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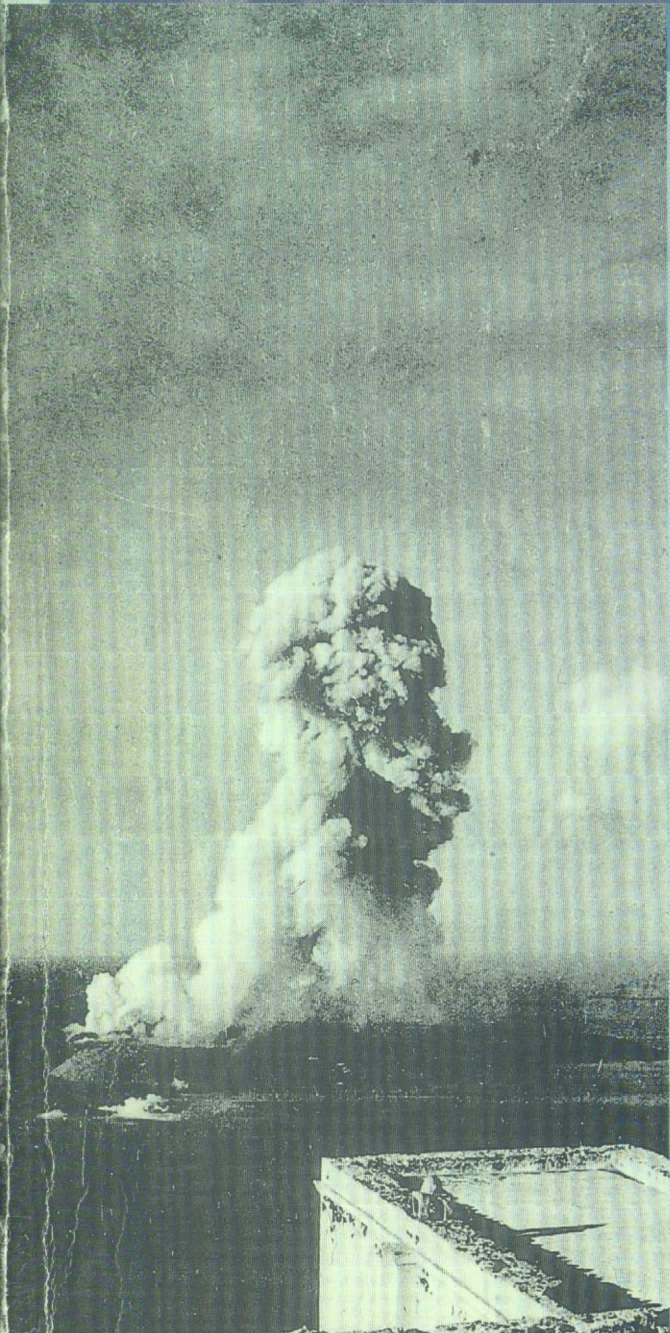

# The European laboratory volcanoes

Proceedings of the second workshop
Santorini, Greece
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# ACTIVE DEFORMATION OF SANTORINI

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## SUMMARY

An extensive field study of various structural features (striated faults, joints, dykes and morphotectonic structures) on the Santorini (Thera) and Christiana island groups has been carried out in order to estimate the stress field that dominates the area. Since the majority of these features is located in recent volcanic products, this stress field is the active one. The strike, dip and width of all the dykes outcropping on the caldera walls from Ia to Skaros were measured. The rose diagrams of the dykes' strike show a maximum orientation in a NE - SW direction (N 40°), while some minor concentrations occur in NNE - SSW (N 10°) and NW - SE (N 150°) directions. This indicates that the dykes were formed along pre - existing open fractures and normal faults, thus being clearly of tectonic rather than radial volcanic origin, as has been thought up to now. The NE - SW direction coincides with other lineaments in the Santorini island group (i.e. alignment of volcanic centres, photolineaments, orientation of geophysical anomalies, surface fault measurements etc.), thus supporting a tectonic origin. Stress orientation (NNW - SSE direction of $\sigma_3$) as derived by fault data (normal and dextral oblique fault mechanisms) coincides with the one calculated by extensional joint data. Thus the fracture pattern on the island could be interpreted as the result of a dextral shear zone, or, alternatively, a biaxial extension pattern similar to that proposed for other Cycladic islands. It is important to note that no deformation was found in products of the Minoan eruption, indicating an entirely pre - Minoan tectonic activity. Geomorphological observations all over Santorini island show some features indicating recent fault activity. For example, the area of deep erosion at the southern part of the island seems to have been affected by a blind fault.

## 1. INTRODUCTION

The continental collision of the Eurasian and African plates, south of Crete, and particularly the subduction of the African plate under the Aegean is the most widely accepted model to account for the extensional tectonics and the past and present volcanism of the Aegean Arc[1,2,3]. The volcanic centres of Nisyros, Santorini (Thera), Melos, Methana - Aegina and Sousaki are located about 200 km north of the frontal compression area and form the Southern Aegean Volcanic Arc.

The central part of the southern Aegean region, which includes Santorini, belongs to the Atticocycladic geotectonic zone. Two main rock groups are generally present in the Cycladic islands: a crystalline lower unit of metamorphic rocks, and an upper unit of metamorphics and granitoids, metamorphosed sediments and volcanics. The lower group, known as the *Cycladic Blue Schist Unit*, was affected by high - P metamorphism during the Eocene and was intruded by granitoids, while the upper one was affected by low - P metamorphism in the late Cretaceous. The Blue Schist Unit consists mainly of metasediments and metavolcanics, probably of Mesozoic age, that were metamorphosed under blue schist and eclogite facies about 42 Myrs ago. These high - P metamorphic rocks are considered to be the northward extension of the Cycladic massif and also occur within the nape pile that comprises the Hellenides on mainland Greece.

Santorini island is constructed mainly of post - Pliocene volcanic rocks although pre - volcanic rocks, mainly late Mesozoic - early Cenozoic schists and marbles, are also present[4]. The pre - volcanic basement of the island is visible in three areas: *a.* in the Mt. Profitis Ilias - Perissa - Emporio - Pyrgos - Kamari area in the central part of the island, *b.* in the Monolithos area in the eastern part of Santorini, and *c.* in the Cape Athinios area. The first two occurrences consist of lightly metamorphosed carbonate rocks imbricated with phyllites and metaconglomerates, while the third consists of a unit of intercalated metamorphosed carbonate, pelitic, conglomerate, quartzitic and magmatic rocks of unknown age.

Southern Thera consists of a 200 m thick succession of pyroclastic rocks, known as the *Thera Pyroclastic Formation* draped over the pre - volcanic basement rocks and the Early to Mid - Pleistocene Akrotiri volcanics[5]. The pyroclastics interdigitate with lava formations of northern origin, suggesting alterations of explosive and effusive activity during the evolution of the volcanic field. There have been at least twelve major explosive eruptions during the last 400 ka. Each of the major eruptions started with a pumice fall phase and most culminated with emplacement of pyroclastic flows and surges. At least eight eruptions tapped heterogeneous magma chambers. Four of them vented large volumes of dacitic or rhyodacitic pumice and triggered caldera collapses. The last major, and most famous, event was the "Minoan" eruption[6,7,8], so named because it is believed to have destroyed the Minoan civilisation in Crete (ca. 1570 ± 50 BC).

The position of the vents, both for the pre - and post - Minoan volcanic activity, was largely controlled by two NE - SW trending volcanotectonic lines, the Kameni and Kolumbo lines, which acted as paths for magma intrusion. Five major explosive eruptions focused on the Kameni line as well as on the Aspronisi tuff ring. The Kolumbo line controlled the vent position of two major events; dyke swarms, cinder cones and the Cape Kolumbo tuff ring northeast of Santorini.

Due to the position of the Santorini island complex with respect to the Africa - Eurasia subduction zone, it is considered to be a very seismically active part of the Volcanic Arc[9]. The last big seismic event that occurred near to Santorini was that in Amorgos island (50 km on the north) on 9 July 1956[10]. The earthquake, of magnitude $M_s = 7.4$, was the largest crustal event in Greece during the present century. More than 50% of the destruction and damage was in the towns of Ia, Imerovigli and Fira on Santorini island. It was reported that on Santorini most of the damage occurred after the largest aftershock (12 km from the villages mentioned above), although the main shock was more intensely felt. It is interesting to note that the epicentres of the 1956 main shock and its largest aftershocks are aligned with the volcanic centres of Thera

(Santorini) at 36.404° N, 25.396° E, Christiana (located 25 km southwest of Santorini) and Kolumbo (located about 6.5 km northeast of Santorini).

## 2. NEOTECTONIC FEATURES

As far as the structural geomorphology of the island is concerned, its most important feature is the large morphological depression of the northeasternmost part of Santorini, located between Imerovigli and Ia. This depression has a roughly NE - SW trend, thus coinciding with the right - lateral strike - slip fault zone of Mt. Mikros Profitis Ilias *(see below)*. Another important morphotectonic feature of the island is the area between the Akrotiri archaeological excavations and cape Eksomitis - at the southern end of the island - which has been heavily eroded, although the area is not as weatherable as the northern part of Santorini. According to our interpretation, this area represents the upward termination of a buried blind fault zone trending E - W. This morphotectonic clue seems to be a realistic approach, as a geothermal field of about $70^0$ C has been detected by I.G.M.E. in a zone perpendicular to the area mentioned above.

The island's faults were divided into three categories, briefly described in the following paragraphs.

### *The right - lateral strike - slip fault zone of Mt. Mikros Profitis Ilias*

To the north, Santorini gets very narrow, as has already been mentioned. Several fault sites have been studied in this part of the island. These sites present intense strike - slip and normal faulting that is limited to a NE - SW trending zone which coincides with the Kameni - Kolumbo line. The deformed rocks are the Mikros Profitis Ilias lavas and some older tuff rings. At the southern boundary of this zone the faulting is more intense, and the slickenlines give a clear idea of the movement. In some sites step - like structures were observed, not necessarily of tectonic origin, as they can also be explained as magma cooling structures. A major dextral strike - slip fault zone of NE - SW strike (35 - 40° N) bounds the deformation zone to the south, while smaller normal faults of NE - SW strike (40° - 70° N) belong to the same zone. The northern boundary of this deformation area is defined by a fairly large topographic depression that marks a zone of mainly normal faulting. Many secondary small faults of different strikes constitute a fractured fault zone where signs of geothermal activity are visible. At cape Kolumbo, the continuation of this fault

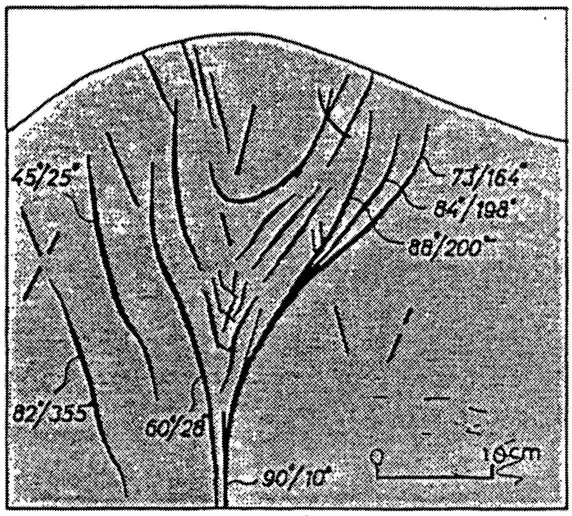
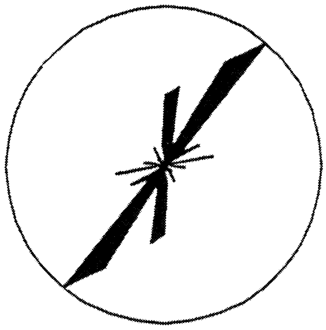



Fig. 1. Field sketch of a flower structure in ignibrite at Cape Archangelos. Numbers indicate dip angle and direction of dip respectively for each fault.

zone is visible as a series of mainly NNE - SSW trending conjugate normal faults and accompanying joints.



*Caldera walls Dykes* *Population: 64*

Fig. 2. Rose diagram of the dykes present in the caldera walls of the northeastern part of the island. Their orientation coincides with that observed in the field, as well as with the morphological depression.

### *The Mt. Profitis Ilias faults*

Mount Profitis Ilias, the largest peak of Santorini island, is composed of bedrock carbonate rocks. It is deformed by many mainly normal faults of both WNW - ESE and NE - SW strike. The former roughly define the basement - volcanics contact, while the latter occur in the limestone massif. There are some big normal fault slickensides west of Kamari, with older strike - slip movement indications.

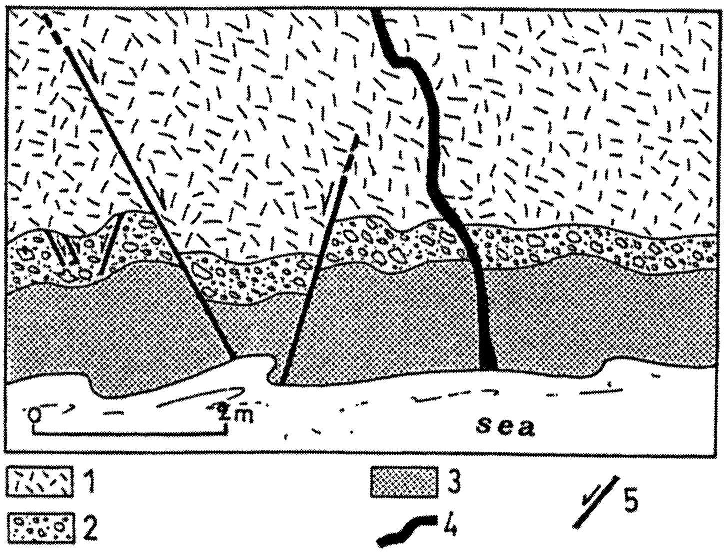


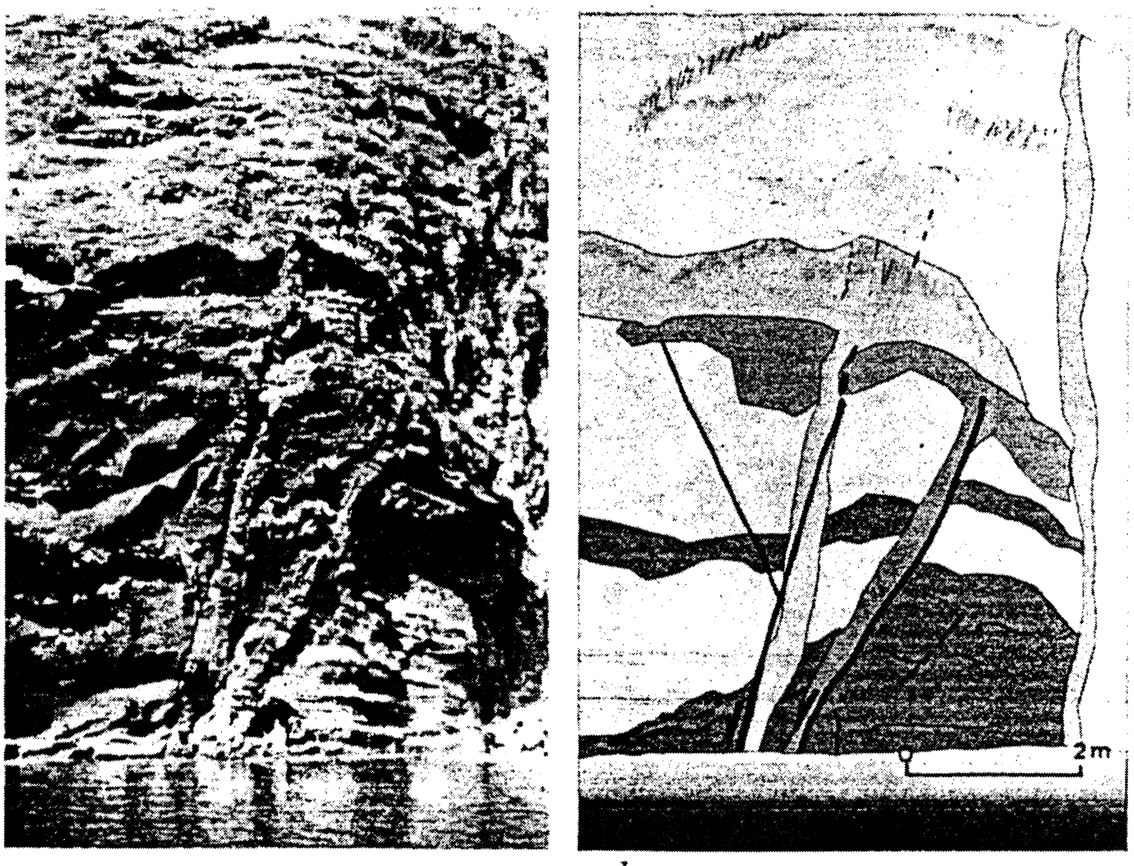

Fig. 3. Normal faults and dyke within Profitis Ilias Mt. volcanics. 1.Upper lavas 2. Debris flow 3. Lower lavas 4. Dyke 5. Normal faults.

### *Akrotiri area faults*

The southern part of the island is dominated by faults of extensional character orientated N $100^0$ - $170^0$. Some of the fault sites studied are situated in the Akrotiri, Cape Archangelos *(Fig. 1)* and Cape Maurorachidi areas. In Akrotiri, just south of the village, a faulted zone has been observed in a gully. The faults cross-cut the whole series of the oldest volcanic rocks of the island (mainly water lain vitric tuffs, tuffites and breccias in the area), while some of them were striated.

The dykes present along the caldera walls acted as lava pathways during past eruptions. These dykes are concentrated mainly in the northeastern part of the caldera, in the aforementioned Mt. Mikros Profitis Ilias right - lateral strike - slip fault zone. In order to establish a model for their origin, we measured the strike, dip and width for all of them. The data were collected at the dykes' lowermost part, right at the sea level. They form two main systems *(Fig. 2):* a primary system trending NE - SW (N 30° - 40°) and a secondary one trending N - S (N 0° - 10°). The NE - SW main strike is in agreement with many other lineaments defined in the Santorini island complex (photolineaments, geophysical anomalies, emplacement of the volcanic centres, etc.). Many of them coincide with faults, as is indicated by displaced volcanics alongside their walls *(Fig. 4).*

This positioning of the dykes indicates that they are of tectonic origin, and not of volcanic, as they were considered to be up to now. If they had been volcanic their strike would be expected to be more or less concentrically arranged in a uniform manner, spanning a wide range of orientations. This radial arrangement, which has been observed in other cases worldwide, is created during subsequent eruptions of the volcano, converging towards the central part of the caldera. This is definetely not the case for Santorini, as has been explained here. The NE - SW main alignment of the dykes indicates a principal extension with $\sigma_3$ being of NW - SE direction, while a secondary extension axis lies in a NE - SW direction. This stress regime is in agreement with that calculated using the methods described in the following chapter.




*a.* *b.*

Fig. 4. a. Dykes and small normal faults at the northeastern part of the caldera, and b. their interpretation. Many dykes were formed along pre-existing normal faults that acted as pathways for the lava. Orientation of the faults is the same with that of the dykes and coincides with the Mt. Mikros Profitis Ilias dextral strike-slip fault zone.

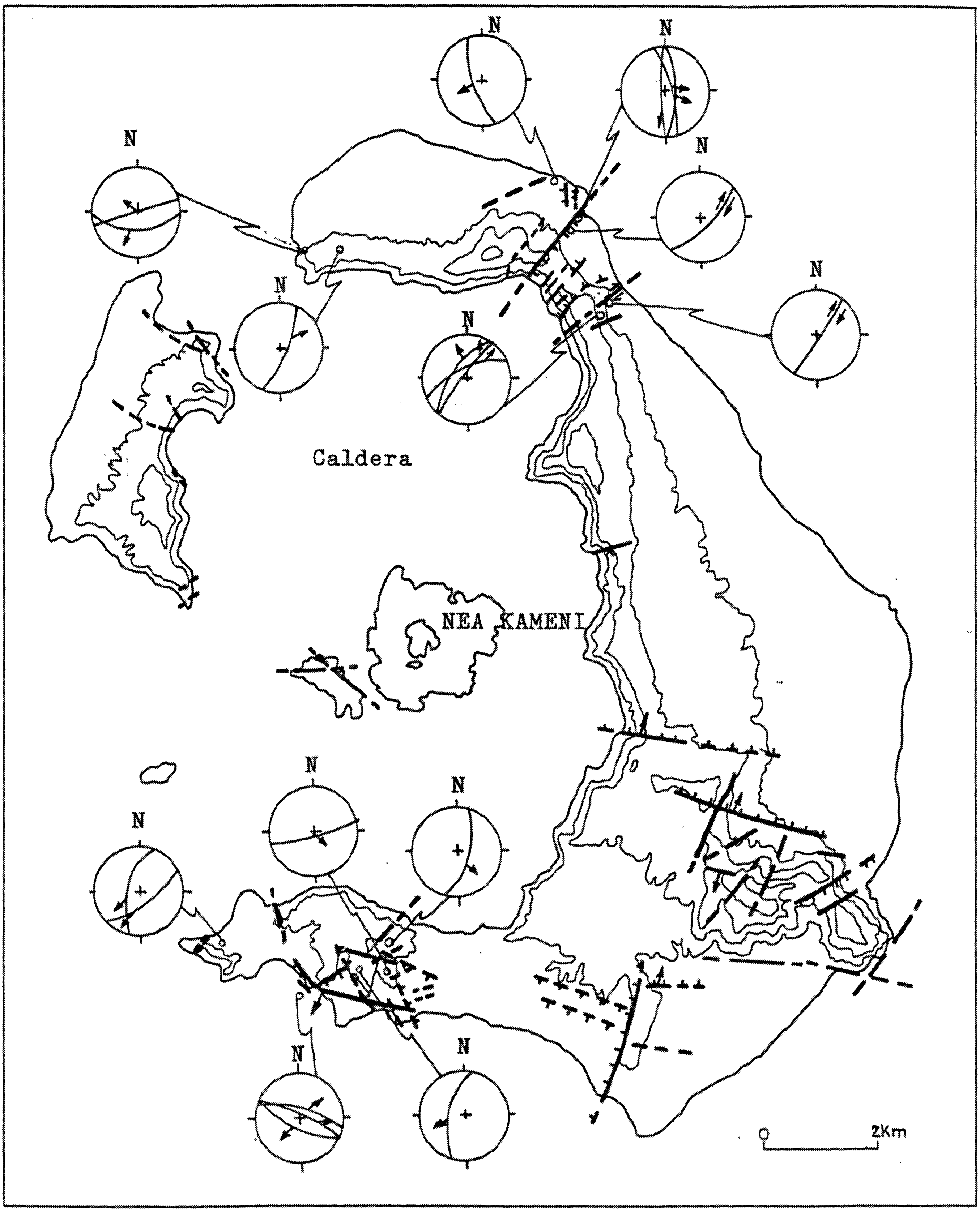



*Fig. 5. Neotectonic map of Santorini island. Heavy lines represent faults, with tick marks towards hangingwall. Stereographic lower hemisphere projections of selected faults are also shown.*

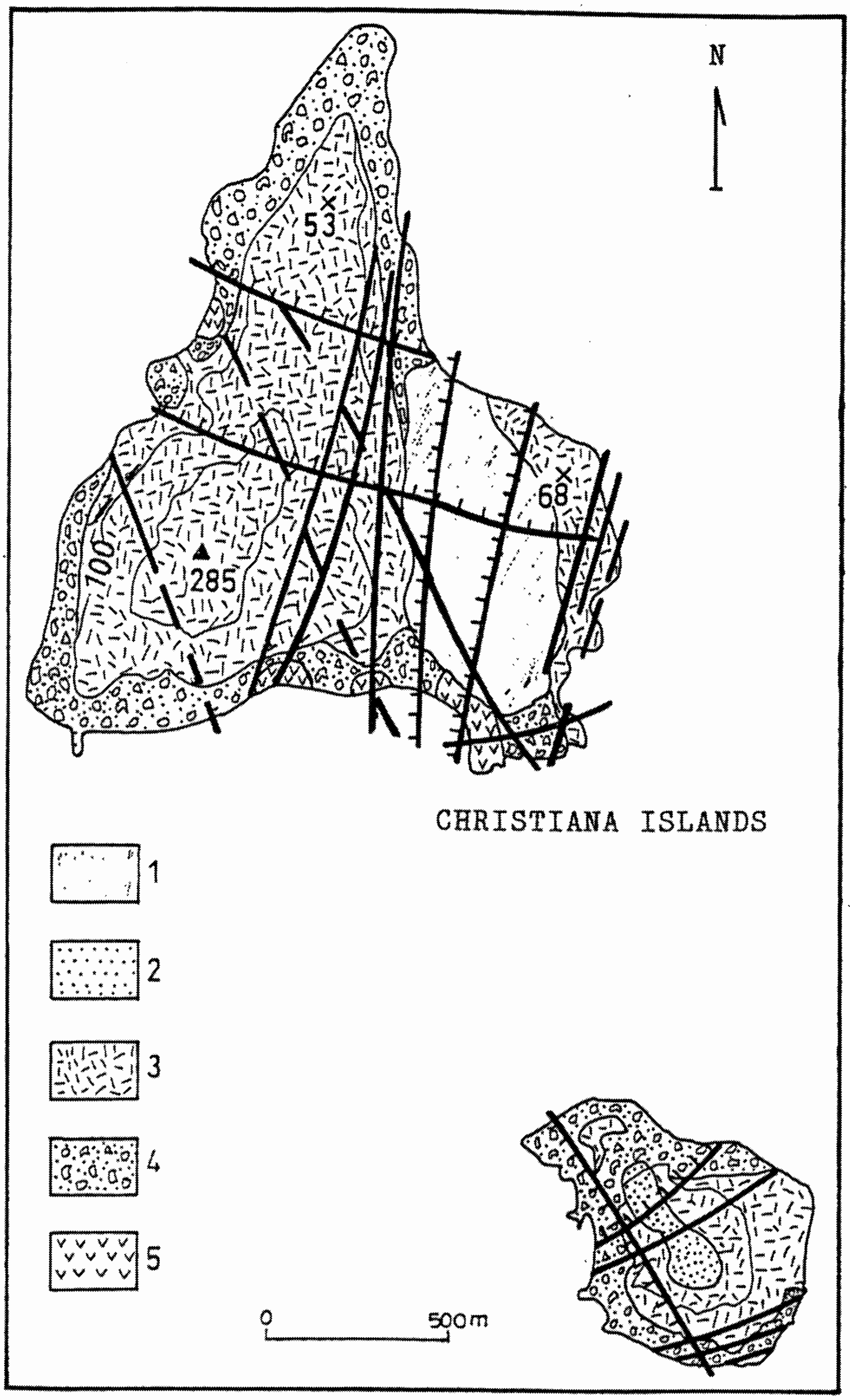



*Fig. 6. Neotectonic map of Christiana island group. Legend: 1. Paleosoils, 2. Pumice flows - block and ash flows, 3. Upper lavas, 4. Volcanoclastic sequence, debris flow, 5. Lower lavas. Faults are represented as heavy lines with tick marks towards the down-thrown block.*

The nearby Christiana islands were also mapped in the frame of the current study, in order to compare their fault geometry with the one for Santorini *(Fig. 6)*. They consist mainly of lavas and pumice flows. Faults on Christiana are small, normal ones, and they form two groups with strikes similar to the ones observed on Santorini (NNE - SSW and WNW - SSE).

## 3. ACTIVE STRESS REGIME

The extrapolation of the active stress field of the Santorini island complex was done using standard numerical stress calculation techniques[11,12,13,14]. These methods use fault data as measured in the field, i.e. fault strike, dip and dip direction, and slickenline dip to calculate the stress field. Most of the aforementioned methods involve a minimisation technique called the *conditioned square minima method* that is applied to the areas of maximum probability obtained either with the right dihedral method, or the P and T axes method. We used the IBM PC - compatible computer software FAULT[15] for data processing with both methods.

Another methodology applied in Santorini for this study was the estimation of the stress field using joint data, i.e. joint strike, dip, dip direction and width[16]. Joints have not been widely used in stress field calculation, apart from only a few cases[17,18,19].

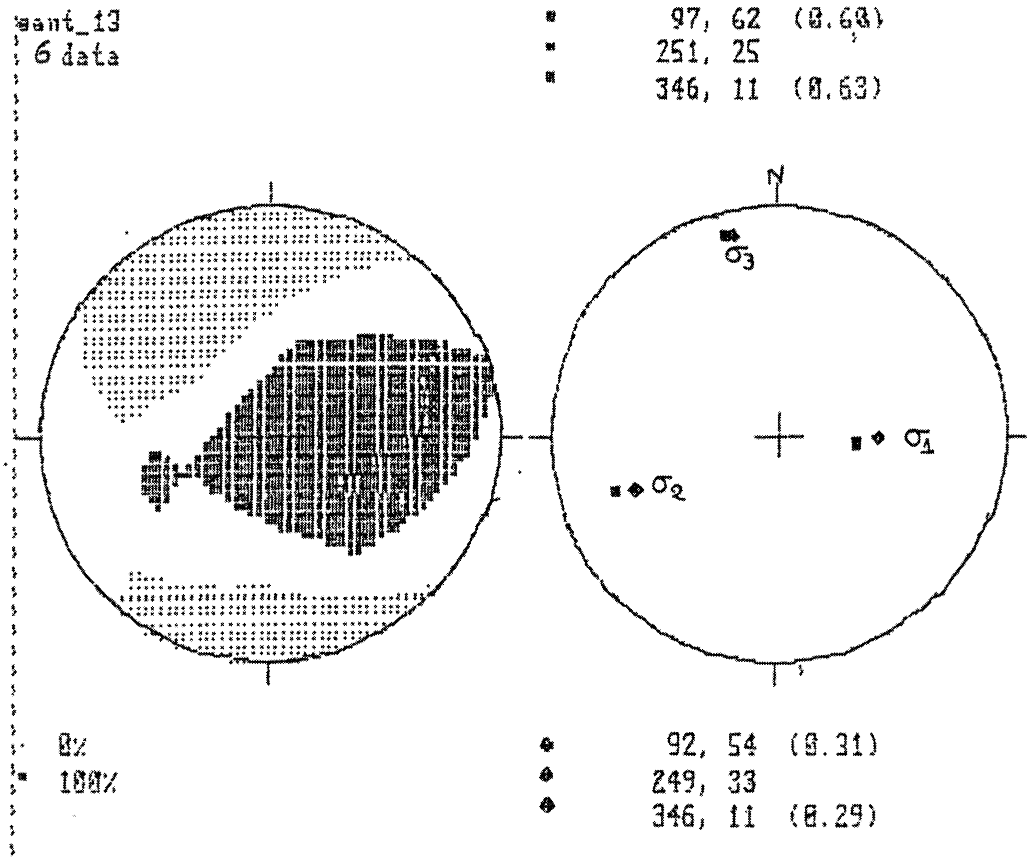



Fig. 7. Examples of stress analysis on faults of the island. Stress pattern as obtained by a. the right dihedral method (light and dark areas represent areas of extension and compression respectively), and b. P and T method.

To process the collected data we used computer software JOINT[20]. Data were collected from volcanic dykes along the caldera walls, as well as from selected joint sets at sites on land.

Existing stress calculation data[21,22] indicate that the active stress axis ($\sigma_3$) lies in a general N - S direction in the southern Aegean area with small local variations (NNW - SSE to NNE - SSW). In many case block rotations have been observed[23]. In Santorini the active stress field was calculated using a limited number of faults and joints[24].

In our study, the use of a much larger data set of both striated faults *(Fig. 7)* and joints indicates that the active stress field of the island generally coincides with the ones previously calculated, as well as the extension that was induced from the dyke orientation. The kinematic analysis of the neotectonic data shows that the extension axis $\sigma_3$ lies in a NNW - SSE direction, as it was expected by the fault orientation.

## 4. ACTIVE TECTONICS OF SANTORINI - CONCLUSIONS

The field observations and the interpretations were based on the new considerations of structural geology, taking into account, along with the general structural analysis the rotational component of the strain, studying microstructures as shear criteria and particularly the kinematic indicators.

The main characteristics of the island of Santorini, as defined by the structural geomorphology and kinematic analyses, show that the island is dominated by a NNW - SSE extensional stress regime that produces certain lineaments, such as the well known Kammeni line, the morphological depression of the northeastern part of Santorini, and its connection to the submarine volcanic centre of Kolumbos. These lines lie in an *en echelon* pattern, leading to the conclusion that they are Riedel shears, parts of a large dextral shear zone that extends towards the island of Amorgos *(Fig. 8)*. This is in agreement with the alignement of small earthquakes in the area between these two islands[25]. The same strike (N 50°E) of normal and right-lateral faults further enhances these observations. The faults and joints observed on the island are entirely pre-Minoan, thus indicating that there is no post-Minoan tectonic activity.

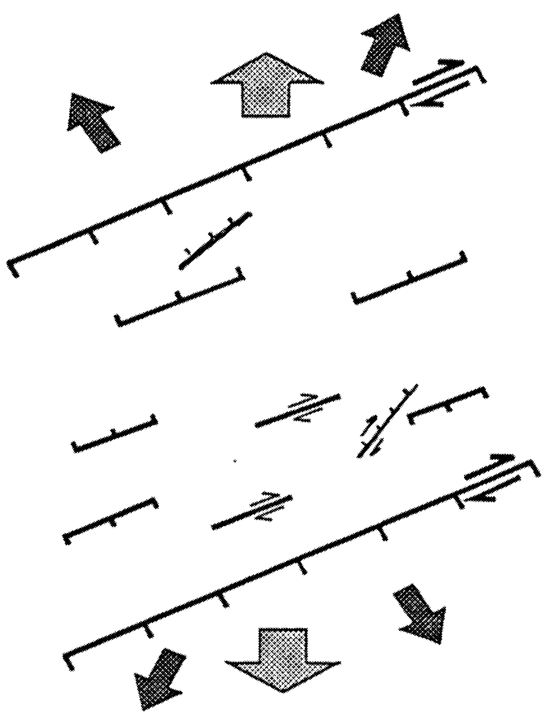


*Fig. 8. Sketch of a general model for the stress pattern of Santorini that is proposed here. The main dextral strike-slip deformation is connected to the regional extension, while small deviations in extension direction create a local stress field.*

Stress orientation (NNW - SSE direction of $\sigma_3$) as derived by fault data (normal and dextral oblique fault mechanisms) coincides with the one calculated by extensional joint data. Thus the fracture pattern of the island could be interpreted as the result of a dextral shear zone, or, alternatively, a biaxial extension pattern similar to that proposed for other Cycladic islands. It is important to note that no deformation was found in the Minoan eruption products, indicating an entirely pre-Minoan tectonic activity.

Geomorphological observations all over Santorini island show some features indicating recent fault activity. For example, the deep erosion area at the southern part of the island seems to have been affected by a blind fault.

## 5. AKNOWLEDGEMENTS

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