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Geomorphological Observations in the Coastal Zone of Kyllini Peninsula, NW Peloponnesus-Greece, and their Relation to the Seismotectonic Regime of the Area

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ABSTRACT

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The Kyllini Peninsula comprises an isolated hilly region and occupies the western part of the alluvial plain of Peneios River. It owes its morphology to a Triassic salt dome intrusion active since Miocene times. During the Quaternary it was covered by the sea, became an island and was finally joined to Peloponnesus with the alluvial deposits of Peneios River.

In this study an attempt is made to correlate the coastal landforms with the seismotectonic regime of the broader area of Kyllini Peninsula.

Raised Tyrrhenian shorelines occur at elevations ranging from sea-level up to 60 m. Holocene uplifted shorelines, wave cut benches, abrasion platforms and notches have been observed, at heights between 0.3 to 3 m. Furthermore, the coastal zone is characterized by beachrock and a series of dunes of two different generations as well as raised aeolianite.

Geophysical investigations of the deep geological structure of the region have also revealed the offshore presence of salt diapirism as well as large faults in the area of Zakynthos Straits. The seismicity of the area is known to be high, with the epicenters of many earthquakes located mainly along the Zakynthos Straits. Examples of such activity are the five shallow earthquakes with magnitudes greater than 5.5 on the Richter scale, that have been recorded in this century.

Based on the study of the coastal landforms, radiocarbon dating and the seismotectonic regime of the area, it is concluded that the uplift is primarily the result of neotectonism and secondarily, diapirism.

INTRODUCTION

The peninsula of Kyllini comprises an isolated hilly region of about 130 km^2 and is located at the westernmost end of Peloponnesus (Figure 1). It is formed by a morphological rise (244 m at Kastron, the highest point) connected to mainland Peloponnesus in the east by the floodplain of Peneios River (plain of Elis). North of Kyllini extends the gulf of Kyllini, south of it the Chelonitis gulf and in the west the straits of Zakynthos.

The Kyllini promontory was called 'Chelonatas' in ancient times, probably due to its form, resembling the back of a turtle ('Chelona' = turtle). The broader area of the plain of Elis has been inhabited since prehistoric times and the earliest signs of human occupation are placed in the palaeolithic period (Mousterian finds at Kastron, CHAVAILLON *et al.,* 1967, 1969). According to RAPHAEL (1973), the conspicuous absence of pre-Classical archaeological sites in the Holocene Peneios floodplain suggests that Kyllini Peninsula could have been an island at those times. Subsequent progradation of the Peneios delta joined Chelonatas to the Eleian seaboard. RAPHAEL (1973) estimates rates of coastal accretion as high as 1.85 m/yr during the Roman occupation. From the writings of Strabo, it is known that the Peneios River emptied into the gulf of Kyllini in antiquity, whereas today it debouches to the south-east of Chelonatas. The shift probably took place in the late 18th century.

The ancient harbor of Kyllini prospered in classical times as the seaport of nearby Elis, the city-state responsible for the organization of the festivities in honor of the Olympian Zeus, part of which were the well-known Olympic games. The exact location of ancient Kyllini is unknown, since finds related to the city are scarce.

Based on relative and absolute dates of the coastal features an attempt is made to correlate the coastal landforms of the Kyllini Peninsula with the seismotectonic regime of Western Peloponnesus in order to draw conclusions on whether the

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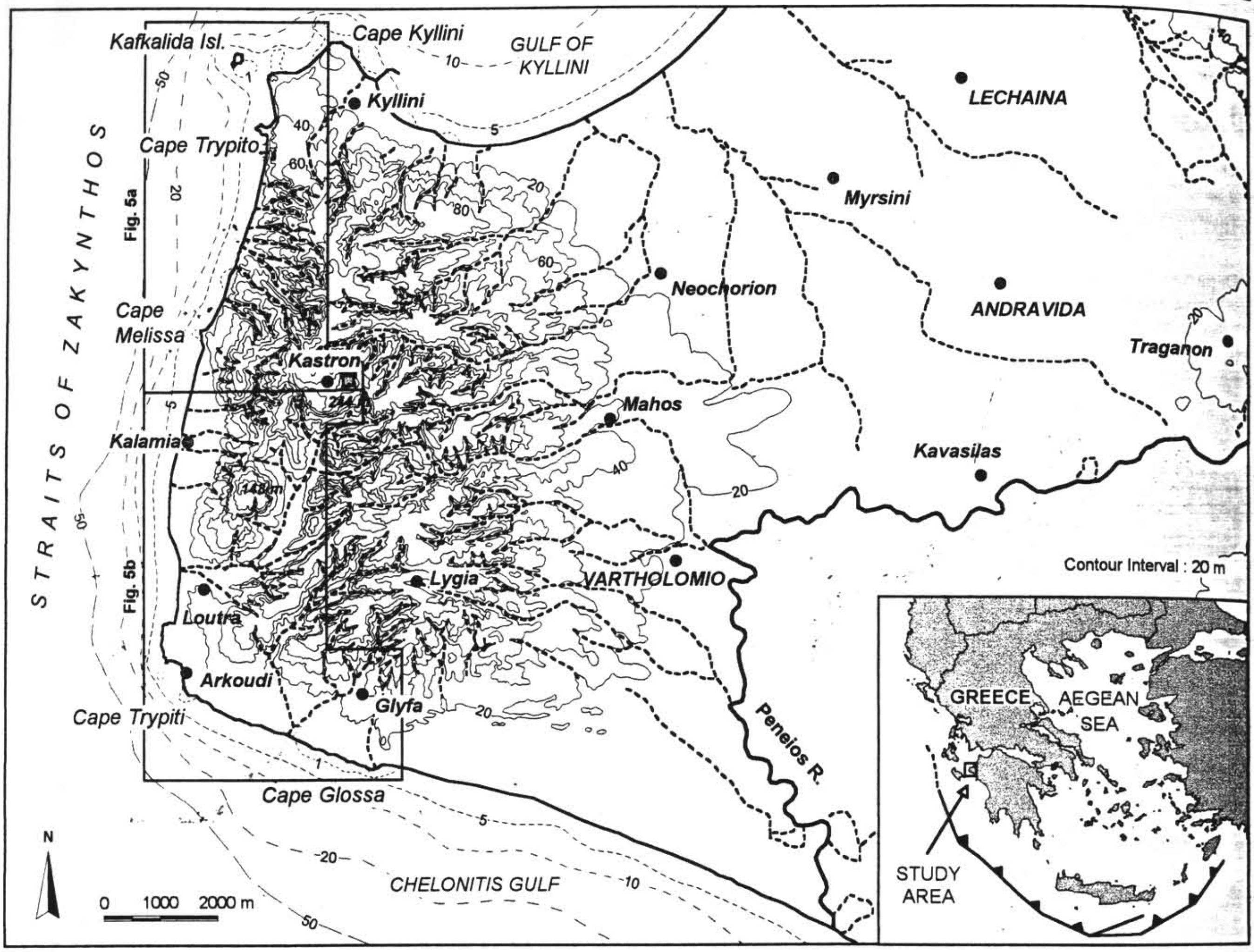


Figure 1. Topographic map of the Kyllini Peninsula based on 1:50.000 H.A.G.S. maps (Vartholomion sheet). Inset shows the location of the study area in Greece as well as the Hellenic trench.

observed uplift movements are attributed to neotectonism or local diapiric phenomena.

GEOLOGY

In the peninsula of Kyllini post-alpine formations prevail, with only a few outcrops of the alpine basement present (Figure 2). The alpine rocks belong to the Ionian geotectonic unit and they include the white thin-bedded Cretaceous-Eocene limestones of Trypito, Kastron and Oros, as well as the diapiric intrusions of Triassic evaporites which crop out at the western part of the peninsula (CHRISTODOULOU, 1969). The diapirism has been active since Miocene times.

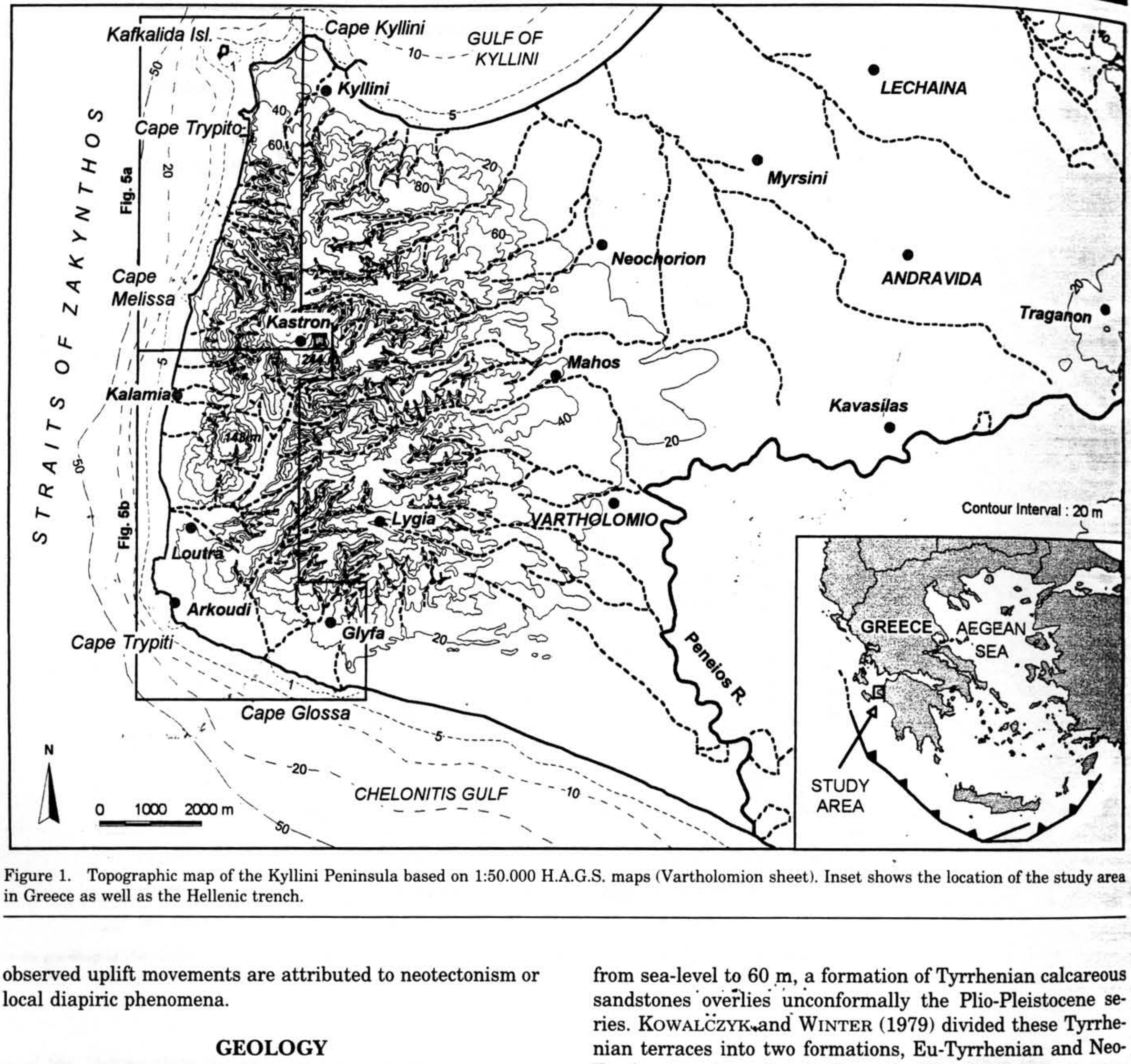
Above the alpine formations are found the Lower Pliocene conglomerates and a Plio-Pleistocene series of sands, sandstones, clays and marls that is at least 400 m thick. This series, which is dominant in the peninsula, is characterized by an alternating shallow marine, brackish and lacustrine facies.

Peripheral to the Chelonatas hills, at elevations ranging from sea-level to 60 m, a formation of Tyrrhenian calcareous sandstones overlies unconformally the Plio-Pleistocene series. KOWALCZYK and WINTER (1979) divided these Tyrrhenian terraces into two formations, Eu-Tyrrhenian and Neo-Tyrrhenian. According to them the Neo-Tyrrhenian terrace (Wurm I/II interstadial age) has formed at elevations of 3–4 m in the coastal zone between Cape Glossa and Loutra and has a thickness of a few meters, while the Eu-Tyrrhenian terrace which is of Wurm-Riss interglacial age, reaches inland to its highest elevations in the northern part of Kyllini Peninsula. MARIOLAKOS et al. (1991) report the same formation at an elevation of about 150 m (near Kastron), but this determination was not verified in the present study.

The recent formations consist of alluvial deposits occupying the lowlands made up of colluvium, talus, fluvio-torrential sediments, coastal dunes and beach material.

TECTONICS

The area of western Peloponnesus is characterized by a compressional regime undergoing the consequences of the



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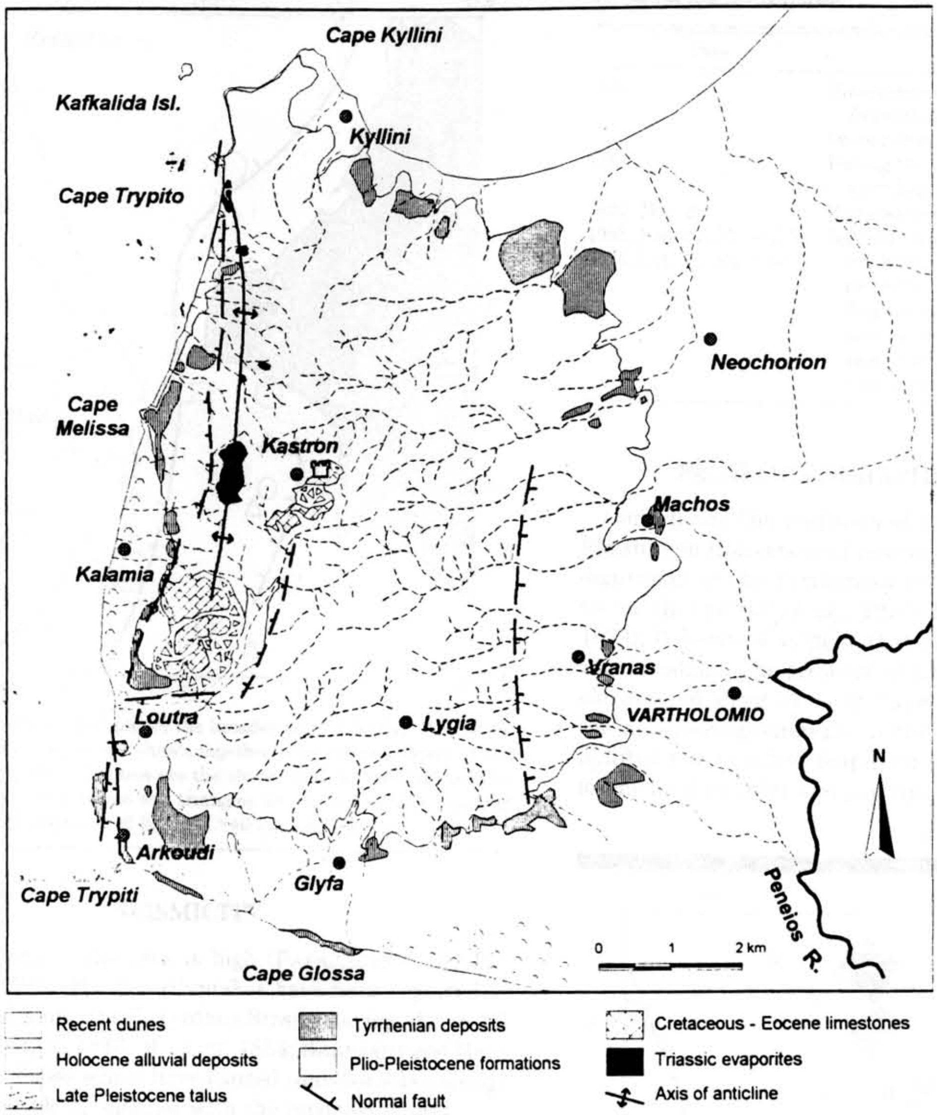

Figure 2. Geologic map of the Kyllini area (after CHRISTODOULOU, 1969; KOWALCZYK and WINTER, 1979, and field observations).

subduction of the African plate beneath the Eurasian plate. The subduction is taking place along the Hellenic Trench located offshore. The compressional regime is well documented by the reports of different researchers (SOREL, 1976; MCKENZIE, 1978; ANGELIER *et al.*, 1982; HATZFELD *et al.*, 1990).

On the contrary, the strait between the peninsula of Kyllini and the island of Zakynthos, is a linear submarine valley system of tectonic origin which runs parallel to the seaboard of Peloponnesus (Figure 3). This graben has been clearly mapped from geophysical investigations and it is bounded by two major normal faults (BROOKS and FERENTINOS, 1984). The valley floor is flat and it is about 7.5 km wide. The side walls are very steep, with an average height of 300 m. The average slope is 1:5, but in some places it is as steep as 1:2.5 (FERENTINOS *et al.*, 1985). The graben is considered to have been formed during the middle Pleistocene (KOWALCZYK and WINTER, 1979).

In the Kyllini Peninsula, active salt diapirism since the Miocene is another tectonic factor. The pressure of the overlying sediments and the lateral eastward compression have triggered off diapiric phenomena in the basement evaporites (UNDERHILL, 1988). The evaporite intrusions are located along a NNW-SSE axis, uplifting the Plio-Pleistocene sedimentary cover into an asymmetric anticline with the same trend and dipping NNW. Associated with diapirism, many normal faults and joints striking mainly N-S and E-W dissect the Plio-Pleistocene formations. Related to diapirism-induced faulting, is the presence of hot springs in the south-western part of Kyllini (Loutra).

It is therefore evident that the area of Kyllini Peninsula is mainly affected by the faults located in the Zakynthos straits and the local ones formed during the process of diapirism.

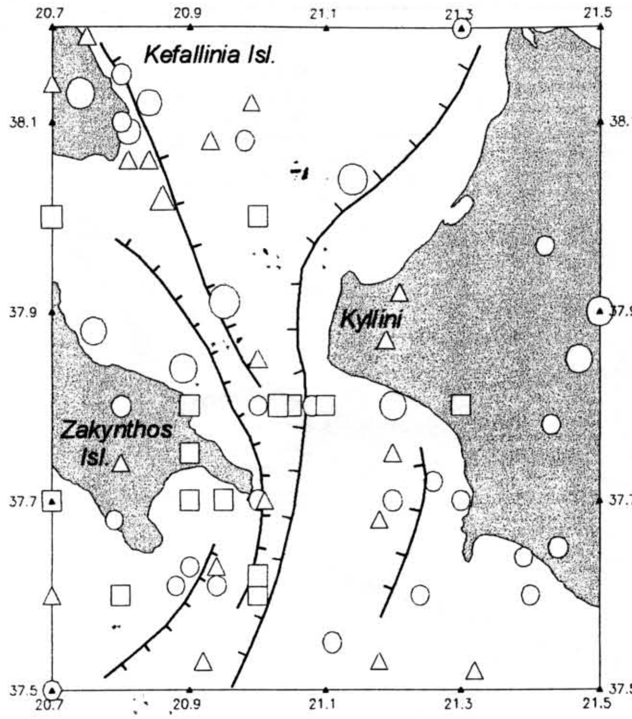

Figure 3. Seismotectonic map of the broader area of Kyllini Peninsula. The main offshore faults are shown together with the epicenters of the strongest earthquakes. Squares are the shocks that occurred during the historical period while circles and triangles are instrumentally recorded earthquakes with depths ≤40 km and >40 km respectively.

SEISMICITY

The seismicity of the area is high (PAPAZACHOS and PAPAZACHOU, 1997). Many earthquakes have been reported to have occurred along the Zakynthos Straits during the last 5 centuries (PERREY, 1848; MALLET, 1854; BARBIANI and BARBIANI, 1864). Those which have caused considerable damage are listed in Table 1, together with the reported effects.

In the present century, 5 shallow earthquakes (Figure 3) with magnitudes greater than 5.5 of the Richter scale were recorded in the area; those of 1903 (March 15, Ms=5.7), 1909 (July 15, Ms=5.7), 1926 (February 26, Ms=5.6) and 1968 (March 28, Ms=5.9).

The most recent earthquake activity occurred in 1988 with strong shallow shocks (Figure 4). The stronger foreshock of Ms=5.5 was that of September 22 (38.04°N–21.14°E, h=10 km) (PAPANASTASSIOU, 1996). Several shocks with Ms≥4.0 were recorded between September 22 and October 15. The activity shifted southwest and on October 16 a strong earthquake (Ms=6.0) occurred (37.91°N–20.95°E, h=14 km; PAPANASTASSIOU, 1996). The aftershock activity continued during the next months but was not significant. This activity was correlated with activation of the submarine normal faults of the Zakynthos Straits (PAPANASTASSIOU ET AL., 1992), in accordance with the CMT Harvard solution, which corresponds to normal faulting with a significant horizontal component on fault planes having directions 301° and 32° and dipping 76°NE and 87°SW respectively.

Table 1. *Known earthquakes that have affected the Zakynthos Straits during the last five centuries.*

Date	Effects
1633	Emergence of land in the southern coast of Zakynthos Island. Occurrence of a tsunami
1791	During the aftershock sequence, fishermen were hearing roars from the sea
1820, Dec. 29	Occurrence of a tsunami
1988, Sep. 22, Ms = 5.5 1988, Oct. 15, Ms = 6.0	Serious damage particularly in the area of the Kyllini Peninsula. Rockslides, minor rockfalls, wedge failures as well as surface fissures and liquefaction phenomena have been observed in the epicentral area, but along the coast no vertical movements were identified (Fritzalas *et al.*, 1992).

PALAEOGEOGRAPHIC EVOLUTION

Considering the evolution of the Kyllini area in the Late Pleistocene-Holocene and taking into account the peripheral occurrence of the Tyrrhenian deposits up to an elevation of 60 m (KELLETAT *et al.*, 1976; KOWALCZYK and WINTER, 1979), it becomes evident that about 10^5 years ago Kyllini was an island. The presence of Eu-Tyrrhenian deposits at an elevation of about 47 m at Cape Melissa, 15 m higher than the neighboring outcrops, indicates that this area has been uplifted due to active diapirism in the Late Pleistocene-Holocene by that order and perhaps a little more in the area of

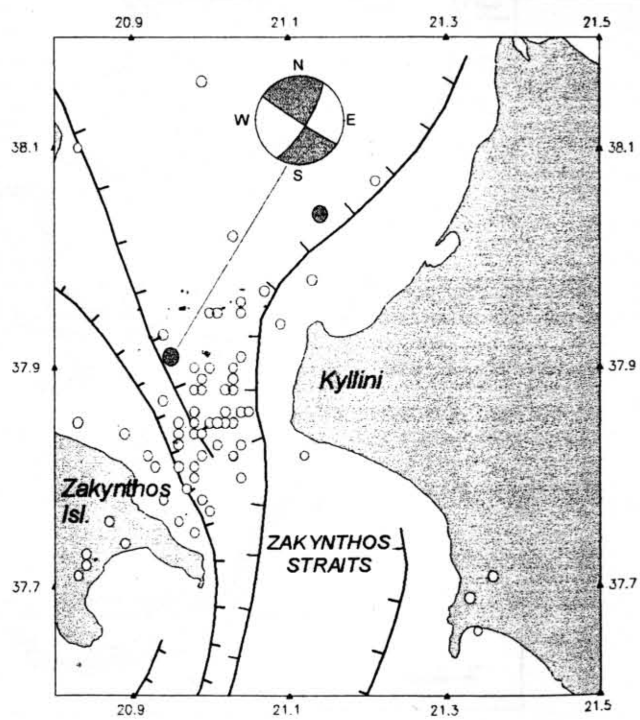

Figure 4. Spatial distribution of the epicenters of the earthquakes with Ms ≥4.0, recorded during the seismic activity of September–October 1988. The focal mechanism (CMT Harvard solution) of the shock of 16th October, 1988 is also shown.

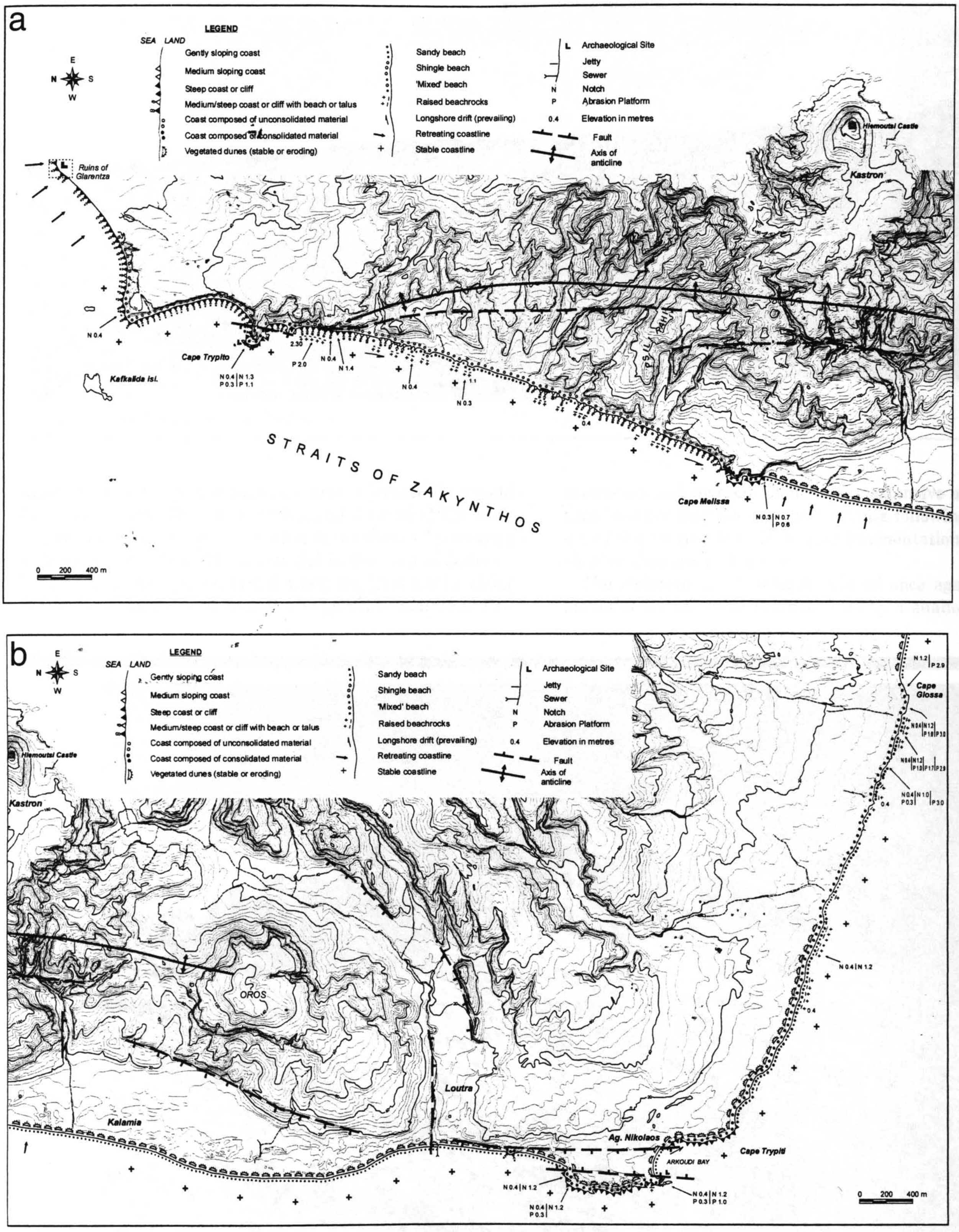

Figure 5a,b. Geomorphologic map of the coastal zone of Kyllini Peninsula.

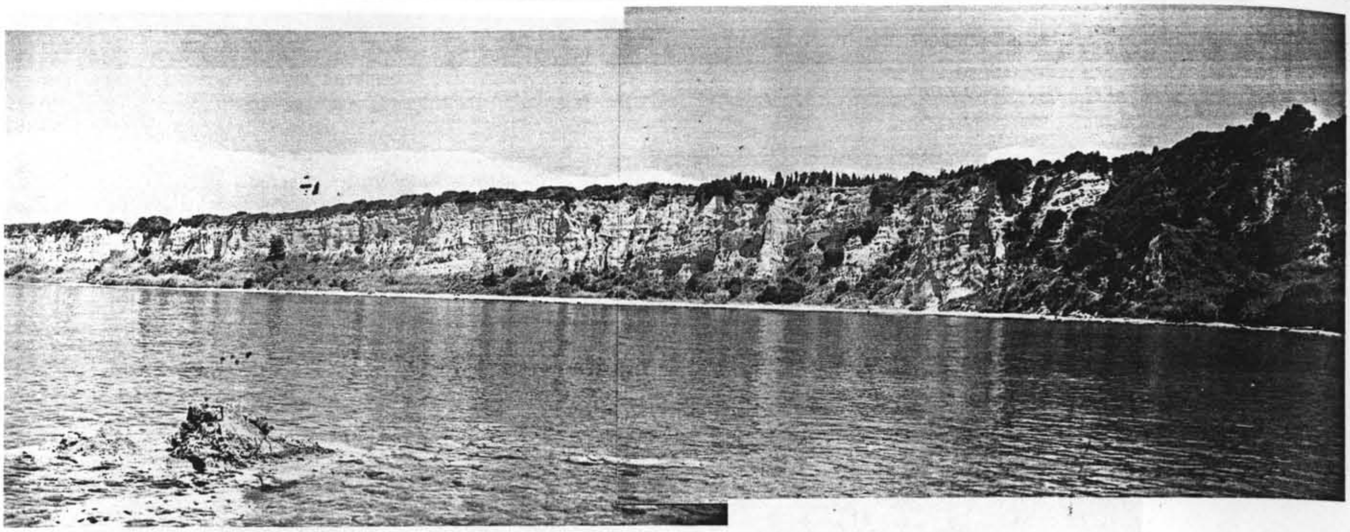

Photo 1. The cliffs north of Cape Trypito.

Kastron–Orös where the anticline axis is located. It should be noted however that KOWALCZYK and WINTER (1979) have found "Strombus bubonius" in what they call Neo-Tyrrhenian terrace of age Würm I/II interstadial in the area of Loutra.

During the last glacial period when sea level fell by about 120 m, the peninsula of Kyllini was joined to mainland Peloponnesus and covered a much more extensive area. At that time, downcutting became more intense following the lowering of the marine base level, and fragmentation of the Tyrrhenian deposits took place.

The Holocene transgression isolated once again the peninsula of Kyllini from Peloponnesus by a shallow strait. In

Photo 2. Tyrrhenian terrace covered by eroding Holocene dunes.

Photo 3. Eroding raised beachrock north of Cape Melissa.

Late Holocene, the Peneios River advanced towards Kyllini filling up the shallow sea first in the northern side and in the last two centuries the southern portion, where an extensive coastal dune field has developed.

COASTAL GEOMORPHOLOGY

The evolution of Kyllini Peninsula has produced an interesting assortment of coastal landforms. Impressive active cliffs are found at the northern extremity of the peninsula (Cape Kyllini), which gradually retreat and give place to less steep coasts with narrow beaches (midway C. Trypito and Psili Rahi). Cliffs show up again towards Cape Melissa, while further south beaches are much wider with coastal dune fields. The dune formations extend all along the southern shores of Kyllini and become even more widespread to the east. At some locations the landforms reflect the combined influence of regional tectonics and diapirism.

Detailed 1:5.000 coastal geomorphological mapping of the area was carried out (Figures 5a and 5b). All field measurements were double checked for possible daily sea level changes although the mean tidal range in the vicinity is only 10 cm (H.S.H.N., 1991).

Cliffs

The coast stretching between Cape Kyllini and Cape Trypito is composed of high cliffs carved on relatively soft Plio-Pleistocene formations. At Cape Kyllini, land retreat is rapid, due to the favorable lithology and a high energy wave regime. An early 13th century fortress was strategically situated on top of the cape, defending the very important harbor of Glarentza. Today, fallen fortress walls litter the beach and the nearshore zone, in front of retreating cliffs 15 m high. The remains of the port facilities are clearly discernible several meters from shore indicating a small submergence of Cape Kyllini. West of Cape Kyllini (at Cape Chelonatas), the shadowing effect of Kafkalida islet has allowed significant beach development in front of the high cliffs, resulting in much slower rates of cliff retreat. A vegetated debris apron covers the base of the cliffs all the way to Cape Trypito (Photo 1), which is composed of resistant limestone. A possible uplift of the Cape Chelonatas–Trypito coast could be attributed to fault re-activation. Along the Chelonatas–Trypito cliffs, the Pio-Pleistocene strata have a general dip of 20°–35° to the N and NE owing primarily to diapirism. The morphologic slope on the other hand is towards the North.

South of Cape Trypito occurs the only coastal outcrop of evaporites in Kyllini. It has formed steep cliffs and corresponds to the point where the anticline axis plunges into the sea. Other appearances of cliffs are located in the Cape Melissa and Cape Trypiti–Arkoudi areas (the latter are less high).

Dunes

The dunefields in the peninsula can be distinguished to a relatively narrow strip of low coastal dunes extending from

Photo 4. Uplifted beachrock south of Cape Trypito at 2.3 m, resting on a limestone bench. In the background is a notch at 1.4 m.

Cape Melissa to Cape Trypiti (Figures 5a & 5b), and a much wider area of dunes from Cape Glossa to the mouth of the Peneios River in the east.

The narrow coastal zone of dunes between Cape Melissa and Trypiti, has a width of up to 200 m and a height of up to 12 m. At some points, the dunes attain heights of 20 m or more due to the fact that they overlie uplifted Tyrrhenian deposits although their actual thickness is only 3–4 m (Photo 2). Near Loutra and Kalamia, two generations of dunes are present and the older one is a compact aeolianite. Aeolianite is also reported overlying the elevated Tyrrhenian deposits at Cape Melissa (KOWALCZYK and WINTER, 1979). The dunes' total thickness at Kalamia reaches 12 m, most of which is aeolianite.

Most of the dunes in the area are stabilized and covered by bush vegetation (Euforbia terracina and Amophiletina arenacia) but in some cases they are eroding today. The sand is more or less reddish in color due to oxidation meaning that the dunes have remained inactive for a considerable time.

The shoreline east of Cape Glossa is occupied by an extensive Holocene dune field, the easternmost part being very recent and related to the course shift of the Peneios River. This dune field has a width of more than 2 km and reaches heights of more than 20 m. At this stretch of coast the Tyrrhenian formations retreat inland behind the dune field indicating the position of the old Tyrrhenian shoreline. The dunes are stabilized and are covered by an artificial pine forest planted a few decades ago. The great extent of the dunes in this region is favored by: a) the prevailing wind direction which is from the western quartile for most of the year, b) the ample supply of sand by the nearby easily erodible formations, c) the low and extensive relief of the area, and d) the gentle and shallow neighboring sea bottom.

Based on eustatic sea level changes, we conclude that the dunes' age should not be more than 5000–6000 years old, about the time sea level reached today's levels.

Beachrock

Beachrock is generally formed within the intertidal zone. It becomes more difficult to determine a beachrock as a sea-level indicator when the intertidal zone is very high (HOPLEY, 1986). In the case of the Kyllini Peninsula beachrock is a significant sea-level indicator because the tidal range of this coast is minimal (~8 cm). Beachrock is observed along the coast between Capes Trypito and Melissa (Photo 3) and along the rocky coasts south of Loutra and between Agios Nikolaos (Arkoudi) and Cape Glossa.

On the coast south of Trypito and as far as Cape Melissa, beachrock formations are abundant. They have a thickness of up to 1.3 m and are composed of pebbles and cobbles with intercalations of coarse sand. At places they rest on an abrasion platform carved on Pliocene conglomerates with a mat of consolidated beach material on top. This beachrock has been uplifted by about 0.8 m and has a notch carved in it at 0.4 m. The presence of springs on the coast seems to favor

Photo 5. Uplifted notch at 1.3 m on limestone at Cape Trypito.

beachrock formation, as a second generation of undisturbed modern beachrock is present. Just south of Cape Trypito and very close to an outcrop of evaporites (gypsum), a limited beachrock formation rests on a limestone bench, at a height of 2.3 m maximum (Photo 4).

The beachrock of Arkoudi–Cape Glossa is less extensive. It has a thickness of about 0.5 m, consists of medium to coarse sand with a few pebble intercalations and it is uplifted by about 0.4 m. Bivalve shells recovered from this formation at Cape Glossa were radiocarbon dated at 2905± 75 C^{14} years BP (C-13 corrected—Laboratory number GX-23063).

Abrasion Platforms, Wave Cut Benches and Notches

Several platforms with corresponding notches which are carved in resistant limestones and Tyrrhenian formations can be found along the Kyllini coastline. These are:

(1) at Cape Trypito, in limestone, two distinct platforms at elevations of 0.3 m and 1.1 m having corresponding notches at 0.4 m and 1.3 m (Photo 5).

(2) south of Cape Trypito, near an evaporite outcrop, a raised wave-cut bench at 1.8 m composed of limestone and covered by an old beachrock formation. A few meters away, there is a notch at 1.4 m.

(3) at Cape Melissa a platform at 0.6 m with its corresponding notch at 0.7 m (Photo 6). An additional notch is found at 0.3 m.

(4) in the area of Arkoudi bay, a wave cut bench at an elevation of 0.4 m (Photo 7).

(5) in the area of Cape Glossa, platforms at 0.3 m, 1 m, 1.7 m and 3 m with corresponding notches at 0.4 and 1.2 m.

Thus the prevailing wave cut benches and platforms are found at elevations 0.3–0.4 m and notches at 1.2 m–1.4 m.

DISCUSSION–CONCLUSIONS

The overall coastal morphology of the Kyllini Peninsula is due to the normal faults of the Zakynthos Straits as well as to the compressional regional tectonics. Another factor is diapirism, which at a slower rate, caused strong but local vertical displacements of the Tyrrhenian terraces in the neighborhood of the evaporite intrusions. The uplifted Tyrrhenian terraces observed around the promontory of Kyllini as well as the elevated wave-cut notches and abrasion platforms make it obvious that tectonism has played the most important role in the evolution of the Kyllini Peninsula.

The existence of the 0.4 m tectonically uplifted notch and its corresponding platform of 0.3 m, observed at the same heights at several locations along the coastline, indirectly dated at 2905±75 C^{14} years BP, indicate that during the last 3000 years diapirism has not played any significant role in the vertical movement of the area.

The tectonically uplifted notch of 1.2 m along the southern part of the coast is found to be higher by 10–20 cm near the salt intrusion (Cape Trypito) in the north, and suggests that this small differential uplift is caused by the diapirism with very slow rates.

The oldest Holocene abrasion platform is found at 3 m at

Photo 6. Cape Melissa: raised abrasion platform at 0.6 m and notch at 0.7 m.

Photo 7. Modern abrasion platform west of Arkoudi bay. An uplifted wavecut bench is visible at 0.4 m.

Cape Glossa. This does not mean however that this feature represents the oldest tectonic event in this area.

The two uplifted notches at 0.4 m and 1.2 m and the obtained date of 2905±75 C^{14} years BP from the beachrock of 0.3 m at Cape Glossa, suggest that the uplifts were caused by two seismic events the older one having occurred before 2900 years BP and the younger one since that time.

The seismicity of the area is high and the occurrence of tsunamis is frequent. The epicenters of many strong shocks are located along the Zakynthos strait. For some earthquakes that struck the eastern part of the island of Zakynthos, emergence of the coast was also reported like that of 1633 A.D. Observations made by PIRAZZOLI *et al.* (1994) of uplifted shorelines at the southeastern tip of Zakynthos island at elevations of 0.95±0.15 m were attributed to coseismic uplift during the period of 200–500 A.D. This uplift, although younger, is higher than that observed in Kyllini Peninsula in this study, which means that the normal faults of the straits have different rates of uplift, either the western one being more active or the eastern tip of Zakynthos is additionally affected by a thrust zone existing in Ionian islands. However the historical seismological data are not sufficient to correlate the observed uplifts to particular seismic events.

Although tectonic activity is the crucial factor in the evolution of the Kyllini Peninsula, further studies are required to clarify the dating of extant features, corresponding seismic events and uplift rates.

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