterranean, 6-15 km. This movement marks a progressive migration of the bending of continental margins towards the continent with a general tendency of the coasts to sink, which often neutralizes the rising tectonic movements that are produced by subduction or collision phenomena.

Actually there are some zones of subduction in the Mediterranean. One of them is associated with the Hellenic Arc which is geocrhonologicaly situated in the Serravallian-Quarternary (Mc KENZIE, 1978; MERCIER, 1981; LE PICHON & ANGELIER,

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* Αποτελέσματα βαρυτομετρικών μετρήσεων των τελευταίων 7 χρόνων στην Κρήτη (Ελλάδα) και συμβολή τους στην κατανόηση της πρόσφατης ενεργού παραμόρφωσης της περιοχής.

** University of Athens, Department of Geology, Panepistimiopolis, (15784) Athens, Greece.

1979). The distribution of seismic activity and tomographic results allow us to estimate that 200 km (Mc KENZIE, 1978; LE PICHON & ANGELIER, 1979; MERCIER, 1981) to 600 km (SPAKMAN et al., 1988; MEULENKAMP et al., 1988) of the African plate have dissapeared under the arc.

These tectonic movements have made the watery balance very delicate. The Mediterranean is joined with the Atlantic ocean and the Black Sea by shallow and narrow straits which are easily influenced by tectonics. If, for instance, the straits of Gibraltar were closed, then, under the present conditions, the Mediterranean would dry up in approximately 3,000 years. This phenomenon occurred during the Messinian when Evaporites were deposited at the bottom of the basins.

The sea water's level rose again during the Pliocene, when the straits were opened again. It seems that during the Quaternary the straits remained open, although they were gradually becoming shallower since the Lower Pliocene. That is why the Mediterranean was influenced by the eustatic movements of the Atlantic ocean.

On the other side, the Black Sea, had been connected to the Mediterranean Sea during the main interglacial periods (STANLEY & BLANPIED, 1980).

According to data supplied by the «SEASAT» satelite, extensive depression is manifested in the Eastern Mediterranean, around the Hellenic Arc, in the area of the Ionian Trench and of Pliny and Strabo trenches. The inclination of the median surface level is very pronounced between this depression and the Aegean Sea.

The sea-floor relief reflects the differences in density in the Earth's interior, according to the geological history. That is why the relief gradually becomes more pronounced from West to East, which is in accordance with the increasing relative displacement between Europe and Africa. It is indeed particularly pronounced near the areas where the lithospheric convergence is active or recent. In general the sea-floor surface slopes towards Africa, while the subduction zones are characterized by a great depression of the level. A contrary phenomenon can be observed in the area of the Calabrian Arc.

If we take into consideration the intense-tectonic activity of the Mediterranean basin, we can state that the relief of its sea-floor surface is not static but changes gradually. According to a model proposed by RHIZO (1983) it has been predicted that the present relief will become even more pronounced, with an increase in the inclination of the geoid surface of about 5-10 cm per century.

Vertical displacements of Crete are closely related to the mechanisms of the Hellenic subduction zone. To determine the distribution and the succesion of vertical displacements, a thorough study of the structure of the Alpine nappe system (which provides a key to the evaluation of neotectonic deformation, inferred from vertical offsets of the faults which cut the nappe pile) and the stratigraphy of Neogene (dating of the neotectonic events) is necessary.

2. GEOLOGICAL BACKGROUND

The Alpine units of Crete have been studied thoroughly in the last twenty years (AUBOUIN & DERCOURT, 1965; FYTROLAKIS, 1967, 1972, CREUTZBURG & PAPASTAMATIOU, 1969; BONNEAU, 1970, 1972, 1973a, b, 1984; SANNEMANN & SEIDEL, 1976; AUBOUIN et al., 1979; BONNEAU et al., 1977; CREUTZBURG & SEIDEL, 1975; SANNEMANN & SEIDEL, 1976; CREUTZBURG & coll., 1977; BONNEAU & KARAKITSIOS, 1979; KARAKITSIOS, 1979, 1987, 1989; HALL et al., 1984; ALEXO-

POULOS, 1990). Based on the literature the Alpine sequence of Crete synthetically consists by:

- the parautochtonous «Ida-Talea ori» unit, which corresponds to the metamorphic Ionian series of the Western Greece;
- the «Tripali unit» known only in Western Crete, which probably corresponds to the lower part of the parautochtonous sequence from which it was tectonically detached;
- the Tripolis nappe s.l. which consists of two units: the underlying «metamorphic phyllitic nappe» and the calcareous Tripolis nappe s.s. on top of it. The tectonic contact that separates the two units corresponds to a «Rabotage basal» that affected the base of calcareous Tripolis nappe s.s., showing that the tectonic emplacement of the Tripolis nappe s.l. has been multiphase;
- the Pindos-Ethia nappe constitutes the extension of the Olonos-Pindos series from mainland Greece to Crete;
- the «upper tectonic nappes» that include: the «intermediate units» (Miamou, Vatos, Arvi), the Asteroussia nappe s.s. and the ophiolitic complexe on top.

The stratigraphic data confirm the initial continuation of this system of nappe pile despite the neotectonic faulting of Crete.

The neotectonic analysis, of Crete mainly concerns the period after the latest orogenetic movement. The big thrusts of the most external Cretan series took place after the Lower Oligocene and before the Serravallian-Tortonian. This has been concluded from the fact that both the flysch of the parautochtonous series has a Lower Oligocene age (BIZON et al., 1976; BARRIER, 1989), and the first post-alpine sediments which are in discordance with the Alpine formations of Crete are molasses of Serravallian-Tortonian age (DROGER & MEULENKAMP, 1973). Consequently, **the tectonic emplacement of nappe system corresponds to the interval between -35 and -13 million years. Therefore the Neotectonic evolution of Crete started 13 million years ago.**

The Neogene sedimentary record of Crete provides ample evidence of repeated, dramatic changes in the paleogeographic configuration, which were in most cases connected with major tectonic events. From the Middle Miocene onward the Cretan area became transformed into a mosaic of horsts and grabens (fig. 4), the differential vertical movements varying in intensity both in space and time (cf. infra). The complex interplay of tectonics and sedimentation resulted in a large variety of sediment types and in a rapid lithological changes both in a horizontal and in a vertical sense.

More than 60 formal and informal rock units have been recognized in the last twenty years (e.g. DERMITZAKIS, 1969-1973; FREUDENTHAL, 1969; MEULENKAMP, 1969; DE BRUIJN et al., 1971; GRADSTEIN, 1973; FORTUIN, 1977; DERMITZAKIS & SONDAAR (1978) DERMITZAKIS et al., 1979; DERMITZAKIS & PAPANIKOLAOU, 1981; DE BRUIJN & VAN DER MEULEN, 1981; ZACHARIASSE, 1983; FORTUIN & PETERS, 1984, PETERS, 1985). These rock units can be classified (MEULENKAMP et al., 1979; fig. 1) into six groups of formations (most groups can be recognized all over the island):

1-*Prina Group.* Sediments attributed to the Prina Group consist of dark limestone breccias and brecciocongIomerates. As a rule the components are embedded in a well-cemented, calcareous matrix. The breccias and brecciocongIomerates were deposited in non-marine to brackish or shallow-marine environments.

The Prina Group forms either the local base of the Neogene sequence, or it represents a lateral equivalent of part of the next-higher Tefeli Group. At some places the Prina Group contains large slabs of gravity-displaced preneogene limestones.

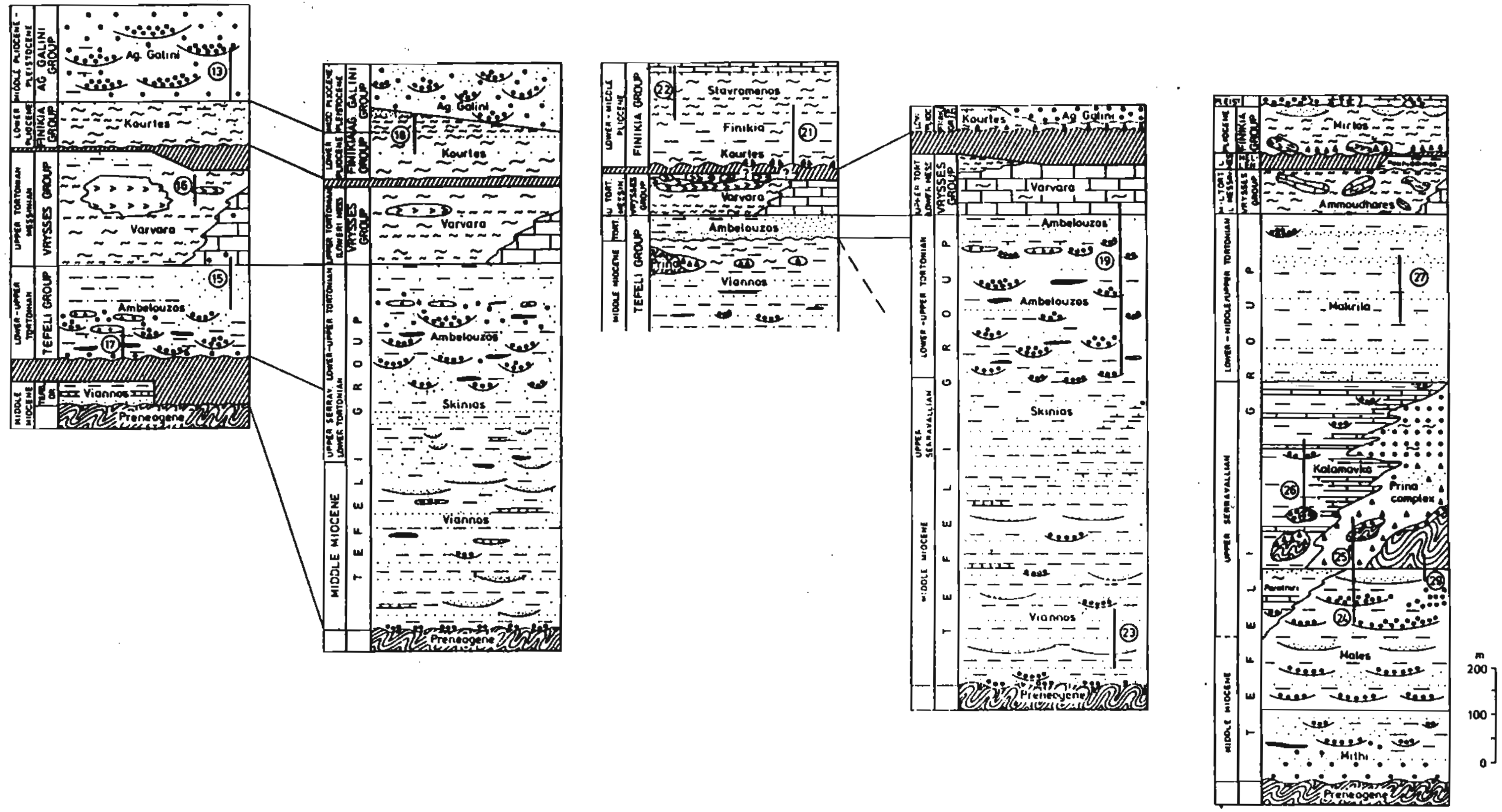

Fig. 1. Correlation table of the biozones of marine sediments, pollen and mammals that have been recognised in Crete, and chronostratigraphic development of the lithostratigraphic units of Crete (after MEULENKAMP & al., 1979).

2–*Tefeli Group.* The Tefeli Group comprises all «non-consolidated» terrigenous-clastic formations overlying the Prina Group or the preneogene basement and underlying the calcareous successions of the Vrysses Group. The formations incorporated in this group are predominantly composed of conglomerates, sands and clays reflecting deposition in fresh-water, brackish and marine environments.

3–*Vrysses Group.* Bioclastic, often reefal algal-coral limestones which constitute in part the lateral equivalent of alternations of laminated and hogogeneous, shallow-marine marls. At some places the marls contain intercalations of gypsum. The Vrysses Group overlies the Tefeli Group, the preneogene basement or, occasionally, the Prina Group.

4–*Hellenikon Group.* The Hellenikon Group consists of reddish, non-marine conglomerates, fluvio-lacustrine, relatively fine-grained successions and, occasionally, brackish and lagoonal deposits with some gypsum. The group unconformably overlies the Vrysses Group, older Neogene strata or, at some places, the preneogene basement.

5–*Finikia Group.* All formations consisting of open marine marls and clays which overlie the Hellenikon Group or the Vrysses Group are incorporated in the Finikia Group. Often the marls and clays display laminated, sometimes siliceous interbeds. At many places the base of the Finikia Group is formed by a marl breccia.

6–*Ag. Galini Group.* Coarse, generally reddish, non-marine conglomerates and sands, which overlie, and are in part the lateral equivalent of, sediments of the Finikia Group. The Ag. Galini Group represents the highest Noegene rock unit on Crete.

7–*Pleistocene.* No formal subdivision was made for the Pleistocene marine terraces and continental deposits. The Pleistocene sediments unconformably overlie Neogene or preneogene rocks.

3. NEOTECTONICS

In Crete, the analysis of the entire Neotectonic period, shows that extentional movements (fig. 2) took place during Upper Miocene times in faulted basins (fig. 4), as shown by syn-sedimentary faulting.

The main characteristics of this tectonics are the large amplitude and the long duration of extentional movement related to normal faulting since Miocene times. On the contrary, the observed compressional events in the interval of the same period, have quite different intensities and seem all brief (ANGELIER, 1979; GOURNELLOS & KARAKITSIOS, 1987).

The average speed of differential deformation related to the vertical motions for the entire Neotectonic period (=13 Ma), as this results from the actual disposition of nappes (fig. 3), ranges between 4 to 5 cm/100 years. According to MOURTZAS (1990) the uplift of Crete started during the Late Pliocene-Early Pleistocene and the uplift rate, during the last 130000 years had not been more than 0.63 cm/100 years that is very different of the uplift rate accepted by ANGELIER, 1979 (3.2 to 4.6 cm/100 years) or PETERS, 1985 (6 cm/100 years). Due to the big difference in between the rate values proposed by MOURTZAS (1990), ANGELIER (1979) & PETERS (1985), the latest proposals seem to be more reasonable.

Radiometric dating of the Quaternary shorelines made from various investigations (THOMMERET et al., 1981; PIRAZZOLI, 1986), shows that the average speed of some uplifts from Tyrrhenian up to the last thousand years ranges between 5 to 6 cm/100 years. This speed is approximately the same with the speed of the differential vertical

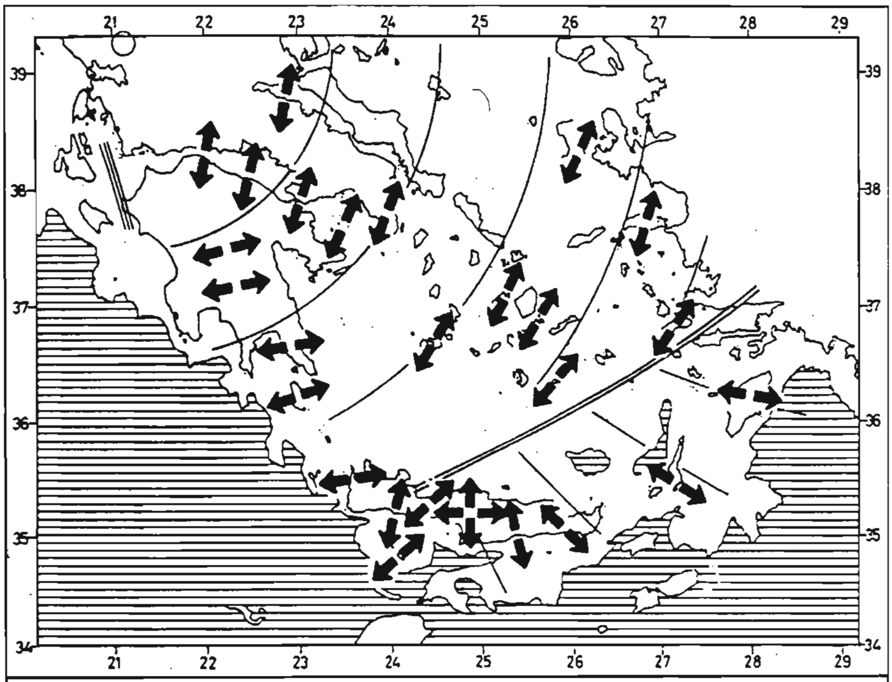

Fig. 2

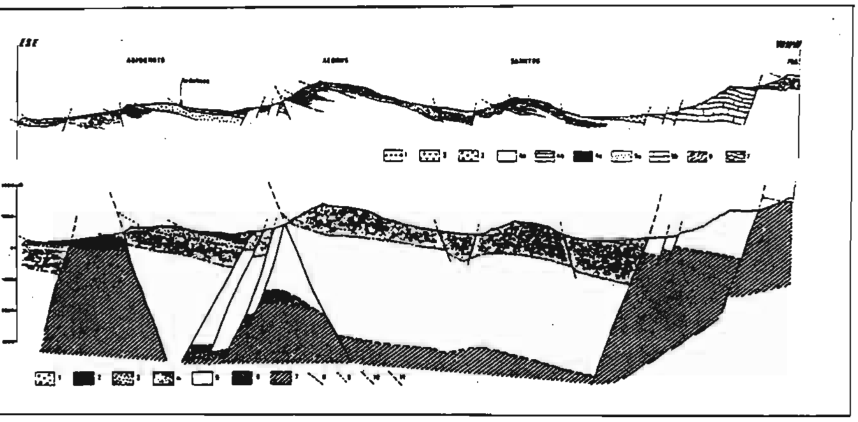

Fig. 3

Fig. 2. Dominant directions of neotectonic extension in Middle-Southern Aegean (after ANGELIER, 1979). Double arrows: dominant regional directions of minimum stress N3. Simple line: approximate extensional trajectories. Double line: limit of the two domains with sub-orthogonal dominant directions. Triple line: Western limit of Ionian islands compressive zone.

Fig. 3. Mont Ida to the sea section, showing the superposition of nappes and their actual disposition, controled by faults structure (after BONNEAU & al., 1977).
1: Neogene; 2: Ophiolites; 3: «Vatos shales» (Miamou nappe); 4: Pindos-Ethia nappe (a-Eocene flysch, b-Upper Cretaceous to Lower Eocene Limestones, c-Radiolarites and infra-Radiolaritic series); 5: Tripolis nappe (a-Priabonian to Oligocene flysch, b-Triassic to Lutecien Limestones); 6: Phyllitic nappe; 7: Parautochtonous Ida unit; 8, 9, 10 and 11: thrusts of Vatos nappe Ophiolites, Pindos nappe, Tripolis series s.l.

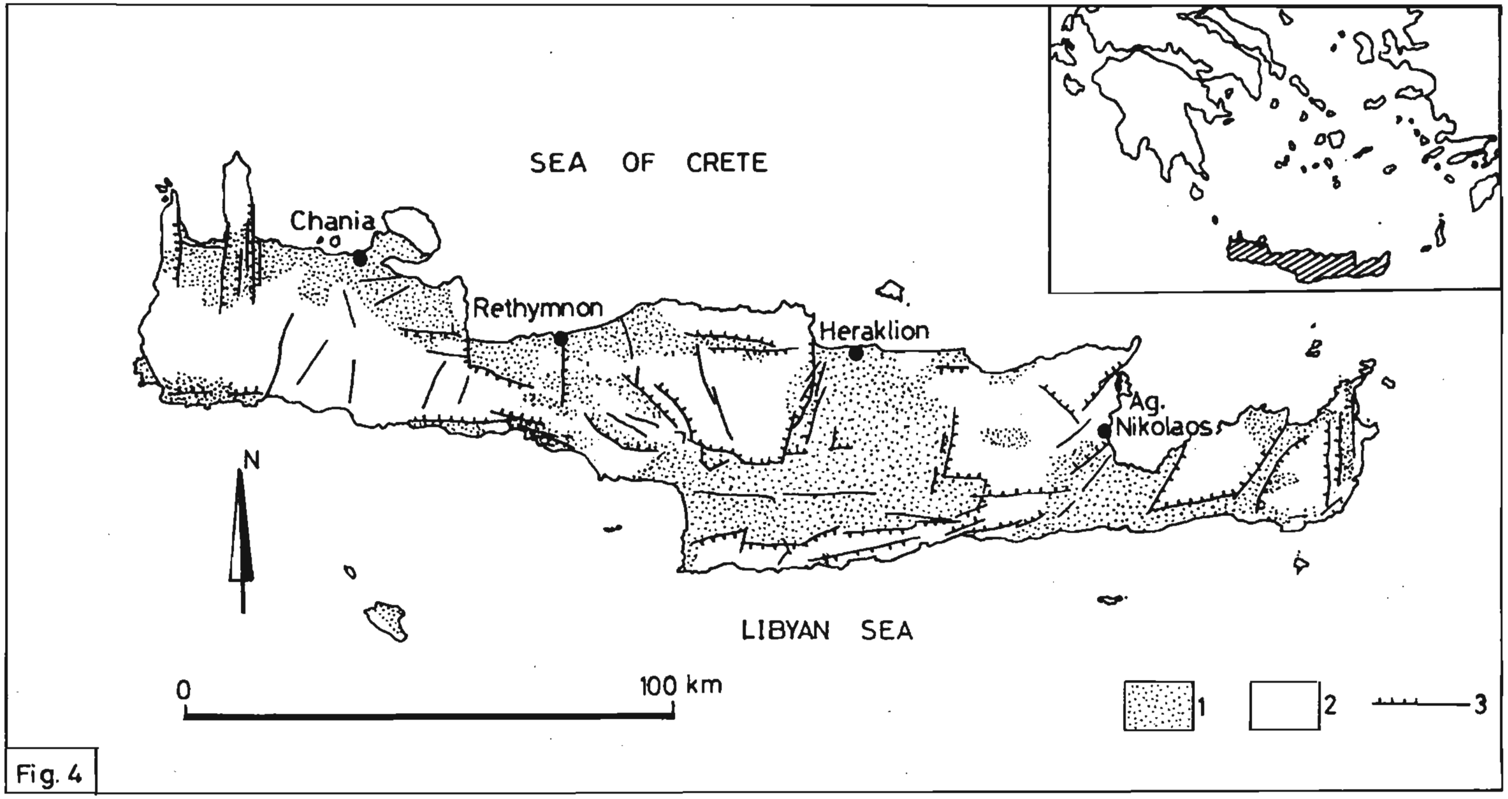

Fig. 4

Fig. 4. Schematic map of Crete showing the post-nappe reliefs (principal tectonic horsts and grabens). 1: post-alpine formations; 2: alpine formations; 3: big normal faults (dented-marks show the uplifted block).

deformation of the entire Neotectonic period. On the contrary, some uplifts that began 1500 years B.P. (PIRAZZOLI et al., 1982) show very higher rates of average speed of vertical deformation (about 60cm/100 years).

From a kinematic point of view, this extension due to large normal faulting implies an expansion of the Aegean region towards the Eastern Mediterranean basin (LE PICHON & ANGELIER, 1979; ANGELIER, 1979), as well as an increase of the curvature and perimeter of the Hellenic arc (fig. 5).

4. RECENT VERTICAL DEFORMATION OF CRETE

A network of about 60 gravity stations (fig. 6) was established in Crete in 1983 and was remeasured on an anual basis. Rigorous measuring prosedures as well as advanced processing and adjustement techniques were applied on the independent gravity observations to attain high accuracy. Corrections due to atmospheric pressure and groundwater level variations were also applied recently in a systematic manner. The obtained accuracy in an individual gravity station is approximately 4-5 μGal, corresponding to 2-2.5 elevation change applying the Bouquer gravity gradient (LAGIOS & HIPKIN, 1986; LAGIOS et al., 1989).

The purpose of the Crete high accuracy gravity network is to detect gravity changes associated with tectonic motions. If uplift is systematically observed in an area, where non-tectonic movements (groundwater level change) are not taking place, then a decrease in the value of the local gravity field is expected, which results to a positive gravity change value. The opposite should normally be expected in case of subsidence.

The gravity observational points (gravity stations) were established not only along the E-W axis of Crete, but also in a perpendicular to this direction, where it was feasible depending on the road system of Crete. Emphasis, however, has been given to the western part of Crete. As a consequence, the stations lie on different tectonic blocks which are either horst or grabens (compare fig. 4 with fig. 6). The kinematic picture along these tectonic blocks is different. It has been reported (e.g. FYTROLAKIS, 1980) that the blocks characterized as horsts have the tendency to be uplifted, whereas those known as major grabens have the tendency to subside.

Some results of the remeasurement of the network since 1983 are shown in this study. The analytical behaviour of stations mainly along the E-W direction is presented here in *figure 7*. The 1983 values of the network comprise the observational basis for the subsequent years and, therefore, the gravity change for each station is resulted by subtracting the estimated adjusted gravity value of the remeasurement of each year from the initial one in 1983.

Even thoguh the gravity changes at each station do not represent a comprehensive picture of a systematic pattern related to uplift or subsidence, the bottom of *figure 7* is more explanatory. The identified grabens and horsts along the selected E-W profils were marked together with the stations fallen in those tectonic regions. Subsequently, the average value of the resulted gravity change for all years is estimated for each station belonging on a graben or horst. The final result of this adopted procedure is represented by heavy line in the bottom of *figure 6*.

It is therefore shown that almost all stations established on grabens tend to subside, while those on horsts tend to be uplifted. There are some exceptions of the rule but the observed deviation is within the error limits of the (horizontal) baseline. However,

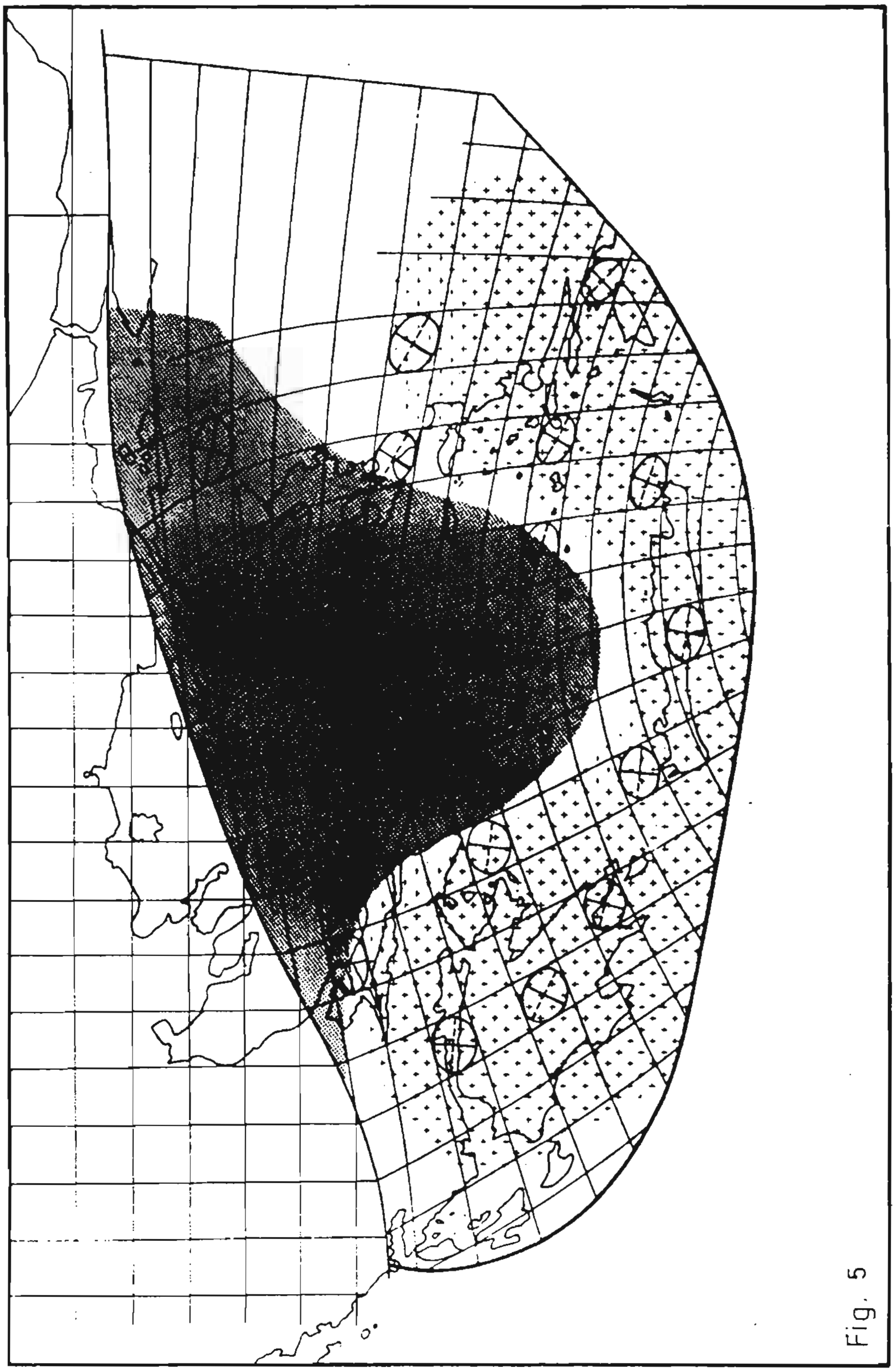

Fig. 5

Fig. 5. Aegean deformation from 0 to 13 M. years (after LE PICHON & ANGELIER, 1979).

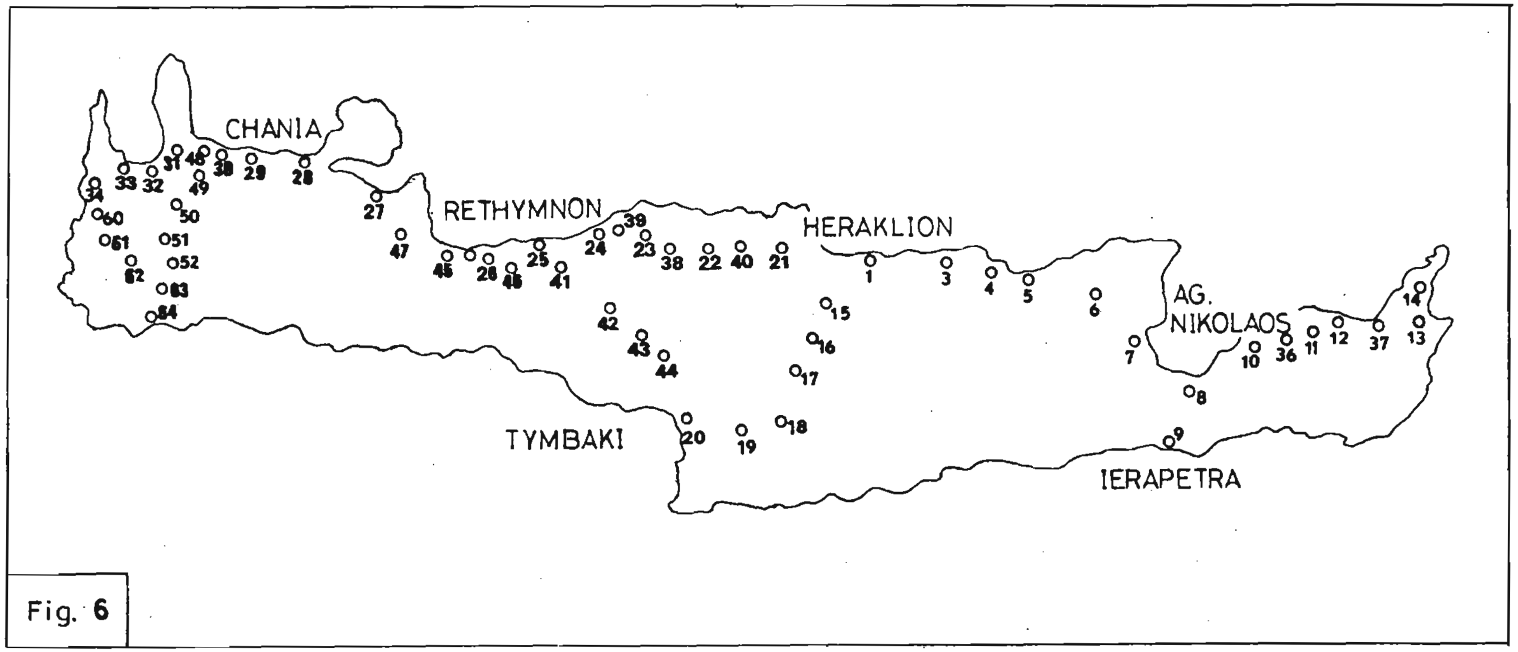

Fig. 6

Fig. 6. Distribution of microgravimetric stations in Crete.

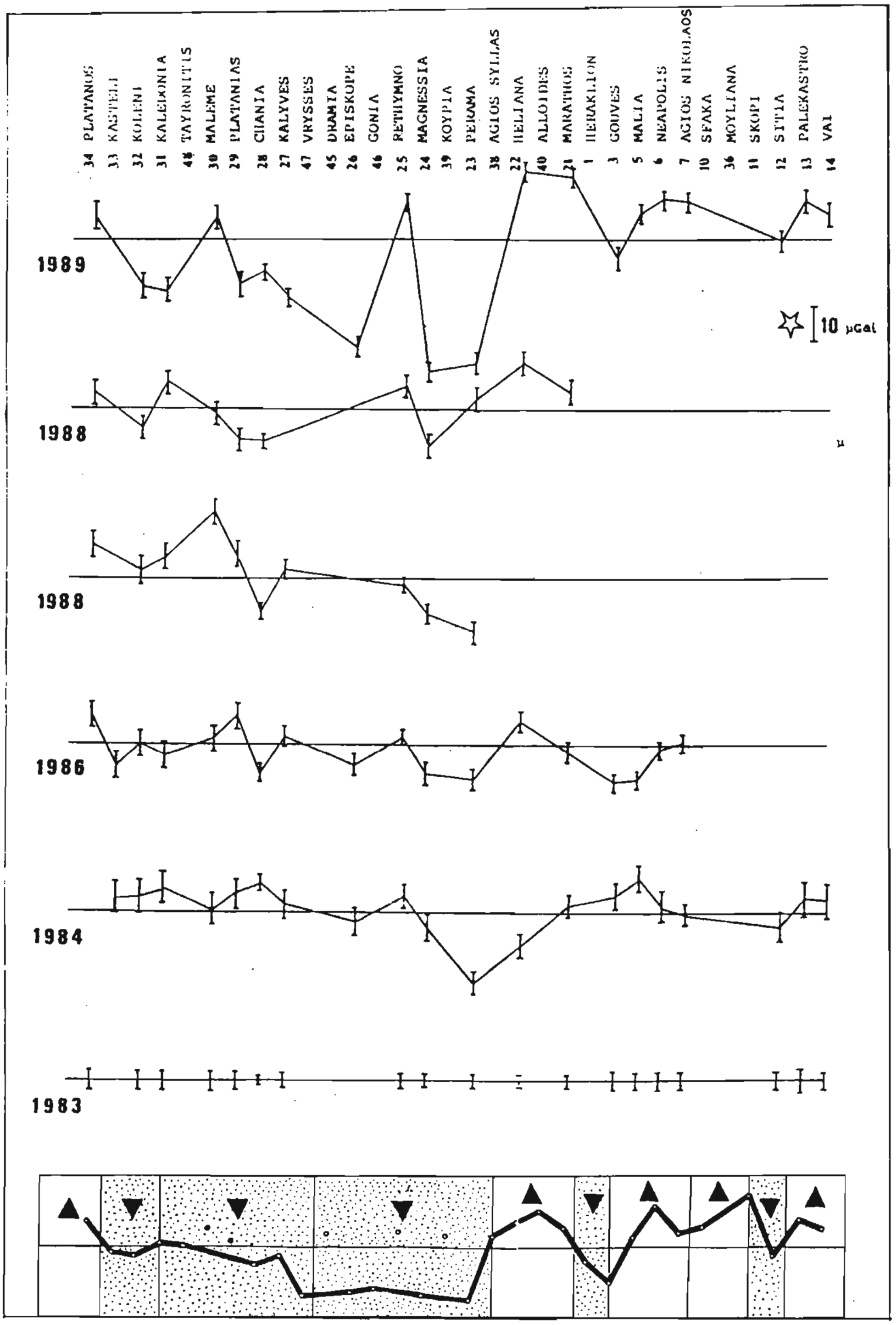

Fig. 7. Distribution in time and space of the observed gravity differences of the Crete network. Reference is the 1983 adjusted gravity values.

before coming up to final conclusions, longer time observational procedures is required. Some preliminary maximum values of subsidence or uplift may be deduced though.

It is estimated (fig. 7) that the maximum gravity change value observed as an average in Crete is 12-15 μGal (± 6 μGal) corresponding to 6-7 cm (± 3 cm)/7 years (=100 cm/100 years) of uplift or subsidence in an average manner.

5. DISCUSSION AND CONCLUSIONS

New data on the structure of the Upper Mantle underneath the Aegean area -tomographic images of the Aegean/Eastern Mediterranean Upper Mantle in cross section by SPAKMAN et al., 1988- indicate that the duration of the Hellenic subduction zone ranges from 26 to 40 ma (SPAKMAN et al., 1988, MEULENKAMP et al., 1988). This is considerably longer than earlier estimates which vary between 5 (MERCIER, 1981) and about 13 Ma (LE PICHON & ANGELIER, 1979). According to MEULENKAMP et al. (1988) this implies that the geological processes around 12 Ma ago, such as fragmentation of Crete into several basins, are not to be attributed to the initiation of subduction in the Hellenic Trench, but they are associated with the inception of the roll-back process (south-southwestward migration of the Hellenic Trench system). Consequently, the role of compressional tectonics in the tectonic evolution of Crete is more important than hitherto thought. The stretching of the Aegean lithosphere is accommodated by along low angle shear zones. Along such zones (MEULENKAMP et al., 1988) a supracrustal slab became detached and began to slide in southward direction. In the frontal part of this slab (containing the Cretan segment) compression may be generated. Folding and thrusting within the southern extreme of the supractrustal slab has caused the recent overall uplift of Crete, being stronger in the south, coupled to a northward tilting of large parts of the island. During periods without tectonic transport of the supracrustal slab, almost vertical maximal stress σ_1 (gravity) generates almost universally oriented extension within the supracrustal slab. If this is true vertical movements are also possible for the period of the tectonic emplacementr of nappe system s.s. of Crete (between -35 and -13 Ma) and one has to distinguishe the comressional and extensional structures of this period. This a new problem open for research which is beyond the aim of the present study.

Summing up, the already published results of Neogene-Quaternary stratigraphy, sea-level changes (shorelines uplift) and recent gravimetric measurements in Crete show that:

- the rate of differential deformation for the entire Neotectonic period (-13 Ma) is estimated to be similar to the speed of the fossilized pleistocenic shorelines;
- shorelines of the last 1500 years, involve an acceleration of vertical mouvement;
- the upward and downward movements, recorded from a microgravimetric network, for the last 7 years in the horsts and grabens respectively, show that vertical mouvement is still continuing in an increasing speed. This phenomenon is probably related to a particular stage of subduction or even, to the onset of the continental collision between Africa and Europe.

ABSTRACT

In Crete, the analysis of the Neotectonic period faults shows that these are asso-

ciated with a strong extensional regime, in a perpendicular direction to the longer dimension of Crete (and in general to the Aegean arc). This extension that has been expressed with normal faults, has caused a gravitational spreading of Aegean towards the Ionian sea in an extremely large scale, especially in Crete. This phenomenon is associated with the subduction of the African plate under the Aegean plate. In the interior of this regime, compressional events have been observed.

Shorelines of the last 1500 years «record» revolving upward movements in West Crete with maximum rising approximately 10 m. This uplift involves an acceleration of vertical deformation. In Crete, the speed of differential vertical deformation for the entire Neotectonic period (approximately 13 million years) is estimated to be similar with the speed deduced from the fossilized Pleistocenic shorelines.

Gravimetric measurements of the last 7 years in Crete show that the upward and downward movements in the horsts and the grabens respectively, are still continuing in an increasing speed. This phenomenon is probably related to a particular stage of subduction or even, to the onset of the continental collision between Africa and Europe.

ΠΕΡΙΛΗΨΗ

Στην Κρήτη η ανάλυση των ρηγμάτων της Νεοτεκτονικής περιόδου δείχνει ότι αυτά συνδέονται με ένα ισχυρό εφελκυστικό καθεστώς, με διεύθυνση κάθετη προς την μακρύτερη διάσταση της Κρήτης (και γενικότερα του τόξου του Αιγαίου). Ο εφελκυσμός αυτός που εκφράστηκε με κανονικά ρήγματα, προκάλεσε σε μεγάλη κλίμακα την επέκταση λόγω βαρύτητας του Αιγαίου και ιδιαίτερα της Κρήτης προς την Ιόνια θάλασσα. Το φαινόμενο αυτό συνδέεται με την υποβύθιση της Αφρικανικής πλάκας κάτω από την Αιγαία πλάκα. Στο εσωτερικό αυτού του καθεστώτος παρατηρήθηκαν συμπιεστικά συμβάντα.

Οι ακτογραμμές των τελευταίων 1500 ετών καταγράφουν περιστροφικές ανοδικές κινήσεις στην Δυτική Κρήτη με μέγιστη ανύψωση περίπου 10 m. Στην Κρήτη η ταχύτητα της διαφορικής κατακόρυφης παραμόρφωσης για τη συνολική Νεοτεκτονική περίοδο (κατά προσέγγιση 13 εκ. έτη) εκτιμάται ως παρόμοια με την ταχύτητα που συνάγεται από τις απολιθωμένες Πλειστοκαινικές ακτογραμμές.

Οι βαρυτομετρικές μετρήσεις των τελευταίων 7 ετών στην Κρήτη δείχνουν ότι οι ανοδικές και καθοδικές κινήσεις στα τεκτονικά κέρατα και τις τεκτονικές τάφρους αντιστοίχως, συνεχίζονται ακόμα με αυξανόμενη ταχύτητα. Το φαινόμενο αυτό πιθανώς συνδέεται με ένα ιδιαίτερο στάδιο υποβύθισης ή ακόμη, με την έναρξη της ηπειρωτικής σύγκρουσης μεταξύ Αφρικής και Ευρώπης.

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