Downloaded from rsta.royalsocietypublishing.org

The Aegean Sea [and Discussion]

X. Le Pichon, J. Angelier, M. F. Osmaston and L. Stegena

Phil. Trans. R. Soc. Lond. A 1981 **300**, 357-372
doi: 10.1098/rsta.1981.0069

Email alerting service Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 1981 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

Phil. Trans. R. Soc. Lond. A **300**, 357–372 (1981)
Printed in Great Britain

The Aegean Sea

By X. Le Pichon and J. Angelier
Laboratory of Geodynamics, Pierre and Marie Curie University,
4 *Place Jussieu, T.*15, *E.*1, 75230 *Paris cedex* 05, *France*

We summarize briefly the main features of a kinematic model of evolution of the Aegean area since 13 Ma. The formation of the Aegean Sea by extensional tectonics is related to the subduction of the Mediterranean floor below the Hellenic arc. We then make a quantitative estimate of vertical movements in the Aegean area, on the basis of geological data, and demonstrate that the outer arc was built since the beginning of this episode of subduction by vertical uplift. The easiest way to explain the uplift is by underplating. Finally, we discuss briefly the dynamics of the subduction – marginal sea formation processes in this continental collision framework.

Introduction

We call Aegea the land mass that includes southern Greece, the Aegean Sea and western Anatolia and which is now characterized by a tensional stress régime as shown by seismological (McKenzie 1978) and tectonic studies (Mercier, this symposium). Aegea is overriding the Mediterranean sea floor toward the southwest along the Hellenic trench (see figure 1) (McKenzie 1978). Yet, except in the westernmost portion of northern Peloponnesos, near the northern termination of the Hellenic trench, extension seems to prevail right down to the Hellenic trench (Angelier 1979; Lyberis & Bizon 1980). For example, extension is active on the island of Gavdos, to the south of Crete, 20 km away from the axis of the trench (Angelier 1979). On the other hand, the floor of the Hellenic trench shows clear indications of SW–NE shortening, as revealed by submarine studies (Le Pichon *et al.* 1979). And the Mediterranean ridge, south of the Hellenic trench, is apparently also affected by shortening (Stride *et al.* 1977; Le Pichon *et al.* 1979). Thus the main characteristic of the present situation of Aegea is the discontinuity of the stress pattern along the subduction zone, except near its northwesternmost termination where compressional stress overlaps part of Peloponnesos.

Figure 2 shows some remarkable features of the morphology of Aegea. Sometime after the Lower Oligocene and before the Serravallian (upper Middle Miocene, 13 Ma ago), the last nappes, coming from the northern internal zones, were put into place over the southern continent. The resulting Aegean landmass was levelled by erosion (see discussion in Angelier (1979)). Then a major palaeogeographic change occurred at the end of the Serravallian (Drooger & Meulenkamp 1973). This was the progressive fragmentation of the Aegean landmass, which has resulted in the present shallow sea dotted with a great number of islands (see figure 2, 0 m isobath). Simultaneously, a well developed semicircular continuous non-volcanic external arc was progressively uplifted, isolating the relatively deep sea between Crete and the inner volcanic arc (figure 2, 800 m isobath). Note that the Sea of Crete, which is the only significant deep portion of the Aegean Sea, is not situated behind the volcanic arc, as in most present-day active marginal basins, but rather between the external arc and the inner volcanic arc. This is a very important point: extension is not confined to a narrow zone behind the volcanic arc but affects the whole Aegean continent.

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to
Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.
www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

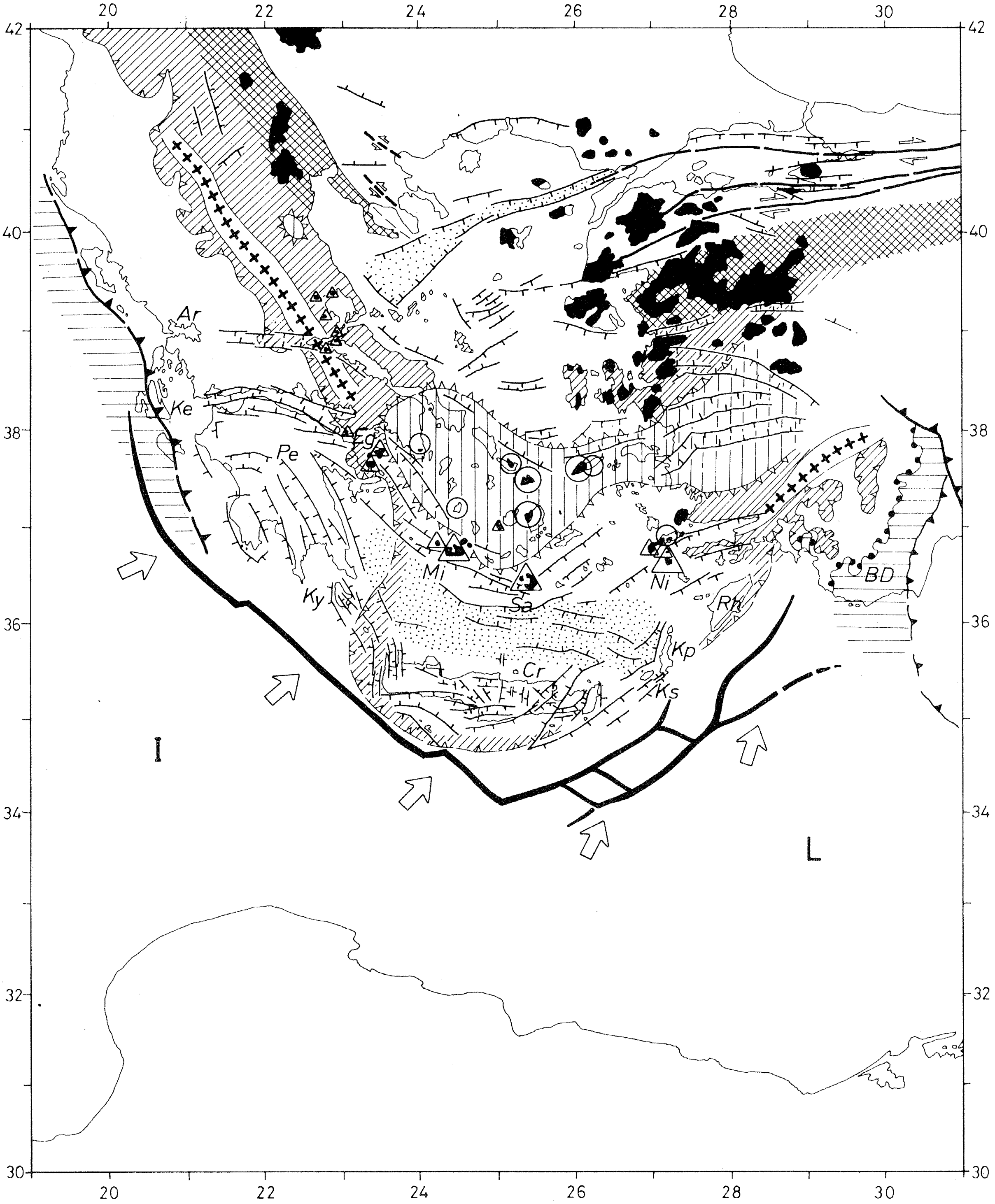


Figure 1. General framework of the Aegean region.

Main geographical and morphological units. Hellenic Trenches: thick black lines, along the Ionian (I) and Levantine (L) basins of the eastern Mediterranean Sea. Main Aegean basins: dotted pattern (Cretan Sea near 36° N, North Aegean trough near 40° N). Outer Hellenic arc between the Arta Gulf (Ar) and the Bey Daglari (BD): Kefallinia (Ke), Peloponnesos (Pe), Kythira (Ky), Crete (Cr), Kassos (Ks), Karpathos (Kp), Rhodos (Rh). Inner, volcanic, Hellenic arc: Aegina (Eg), Milos (Mi), Thira or Santorini (Sa), Nisiros (Ni).

(continued opposite)

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

The 2000 m isobath (figure 2) marks the southern limit between Aegea and the Mediterranean sea floor. The most striking characteristic of this limit is that it is subangular. The western portion is rectilinear and exactly perpendicular to the direction of underthrusting of the sea floor (see figure 1). The eastern portion is more complex but approximately parallel to it. It is hard to believe that this peculiar geometrical relation between direction of subduction and edge of Aegean continent is fortuitous. Apparently, the stresses related to subduction maintain a rectilinear boundary along the western convergent zone. This containment does not exist on the eastern, mostly transform boundary where a rather complex topography prevails (Le Pichon & Angelier 1979).

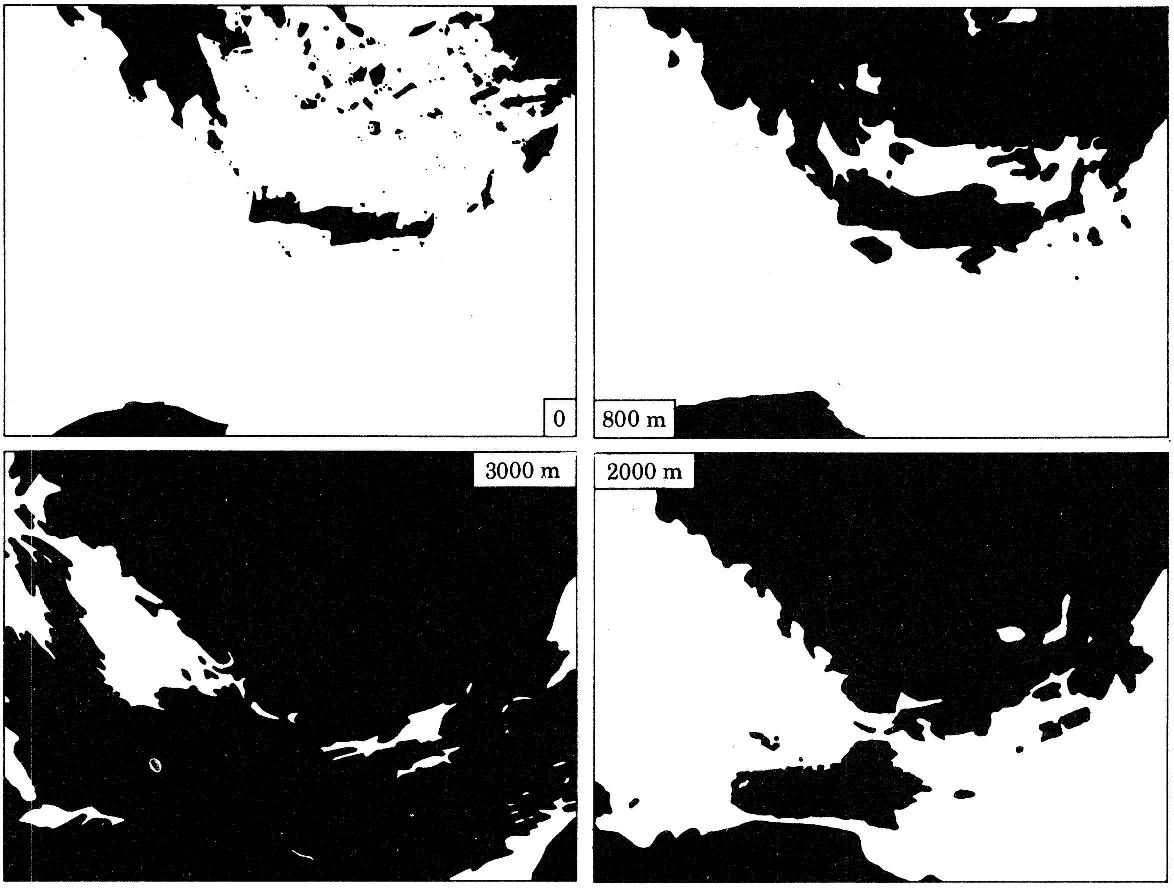


FIGURE 2. General morphology of the Hellenic arc and adjacent Mediterranean basins. Areas where the depth is greater than 0, 800, 2000 and 3000 m respectively are left white.

Main units of the alpine belt (Dinarides–Hellenides–Taurides). Innermost, ophiolitic, zones: cross-hatching; other inner zones: oblique hatching; outer zones: white, except the outermost parts (E–W hatching). Aegean tectonic windows: N–S hatching.

Main Neogene and Quaternary features. Lines of crosses: Meso-Hellenic and Tavas molassic troughs (Oligocene, early Miocene). Black: Oligo-Miocene plutonism and volcanism of northern Greece and NW Anatolia. Circles: granodioritic intrusions of Miocene age in the central Aegean region. Triangles: Plio-Quaternary volcanoes of the inner Hellenic arc. The main normal faults and extensional grabens of Late Miocene and Plio-Quaternary age are shown by thin barbed lines. In the Northern Aegean region, double arrows indicate the sense of strike-slip faults. Large open arrows near the Hellenic Trench indicate the direction of Africa–Hellenic arc relative motion, inferred from focal mechanism of earthquakes.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Downloaded from rsta.royalsocietypublishing.org

Note also that the southernmost tip of Aegea is now very close to the Libyan portion of Africa and that, as a result, the Mediterranean ridge has apparently been squeezed within the narrow remaining basin, as suggested by the abnormally small depth of the ridge there. Finally the 3000 m isobath outlines the Hellenic trench with its single deep western Ionian branch and its double relatively shallow eastern branch.

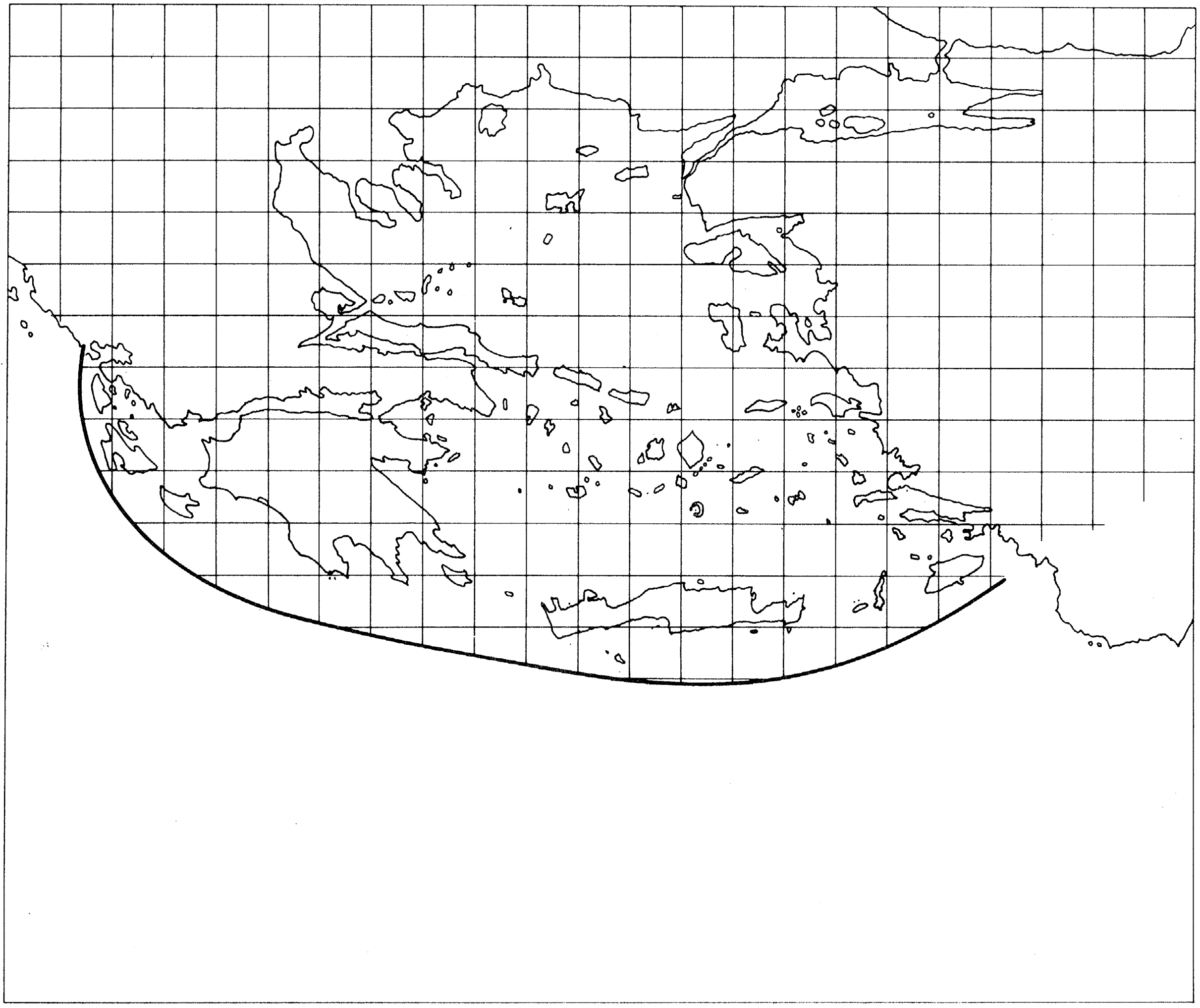


Figure 3. Reconstruction of the Aegean region before Hellenic subduction and associated Aegean expansion. Configuration 13 Ma ago (Middle–Upper Miocene transition). Present coasts, deformed, are used as reference lines. A square, N–S and E–W grid (relative to Eurasia) is added.

Brief summary of the kinematic reconstruction due to Le Pichon & Angelier (1979)

We shall first summarize briefly the main results of our earlier kinematic reconstruction. The amount of subduction, as given by the length of the intermediate seismic zone, is much larger than the amount of deformation of the Hellenic arc. Thus, to a first approximation, the Africa–Hellenic arc convergence can be described by a rigid rotation of 30° about a pole situated near

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

40° N, 18° E. Taking into account the Africa–Europe motion, the resulting Hellenic arc–Europe divergence is a rotation about a pole situated near Arta (see figure 1) with a magnitude of also about 30°. As a result, subduction and Aegean extension are closely coupled. Kinematic and geological considerations converge on a Serravallian–Tortonian date, 13 Ma ago, for the beginning of the present subduction–extension system which is at the origin of the new palaeogeography with fragmentation of the Aegean landmass.

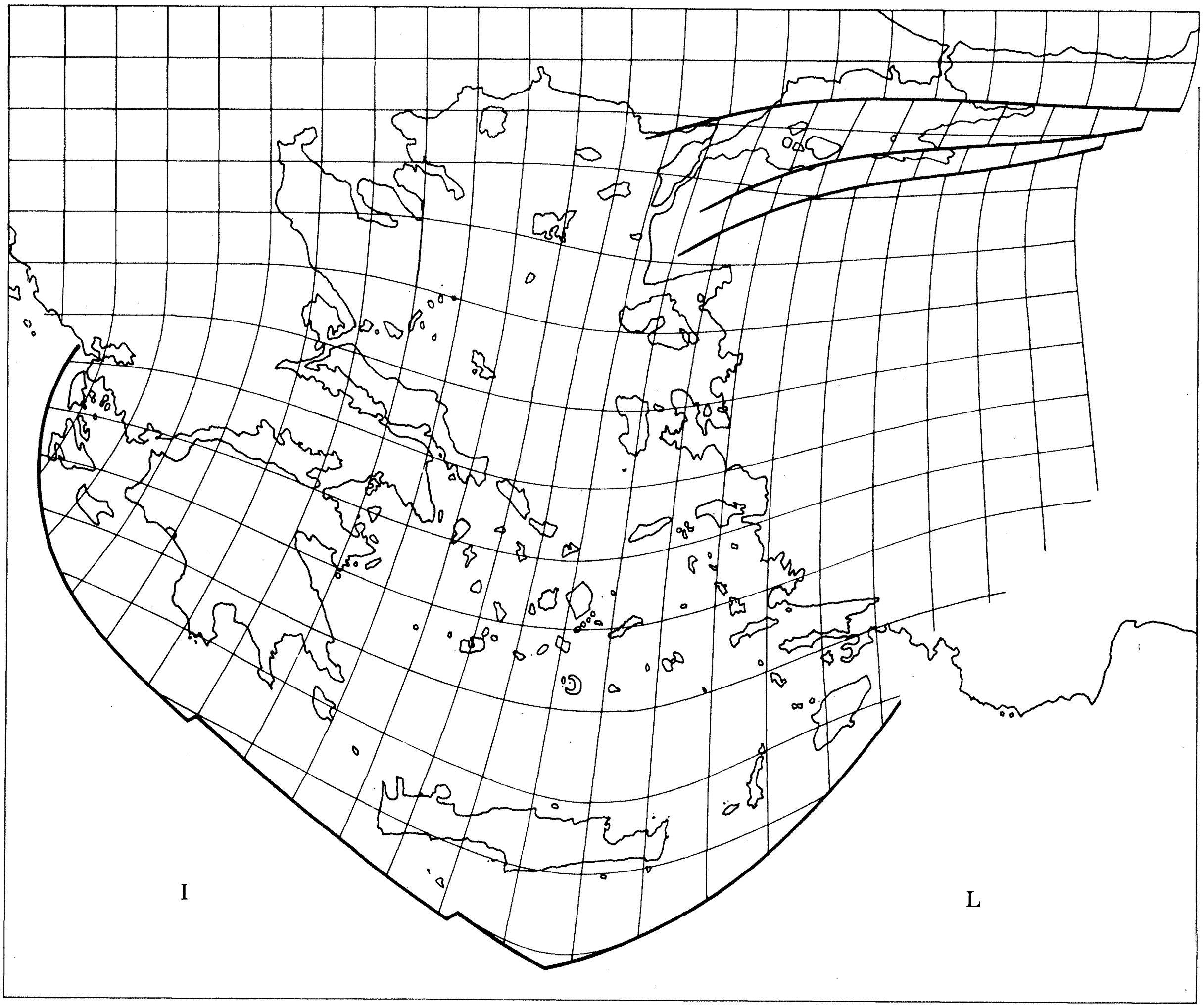


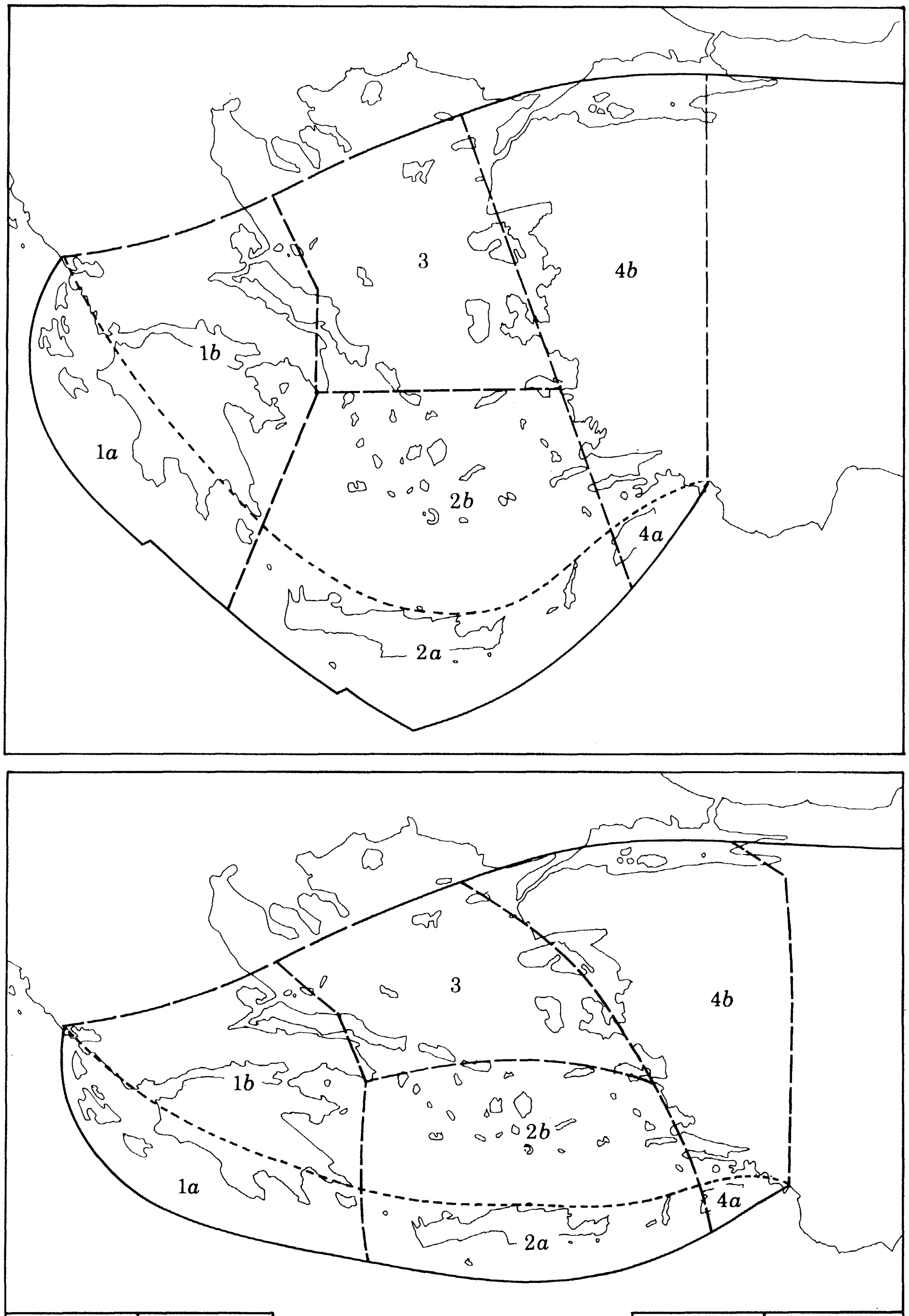
Figure 4. Present configuration of the Aegean region. The total deformation is shown by the deformed grid of figure 3. I, L: Ionian and Levantine basins.

Figure 1 shows that the main normal faults and extensional grabens of Late Miocene and Plio-Quaternary age are aligned along a radius about the Arta pole of rotation, except in SE Aegea, where they are parallel to the transform portion of the subduction zone. Thus the overall pattern of extension agrees with the predicted divergence between Europe and the Hellenic arc. Phases of compression have been identified and described within this 13 Ma time span (see discussion in Mercier, this symposium). However, the resulting shortening is quantitatively much smaller than the extension. For example, in Crete, normal faults with several kilometres

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



3+2	3+2*b*	1*a*+2*a*+4*a*	1+2+3+4
1.39	1.33	1.41	1.30

1	1*a*	1*b*	2	2*a*	2*b*	3	4	4*a*	4*b*
1.23	1.21	1.25	1.50	1.62	1.43	1.23	1.21	1.58	1.19

FIGURE 5. Average regional rates of expansion in the Aegean region. Aegea is divided into four main areas by dashed lines. The table gives the rates of expansion for various areas, as computed from the reconstruction of figures 3 and 4.

Downloaded from rsta.royalsocietypublishing.org

offsets are obvious everywhere, whereas reverse faults are rare, of very small amplitude and difficult to detect (Angelier 1979).

Finally, to obtain the Serravallian reconstruction, it is still necessary to replace Turkey in its position with respect to Europe. Le Pichon & Angelier (1979) assumed 110 km of right lateral motion along the Anatolian fault since Serravallian, following Bergougnan (1975). This estimation is close to the 80–90 km of Dewey & Sengör (1979) for the same period.

Figures 3–6 give the main characteristics of this tentative reconstruction of Aegea, which is based on a geometric reconstruction of its boundaries. The internal deformation within this frame is distributed according to two criteria. First, following the proposition of McKenzie (1978), it is assumed that the deformation of continental crust did not modify its total volume; thus the present thickness of crust reflects the amount of thinning produced by extension.

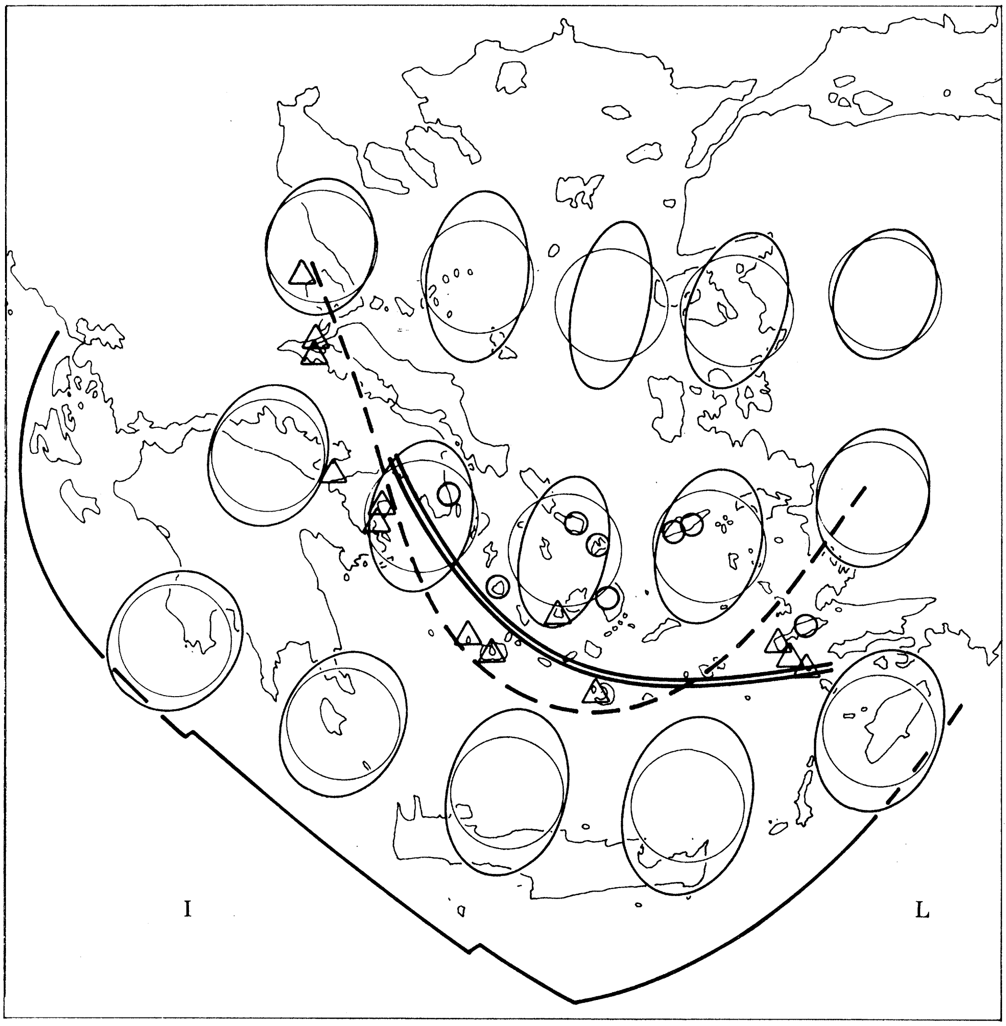


FIGURE 6. Ellipses of deformation in the Aegean region, deduced from the model of figures 3 and 4. Original circles have been deformed into ellipses. Dashed line separates areas where pure multidirectional extension prevails (to the south: normal faults only) and areas where secondary E–W shortening accompanies main N–S extension (to the north: normal faults + strike-slip faults + compressional structures). The double line is the southern boundary of areas where important compressional tectonics occurred during Middle–Upper Miocene times and Pliocene to Quaternary transition. Triangles: Plio-Quaternary volcanoes of the Inner Hellenic Arc. Circles: grano-dioritic intrusions of Miocene age in the central Aegean region.

Downloaded from rsta.royalsocietypublishing.org

Secondly, the main geological features are continuous throughout Aegea, from mainland Greece to Eastern Anatolia. Any reconstruction should preserve the continuity of structures.

The *average* amount of extension after 13 Ma implied by the reconstruction corresponds to a stretching factor of 1.3 (see figure 5). The stretching factor is maximum in the southern Aegean Sea, where it averages 1.5 (zone 2). It is maximum in the Sea of Crete where it reaches 2. Direct neotectonic estimates of the amount of extension in Peloponnesos and Crete are compatible with the values proposed and definitely show an increase in stretching from the Peloponnesos toward Crete (Angelier 1979).

Figure 6 summarizes the *average deformation* implied by our model. To the south of the dashed line, the deformation is purely extensional. The corresponding stress tensor would have its minimum component (σ_3) horizontal and orientated NE–SW to N–S, whereas σ_2 would be horizontal. North of the dashed line, E–W shortening accompanies N–S extension. This deformation also implies a N–S σ_3, but it is now the σ_1–σ_3 plane that would be horizontal. Consequently, both normal faults and strike-slip faulting might be expected there. This is quite compatible with the neotectonic data, which indicate that brief compressional phases invaded most of Aegea during Upper Miocene and Plio-Quaternary times; however, these phases were minor in the southern area and well expressed to the north (Angelier 1979). This is of course what would happen if an additional E–W compressive stress was added to the pattern implied in figure 6. Note that, at present, strike-slip faulting does occur in the northern area, whereas faulting is purely extensional in the southern area (Mercier, this symposium).

It was pointed out by Le Pichon & Angelier (1979) that the limit between two different strain patterns coincided with the zone of 10–12 Ma granodioritic intrusions and with the present zone of volcanism. This has consequently been a zone of hot, thin and weak lithosphere, presumably since the beginning of the extension. It apparently concentrated the southward flowing Aegean lithosphere, the lines of flow converging toward the median part of the Aegean Sea and diverging south of it. We shall come back later to the dynamics of this tectonic pattern.

VERTICAL MOVEMENTS: FORMATION OF THE NON-VOLCANIC EXTERNAL ARC

As shown in figure 5, there is no indication that the external arc has been less affected by extensional tectonics than the main part of the Aegean Sea, except for the deepest portion of the Sea of Crete. Stretching of the continental crust should result in subsidence. We shall follow here the analysis of McKenzie (1978). Assuming that the whole lithosphere is involved in the stretching and taking an initial thickness of crust of 32 km for zero elevation and an initial lithospheric thickness of 110 km (values chosen to fit the Sea of Crete data), we have an initial subsidence (in kilometres) immediately after stretching, supposed to be instantaneous, of

$$S_i = 5(1-1/\beta),$$

where β is the stretching factor. After an infinite time, the lithosphere has thickened by cooling to its initial equilibrium thickness and the total subsidence is

$$S_t = 7.8(1-1/\beta)$$

(Le Pichon & Sibuet 1980). We adopt the same constants as Le Pichon & Sibuet: the temperature of the asthenosphere as 1333 °C, the zero degree density of mantle as 3.35 g cm^{-3} and of

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

crust 2.78 g cm^{-3}, and the coefficient of thermal expansion, α, as 3.28×10^{-5} K^{-1}. Taking into account the fact that stretching was not instantaneous, but started 13 Ma ago, we finally adopt

$$S = 5.4\ (1-1/\beta).$$

The average water depth across a Santorin-Crete section of the Sea of Crete is 1.5 km and the average sediment thickness 1.6 km (Angelier 1981). Taking the density of sediment as 2.4 g cm^{-3}, the isostatic subsidence is then 2.15 km, giving β equals 1.65. Similarly, on a Milos–Crete section of the Sea of Crete, the isostatic subsidence is 1.6 km, giving $\beta = 1.4$. The average

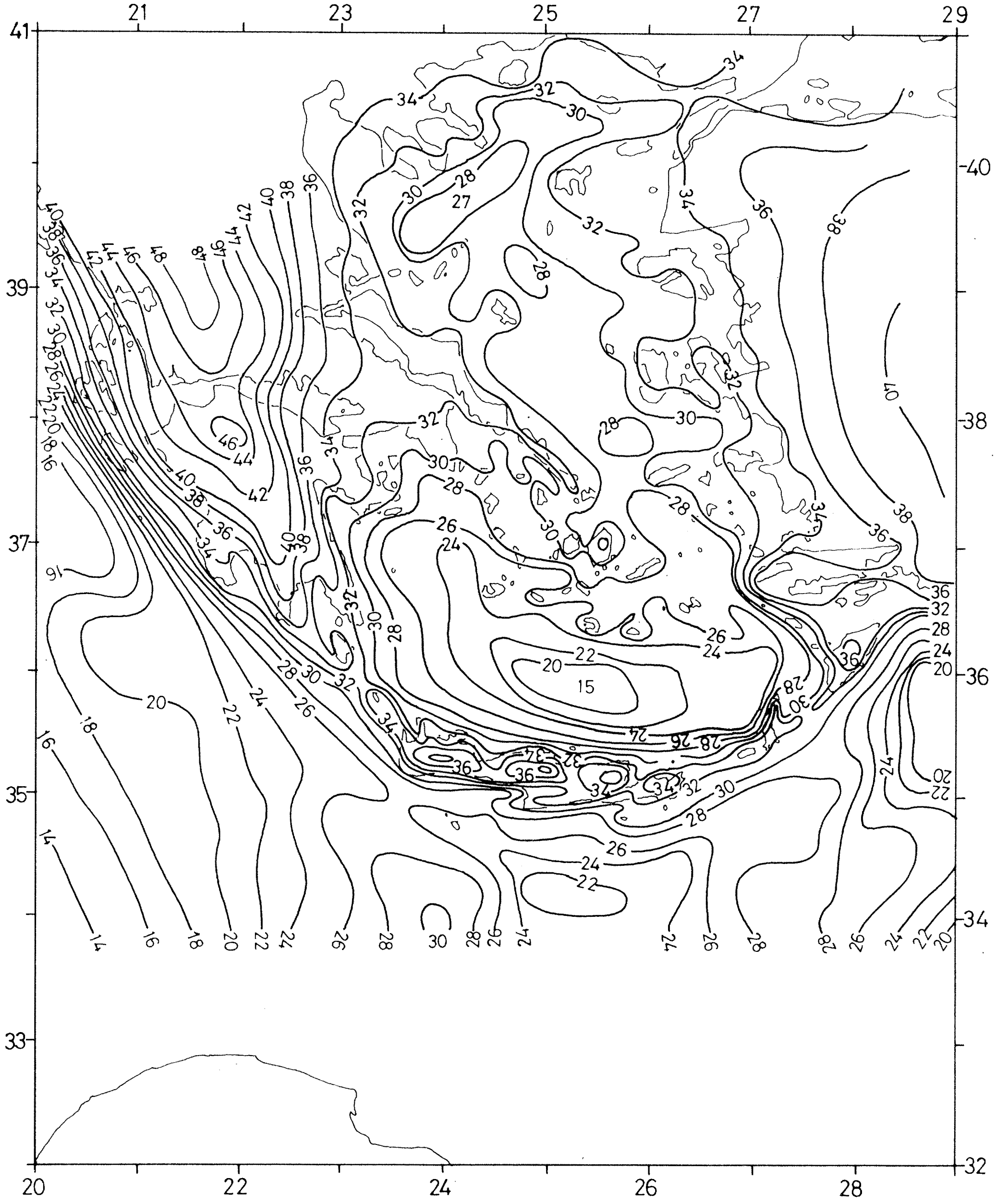


FIGURE 7. Approximate crustal thicknesses (kilometres) in the Aegean region, assuming that no process of thinning or thickening has acted since. Derived from the Moho-depth map published by Makris (1977), with corrections including topography and bathymetry. Note that we have added the approximate amounts of erosion and removed the approximate thickness of sediment since 12–13 Ma.

Downloaded from rsta.royalsocietypublishing.org

present thicknesses of crust are respectively 19 and 24 km, giving computed pre-extensio thicknesses of crust of 31.5 and 33.5 km respectively. These are compatible with the assumed 32 km pre-extension thickness and show that subsidence in the Aegean Sea can be explained by stretching.

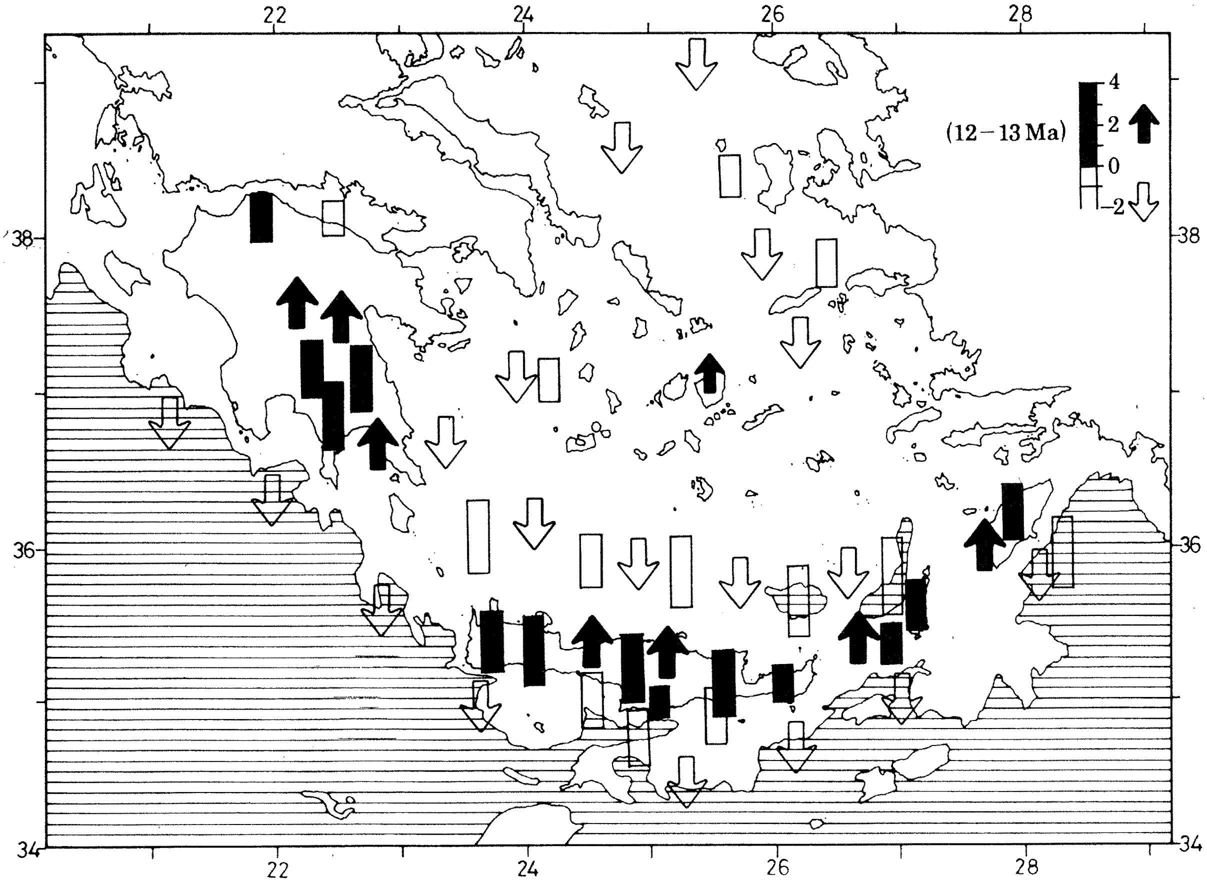


FIGURE 8. Average rates of uplift (black columns and arrows) or subsidence (white symbols) in the Aegean region, for the 13–12 Ma to 0 Ma period. Arrows indicate general tendencies to uplift or subsidence, without scale. Columns refer to local estimates. Scale in centimetres per century (upper right-hand corner).

However, by using the values given in figure 5, the average stretching factor over the external arc is 1.4 and this is confirmed by field data (Angelier 1979). We know that in middle Miocene time, Crete was part of the Aegean landmass on which the nappes had travelled from north to south and that it had been eroded and levelled after nappe emplacement. We know further that in Tortonian time (10 Ma ago), most of the external arc was marine or very close to sea level (Angelier 1979). Thus, the thickness of crust at this time should have been close to 30–32 km. With a stretching factor of 1.4, the present thickness should be 21–23 km and the present subsidence 1.4 km. Instead, topography as high as 2000 m exists in Crete and the main part of the external arc has been continuously uplifted since at least middle Miocene. Further, the present altitude of the external arc is roughly compatible with the present thickness of crust. This is shown by figure 7, derived from the Moho depth map of Makris (1977) and obtained by adding to the present thickness of crust the amount of erosion and subtracting the amount of sedimentation since 13 Ma. Figure 7 indicates what would have been the thickness of crust 13 Ma ago assuming that no process of thinning or thickening acted since.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

To summarize, the formation of the external arc probably started some time near the Middle–Upper Miocene boundary, which is about the time at which subduction with coupled extension started. The width of the zone of uplift is shown by the present width of crustal root, that is about 70 km, which is fairly narrow and excludes any deep cause. The palaeogeography of the Middle Miocene suggests that, if anything, the crust was thicker under the Aegean Sea than under the external arc. This situation is now reversed. The main process of uplift then was the relative thickening of a crustal root below the external arc in spite of the overall stretching. In any case, an uplift due to uncompensated tectonic forces is precluded as there is no associated gravity high (see, for example, Makris 1977). From figure 7, the average thickness of crust over the external arc (erosion included) is about 32–34 km instead of 21–23 km. Consequently, about 11 km of crust must have been added from below since 13 Ma ago to produce the uplift.

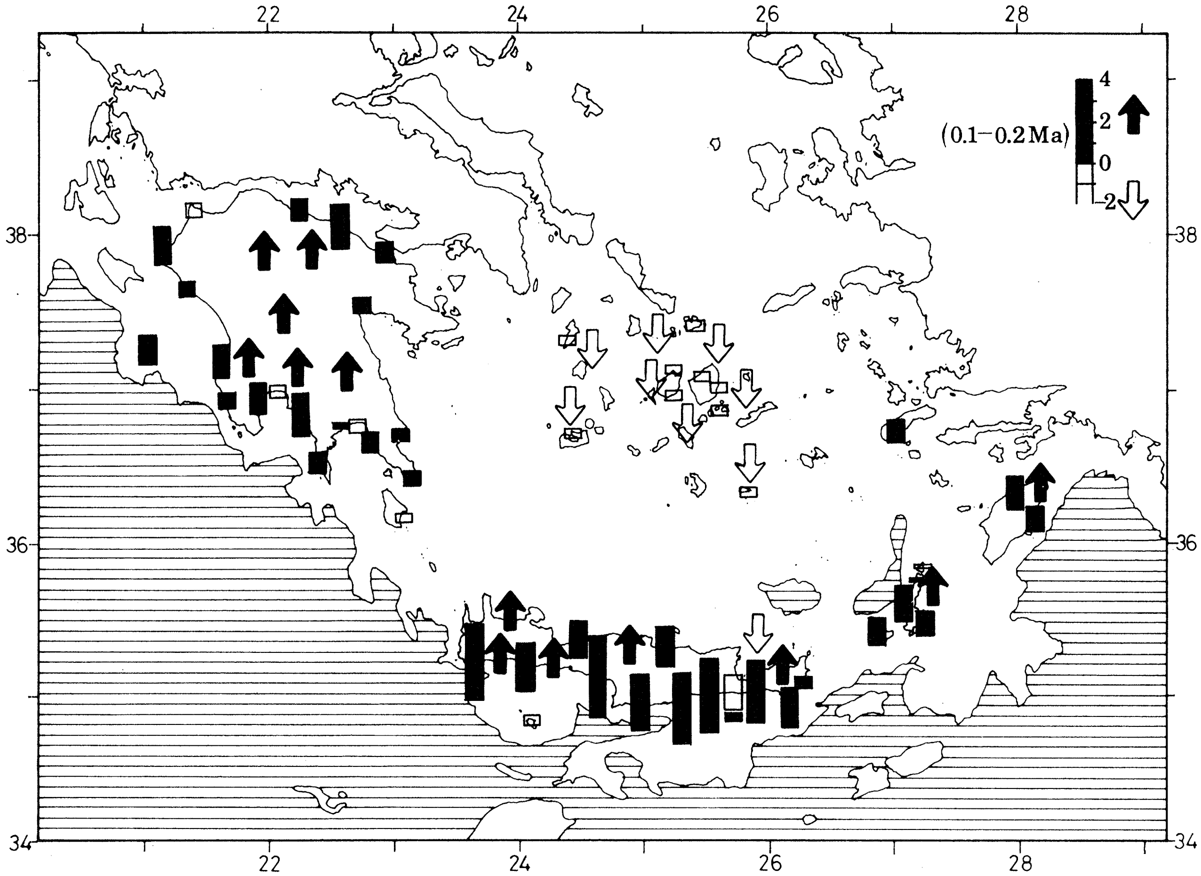


FIGURE 9. Average rates of uplift or subsidence in the Aegean region, for the Upper Pleistocene to present period (approx. 0.2 Ma to 0 Ma). Legend as for figure 8. On Crete and Karpathos, rates are estimated by using radiometric ^{230}Th/^{235}U and ^{231}Pa/^{235}U dates (for details, see Angelier (1979), for Crete; and Barrier (1979), for Karpathos). Other rates were calculated by using probable stratigraphic equivalences between Quaternary marine terraces of Crete and other areas (for Peloponnesos, most data are heights given by Kelletat *et al.* (1976)). Note that subsidence rates are only minimum values, since real depths of Quaternary shorelines are unknown.

Let us now examine the geological evidence for uplift to evaluate how much absolute uplift has occurred and whether this has been a more or less continuous process since the beginning of subduction. The reader is referred to Angelier (1979) for a detailed discussion. A first, rather

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

imprecise, method is to assume that the surface of the Oligocene (Lower Miocene?) nappes was roughly horizontal in the Middle Miocene. Provided we can estimate their thickness and that this thickness does not change too much laterally, we can estimate the amplitude of the vertical motions to which they were submitted since. In Crete, the structure of the nappes has been studied in detail (Aubouin & Dercourt 1965; Bonneau 1976; Bonneau *et al.* 1977; Creutzburg *et al.* 1977). The summits of the highest mountains consist of the lower member of the nappes sequence, whereas the uppermost member is presumably lying at a depth of 3–4 km in the Sea of Crete, which indicates a differential uplift exceeding 7 km between the Sea of Crete and Crete.

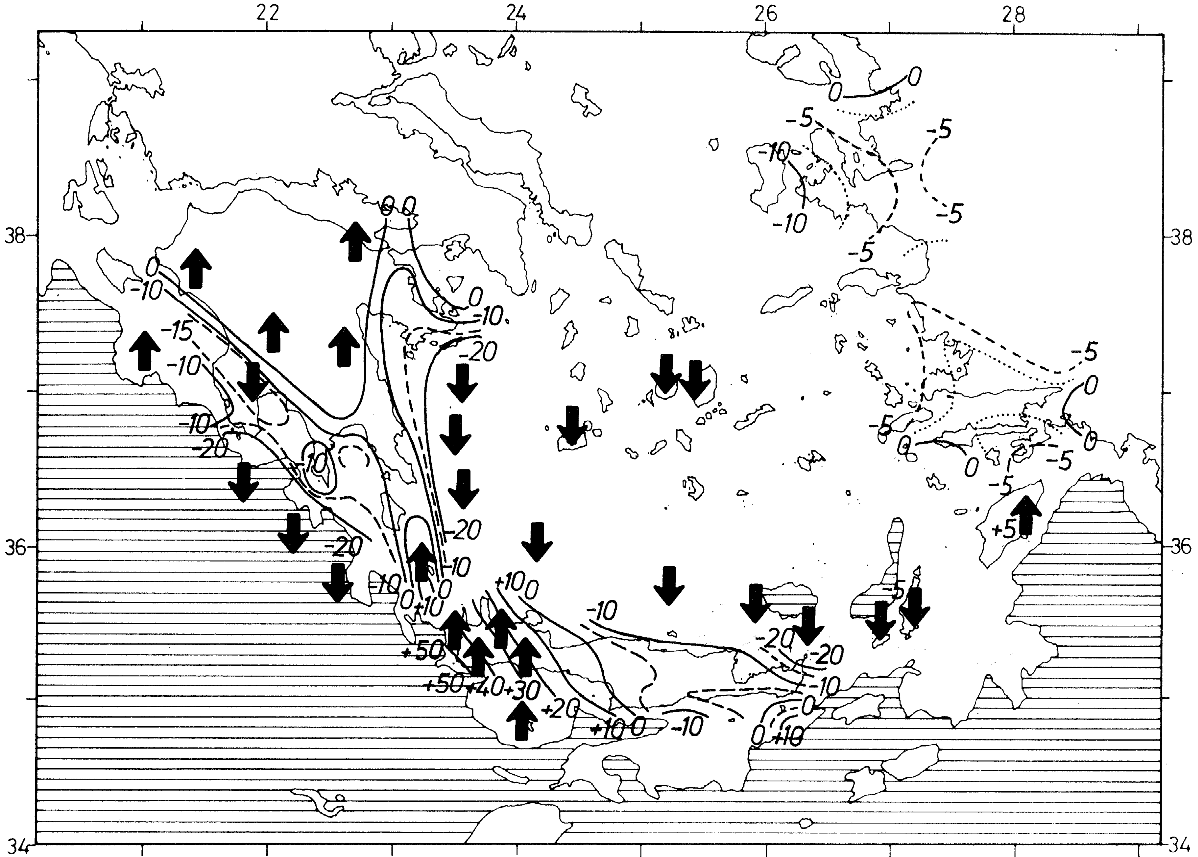


FIGURE 10. Averages rates of uplift (+) or subsidence (−) for the Recent period (less than 5000 years). Most data and iso-rate curves published by Flemming (1978), here in centimetres per century. Additional qualitative data from E. Barrier (Kassos, Karpathos), J. C. Vilminot (Milos) and J. Angelier (Paros, Naxos). Black arrows indicate tendencies to uplift or subsidence.

It is on this basis that figure 8 has been derived. The average rates of uplift or subsidence are not isostatically corrected and include the effect of erosion and sedimentation. These rates are of the same order of magnitude, about 2–3 cm/century. A comparison of figure 8 with figure 7 shows that the zone of uplift coincides with the present zone of thickest crust of about 70 km width.

The above estimates only give rough evaluations of the average rates of uplift or subsidence over 10–13 Ma. We can fortunately make a more precise evaluation of the vertical movements

Downloaded from rsta.royalsocietypublishing.org

during the last 0.2 Ma by a study of the uplift of shorelines that have been independently dated by radiometric methods (^{231}Pa/^{235}U and ^{230}Th/^{234}U) (Pierre *et al.* 1979). Although our knowledge of the eustatic sea level is still imprecise, we can obtain reasonable estimates from the eustatic variations curve (see, for example, Bloom *et al.* 1974). Figure 9 summarizes the results obtained by Angelier (1979) for the last 0.2–0.1 Ma. The similarity with figure 8 is striking, both in distribution and rates. It should be pointed out, however, that there are clear indications of Pliocene transgression in Rhodes and some evidence of transgression in Karpathos. Thus, at times, parts of the arc may have temporarily subsided. This has also been so for eastern Crete.

That there are shorter-term variations in the rates of vertical motion is demonstrated by figure 10, which summarizes the results for the last 5000 years based in great part on the work of Flemming (1978). The measured rates of uplift or subsidence are an order of magnitude larger than the previous rates (up to 50 cm/century in western Crete) and the distribution is quite different. The whole eastern branch of the arc is subsiding, whereas the western branch is being uplifted. There are no reasons to believe that the pattern of uplift suddenly changed 5000 years ago. It is more reasonable to conclude that the vertical motions are quite irregular on a scale of 5000 years and only average out over a few tens of thousands of years, that is over a period equal to two or three times the decay time constant of the asthenosphere (see, for example, Cathles 1975).

Dynamics of the subduction–expansion process

Figure 11 very schematically shows the present dynamic situation in the eastern Mediterranean area. With Africa as a frame of reference, Europe is moving roughly due south at velocity L_1 (1 cm/a) (Chase 1978). But the Hellenic arc is moving to the southwest at velocity L_2, which must be greater than Europe's velocity; we can estimate L_2 at 4 cm/a if the motion has been constant. We can thus, for the discussion of the dynamics, assume that $L = L_2$ and that L_1 is negligible. Everything happens as if Africa were fixed to Europe. The underlying asthenosphere can also be considered as fixed to Africa and Europe. In this system, the only possible motion for the sinking lithosphere is a relative migration to the south, which is caused by the component F_2'' of the negative buoyancy force. The retreat of the subduction zone to the south is helped by force F_1 due to the hydrostatic head caused by the elevation of Aegea with respect to the Mediterranean sea floor. As a result, the subduction zone is moving relatively to the south as Aegea is spreading and its crust is progressively thinned.

This process should apply to all land-locked oceanic basins in the last stages of collision between continents (Le Pichon 1979). In the last stage of closing, the sinking lithosphere should progressively become vertical and then disappear. Although force F_1 continuously decreases as stretching proceeds, force F_2'' increases and the extension of the fractured and thin continental lithosphere becomes easier. Thus this process may lead to the complete disappearance of the earlier oceanic basin and the formation of a thinned crust continental basin (like the Pannonian basin) or even a new oceanic basin (like the Tyrrhenian basin).

An interesting point concerns the motion of the asthenosphere. If it is assumed to be immobile with respect to the Africa–Europe frame of reference, the migration of the subduction zone to the south implies a flow of asthenospheric material from south to north. The easiest path for this flow is probably laterally, on each flank of this relatively short sinking slab. This flow may then explain the amphitheatre shape of the Aegean and Tyrrhenian slabs.

Finally, figure 12 summarizes the geological consequences of the Hellenic subduction. The

Downloaded from rsta.royalsocietypublishing.org

flexure of the Mediterranean lithosphere is progressively migrating to the south with respect to Europe and exerts a suction on the Aegean lithosphere which, under the additional force due to its hydrostatic head, spreads apart and consequently subsides. But the Mediterranean lithosphere is covered by a great thickness of sediments: a few hundred metres of Plio-Quaternary marls, up to 1 km of Messinian evaporites and 5–8 km of pre-Messinian sediments. The evaporites do not seem to be subducted but apparently accumulate in the trench area forming an evaporite basin (Le Pichon *et al.* 1980). But the underlying sediments disappear below the arc. We have seen that the uplift of the external arc requires the emplacement of about 10 km of new crustal root over an average width of 50–100 km. It seems reasonable to assume that the total volume of about 1000 km³ per km of arc of new crustal root comes from the sediments of the subducted Mediterranean lithosphere. As the average length of subducted lithosphere is about 300 km, this is equivalent to a thickness of about 4 km of sediments being continuously scraped off the plate (taking into account the probable compaction). It is thus of the right order of magnitude to account for the sediments of the Mediterranean crust. We see no other hypothesis that could account for the simultaneous large and continuous uplift and large extension over a band that is less wide than the lithosphere is thick, and in the absence of any large associated gravimetric anomaly.

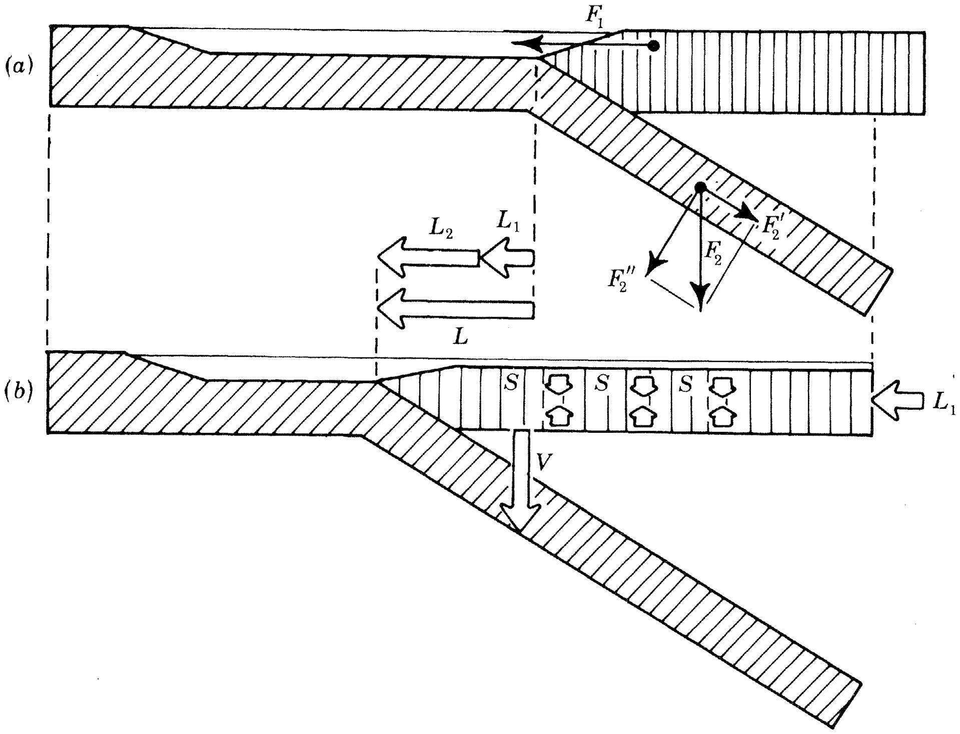


FIGURE 11. Schematic section of the Hellenic subduction zone with relative motions and gravitational forces.
(*a*) F_1, outward component of the gravitational force acting on the Aegean region, owing to its hydrostatic head with respect to adjacent Mediterranean sea crust. F_2, negative buoyancy force acting on the sinking slab, with components F_2' and F_2'', parallel and perpendicular to the slab, respectively.
(*b*) L_1, displacement of Eurasia relative to Africa; L_2, displacement of the Hellenic arc relative to Eurasia, due to the Aegean expansion (L_2 is approximately 3 or 4 times larger than L_1); L, total displacement of the Hellenic arc relative to Africa; S, subsidence of the Aegean region due to lithospheric thinning (double arrows), and subsequent transgressions; V, vertical motion of the sinking slab.

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

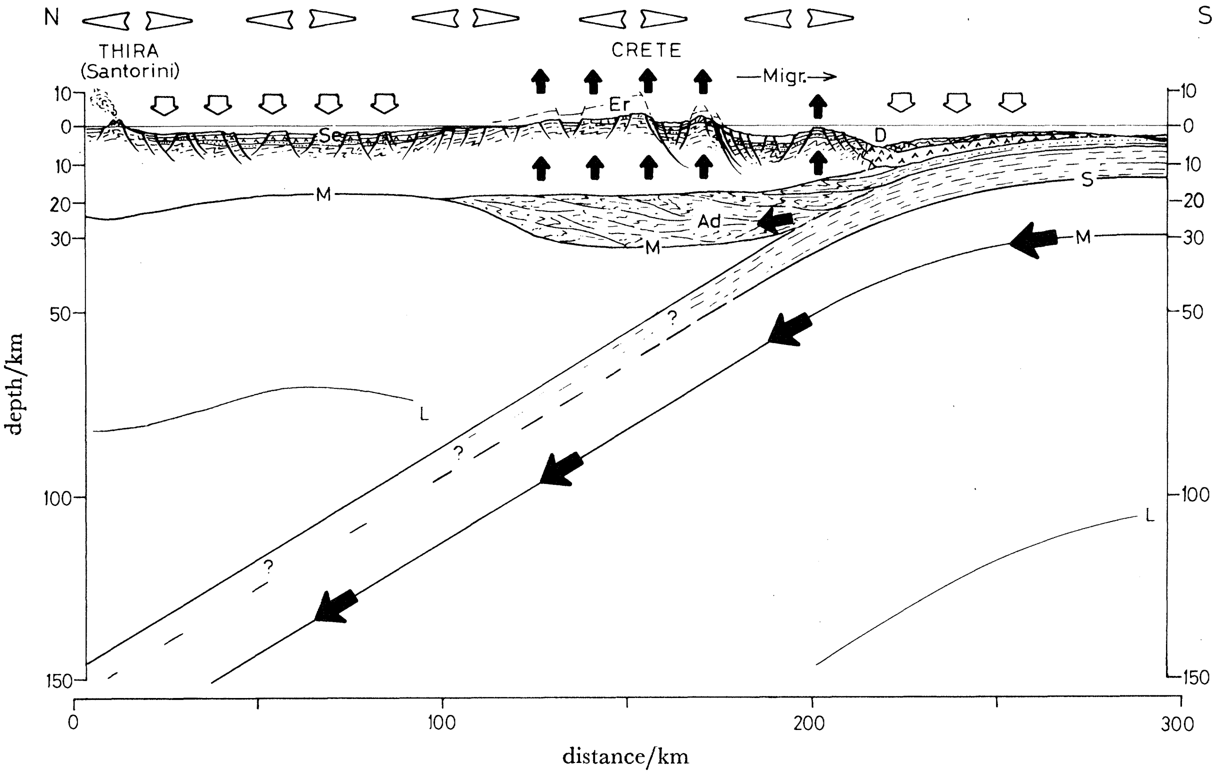


Figure 12. General schematic section of the Hellenic subduction zone and Southern Aegean region. Sediments (Se), including Plio-Quaternary (white), Messinian evaporites (inverted v pattern) and Middle–Upper Miocene (dotted), are schematically distinguished from the pre-Neogene basement in the Southern Aegean region. The same sediments are shown in the Mediterranean basin, overlying thick Mesozoic-Cainozoic sedimentary layers (base at S). D, Diapiric zone in front of the Hellenic arc, with tectonic accumulation of Messinian evaporites; Ad, tectonically added material at the base of the crust under the outer arc; Er, eroded part of the uplifted arc; M, Mohorovičic discontinuity; L, base of the lithosphere. Thicknesses of superficial layers (sediments, erosion) are exaggerated. Large black arrows indicate the motion of the sinking slab relative to the arc, and the tectonic addition of sediments under the arc. Small black arrows indicate the uplift of the arc; Migr., migration of uplift southward. Large white arrows indicate subsidence and double white arrows show the horizontal expansion of the Aegean region.

This paper was supported by C.N.E.X.O. and A.T.P. Ipod within the framework of the Heat (Hellenic Arc and Trench) programme.

References (Le Pichon & Angelier)

Angelier, J. 1979 *Néotectonique de l'arc égéen* (*Société géologique du Nord, publication* no. 3). (418 pages.)
Angelier, J. 1981 *Annls Géophys.* (Submitted.)
Aubouin, J. & Dercourt, J. 1965 *Bull. Soc. géol. Fr.* (7) **7**, 787–821.
Barrier, E. 1979 Thèse, Université Paris VI.
Bergougnan, H. 1975 *Bull. Soc. géol. Fr.* (7) **18**, 1045–1057.
Bloom, A. L., Broecker, W. S., Chappell, J. M. A., Matthews, R. K. & Mesolella, K. J. 1974 *Quat. Res.* **4**, 185–205.
Bonneau, M. 1976 *Bull. Soc. géol. Fr.* (7) **18**, 351–353.
Bonneau, M., Angelier, J. & Epting, M. 1977 *Bull. Soc. géol. Fr.* (7) **19**, 87–101.
Cathles, L. M. 1975 *The viscosity of the Earth's mantle.* (388 pages.) Princeton University Press.
Chase, C. G. 1978 *Earth planet. Sci. Lett.* **37**, 355–368.
Creutzburg, N. *et al.* 1977 *Geological map of Greece, Crete Island,* 1:200000. Athens: Institute of Geological and Mining Research.

Downloaded from rsta.royalsocietypublishing.org

Dewey, J. F. & Sengör, C. A. M. 1979 *Bull. geol. Soc. Am.* **90**, 84–92.
Drooger, C. W. & Meulenkamp, J. E. 1973 *Bull. Soc. géol. Grèce* (10) **1**, 193–200.
Flemming, N. C. 1978 *Phil. Trans. R. Soc. Lond.* A **289**, 405–458.
Kelletat, D., Kowalczyk, G., Schröder, B. & Winter, K. P. 1976 *Z. dt. geol. Ges.* **127**, 447–465.
Le Pichon, X. 1979 *C. hebd. Séanc. Acad. Sci., Paris* D **288**, 1083–1086.
Le Pichon, X. & Angelier, J. 1979 *Tectonophysics* **60**, 1–42.
Le Pichon, X. & Sibuet, J. C. 1980 *J. geophys. Res.* (In the press.)
Le Pichon, X., Angelier, J., Boulin, J., Bureau, D., Cadet, J. P., Dercourt, J., Glaçon, G., Got, H., Karig, D., Lyberis, N., Mascle, J., Ricou, L. E. & Thiébault, F. 1979 *C. r. hebd. Séanc. Acad. Sci., Paris* D **289**, 1225–1228.
Le Pichon, X., Angelier, J. *et al.* 1980 *C. r. hebd. Séanc. Acad. Sci., Paris* D **290**, 5–8.
Lyberis, N. & Bizon, G. 1980 *Mar. Geol.* (In the press.)
Makris, J. 1977 *Hamburger Geophysikalische Einzelschriften*, vol. **34**. (124 pages.)
McKenzie, D. P. 1978 *Geophys. J.R. astr. Soc.* **55**, 217–254.
Pierre, G., Hoang, C. T., Angelier, J., Barrier, E., Delibrias, G. & Lalou, C. 1979 In *Abstr. comm. 7e réun. ann. Sciences de la Terre*, Lyon, p. 369.
Stride, A. H., Belderson, R. H. & Kenyon, N. H. 1977 *Phil. Trans. R. Soc. Lond.* A **284**, 255–285.

Discussion

M. F. Osmaston (*The White Cottage, Sendmarsh, Ripley, Surrey, U.K.*). The authors' arguments that the Cretan Sea basin has formed by crustal stretching while in a back-arc setting have not, I think, paid sufficient regard to the alternative possibility that the basin was formed by a limited amount of ocean floor spreading at an earlier time. An unpublished analysis of the region that I did about 6 years ago led me to infer that the basin had probably been formed by (almost due) southward and slightly clockwise motion of Crete relative to the Peloponnese, at some time between the mid-Eocene(?) completion of primary nappe emplacement on Crete and the onset of Hellenic arc subduction. The motion appeared to correlate with the rupturing responsible for the present Gulf of Corinth. I favour an Oligocene (probably Upper, but pre-Aquitanian) date for the motion. That would correlate with an Oligocene phase in the Red Sea and with the rotation of Corsica and Sardinia, which probably required an increase in the distance between Europe and Africa. Later southward minor sliding on Crete could have been caused by the consequent epeirogenic tilting, which is still being reversed by the post-Miocene subduction activity.

L. Stegena (*Department of Cartography, Lorand Eötvös University, Budapest, Hungary*). It appears to me that the presented horizontal deformation network for the area under consideration suggests only little or no extension for the central Aegean region, because here NW extension is more or less compensated for by E–W compression.

X. Le Pichon. The extension obtained is about 1.2 for the northern Aegean region (see figure 5).