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NEOTECTONIC AND ENGINEERING GEOLOGICAL MAPPING OF THE AREA OF RHODOS MUNICIPALITY, GREECE, AS A TOOL FOR EARTHQUAKE PLANNING AND ORGANIZATION

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ABSTRACT: The main outcomes of a pilot research project are presented, concerning the usefulness of the knowledge of the particular geological, neotectonic and geotechnical conditions for the elaboration of an earthquake planning and organization of a city, applied on the case of Rhodos Municipality, Greece. The various geodynamic destructive phenomena which may occur following a seismic activity (reactivation of active fault zones, rock falls, landslides, liquefaction, shoreline displacement, e.t.c.) have been studied and drawn on a detailed map of the area.

1 INTRODUCTION

The city of Rhodos lies at the very north edge of Rhodos island, the biggest and most touristically developed island of Southeastern Aegean. Its neighborhood to the eastern part of the active Hellenic Arc, along which a sinistral almost horizontal movement between the underlying African Plate and the overlying Aegean (European) Plate is in progress, is responsible for its high seismicity (McKenzie 1977, Le Pichon & Angelier 1979, Drakopoulos et al 1988, Mariolakos & Papanikolaou 1984, Papazachos & Papazachos 1989).

The high relief of the island, the numerous active faults and fault zones, the deformation of the Pleistocene and Holocene sediments, the vertical displacement of shorelines, as well as the historical reports on destructive earthquakes in the Antiquity and the results of the instrumental seismology in the recent years compose the profile of a very active area in terms of neotectonic and seismicity.

Since the city of Rhodos itself is characterized by a rapid and rather anarchous growth during the last years, a large population (about 50.000 people) and an enormous touristic development it therefore belongs to the most seismic risky areas of Greece.

For that reason the city of Rhodos and the adjacent areas belonging to it have become the object of a pilot applied research project elaborated by the Department of Dynamic, Tectonic and Applied Geology of the University of Athens and financed by the Municipality of Rhodos. The main goal of the project was the creation of a detailed and composite geological, neotectonic and geotechnical map of the area which will be used as the main tool for the earthquake planning and organization of the city.

The methodology followed on this project as well as the most important results and the geological - neotectonic map of Rhodos Municipality are presented below.

2 GEOLOGICAL-NEOTECTONIC FRAME OF RHODOS ISLAND

Sedimentary, metamorphic and ophiolitic rocks consist the alpine basement of Rhodos island. They belong to six alpine units, the most of which are known from Mainland Greece and which are the Lindos/Mani unit, the Wild Flysch of Laerma, the Attavyros/Ionian unit, the Archangelos/Tripolis unit, the Profitis Ilias/Pindos unit and the Ophiolitic Nape. Molassic rocks of Oligocene age occur also on the island (Mutti et al 1970, Lekkas et al 1993).

Four main postalpine Neogene - Pleistocene basins are visible on the island. Their evolution is clearly controlled by major marginal fault zones, dividing the postalpine sediments from the alpine basement. Many of these fault zones, usually

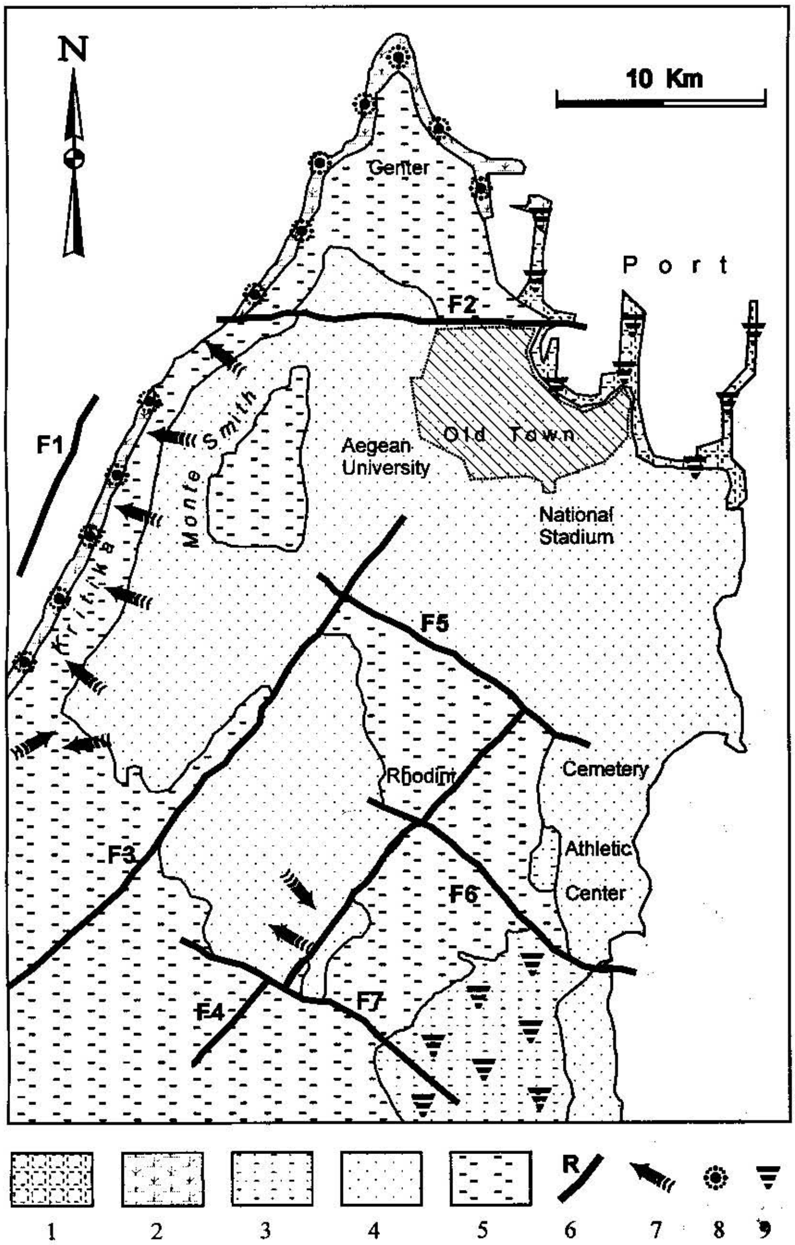

Fig. 1. Simplified geotechnical map of Rhodos Municipality. (1) reclaimed land, (2) coastal deposits, (3) alluvial deposits, (4) "Rhodos" formation (5) "Asgourou" formation, (6) faults and fault zones, (7) areas dangerous for rock falls and landslides, (8) areas dangerous for liquefaction phenomena, (9) areas dangerous for subsidence phenomena.

trending E-W, are still active up today, creating thus significant large scale morphological discontinuities between the mountainous alpine area and the low relief postalpine area. The most important fault zone of the island with significant dextral strike slip movement trends E-W is located in the central part of it. It divides the island to a northern and a southern part with many differences in their geotectonic evolution. This fault zone may represent the reactivation of an older alpine feature in the postalpine time.

Numerous active faults and fault zones create a puzzle like structure mainly along the eastern coast of the island, where small high relief areas built up by alpine rocks alternate laterally or rise above the younger Plio-Pleistocene sediments (Gauthier 1979, Lekkas et al 1993). The entire island undergoes an eastward rotation around horizontal axis striking NE-SW, parallel to the long axis of the island (Laj et al 1978). Strong evidence of this rotational movement is the asymmetric development of the drainage system of the island and of the superficial distribution of the younger postalpine Plio-Pleistocene sediments.

3 GEOLOGICAL FRAME OF RHODOS MUNI-CIPALITY

The area occupied by the Municipality of Rhodos is located in the northeastern part of the postalpine basin of Northern Rhodos.

Three geological formations (Fig. 1) outcrop in the city of Rhodos and the adjacent areas: the Upper Pliocene - Lower Pleistocene Asgourou Formation, the Pleistocene Rhodos Formation and the recent Holocene Deposits.

3.1 *Asgourou Formation*

The oldest Asgourou Formation covers the greatest part of the Municipality area. It consists mainly by lacustrine mars, clays and silts with some remarkable intercalations of conglomerate and sandstone horizons. The Upper Pliocene - Lower Pleistocene age of the Formation has been established by numerous micro- and macrofossils (Mutti et al 1970, Meulenkamp et al 1972, Broekman 1974).

Typical outcrops of the lithostratigraphic sequence of the Asgourou Formation occur along the northwestern flanks of Mt. Smith in Kritika area. The maximum thickness reaches 130 m, measured in Kritika area, where only its upper contact to the Rhodos Formation is visible. The lower contact of the Asgourou Formation to the Miocene(?) - Pliocene sediments (“Levantin” after Mutti et al 1970) does not outcrop within the area of Rhodos Municipality. A few kilometers to the west, in Filerimos, the maximum thickness of the formation exceeds 200 m.

Within the 130 m thick marls, clays, silts and fine sands of the formation outcropping in Kritika area there are at least three conglomerate horizons of up to 10 m thickness visible. They interrupt the uniform relief of the slope creating significant morphological discontinuities.

The frequent lateral and vertical lithological alterations within the Asgourou Formation reconstruct the rapid changes of its deposition environment between lacustrine, fluvial, deltaic and brackish conditions.

The Asgourou clastic sediments dip usually with 5^{o}-10^{o} to ESE except in the vicinity of faults where the bedding is disturbed.

3.2 *Rhodos Formation*

The Pleistocene Rhodos Formation overlies conformably or slightly unconformably the clastic sediments of the Asgourou Formation. The transition to the Rhodos Formation marks a final change of the deposition environment from terrestrial - lacustrine - brackish to marine conditions. The upper beds of the Asgourou Formation just below the contact to the Rhodos Formation are characterized by cm-thick horizons of brown to yellow marls and silts alternating with white calcitic horizons.

Rhodos Formation itself consists mainly of marine bioclastic massive limestones of up to 10 m thickness. They crop out within the city of Rhodos and build up usually the top of the hills of the Municipality. Although mapping the Rhodos limestones was easy for the greatest part of the area, it was very problematic within the city, where outcrops are limited to excavations, archaeological sites or river sides and steep slopes.

The massive limestones of Rhodos Formation control clearly the morphotectonic evolution of the area where they outcrop. The most extended terraces and flattening surfaces have been developed on the roof or the bedding of the limestones and follow their dip. Typical examples are the eastern slope of Mt. Smith and the area of the Old City of Rhodos. Both of them dip slightly to ESE following the bedding of the Rhodos limestones.

3.3 *Holocene Deposits*

The youngest geological formation of Rhodos Municipality are the Holocene and recent alluvial, coastal and river deposits and the debris flows and rock falls outcropping along the steep slopes of the area.

The most of them are of minor interest due to their limited spreading and because they mainly occur in areas of no building activities as the beaches and the river beds.

On the contrary the localization of the previously existing debris flows, landslides and rock falls is very important. All these deposits represent a possible future threat for the areas lying along the foot of the steep slopes where they occur. Typical outcrops of such deposits are visible along the northwestern slopes of Mt. Smith, which are built up by the clastic sediments of the Asgourou Formation overlain on top by the Rhodos massive limestones.

4 NEOTECTONIC STRUCTURE OF RHODOS MUNICIPALITY

The area of Rhodos Municipality follows the ESE-ward rotational movement of the entire island, which seems to be the dominant neotectonic process.

The effects of this rotational movement in the Municipality area can be seen in the clearly asymmetric, ESE-ward verging, development of the geological and geomorphological features of the area (Fig. 1). These are (i) the constant ESE-ward dipping of the bedding of the Asgourou clastic sediments and of the Rhodos limestones as well as the surfaces of the slight angular unconformities and of the terraces and flattening surfaces which follow the bedding, (ii) the asymmetric development of the drainage pattern and (iii) the asymmetric distribution of the morphological slopes in SE-NW direction - the NW-facing slopes are almost always much steeper than the SE-facing ones.

The rotational movement in the Municipality area is under the control of the interaction of two fault systems running perpendicular to each other.

The first fault system contains three (F1, F3 and F4) normal faults/fault zones of SW-NE trending, which run parallel to the bedding and to the axis of rotation and dip NW-wards, antithetically to the bedding. This fault system offsets stepwise the bedding of the Asgourou and Rhodos sediments creating steep NW-dipping slopes and slightly inclined, SE-dipping terraces and flattening surfaces following the bedding of the sediments. The vertical displacement between the foot wall and hanging wall of each of F3 and F4 fault zones is 30 - 40 m while the total vertical offset along the F1 fault zone must exceed 200 m.

The F1 fault zone runs offshore, parallel to the northwestern coast of the Municipality. It is responsible for the creation of the steep northwestern slopes of Mt. Smith along which rock falls and land slides are very frequent. Falling rocks of up to 10 m diameter or more are visible along the coastal road connecting the Kanaris Beach of the city of Rhodos with the Kritika area. They derive either from the conglomerate horizons of the Asgourou Formation occurring along the slope within the thick marls and clays and/or from the bioclastic limestones of Rhodos Formation resting on top of the slope.

The F3 fault zone runs across the western part of the Municipality from Rhodopoula in the SW to the Arapaki area within the city of Rhodos in the NE. It produces a clear offset of the base of Rhodos limestones and creates a remarkable morphological discontinuity running parallel to Petridis street in the southwestern part of the city.

The F4 fault zone runs parallel to the Rhodos - Lindos road and to the Rhodini river in the southern part of the city crossing the Rhodini area.

The second fault system includes four faults/fault zones (F2, F5, F6 and F7) which trend E-W to SE-NW, perpendicular to the bedding and the traces of the first fault system. They are normal faults/fault zones dipping to N or NE and are characterized by an increasing vertical offset going from E/SE to W/NW along their trace. This differential movement between the edges of the fault traces supports or is caused by the ESE-ward rotational movement of the area.

The F2 fault zone runs E-W along the foot of the northern slope of Mt. Smith and through the northern branch of the Medieval Trench, dividing the northern flat part from the rest of the city. The vertical displacement of the base of Rhodos limestones at the western edge of the fault zone exceeds 60 m. Further to the East, near D'Amboise Gate, it is reduced to 10 - 15 m, while at the eastern edge of the zone, near the port, it is worthless.

The F5 fault zone runs NW-SE through the city of Rhodos, parallel to the Anna-Maria street and is visible from the Arapaki area to the eastern coast of the city. The vertical offset of the Fault zone at its northwestern edge is about 20 m while at the eastern coast is reduced to less than a few meters. It is worth noting that the Rhodini river, running SW-NE parallel to the F4 fault zone at its longest part, turns to SE parallel to the F5 fault zone at their crossing.

The F6 and F7 fault zones produce only slight morphological discontinuities and displace the trace of the F4 fault zone.

All the above described faults/fault zones cut off the Pliocene and Pleistocene sediments of the area and produce more or less remarkable geomorphological structures. Therefore they can be undoubtedly considered as active faults.

5 ENGINEERING GEOLOGICAL ENVIRONMENT - GEODYNAMIC DESTRUCTIVE PHENOMENA

The various geological formations outcropping in the area of Rhodos Municipality show different geotechnical characteristics.

The massive bioclastic limestones of Rhodos Formation offer a very good foundation basement due to their massive character. It is worth noting that the entire Old City of Rhodos with its surrounding Wall has been built up on these massive limestones. The bioclastic limestones have been also used during the previous times (Antiquity, Roman and Medieval times) as construction material. There are many archaeological sites within and around the city of Rhodos evidencing ancient constructions either cultivated on the Pleistocene limestones or constructed by using blocks from them.

The various finegrain sediments of the Asgourou Formation, as marls, clays, silts and semicoherent sands consist a more or less negative foundation basement due to their poor cohesiveness. The greatest part of the new city of Rhodos is based on top of these materials.

The allouvial, fluvial and coastal loose deposits of Holocene show very negative geotechnical coefficients and therefore any building activity upon them should be avoided.

Beyond the various geotechnical characteristics of the geological formations outcropping in the area of Rhodos Municipality there are also some other factors, which clearly influence the engineering geological environment as well as the seismic hazard of the city and were evidenced during the mapping of the area.

A very important factor is the presence of the numerous active faults and fault zones which cross the area of the Municipality and create significant morphological discontinuities even within the city of Rhodos. It is remarkable that the F2, F3, F4 and F5 fault zones run through the houses, hotels and public buildings of the city and consist a serious possible future threat. For example the General Hospital of the Island lies about 100 m away from the trace of the F2 fault zone. This fault zone divides also the triangular northern part of the city from the rest of it. A possible reactivation of it could cause serious damages and destroy the roads connecting the two parts of the city. Similar phenomena may also appear following a possible reactivation of the other fault zones crossing the city.

Rock falls and landslides are also common destructive phenomena which appear along the steep slopes of the area either independently or following a seismic activity. The NW-facing fault-created steep slopes of the area are the most hazardous areas for their appearance, which is favored by the geological structure. The cohesive conglomerate horizons intercalated within the soft marls of the Asgourou Formation as well as the massive Rhodos limestones resting on top of the Asgourou marls are the source horizons of the falling rocks. They are visible along many slopes of the area but most impressively along the road connecting the city with the Kritika area at the northwestern coast. Additionally the soft marls and clays of the Asgourou Formation favor the appearance of landslides.

Liquefaction and ground sinking phenomena may also appear in areas covered by allouvial deposits as effects of a seismic activity.

An additional phenomenon which might be caused by a possible reactivation of the fault zones running through the area of Rhodos Municipality is the differential vertical displacement of the shorelines. Several paleo-shorelines are visible mainly along the eastern coast of the island lying up to about 4 m above the present mean sea level. Pirazzoli (1988) and Pirazzoli et al (1989) studied them and proved repeated vertical movements of the coastal region during the last 6.000 years caused by fault activity. The most impressive event was the sudden uplift of about 3,8 m of the northernmost part of the island, including the area of Rhodos Municipality, which is likely to be linked with the earthquake which destroyed the Colossus in 227 B.C.

6 CONCLUSIONS

The previous described geological and engineering geological conditions, including the possible destructive geodynamic phenomena which may occur following a seismic activity in the area of the city of Rhodos, enlist it to the most seismic risky areas of Greece. Therefore the elaboration of the earthquake planning and organization of the Municipality of Rhodos is indispensable.

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