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TECTONIC STRESSES ON THE MAINLAND OF GREECE: IN-SITU MEASUREMENTS BY OVERCORING

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ABSTRACT

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Direct in-situ measurements of the horizontal stresses in continental Greece indicate a predominantly N–S extensive stress. Considerable scatter of the azimuth of the axis of extension is found in Thrace in contrast to a more homogeneous pattern in Macedonia and Peloponnesus. These results are obtained with an overcoring technique in boreholes of a few meters. They can be compared with neotectonic and seismic data to evaluate the present deformation process in this basin.

INTRODUCTION

In recent years, in-situ stress measurements have been performed to determine the principal axes of regional stress fields. A successful illustration is given by the homogeneous N-NW–S-SE compression found in the perialpine basins and grabens (Greiner and Lohr, 1980; Froidevaux et al., 1980). There, good use has been made of two different techniques which are relatively simple and inexpensive. The one is based on overcoring around a biaxial strain gauge in a shallow borehole, and the other in making saw-cuts in the surface rock and applying a flat-jack to balance the tectonic stress. Most of these measurements were performed in limestones or marbles. This choice may be essential to avoid the superposition of past stresses to the present tectonic field. Indeed, we believe that dissolution by water can quickly relax any locked-in stresses in a carbonate, so that only the present-day stress is operating.

Here, we have extended these methods to a region of great tectonic activity: the Aegean domain. The regional framework includes the convergence along the Hel-

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lenic trench, the continent–continent collision along the Ionian border and the westward advance of the Anatolian microplate (McKenzie, 1972, 1978). The dominant phenomenon is extension, which led to crustal thinning (Makris, 1977) and the formation of the Aegean basin. The analysis of the focal mechanisms of earthquakes (Soufleris et al., 1981) and of stress sensitive geological deformation (Mercier et al., 1976; Angelier, 1979; Mercier, 1981) gives a great deal of information about the prevailing stress field. But all methods, including the one described in this paper, have specific advantages and shortcomings so that it is worthwhile to combine them when possible. In particular, in some regions where no neo-tectonic data are available our method may turn out to supply some results.

THE EXPERIMENTAL PROCEDURE

Twenty sites have been selected on the mainland of Greece in order to achieve a regional coverage. The starting idea was to define pairs of sites less than fifty kilometers apart. They were chosen in limestone or marble massifs, possibly of kilometric thickness, of good mechanical quality, although the presence of fractures cannot be avoided, and away from marked topographic changes. Sixteen localities yielded results of acceptable quality on a purely technical basis. Four were dismissed because the rock turned out to be karstic or densely fractured. Several geological provinces, in particular the Pindos, had to be left out because of the topography and of the predominance of flysch or igneous rocks.

The overcoring technique using strain gauges, glued on the bottom of a shallow borehole, is the most convenient for the type of geological setting met in Greece. Yet, in one quarry (Farsala, site 4), the floor was sufficiently fresh for the flat-jack technique to be brought into play. Elsewhere, a vertical hole, with diameter 76 mm, was drilled down to four to six meters, presumably well beyond the superficial layer altered by weathering. About every fifty centimeters, a biaxial cell (CSIR system) is fixed on the polished flat bottom (Leeman, 1969). This cell is comprised of four strain gauges, oriented 45° apart. Three gauges are sufficient to characterize the deformation in the horizontal plane, after overcoring. The fourth gauge, however, is for internal consistency. This yields the principal values $\epsilon_{H\max}$ and $\epsilon_{H\min}$ of the deformation and the azimuth θ of one principal axis for each depth.

The principal axes of the measured strain coincide with the principal axes of the stresses in the rock mass if the rock has isotropic elastic properties in the horizontal plane. This can be checked promptly by inserting the extracted core with attached cell in an annular pressure chamber (Fig. 1). The response of each of the four gauges can be recorded. Figure 2 depicts the measured strain versus radial pressure for a typical core. For clarity, the four responses have been shifted vertically. The lines drawn through the data points are parallel within 3%: thus the departure from isotropy is negligible.

The conversion of the strain data into horizontal principal stresses: $\sigma_{H\max}$ and

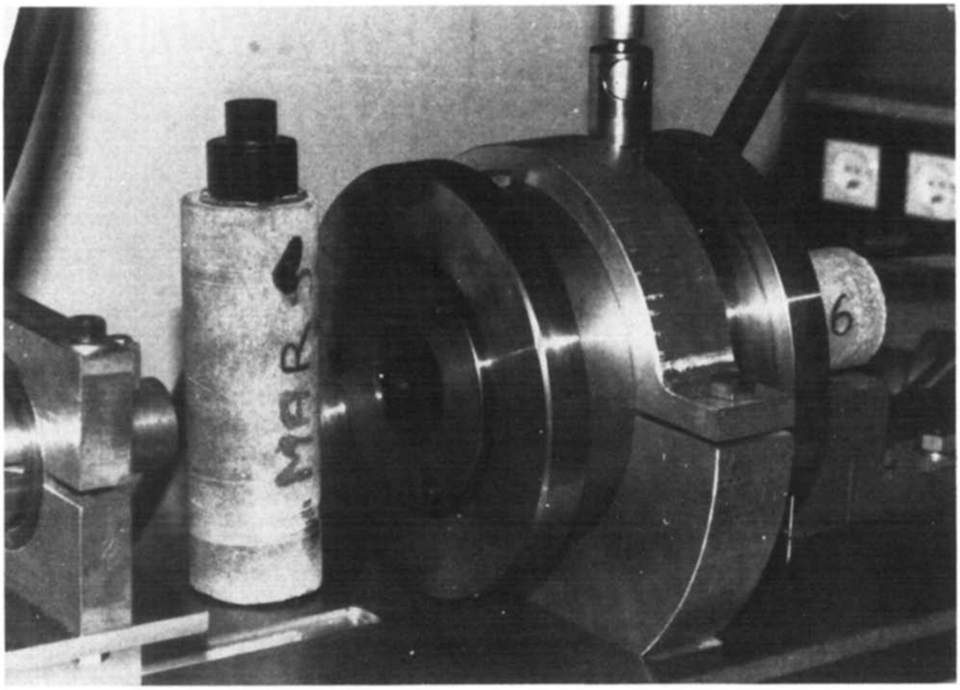
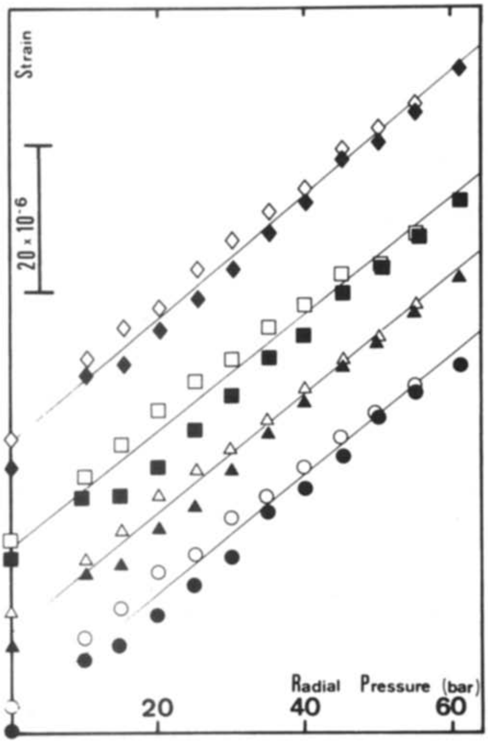


Fig. 1. Annular pressure chamber with core (marked 6) inside and electrical connector of strain gauge cell visible in the center. Another marble core (marked *MAR*) is also shown on the picture in order to visualize the whole cell. The core diameter is 54 mm.

$\sigma_{H\min}$, requires the knowledge of the elastic moduli. To achieve this, small cylindrical samples were drilled out along the radial dimension of extracted cores. Figure 3 shows such a probe with attached strain gauges, 90° apart. The applied uniaxial stress generates a longitudinal strain ϵ_L, and the corresponding transversal strain ϵ_T. They lead to the determination of Young's modulus E, and Poisson's ratio ν. Figures 4 and 5 show two sets of results, one for marble, the other for limestone. Each figure pictures the measured data for two different probes. The best straight line, obtained by linear regression, is drawn through each set of points. The slope of the right-hand straight line is equal to E^{-1} and the slope of the left-hand straight line to ν^{-1}. For the two probes of a given site, the ν values do not differ by more than a few per cent. On the other hand, as expected, the E values scatter more strongly, up to ±20%. In fact, about ten probes were tested, on each site corresponding to the above pictures. The result shown are those yielding the extreme values of E. All other sites were studied in this way, not always so extensively. The elastic moduli being determined, the principal stresses at the borehole bottom can readily be computed. The concentration of stresses at the borehole bottom further requires a



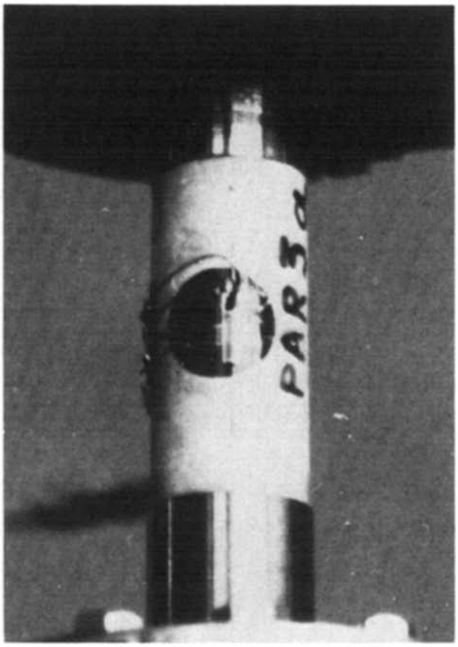


Fig. 2. Measured strain of the 4 gauges of a given cell versus radial pressure applied in the annular pressure chamber. The 4 data sets have been displaced vertically to avoid confusion. Black symbols refer to increasing pressure, white symbols to decreasing pressure. The straight lines are simply obtained by linear regression through all the points.

Fig. 3. Small rock probe with double strain gauge mounted in uniaxial apparatus. Diameter 20 mm.

correction by a concentration factor chosen to be equal to 1.25 ± 0.06 (Crouch, 1969).

FIELDWORK RESULTS FOR 1979 AND 1980

The number of successful straingauge cells on a given site, i.e. in a given hole, varies from 2 to 10. It is too small for a statistical analyzis. Yet mean values of $\epsilon_{H\max}$, $\epsilon_{H\min}$ and $\theta_{\min}$ have been computed. They are found in Table I which first lists the numbers, name, geographical coordinates of the sixteen sites. Besides each site is characterized by its rock type (L = limestone, M = marble, M.C.L. = micro crystalline limestone), by a quality factor, A (excellent), B (good), or C (satisfactory) taking account of the mechanical quality of the rock and of the local topographical conditions, and by the number of successful cells. The azimuth $\theta_{\min}$ defines the axis of $\epsilon_{H\min}$ as well as of $\sigma_{\min}$. As no statistical deviation can be computed, $\Delta\theta_{\min}$ simply

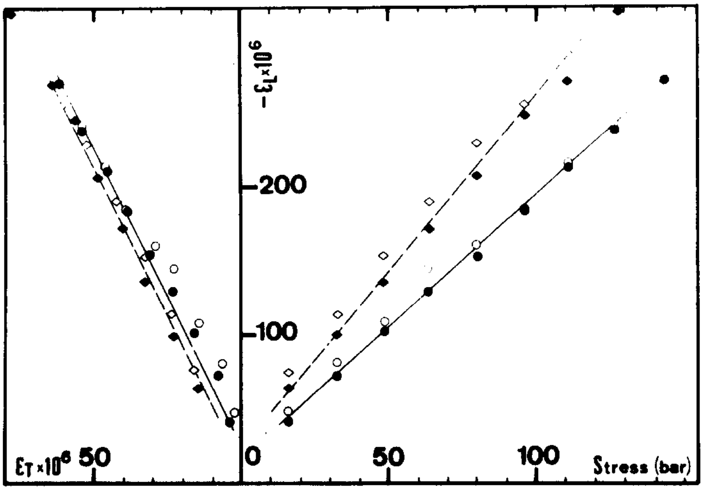


Fig. 4. Deformation of two different marble probes in the uniaxial apparatus. The probes are both from site 5 listed in the table below. Black, resp. white, symbols are again for increasing, resp. decreasing, stress. Best-fit straight lines are drawn through each data set. The longitudinal strain ϵ_L versus stress yields the Young's modulus, whereas ϵ_L versus transversal strain ϵ_T yields Poisson's ratio.

indicates the overall spread of the measured values of θ_{min}. Next, the table lists the mean measured values of the elastic moduli E and ν. Finally, the derived principal horizontal tectonic stresses are given by round numbers with an accuracy of 5 bar.

The measured principal stresses for each site are also pictured in Fig. 6. The broad double arrow depicts $\sigma_{H_{min}}$ along the azimuth θ_{min}. It is found to be extensive in all sites. The straight double arrow representing $\sigma_{H_{max}}$ is either compressive or exten-

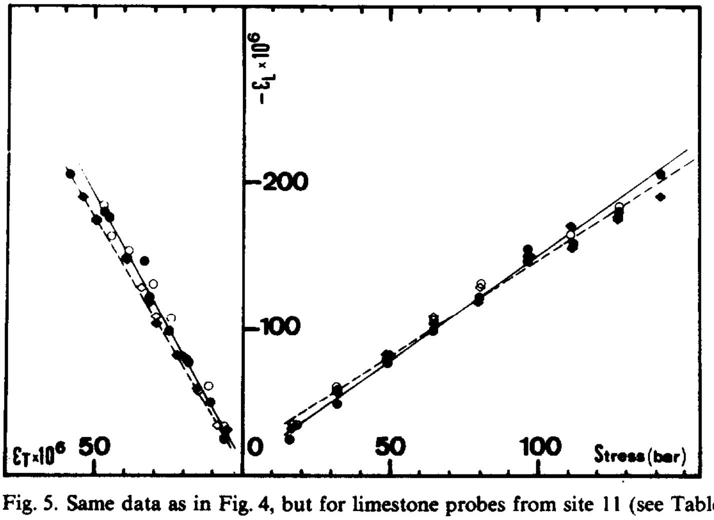


Fig. 5. Same data as in Fig. 4, but for limestone probes from site 11 (see Table I).

TABLE I

No.	Sites	Latitude N Longitude E	Rock type	Quality factor	Number of cells	$\epsilon_{H\max} \times 10^{+6}$
1	Vergoritis	40°45′ 21°50′	M	B	8	+10
2	Vaptistis	41°00′ 22°45′	MCL	A	4	+30
3	Messeion	40°45′ 22°50′	M	A	4	+40
4	Farsala	39°20′ 22°25′	MCL	B	–	Flat
5	Marathon	38°10′ 24°00′	M	A	8	0
6	Makri	40°50′ 25°45′	M	A	2	+10
7	Marounia	40°50′ 25°30′	M	B	6	+5
8	Paradisos	41°05′ 24°45′	M	B	7	+10
9	Chalkero	40°55′ 24°25′	M	A	10	+10
10	Vateron	40°15′ 21°25′	L	A	6	−10
11	Karitsa	39°45′ 20°40′	L	A	10	+10
12	Kontsika	39°40′ 20°45′	L	A	7	0
13	Preveza	39°40′ 20°45′	L	C	6	+20
14	Kapsas	37°35′ 22°20′	M	C	7	−5
15	Almyro	37°00′ 22°10′	M	B	5	+75
16	Plitra	36°45′ 22°50′	L	C	5	+150

sive. The scale length in bars is the same for the 2 types of arrows, but the angular dispersion $\Delta\theta_{min}$ to be found in the Table I, is not drawn in this Figure.

In the region northwest and north of Thessaloniki a conspicuous N–S extensive stress reveals a good regional homogeneity. Site 1 is an outcrop of compact marble. The long extracted cores exhibit some weakness zones made of thin filled-in cracks. Sites 2 and 3 are located in ancient quarries; the rock is compact with very limited weathering. Further east, the minimum stress is again extensional and $\sigma_{H\max}$ is close

$\epsilon_{H\min} \times 10^{+6}$	$\theta_{\min}$	$\Delta\theta_{\min}$	$E \times 10^{-5}$ (bar)	ν	$\sigma_{H\max}$ (bar)	$\sigma_{H\min}$ (bar)
−45	N-170° E	+15° −20°	6.0	0.20	0	−20
−30	185°	+10° −15°	7.0	0.30	+20	−20
−75	165°	+5° −10°	5.5	0.26	+10	−30
Jack	200°	+40° −30°	–	–	+10	−1
−45	135°	+35° −25°	5.5	0.25	−5	−20
−35	255°	+1 −1	8.5	0.25	0	−20
−25	165°	+25° −25°	10	0.30	0	−25
−35	215°	+35° −15°	7.5	0.31	0	−20
−35	90°	+10° −15°	7.0	0.25	0	−20
−30	95°	+10° −15°	9.0	0.33	−15	−25
−35	110°	+20° −15°	7.0	0.28	0	−20
−45	110°	+15° −15°	5.0	0.29	−5	−20
−40	160°	+40° −10°	5.0	0.18	+5	−15
−50	190°	+35° −10°	6.0	0.25	−5	−25
−40	190°	+10° −25°	5.5	0.25	+30	−10
−50	185°	+15° −5°	2.5 Est	0.30 Est	+30	−20

to zero. However, the azimuth is strongly scattered, perhaps because of more important local variations in the crustal mechanical properties. Sites 6 and 9 were set up in working quarries where high quality marble is extracted. A test, 2 km away from site 9, in a conglomerate has also given the same stress orientation. Site 8, in an old quarry on a hill side, offers a more fractured marble. Site 7 is an outcrop of strongly metamorphized marble not far from a mountain made of dioritic intrusion. Site 10 and sites 11 and 12 are separated by the Pindos. Yet they yield similar stress

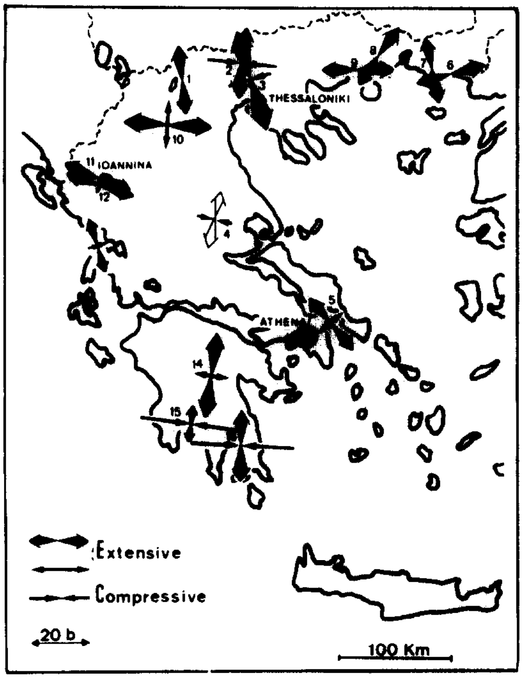


Fig. 6. Map of Greece with sites 1 to 16 where in-situ measurements have been successfully performed. The thick double arrows depict the orientation and magnitude (see scale in bars) of the minimum principal horizontal stress $\sigma_{H\min}$. The thinner double arrows picture the maximum principal horizontal stress $\sigma_{H\max}$.

orientations. The limestone outcropping on site 10 is fractured in the first two meters but becomes compact beyond that depth. Sites 11 and 12 are on a plateau, at an altitude of 800 m, and the thickness of the horizontal limestone beds does not exceed 40 cm. The fine-grained sublithographic limestone of site 13 presents a high density of cracks filled with calcite. In the south, the tensional axis points again regularly in the N–S direction whereas $\sigma_{H\max}$ is strongly compressible for the southernmost sites. The marble of sites 14 and 15 is fractured in the first meters from the surface of the outcrop. Site 16 is a conglomerate with so little mechanical strength that no laboratory test was achieved. Site 5 may be included in this regional group. It consists of an outcrop of good quality marble. Finally, site 4 is an operational quarry with a horizontal floor sufficiently extended to perform measurements with the flat-jack method.

DISCUSSION AND CONCLUSION

The most striking characteristic of our in-situ stress measurements is that they yield an overall extensional pattern in the whole Aegean region. Technically one could have feared that possible fractures in the surface rocks might prevent the transmission of tensile stresses. The results testify to the good mechanical quality of the test sites, i.e. to the overall absence of decoupling joints. The prevailing north–south orientation of $\sigma_{H\min}$ confirms the regional tectonic regime in the Aegean basin. In particular, the homogeneous stress field near Thessaloniki is in full agreement with a north–south orientation of σ_3 derived from neotectonic studies for the Quaternary (Mercier, 1979) and from the mechanisms of the 1978 earthquakes (Soufleris et al., 1981). Of course, surface stress measurements cannot specify whether $\sigma_{H\min}$ corresponds to σ_3 or σ_2 and similarly whether $\sigma_{H\max}$ is to be identified with σ_1 or σ_2. The comparison with geological or seismological observations can resolve the ambiguity. A further example is provided in the region of Athens (sites 5 and 14): the recent Gulf of Korinthos earthquake having activated east–west-striking normal faults. It is again legitimate to identify the orientation of $\sigma_{H\min}$ with that of σ_3 at depth. This also implies that $\sigma_{H\max}$ gives the orientation of σ_2, in this region. The question is whether this conclusion also applies to the southernmost sites 15 and 16. Here the neotectonic analysis yields inconsistent results as far as the orientation of the principal axes are concerned (Le Pichon and Angelier, 1979; Mercier, 1981), but tends to exclude a vertical σ_3. We thus interpret our results in the southern mainland as indicative of a fairly homogeneous N–S extensional tectonic field. The presence of a dominant E–W extensional stress near the Pindos Chain (sites 10, 11, 12), seems to be a true regional effect even if no data from other sources are available for comparison. The thick crustal root of the N–S-trending mountain range may be at the origin of this "anomalous" stress component (Artyushkov, 1973; Fleitout and Froidevaux, 1982).

In conclusion, the overcoring technique has proved its efficiency in investigating regional tectonic stresses. It has become an useful source of additional information where other approaches can be brought into play. In several situations, for example in seismic quiet zones, direct in-situ measurements may remain the only access to the present tectonic stress.

REFERENCES

Angelier, J., 1979. Néotectonique de l'arc Egén. Soc. Géol. du Nord 3, 417, Lille.

Artyushkov, E.V., 1973. Stresses in the lithosphere caused by crustal thickness inhomogeneities. J. Geophys. Res., 78: 7675–7708.

Crouch, S.L., 1969. A note on the stress concentrations at the bottom of a flat-ended borehole. J. S. Afr. Inst. Min. Metall., Dec.: 100–102.

Fleitout, L. and Froidevaux, C., 1982. Tectonics and topography for a lithosphere containing density heterogeneities. Tectonics, Feb. No. 1.

Froidevaux, C., Paquin, C., Souriau, M., 1980. Tectonic stresses in France: in situ measurements with a flat jack. J. Geophys. Res., 85: 6342–6346.

Greiner, G. and Lohr, J., 1980. Tectonic stresses in the Northern Foreland of the alpine system, measurements and interpretation. Rock Mechanics Suppl., 9: 5–15.

Leeman, E.R., 1969. The "doorstopper" and triaxial rock stress measuring instruments developped by the CSIR. J. S. Afr. Inst. Min. Metall., 69: 305–339.

Le Pichon, X. and Angelier, J., 1979. The Hellenic Arc and trench system: a key to the neotectonic evolution of the Eastern Mediterranean area. Tectonophysics, 60: 1–42.

McKenzie, D., 1972. Active tectonics of the Mediterranean region. Geophys. J. R. Astron. Soc., 30: 109–185.

McKenzie, D., 1978. Active tectonics of the Alpine Himalayan belt: the Aegean Sea and surrounding regions. Geophys. J. R. Astron. Soc., 55: 217–254.

Makris, J., 1977. Geophysical investigations of the Hellenides. Hamburger Geophys. Einzelschr. A, 34, G.M.L. Wittemborg.

Mercier, J.L., 1979. The Thessaloniki earthquake. Nature, 278: 45–48.

Mercier, J.L., 1981. Extensional–compressional tectonics associated with the Aegean Arc. Comparison with the Andean Cordillera of South Peru–North Bolivia. Philos. Trans. R. Soc. London, Ser. A, in press.

Mercier, J.L., Carey, E., Philip, H. and Sorel, D., 1976. La néotectonique plioquaternaire de l'Arc Egéen externe et de la mer Egée et ses relations avec la séismicité. Bull. Soc. Géol. Fr., (7), XVIII (2): 355–372.

Soufleris, C., Jackson, J.A., King, G.P., Papazachos, B.C., Scholz, C.H. and Spencer, C.P., 1981. The Thessaloniki 1978 earthquakes: a delayed multiple event sequence. Geophys. J.R. Astron. Soc., in prep.