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NORMAL FAULTS ASSOCIATED WITH VOLCANIC ACTIVITY AND DEEP RUPTURE ZONES IN THE SOUTHERN AEGEAN VOLCANIC ARC

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ABSTRACT

Volcanic centers (volcanoes, fumarolae or solfatara fields), epicenters of strong shallow earthquakes (with focal depths up to 20Km) and epicenters of intermediate depth strong earthquakes (with focal depths between 120Km and 160Km) in the southern Aegean volcanic arc are spatially grouped in five well defined linear clusters trending in an about N59oE direction. This delineations of the shallow earthquakes and volcanic activity is attributed to five corresponding normal faults which are named, here, according to the five corresponding volcanic centers (Sousaki, Methana, Milos, Santorini, Nisyros). This is supported by similar trending of geomorphological features (grabens, islands) and of geophysical features (Bouguer anomalies) as well as by other seismological data (fault plane solutions, tsunamogenesis) and geological information on the caldera of Santorini. The higher volcanic activity in the eastern volcanic centers (Santorini, Nysiros) in respect to this activity in the western volcanic centers (Sousaki, Methana, Milos) is attributed to the higher rate of extensional crustal deformation in the eastern part of the volcanic arc (26mm/yr) in respect to the western part of this arc (2mm/yr). The delineation of the epicenters of the intermediate depth earthquakes along the same five lines indicate the existence of five corresponding rupture zones in the lower (leading) part of the descending lithospheric slab (at depths 120Km-180Km). These deep zones are probably the sources of hot material which is ascending vertically upwards and is intruded in the crust along its fracture zones. The oriention of these zones explains well the focusing of the macroseismic results of these deep shocks at narrow regions of the sedimentary arc (Peloponnesus, Crete, etc).

INTRODUCTION

The Hellenic arc is the dominant tectonic feature of the southern Aegean area. It separates the Aegean Sea from the eastern Mediterranean and has the main properties of a typical island arc (Papazachos and Comninakis, 1971). It consists of an outer (southern) "sedimentary arc", which is a link between the Dinaric Alps and the Turkish Taurids, and the inner (northern) "volcanic

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arc" with Quaternary volcanoes. Between the sedimentary and the volcanic arc the "Cretan trough" with maximum water thickness of about 2Km occurs. In the convex side of the arc (eastern Mediterranean) there is a system of troughs and trenches (Ionian, Pliny, Stravo) which is called Hellenic Trench with maximum water depth of about 5Km.

A well defined very active Benioff zone of intermediate depth earthquakes, dipping form the Mediterranean to the Aegean and associated with this arc, was first discovered by Papazachos and Comninakis (1969). The focal depths of the earthquakes in this zone vary between about 40Km and 80Km under the sedimentary arc (central Peloponnesus-Kythera-Crete-Rhodos), between 80Km and 120Km under the Cretan trough and between 120Km and 180Km under the volcanic arc. Subduction of the eastern Mediterranean oceanic lithosphere, which is the front part of the African lithosperic plate in this area, under the Aegean continental lithosphere, which is the front part of the Eurasian lithospheric plate in this area, is assumed to interprete this Benioff zone (Papazachos and Comninakis, 1971) and other tectonic and geophysical properties of this area. Such properties of interest for the present paper are the compessional stress field and low heat flow in the convex (external) part of the arc (eastern Mediterranean), and the extensional stress field and high heat flow in the concave (inner) part of the arc, that is, in the Aegean, (McKenzie, 1972; Jongsma, 1974).

Recent results (Papazachos, 1990; Papazachos et al., 1991) show that this Benioff zone can be separated in its shallower part (40-80Km) which dips at a mean angle of 23^{o} and in its deeper part (80-180Km) which dips at a mean angle of 38^{o}. Coupling occurs between the underthrusting Mediterranean and overthrusting Aegean lithospheres on the shallower part of this zone and this is the reason why very strong earthquakes occur in this part with magnitudes up to 8.0. On the contrary, the deeper (front) part of the dipping lithosphere is descending in the mantle, without any coupling with other lithospheres, and for this reason only earthquakes with magnitudes up to 7.0 occur in this part.

The volcanic arc is formed by volcanic islands (Aegina, Milos, Santorini, Misyros) and includes three Quaternary Volcanoes (Santorini, Nysiros, Methana) and solfatara or fumarole fields (Sousaki, Milos, Kos). Along the volcanic arc there is a thin (≈20Km) seismogenic layer of shallow earthquakes. Under this shallow seismogenic layer and at depths between about 20Km and 120Km an aseismic layer exist. Under this aseismic layer, that part (120Km-180Km) of the Benioff zone occurs which defines the top surface of the font part of the descending lithospheric slab. The non occurrence of strong earthquakes in the layer between the shallow and the deep seismogenic layers is attributed to the high temperature of the material in this layer. This is supported by the strong attenuation of short period seismic waves which travel through this layer (Molnar and Olive, 1969; Papazachos and Comninakis, 1971).

Much work has been done on the deep tectonics of the southern Aegean. In most of this work, information on volcanic and seismological properties is also included and interpeted by several models (McKenzie, 1970, 1978; Papazachos and

Papadopoulos, 1977; Le Pichon et al., 1979). Previous work on the relation between seismic and volcanic activity in this area is mainly concentrated on the time relation between the intermediate depth seismic activity in the southern Aegean and volcanic eruptions in Santorini (Blot, 1980; Papadopoulos, 1986).

The present paper deals with spatial distribution of the strong ($M_s \geq 6.0$) shallow earthquakes as well as of the strong ($M_s \geq 5.6$) intermediate depth earthquakes (h=120-180 Km) which have their epicenters in the volcanic arc, and with the comparison of these distribution with the distribution of volcanic activity along this arc. The variation of the level of the seismic and volcanic activity along this volcanic arc is also examined.

THE DATA

The data used in the present study are information on the spatial distribution and level of the volcanic activity, the spatial distribution and the magnitudes of the shallow earthquakes, the spatial distribution and magnitudes of the intermediate depth earthquakes which occur in the volcanic arc of the southern Aegean.

Table 1. Information on known shallow earthquakes with magnitudes $M_s \geq 6.0$ in the volcanic arc of the southern Aegean.

Date	$\varphi^o N$, $\lambda^o E$	M_s	C
480 BC	37.9,23.3	6.3	1
411 BC	36.8,27.4	7.0	5
46 AD	36.4,25.4	6.0	4
554 AD	36.8,27.4	7.0	5
1457 AD	37.3,23.5	6.0	2
18:08:1493	36.7,27.0	6.8	5
07:10:1650	36.5,25.4	6.8	4
18:05:1707	36.4,25.4	6.0	4
24:12:1733	37.1,24.8	6.4	3
20:07:1738	36.8,24.5	6.5	3
20:03:1837	37.4,23.6	6.2	2
31:01:1866	36.4,25.4	6.2	4
25:07:1873	37.7,23.2	6.0	1
25:10:1919	36.7,25.6	6.1	4
23:04:1933	36.8,27.3	6.6	5
09:07:1956	36.7,25.8	7.5	4
09:07:1956	36.6,25.7	6.9	4
05:12:1968	36.6,26.9	6.0	5

Data for the volcanic activity in the southern Aegean are mainly based on information given by Georgalas (1962). According to this information, there are three volcanic centers in the southern Aegean (Santorini, Nysiros, Methana). The most active of these centers is that of Santorini which erupted at least nine times during the last 600 years (1457, 1508, 1573, 1650, 1707, 1866, 1925, 1939, 1950). Some of these eruptions produced severe damage in Santorini. The volcanic eruptions in Nisyros are much weaker. At least five weak eruptions occurred in this island during the same time period (1422, 1830, 1871, 1873, 1888). There is only one known volcanic eruption in Methana which occurred in 250 B.C. In addition to the three volcanic centers, there are three centers of solftara or fumarolae fields in this volcanic arc (Sousaki, Milos, Kos). All these six centers of volcanic activity are shown in figure (1). They form five sources and are numbered (1,2,3,4,5) from west to east.

Data on the earthquakes of the present century are based on the catalogue of Comninakis and Papazachos (1986) for the period 1901-1985 and on the bulletins of the Seismological Institute of the National Observatory of Athens and of the Geophysical Laboratory of the University of Thessaloniki for the period 1986-1991. Data on historical earthquakes are based on information given in the book of Papazachos and Papazachou (1989).

Table 2. Date, epicenter coordinates, focal depths h(in Km) surfacewave magnitude, M_S, and cluster number, C, according to figure (1), for the intermediate depth earthquakes in the volcanic arc.

Date	$\varphi^{o}N$, $\lambda^{o}E$	h	M_S	C
21:06:1862	36.9,24.4	150	7.0	3
04:04:1911	36.5,25.5	140	7.1	4
16:07:1918	36.7,25.8	150	6.6	4
05:07:1926	36.6,27.0	150	5.6	5
14:02:1930	36.6,24.4	130	6.7	3
09:11:1934	36.7,25.7	150	6.2	4
28:04:1936	36.7,26.8	170	5.7	5
11:09:1948	37.2,23.2	120	6.4	2
17:07:1964	38.0,23.6	155	6.0	1
27:09:1983	36.7,26.9	160	5.6	5

Information on all known shallow earthquakes with $M_S \geq 6.0$ which occurred in the volcanic arc $M_S \geq 6.0$ have been used. Table (1) gives the date, epicenter coordinates, the surface wave magnitude, Ms, and the cluster number, C, according to their clustering near the corresponding volcanic center. The epicenters of these shallow earthquakes are shown by open circles in figure (1). The errors in the epicenters are of the order of 30Km and the errors in the magnitudes less then 0.4.

It is difficult to get reliable historical information on intermediate depth earthquakes with epicenters in the volcanic arc, because even the strong ones of these earthquakes have very weak macroseismic effects near their epicenters. This is attributed to the strong attenuation of the short period waves in the aseismic layer of hot material which exist between their origin at depth (120-180Km) and the earth's crust (Papazachos and Comninakis, 1971). For this reason mainly instrumental data have been used for this purpose, that is, data on such intermediate depth shocks recorded since 1911 when the first reliable seismograph (Mainka type) was installed in Athens. Even for this period, reliable focal depths can be determined for the stronger ($M_S \geq 5.5$) of these shocks. For this reason, the data sample for intermediate depth earthquakes used in the present study include information on all such shocks which have epicenters in the volcanic arc, magnitudes $M_S \geq 5.5$ and occurred during the period 1911-1991. Information for these earthquakes is given on table (2). Reliable data exist also for one strong ($M_S = 7.0$) historic earthquake which occurred in 1862 and for this reason information for this earthquake is also included in table (2). The epicenters of these shocks are shown by triangles in figure (1).

The available data show that smaller earthquakes $M_S < 6.0$ occur all along the volcanic arc but the majority of these earthquakes also occur in these five linear clusters.

CLUSTERING OF VOLCANIC AND SEISMIC ACTIVITY.

Figure (1) shows that the epicenters of both shallow and intermediate depth earthquakes as well as the volcanic centers form five distinct clusters. We can name these clusters, according to

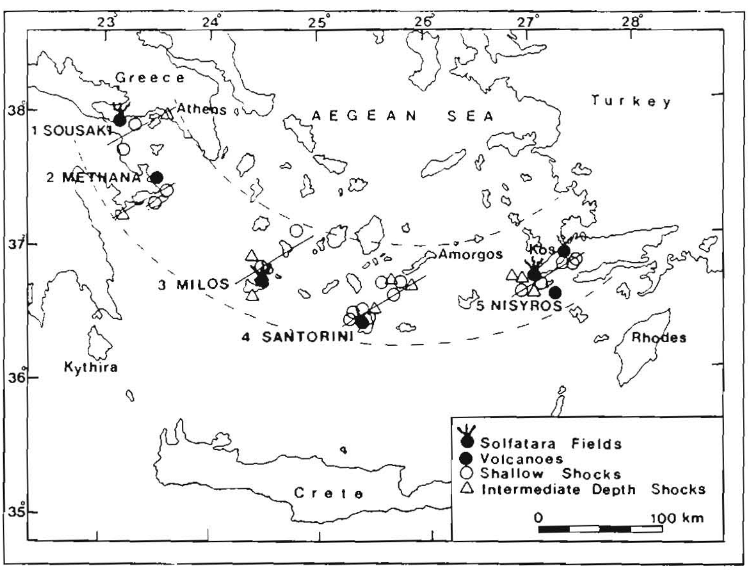

Fig.1. The five seismovolcanic clusters in the volcanic arc ofthe southern Aegean.

the names of the corresponding volcanic centers and we can determine the center of each seismovolcanic cluster by averaging the corresponding geographic latitudes and longitudes. Then we have: 1) Sousaki: 37.9°N, 23.3°E 2) Methana: 37.4°N, 23.5°E 3) Milos: 36.8°N, 24.5°E 4) Santorini: 36.5°N, 25.6°E 5) Nisyros: 36.7°N, 27.1°E.

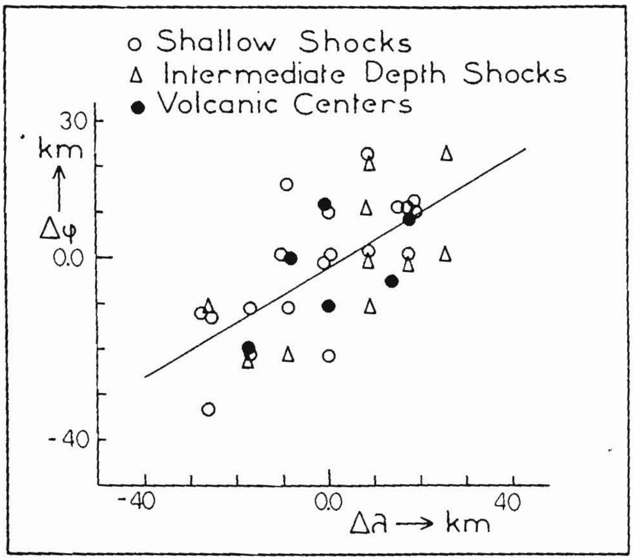

Fig. 2. Direction of delineation of the volcanic centers and of theseismic epicenters in the volcanic arc of the southern Aegean Sea.

Furthermore, the epicenters of the earthquakes and the centers of the volcanic activity in each cluster have a tendency to delineate in an about NE-SW direction. This is clearly expressed in the two easternmost clusters (Santorini, Nisyros) for which the data samples are larger. To determine a "mean" direction of delineation for all five seismovolcanic clusters, the relative latitudes, δφ, and the relative longitudes, δλ, of the epicenters of earthquakes and of the centers of volcanic activity, in respect to the center of each cluster, were determined. Figure (2) shows a plot of δφ (in Km) as a function of δλ (in Km) with corresponding three different symbols (open cirles, triangles, dots) for shallow shocks, intermediate depth shocks and centers of volcanic activity. The line drown through the data is a least squares fit with a correlation coefficient equal to 0.67. Its equation is

$$\delta\varphi = 0.61\ \delta\lambda \qquad (1)$$

This corresponds to a direction N59^{O}E, which is also drawn through each seismogenic cluster on the map of figure (1).

Since the occurrence of both shallow earthquakes and volcanic activity requires rupturing of the earth's crust, we may safely assume that these clusters indicate the existence of corresponding five rupture zones (faults) which have this strike. It is interesting to note that the shallow seismic activity (frequency of shocks, maximum magnitude) is higher in the eastern part of the volcanic arc than in the western part, which is also the case with the volcanic activity. It seems that the magnitude of the maximum shallow earthquake in the western part of the volcanic arc does not exceed 6.5, while this magnitude in the eastern part reaches the value 7.5.

Of particular interest is the observation that the epicenters of the strong ($M_s \geq 5.5$) earthquakes with focal depth between 120Km and 180Km are also distributed along these five linear clusters (see fig.1 and 2). It means that the foci of these earthquakes are also clustered along five parallel rupture zones which are in the top surface of the front part (120-180Km) of the descending lithospheric slab and in the vertical planes which include the corresponding shallow rupture zones. The data of table (2) give no evidence for any clear difference in the seismic activity (frequency, maximum magnitude) between the western and eastern deep rupture zones. The maximum magnitude seems to be around 7.0 in both areas.

DISCUSSION

The occurrence of rupture zones trending in a N59°E direction in the volcanic arc is supported by similar trending of geomorphological features, such as grabens and islands (Kos-Astipalaea, Amorgos-Santorini, Anafi-Milos), and of geophysical features, such as isolines of Bouguer anomalies for Milos (Thanasoulas, 1983) and for Santorini (Budetta et al., 1983).

The occurrence of volcanic activity in these five rupture zones requires a field of extensional crustal deformation. Such an extensional field in the Aegean area is now well established (McKenzie, 1978; Papazachos et al., 1991). Very recently, Papazachos and his colleagues (1992) used fault plane solutions and moment rates of earthquakes and determined velocities of maximum extension of 1mm/yr and 13mm/yr for the western and eastern part of the volcanic arc, respectively, in a mean direction N31°W. This is the seismic deformation, while the total deformation is about two times larger (Papazachos and Kiratzi, 1991). Then, 2mm/yr and 26mm/yr is the total deformation for the western and eastern part, respectively. This explains well the normal faulting on the rupture zones shown in figure (1) as well as the higher volcanic activity in the estern part of the arc.

The most accurately determined rupture zone is that of Santorini because the data sample for the shallow earthquakes of this zone is the largest. This includes the shallow earthquake of July 9, 1956 with M_s=7.5 which was produced by normal faulting stiking in a N65°E direction (Shirokova, 1972). This earthquake generated the largest known tsunami in the Aegean during the last two centuries at least. Galanopoulos (1957) reported values for the heights of this tsunami equal to 25m in the southern coast of Amorgos and equal to 20m in the northern coast of Astipalaea. This indicates that the source of this tsunami is the graben south of Amorgos (Papazachos and Dimitriou, 1991) which has an about NE-SW trend. The length of this rupture zone, as it is determined from the distribution of the epicenters, is about 70Km which corresponds fairly well to the length of the rupture zone for an earthquake of this magnitude. Therefore, the focal properties of this earthquake strongly support the idea for such a normal fault in Santorini-Amorgos area. There is also geological and volcanological evidence for the existence of such a fault (Heiken and McCoy, 1984). The occurrence of the large eruption of 1650 in a distance of some kilometers northeast of the center of the caldera of Santorini also supports the idea for a fault with such strike.

The other rupture zone in the eastern part of the arc includes the volcano of Nisyros and solfatara or fumarolae fields in Kos. This is also well defined. Its length, as it is deduced from the distribution of the epicenters of shallow shocks, is about 50Km which is about equal to the length for an earthquake of magnitude 7.0, which is the magnitude of the maximum shallow earthquake ever observed in this rupture zone. The largest known shallow shock in this rupture zone is the one which occurred in 554 A.D. This earthquake was aslo followed by a very strong tsunami which produced considerable damage in Kos. It is very probable that the source of this tsunami is a graben just south of Kos island which is also trending in an about NE-SW direction.

Although the three western rupture zones are evidenced by both volcanic activity and epicenters of strong earthquakes, there are no enough data available for their accurate spatial definition. Additional seismological data are needed to define these zones accurately.

The delineation of the epicenters of the intermediate depth earthquakes with focal depths between 120 and 180Km indicates that five parallel rupture zones also occur near the top surface of the leading part of the descending under the Aegean lithospheric slab. These inclined rupture zones strike also in a N59°E direction. It means that the physical process which occurs at those depths is directly related to the volcanic activity observed in the earth's surface. It is probable that movements in the descending slab, which occur mainly in these five rupture zones, trigger upward migration of hot material in the mantle which lies between these deep rupture zones and the shallow rupture zones of the volcanic arc. Several hypotheses can be made to excplain this triggering, such as frictional heating at the top surface of the deeping slab, hydrodynamic forces created by the sinking of the slab (Karig; 1971, Toksoz, 1975) or by magma generation at depth due to dehydration of the descending oceanic crust (Anderson et al., 1976). The data of the present paper indicate that such physical process occurs mainly along certain rupture zones near the top surface of the descending slab.

The distribution of macroseismic effects of these deep earthquakes shows some peculiarity. This effects are weak in the inner part of the Hellenic arc (in the Aegean) and strong in the outer part of the arc (Crete, West Peloponnesus). This peculiarity has been attributed to the strong attenuation of short period waves which travel through the hot asthenospheric material in the inner part and to the effective transmission of such waves which travel in the outer cold material of the deeping lithospheric slab (Papazachos and Comninakis, 1971). It seems, however, that this idea interprets very well the low macroseismic intensities observed in the inner part of the area but not the high intensities observed in the outer part, because these high intensities are usually focused in certain locations of the outer part of the area. For this reason, these high intensities need some directivity of the radiated energy from these deep seismic sources, in addition to the effective transmission of seismic waves in the deeping lithospheric material. The orientation of the deep rupture zones (strike N59^{o}E, dip 38^{o}), proposed in the present paper, is in full agreement with such an interpretation. The very strong focusing of the macroseismic intensities in some cases is also interpreted if we assume an upward, and therefore outward, rupture propagation on the deep rupture zones. One such example is the intermediate depth earthquake which occurred on 17 July 1964 at a depth of 155Km just underneeth Athens. The earthquake was weakly felt in Athens and in other places of the inner part of the area but it was felt strongly in places of the outer part (Messinia, Elia) and very strongly at a certain place (with intensity VI at Kynigos) of the western Messinia in a distance of 250Km from the focus of the earthquake. This intensity is clearly higher than the expected one in this distance from seismic waves generated by an earthquake of this magnitude (M_s=6.0) and travelling through lithospheric materials. This earthquake belongs to cluster 1 of figure (1) and its rupture zone, as it is suggested by the model proposed in the present paper, is treding toward the place where the maximum intensity was observed.

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