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GEOLOGICAL MAP OF GREECE.AEGINA ISLAND, 1:25000

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ABSTRACT

The **new geological map of Aegina island** in the Saronic gulf southwest of Athens, on a 1:25 000 scale, is designed as a prototype of a special map series of Greece. Two thirds of the surface of the island is covered by dacitic and andesitic lava flows, plugs and necks, and by large volcanoclastic dacitic flows. The remaining one third is covered by Neogene lacustrine and shallow marine sediments. The basement is mainly comprised of Permian to Upper Cretaceous limestones, covered by flysch and ophiolitic thrust sheets.

A **colored inferred cross section** to approx. 1000 m depth is shown below the map illustrating the polyphase deformation of the Sub-Pelagonian Paleozoic to Mesozoic platform carbonates, as well as the remnants of overthrust sheets including Upper Jurassic to Lower Cretaceous ophiolitic mélange, Upper Cretaceous to Tertiary flysch and Upper Cretaceous limestones.

The **reverse side of the map** shows the following explanation: the Neotectonic evolution in the northwestern Aegean island arc, including a tectonic map; the paleoenvironment during the Early Pliocene; the volcanic and magmatic evolution.

Volcanic activity started approx. at 4.4 ma.with minor eruptions of rhyodacitic ashes and pumice. A larger volcanic edifice was built up consisting of andesitic-dacite flows and plugs. This **first volcanic phase** terminated with the eruption of numerous dacitic plugs and volcanoclastic flows at approx. 2 ma. The **second volcanic phase** started after a long restoration period, uplift and individualization from two volcanic centers (*Oros and Lazarides*) producing minor amounts of pyroclastics and flows of basaltic andesites, high-alumina basalts, and hypersthene andesites.

INTRODUCTION

The volcanic islands of the South Aegean Sea *(Aegina, Methana, Poros, Milos, Santorini, Yali, Nisyros and Kos)* are aligned along an arc which overlies the deepest part of the inferred Benioff Zone. Together with Crommyonia (Corinth), Methana and Poros, the island of Aegina marks the northwestern end of the arc (Fig.1). The arc is regarded as a magmatic result of active subduction of the

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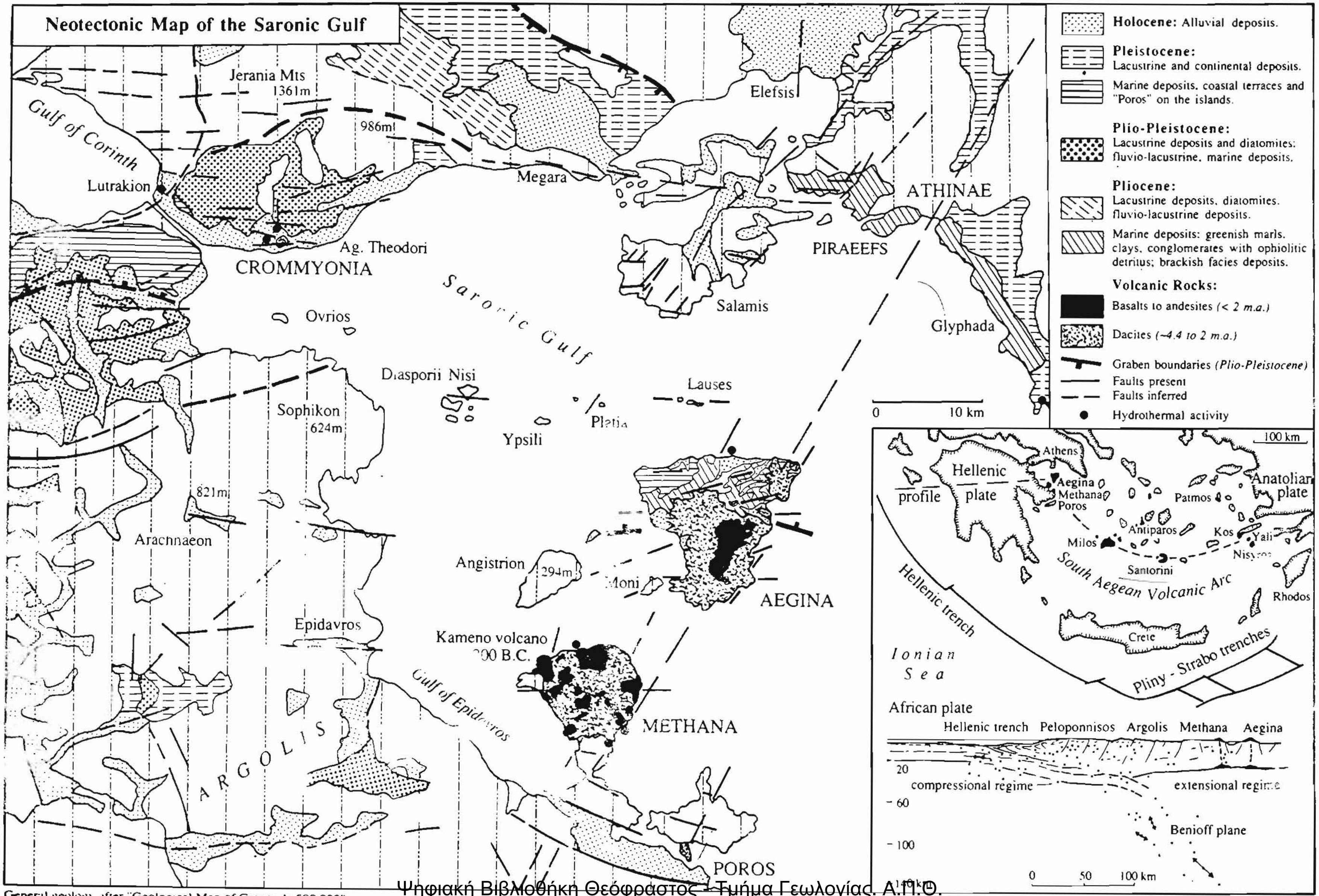


General geology after "Geological Map of Greece 1: 500 000"
Bornovas and Rondogianni-Tsiambaou (IGME,1983)

Fig. 1

Distribution of earthquake epicenters and fault plane solutions
after Berckhemer and Kowalczyk (1978)

African plate beneath the Aegean plate, which may have started in the Middle Miocene (BIJU-DUVAL et al., 1978). Sialic crust is the major constituent of both plates. Dacites and andesites with calc-alkaline characteristics are the dominant volcanic rocks (WASHINGTON, 1894 and 1895; LEYDEN, 1940; DAVIS, 1957).

The magmatic processes which led to the production of dacites and andesites on Aegina island took place over a long time span, starting at ~4.4 m.a. and terminating approx. 1 million years ago.

Aegina island lies close to the boundary between the Cycladic blueschist belt in the southeast, the Sub-Pelagonian Paleozoic and Mesozoic platform carbonates of Attica and the Argolis peninsula in the north and west.

The *basement of the volcanic edifice* is well exposed in northern Aegina as well as in a small tectonic window in the central part of Aegina *(Koutalou)* and a few small outcrops at the shore of *Sarpa Bay (south of Perdika)*. These par-autochthonous Sub-Pelagonian units are composed of faulted and weakly folded Upper Carboniferous to Lower Permian, Triassic and Jurassic to Lower Cretaceous limestones. In one place (*Kamara,Pt.62*) Cenomanian limestones are exposed. At the *Paliomili ridge,* (northern Aegina) as well as in several places on *Moni island,* the platform carbonates are transgressed by late Campanian and Maastrichtian Globotruncana limestones.

The Sub-Pelagonian formations are covered by remnants of allochthonous and tectonically higher thrust sheets of Upper Jurassic to Lower Cretaceous ophiolitic mélange (*south of Paliomili, Alones and south of Kamara)* and Upper Cretaceous to Lower Tertiary flysch (*Paliomili, Souvala*). The ophiolitic volcanics consist mainly of pillow basalt of MORB, IAT and boninitic composition (DIETRICH et al., 1987) overlain by Radiolarian cherts and fine grained polygenic ophiolitic sandstones and breccias. All these rocks show at least one foliation and contain lower greenschist facies mineral assemblages. In the *Paliomili ridge*, the ophiolitic rocks are covered by undeformed and unmetamorphosed Maastrichtian Globotruncana limestones.

NEOTECTONICS IN THE NORTHWESTERN AEGEAN ISLAND ARC

The crust reaches 40 to 50 km thickness in the ***external zone*** (*Peloponnesus, Crete, Rhodos,* see insert of Fig.1). There, compressional tectonics causing low angle thrusts and overthrusts as the dominant features. Earthquake activity is very abundant and the hypocenters in general reach 50 to 60 km depth, in some areas 150 km. Volcanic activity has not been observed within this zone. A poorly defined seismic plane seems to dip from the Hellenic trench behind the external zone with an angle of ~ 35^{o} towards north and northeast reaching a maximal depth of 150 - 170 km. The more ***internal zone*** of the Aegean Sea is geophysically and structurally indifferent. High heat flow and an anomalous high rising mantle up to 20 km beneath the central Aegean have already been reported by MAKRIS (1977).

The ***island of Aegina*** is located more towards the border of the Aegean sea, and is dominated by tensional tectonics, which caused uplift and subsidence leading to horst-graben structures as well as to the emplacement of magmas. The E-W distance from the Hellenic trench axis in the Ionian Sea is about 250 km for Aegina and the vertical distance above the inferred Benioff zone measures ~ 140 km (BERCKHEMER and KOWALCZYK, 1978). PAPAZACHOS and COMNIAKIS (1978) established N-S directed tensional features in the eastern *Peloponnesus* and in the *Saronic Gulf*, based on fault plane solutions of shallow (h<50km) earthquake hypocenters (Fig.1). N-S extension may have been active since Tortonian time, according to geological evidence from five larger E-W striking graben systems in Western Turkey (SENGOER and DEWEY, 1974). This coincides with the first appearance of volcanic activity in the central and eastern Aegean Sea (~7-5 m.a.): *Antiparos, Patmos, Kos and Bodrum.*

Three fault systems (Fig.1) can be recognized on the island of Aegina as well as on Methana and in the adjacent areas. A **major NE-SW striking fault system,** starting in central *Evia* and extending through the Athens basin, runs down along the east coast of *Aegina* and *Methana* and finally terminating in the *Argolis peninsula*. This system marks an important tectonic boundary, dividing the Cycladic blueschist belt to the southeast from the Sub-Pelagonian Paleozoic to Mesozoic platform carbonates to the west. It probably originated as a Tertiary overthrust and experienced a vertical reset during middle to late Miocene time. Due to plate motions and crustal shortening. Since Early Pliocene time it has been reactivated with slight anticlockwise rotation towards a NNE-SSW strike. Major vertical displacements occurred along this system leading to uplift of the eastern part of the island and downfaulting of the seafloor towards southeast.

Vertical displacements also acted since the Pliocene along **second major E-W fault system** (Fig.1) generating the graben structures of the Gulf of Corinth and the connection with the Saronic Gulf.

Since the Plio-Pleistocene boundary, a **third, ENE-WSW striking fault system** (Fig.1) occurred on Aegina island. The extensions of these faults run through *Moni and Angistri islands,* the northern parts of *Methana* into the *Argolis peninsula*. It seems that these faults are aligned to the major fold axis of the anticline structures in the Mesozoic Subpelagonian carbonates. Vertical as well as horizontal displacements can be recognized, probably as a result of the N-S directed extensional movements.

The E-W and ENE-WSW systems may even be regarded as the western extension of the large *North Anatolian transform fault* linked by the NE-SW striking Evia - Athens - Methana faults. Thus, these systems are today deep-tending faultplanes dividing the Hellenic continental plate from the Peloponnesus microplate. The presence of high seismic activity in the whole area of the Saronic Gulf and the appearance of volcanoes since the Early Pliocene at the junctions of the three fault systems are the best indications of such a neotectonic configuration.

THE PALEOENVIRONMENT DURING EARLY PLIOCENE

The area between Aegina and Attica can be regarded as the northwestern termination of a *shallow marine graben system, the Upper Miocene to Pliocene Saronic Gulf* (Fig.1), leading towards southeast into the marine Cretan Sea and towards northeast in to the Aegean Sea with its brackish Parathethyan influx. The Saronic Gulf was bordered by rather irregular coast lines with small lacustrine inlets (e.g. *Skotini, Messagros and south of Alones* on Aegina, see Fig.2). There and in the surrounding areas the topographic relief was not strongly developed and probably showed only less than a few hundred meters of altitude differences. Messinian evaporites have not been observed in the Neogene sedimentary rocks. However, gypsum is present in subordinate amounts in the brackish marls of the lowermost Neogene *(Souvala and Ag. Thomas)*.

The **Saronic Gulf** was bordered at this time to the south by the *Dragonera-Paliomili (ridge) escarpment*. Sedimentation took place in a rather brackic to hypersalinic environment. Fault breccias are developed at the northern flank of Dragonera indicating such a situation.

The **transgressional conglomerates** on top of Eocene flysch and ophiolitic mélange along the northern shores of Aegina (today in a few outcrops between *Kamara* and *Souvala*) can be attributed either to the deep ponding and desiccation or to the subsequent marine flooding of the Mediterranean Sea during the Late Messinian (Pontian) - Early Pliocene (HSÜ et al.,1978). The conglomerates are coarse grained with cobbles up to 20 cm in diameter and consist of basement limestones, ophiolitic detritus, cherts and flysch within a calcite matrix.

The conglomerates pass into yellowish to whitish marls, silts and marly limestones. In the *Leodi-Souvala* Neogene, these sediments have been determined by ostracodes as Pontian (GEORGIADES-DIKEOULIA and DERMITZAKIS, 1983). Yellow to whitish, hard, cellular limestones, partly dolomitic and rich in ostracodes, gastropodes and algees seem also to represent the lowermost Neogene sedimentary cover. They crop out in a few places *(Kypseli,Vigla, Dragonera and Paliomili)*. The limestones grade upwards into marls. Their lateral transition into the more marine Pontian marls and limestones is not clear, but they may represent a lagoon facies and were deposited on top of tectonic heights such as *Dragonera, Paliomili, Alones, Parliagos, Afea, Vigla and Leodi*, which bordered the shallow marine and brackish inlets. Therefore an uppermost Miocene/Lower Pliocene age for their deposition is envisaged.

It seems that the E-W depression south of the *Dragonera-Paliomili ridge* represented a shallow marine connection between the area of *Aegina/Kypseli and Ag. Marina*. At *Ag. Thomas* (Fig.2) a rather **complete Lower Pliocene section** of ~70 m of silty clays, marls and diatomites is present (BENDA et al., 1979). The age of the uppermost marls has been established by nannoplankton stratigraphy of NN14 as Early Pliocene. These marine sediments transgressively overlie fresh-water to brackish brown sands and silts with some limestone interbeds of uncertain age, containing ostracodes and Planorbidae (*Ag. Thomas section*).

The predominant feature is the occurrence of yellow to greenish marls rich in fine grained conglomeratic and sandy intercalations. The greenish colors are the expression of a high content of chlorite, epidote and serpentine minerals. Trace element analysis yields Chromium contents up to 400 ppm and Nickel contents up to 250 ppm. In addition, the occurrence of a typical shallow water mollusk fauna, containing abundant Pectes and Austreas confirm the marine environment. It has been determined with the help of nannoplankton stratigraphy, that the age of the marl sedimentation persisted most probably throughout the Pliocene (NN 14 to NN 17), thus over a time range of at least 2 million years. Besides the ophiolitic detritus, all the marls contain abundant volcanic clasts and crystals; mainly amphiboles, plagioclase, biotite, as well as dacitic and andesitic lapilli. Basaltic components are missing.

No occurrences of green marls have been detected in the south-central part of Aegina. This applies in particular for the occurrences of the Mesozoic limestones in the *Koutalou* window, which connect the *Moni Island* ridge with the *Alones-Messagros* ridge (NE-Aegina). There, the Jurassic and probably Lower Cretaceous limestones of Koutalou are directly overlain by dacitic pyroclastic deposits. However, typical green Pliocene marls occur at the base of the volcanics in the *Skotini gorge*, at the northwestern beaches of *Marathonas*, at the northern bay of *Moni Island* and south of *Perdika* at *Sarpa Bay*.

VOLCANIC EVOLUTION OF AEGINA ISLAND

Volcanic activity started south of the *Dragonera-Paliomili ridge* (Fig.2). The early volcanic phase persisted from 4.4 to 3 m.a. (MÜLLER et al. 1979), according to Potassium/Argon ages on biotites from early pyroclastic deposits topping the Pliocene section at *Ag.Thomas*, and forming the volcanic base of Aegina island. Two different types of volcanic eruptions probably occurred.

FIRST VOLCANIC EPISODE
(the dacitic phases)

The ***earliest phase*** started with rhyodacitic pumice eruptions from a central vent (***Skotini volcano, DA I***) producing the pumice marl intercalations northwest of *Marathonas* (Fig.2). Simultaneous and subsequent eruptions along E-W tending fissures formed the pyroclastic andesitic dacites and dacitic plugs of ***Palaiochora*** *(DA II)*. At this early stage, the melts could rise rather fast from greater crustal depth along a system of E-W, NNE-SSW faults and their intersection. The latter fault pattern is established in the *Palaiochora* as well as along the eastcoast of Aegina between *Cape Tourlos* and *Cape Peninta*.

Four major volcanic areas (Fig.2) dominated the morphology of Aegina island towards the *end of the first dacitic phases* ***(DA I - DAIII):*** the ***Skotini volcano*** in the west, the ***Palaiochora*** and ***Kokkinovrahos volcanoes*** in the north and northeast, the ***Sfentourion*** *and* ***Megali Korifi volcanoes*** in the south and southeastern parts of the island.

Faulting and assymetric uplift occurred along the east coast during a short phase of compressional tectonic activity. Upward movement of new dacitic melts from greater depth led to the collapse of the summits of the early volcanoes. Large dacitic debris flows moved down into the western depressions of the island, forming epiclastic deposits.

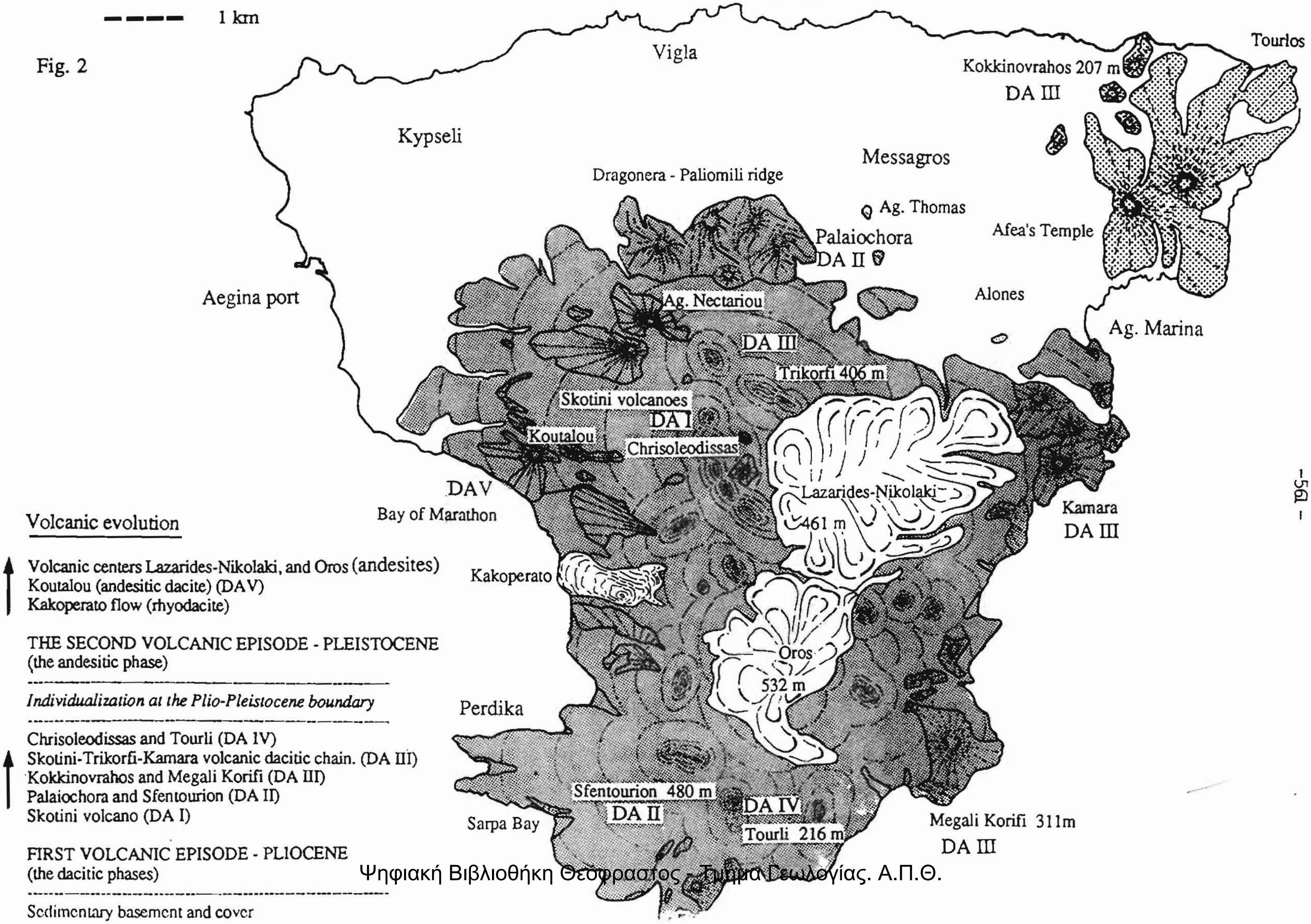
A time gap seems to exist to a later dacitic event in the ***Skotini-Trikorfi-Kamara volcanic dacitic chain.*** *(DA III)*. This feature is evident in the *gorge of Benakides*, west of the ***Kamara volcano*** along the main road between *Ag. Marina* and *Portes* as well as at the shore of *Kypos bay* south of the ***Megalo Korifi volcano*** (Fig.2). Marls and tuffitic sequences mark unconformities between the older dacites and a younger phase at these localities. A marine ingression is evidenced by the presence of a marine shallow water fauna (e.g. Pectes, Cardium) in the Benakides gorge.

Smaller volumes of dacites forming plugs, fissure fillings and local debris flows appeared as the ***terminal phase (DA IV)*** after the emplacement of the large volcanoclastic flows. The fissures are mainly E-W directed. Necks and associated smaller flows occur around the monastery of *Chrisoleodissas* in the central part of the island. In the southern part, three smaller eruption centers were built up.

Geological Map of Volcanic Aegina

1 km

Fig. 2



Time of Individualization at the Plio-Pleistocene boundary

The marine inlets of *Messagros* and *Ag. Marina* were cut off during the period of uplift of the eastern part of Aegina. Probably only small internal lakes and ponds formed between *Ag. Nectariou, Messagros and the Afea's Temple.* This area was bordered to the north by the *Paliomili ridge,* in the east by the *Kokkinovrahos volcano,* in the south by the *Messagros ridge,* and further south by the *Benakides-Kamara* volcanic products. The deposition of calcareous sandstones (the Pleistocene Poros) started along the northern and eastern shores.

The length of the time span during the Plio-Pleistocene boundary is uncertain. It might be that the *period of individualization* persisted for a rather long time, probably even *1 million years*. Indication for a long pause of volcanic activity is based on morphological observations. The surface topography is fairly levelled. The dacitic flow surfaces are often polished. In many cases, they are only covered by Poros deposits.

THE SECOND VOLCANIC EPISODE
(the andesitic phase)

The timing of the **second volcanic episode** is difficult to establish, but it definitely occurred during the Pleistocene. It certainly is linked again to extensional tectonics. It started in the central part of the island at intersections between the NNE-SSW and E-W faults ***(Koutalou, DAV)*** bordering the *bay of Marathonas*.

The first occurrence of volcanic activity has been recognized at the *plain of Portari*. There, phreatic eruptions deposited pumice, lapilli and bombs of rhyodacite on an eroded and polished epiclastic surface from the first dacitic period. Two larger rhyodacitic-dacitic flows were extruded subsequently towards the *shores of Marathonas* (Fig.2). The ***Kakoperato flow*** reaches a maximum thickness of 100 m at a length of 1000 m. The rhyodacitic eruptions are regarded as precurser of the andesitic phase building up the highest ***volcanic centers Lazarides*** *(461 and 447m) and* ***Oros*** *(532m)*.

The emplacement of the magmas occurred mainly along vertically dipping and ENE-WSW striking feeder dikes. The stratigraphic order of the minor pyroclastic deposits (lapilli, bombs and scoria) and thin lavas from bottom to top is: hornblende andesite, high-alumina basalt, andesite and hypersthene-andesite.

Three eruptive centers developed at ***Oros***: one forming the highest top of the dikes and two northern satellite vents from which flows extruded into the *depression of Anitsaion*. The eruptive morphology of Lazarides is quite different. Although the lavas were extruded in the same stratigraphic order as at Oros, eruption started from one or ***two vents at Nikolaki*** and continued from a long fissure of several kilometers eastward down to *Kamara*.

At the end of the andesitic phase, a late morpho-volcanological event occurred and created a steep flanc which now dips down from the top of *Oros* towards northeast into a large channel ending at the village of *Anitsaion*. This phenomenon could be a result of either a late lateral blast from the top vent or a large rock avalanche, due to subsequent doming. It was certainly controlled by the younger ENE-WSW fault system. This volcanolclastic event was the final effect of the second volcanic episode. No further volcanic products or fumarolic activity have been detected in the vicinity of the andesitic vents.

HYDROTHERMAL ACTIVITY

Two hydrothermal zones, approximately N-S to NNE-SSW striking, cross the island. The major zone runs down from the vicinity of *Souvala*. There, thermal waters with low temperatures of ~25°C appear today in two places. Hydrothermal alteration occurs further south in the dacitic edifice north and south of the *Vouno Dendrou* ridge and north of *Koutalou*. The dacites are in parts highly kaolinitized, sulfur impregnations occur. The second zone of hydrothermal alteration is aligned with a vertical dipping, NNE-SSW striking fault zone in the dacites and Neogene sediments at *Cape Kyranitcha*.

MAGMATIC EVOLUTION

As a common feature, all lavas and pyroclastics contain numerous inclusions of basaltic and andesitic composition with quenched and acicular textures. These"pillowed" phenomena may be caused by injecting hot basaltic and andesitic melts into a magma reservoir filled with cooler dacitic to rhyodacitic melt.

Cumulates of hornblenditic to hornblende gabbro composition are rare. Intrusive, metamorphic, and sedimentary xenoliths are missing.

Amphiboles are the most common mafic minerals in all volcanic rocks on Aegina island. They occur as pheno- and xenocrysts in rhyodacitic and dacitic rocks, as well as in basaltic and andesitic rocks. However, the amphiboles show a large variation in mineral chemistry from Mg-rich hastingsite through evolved hastingsite and hornblende.

I. CRYSTAL FRACTIONATION

The **first step of crystal fractionation** led to the production of olivine basalts from an inferred primitive, calcalkaline basaltic melt. Tracers of this process are forsterite-rich olivine and chromespinel inclusions in amphiboles within cumulates. The early olivine (Fo_{90}) phenocrysts must have formed from a water-bearing, primitive low-Ti basaltic melt (x_{mg}=0.74, K_2O=1.9 wt.%, TiO_2=0.9 wt.%, Ba=800 ppm, La=29 ppm, Eu=1.5 ppm, Yb=2.3 ppm, Y=17 ppm, Sc=25 ppm. Besides olivine and Cr-spinel, clinopyroxen and anorthitic plagioclase were involved in this fractionation process.

Mg-hastingsitic amphibole, rich in Al, Ti, Na and K, clinopyroxene, plagioclase (An_{90-85}), and magnetite represent the **second step of crystal fractionation**. Amphibole and anorthitic plagioclase are present in various proportions as the two major xenocryst phases in most of the lavas and thus, appear to be the important "magmatic guide fossils" with respect to fractional crystallization processes. The depth of fractional crystallization can be inferred from the amphibole stability field. Hastingsitic amphiboles are stable at 10 to 18 kb and 460 to 1025°C, thus deep in the crust and probably close to the mantle-crust boundary. The extraction of these minerals, particularly amphibole with its complex composition, drastically changes the composition of the remaining melt by extracting Mg, Ti, Fe, Al, Ca and other elements, leaving a depleted but silica-enriched rhyodacitic melt behind.

Pumice, pyroclastics and lavas of rhyodacitic composition are the first volcanic products in Aegina, Methana and the adjacent volcanic fields in the Saronic gulf area. These rhyodacites are small in volume and lack cumulate relicts.

II. GENERATION OF DACITES by mingling processes (mechanical mixing)

The dacites build up the large edifice during the first volcanic episode with an estimated volume of 95% of the total volcanic rocks on Aegina island. All dacites contain variable amounts of magmatic xenolithic inclusions.

The macroscopic diversity goes down to microscopic scale. Small sized (1-5 mm) xenolithic inclusions and xenocrysts occur in a rhyodacitic matrix. The xenocryst compositions in the dacites are identical with the minerals fractionated in the second stage, whereas the phenocrysts compositionally match the phenocrystsfrom the rhyodacites. No progressive zonations are recorded in the amphiboles and in the plagioclases. The complex textural diversity is also reflected in the bulk chemical composition which changes from one extrusion site to another and even within one flow or plug.

The different types of dacitic rocks can be derived by simply **mingling minerals of the cumulates or pseudocumulates with the rhyodacitic melt**. The process of mingling is regarded as a mechanical mixture which can be achieved by a thermal turnover in the magma chamber.

III. GENERATION OF HIGH-ALUMINA BASALTS AND ANDESITES (magma mixing)

The following magmatic process shall explain the appearance of the small volumes (~5 % of the total volcanic edifice) of hornblende andesite, high-alumina basalt, basaltic andesite and hypersthene andesite during the second volcanic episode on Aegina.

The basalts and andesites exhibit a common feature: resorption and remelting of amphibole and plagioclase. In the basal "hornblende andesites", the amphibole is not a phenocryst phase but always a Mg-hastingsitic xenocryst phase partly transformed into black opacitic aggregates. In the high-alumina basalts, the amphiboles show all steps of resorption and reaction from Mg-hastingsite often including forsteritic olivine to diopsidic augite, magnetite, plagioclase, and glass. Further reaction leads to the recrystallization of these clinopyroxene aggregates to clinopyroxene "phenocrysts". The groundmass phenocrysts are andesine, hypersthene and olivine (Fo_{65}) in a groundmass glass of dacitic to rhyodacitic composition. The hypersthene andesites are texturally and mineralogically fairly homogeneous and show only few and completely resorbed amphibole relics. These strange textural and mineralogical features cannot be explained by simple fractional crystallization olivine, spinel, clinopyroxene and plagioclase from a primitive basaltic melt or by direct melting a small proportion of an upper mantle peridotite.

A partial melting process of the cumulates by continuous replenishment of the deep seated magma chambers with hot and primitive basaltic melt is envisaged. In addition, **mixing of these hybrid melts with various proportions of rhyodacitic melts** in the overlaying magma reservoirs generated the high-alumina basaltic to andesitic melts.

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