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THE MORPHO-TECTONIC STRUCTURE OF KOS-NISYROS-TILOS VOLCANIC AREA BASED ON ONSHORE AND OFFSHORE DATA

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Abstract: The tectonic structure of the volcanic area among the islands of Kos, Nisyros and Tilos is analyzed using as topographic base a digital map covering both onshore and offshore areas. The classification of faults in major and secondary structures separating blocks with Alpine basement outcrops, post-Alpine sedimentary sequences, present-day marine basins and volcanic structures permitted the distinction of neotectonic units. Thus, several tectonic horsts are described with considerable relative uplift of 1-2 km manifested by the outcrops of Alpine basement rocks at high altitudes (Dikeos, Kefalos, Kondellioussa, Tilos). Several tectonic grabens are distinguished by the subsidence of neotectonic blocks at about 600 m depth and the deposition of several hundreds of meters of Quaternary sediments (the basins of Eastern Kos, Western Kos, Western Nisyros, Southern Nisyros and Northern Tilos). Some intermediate transitional tectonic blocks show step-like structures with tilted post-Alpine strata in between the tectonic horsts and grabens (Antimachia plateau, Zipari and Kos – Knidos channel). The Quaternary volcanic structures occur at the central subsided area of the regional tectonic graben between Kos and Tilos forming a positive volcanic relief of more than 1.4 km around Nisyros. The maximum tectonic throw observed between the neotectonic blocks of the area is about 2.5 – 3.0 km based on the displacement of the top of the Alpine rocks.

Keywords: Morpho-tectonic structure, Kos-Nisyros-Tilos, Neotectonic Blocks, volcanic relief

1. Introduction

The Hellenic Volcanic Arc is a magmatic expression of the active northeastward-directed subduction of the East Mediterranean oceanic lithosphere at the northern part of the African plate below the European continental plate (McKenzie, 1972; Le Pichon and Angelier, 1979; Papanikolaou, 1993; Jackson, 1994) (Fig. 1). Recent volcanoes occur at Soussaki, Methana, Aegina and Poros to the west, Milos and Santorini in the centre and Kos and Nisyros to the east of the volcanic arc. These volcanoes were especially active during the Late Pleistocene–Holocene, with some eruptions known in historical times (Fytikas et al., 1976; Liritsis et al., 1996). Volcanic activity at the eastern sector of the Hellenic Volcanic Arc around the islands of Kos, Yali and Nisyros started in the Pliocene (approx. 2.6–2.8 my) featuring large volumes of volcanic products (Pe-Piper and Piper, 2002) including the largest eruption in the Eastern Mediterranean, represented by the ‘‘Kos ignimbrite’ at about 0.16 my ago, which produced more than 100 km^3 of pyroclastic material (Kos Plateau Tuff) whereas ash, pumice and pyroclastic flows devastated an area of more than 3000 km^2 (Keller, 1969; Smith et al., 1996; Allen et al., 1999).

The geodynamic position of Kos-Nisyros-Tilos corresponds to the eastern edge of the Volcanic Arc and of the Back-Arc Cretan molassic basin. The general direction of the Hellenic Arc at its eastern part is ENE-WSW parallel to the morphological trend of Kos Island. NW-SE trending faults are delimiting the ENE-WSW structures of the arc towards the east along the coastal zone of Minor Asia.

The neotectonic structure of the area is shown by the outcrops of the Alpine basement at uplifted blocks – neotectonic horsts separated by the recent and actual marine basins where subsidence has prevailed during the last few millions of years. The Alpine basement in the submarine area occurs at great depths below the sea bottom covered by thick post-Alpine sediments.

Thus, the submarine area between Kos and Tilos

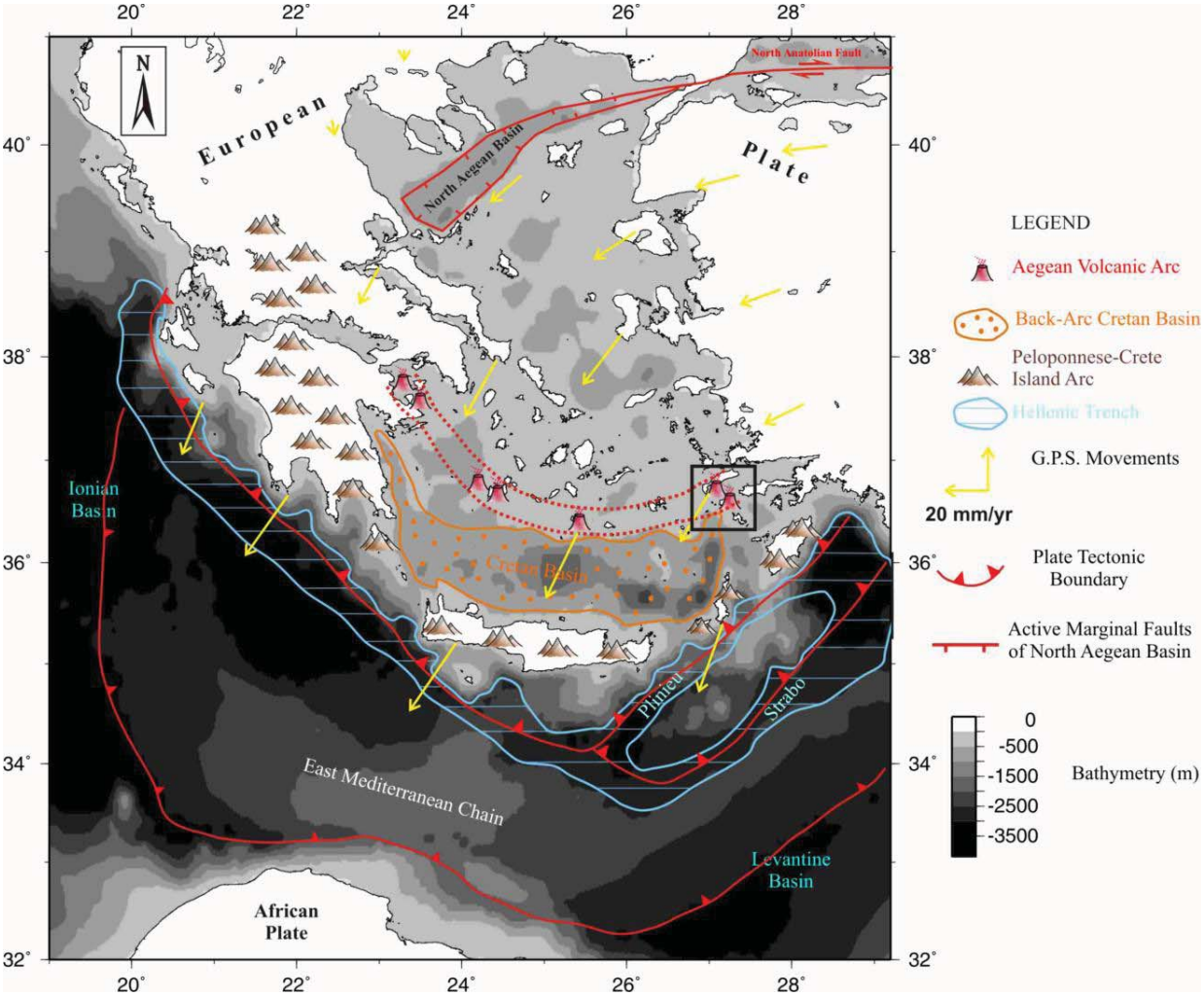

Fig.1. Simplified map of the present day geodynamic structure of the Hellenic Arc.

islands constitutes a regional neotectonic graben (Papanikolaou and Nomikou, 2001) (Fig. 2). Nisyros and surrounding islets represent the volcanic structures that have intruded within this regional graben as this was confirmed by the geothermal drillings in Nisyros (Geothermika Italiana, 1983; 1984) which detected the Alpine basement rocks at 1800 m of depth.

2. Combined Onshore/Offshore data

A large data set was obtained from several multibeam bathymetric surveys carried out on R/W «Aegaeo» during 2000 in the area between Kos, Nisyros and Tilos islands. The resulted bathymetric map was combined with onshore topographic maps of the islands and the result was a synthetic topographic map of the entire area both onshore and offshore with a DEM (Fig. 3). Structural analysis of the area both onshore and offshore permitted the distinction of the faults in major and secondary structures, based on their throw >200m or less (Nomikou, 2004). These faults have been projected on the topographic map of the area together with their main kinematic character of relative vertical motion, with dentitions on the subsiding blocks (Fig. 3).

Morphotectonic analysis of the Kos-Nisyros-Tilos area shows the dominance of structures in the ENE-WSW direction. This trend is controlling the overall morphology of Kos Island and also the three successive basins of Western Nisyros, Western Kos and Eastern Kos. The same ENE-WSW trend is observed in the medial ridge separating the basins north and south of Kondellioussa and Nisyros islands. More to the south towards Tilos Island the ENE-WSW trend is substituted by a NE-SW trend in the west intersected by an E-W trend in the east. Some characteristic ENE-WSW faults are those running parallel to the southern coast of Kos Island and especially the one along the Dikeos Mt. coast and also those observed on both sides of the

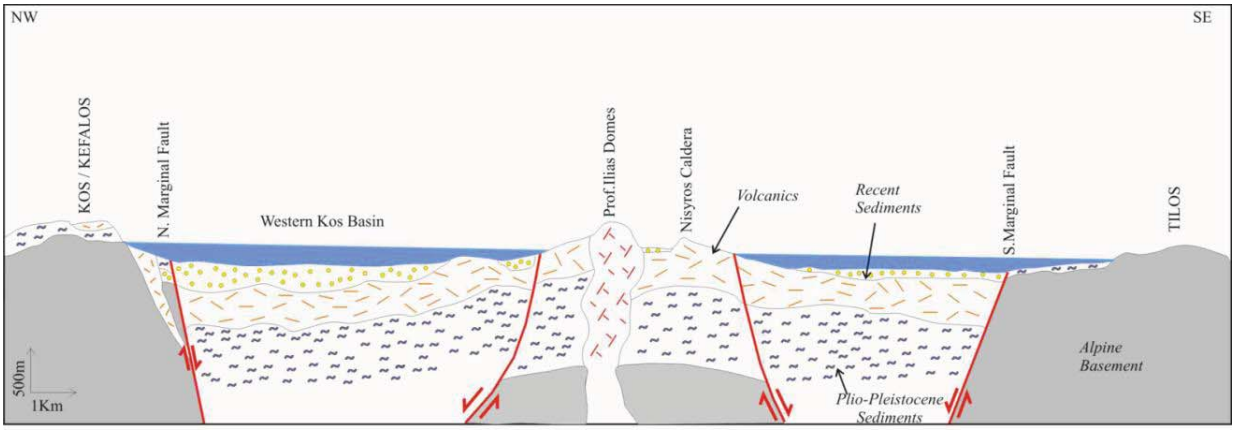

Fig. 2. The general structure of the regional neotectonic graben between Kos and Tilos islands.

Kondellioussa plateau separating the Western Nisyros Basin in the north from the Southern Nisyros Basin in the south. The throw of these ENE-WSW faults is more than 2 km, as this can be estimated by the 900 m of elevation of the deepest tectonic unit of Kos Island, consisting of Palaeozoic metamorphic rocks on Dikeos Mt. on the uplifted block and the subsidence of the Alpine rocks at more than 1200 m depth, because more than 600 m thick Plio-Pleistocene sediments were detected during the lithoseismic air-gun survey of the basin below the 600 m deep sea bottom of the Eastern Kos Basin. The estimation of throw for each fault can be made from the elevation of the geological formations on Kos and Tilos islands using the available maps and tectono-stratigraphic diagrams onshore (Geological Map of Kos Island, sheets Kos 1998 and Kefalos 1994; Geological Map of Tilos, 1985; Papanikolaou and Nomikou, 1998) and the depth of the geological formations offshore using the available bathymetric and geological maps (Nomikou, 2004).

Some major faults with WNW-ESE trend run perpendicular to the regional Kos-Tilos graben system with disruption of Kos Island into three blocks. The central block of the Antimachia plateau forms a neotectonic graben between the two adjacent blocks of Kefalos in the west and Dikeos in the east. The Alpine rocks are cropping out only in the two horsts whereas the Antimachia plateau is made only of outcrops of Plio-Quaternary formations (Willman, 1983). Thus, the WNW-ESE faults are marginal faults of the Antimachia graben which was an area of marine sedimentation during Quaternary between the two horts of Kefalos and Dikeos which for quite a long period were separate islands. It is remarkable that the WNW-ESE marginal faults of the Antimachia plateau continue towards the ESE offshore, controlling the geometry of the marine basins of Western and Eastern Kos.

3. Neotectonic Blocks

The morpho-tectonic map of the area of Kos-Nisyros-Tilos can be transformed to a neotectonic sketch map characterized by the distinction of neotectonic blocks bordered by major faults (Fig. 4). Each neotectonic block is characterised by its morphology which is different across its tectonic margins from that of the neighbouring blocks. The difference may comprise the intensity of the relief, expressed by the slope gradients and/or the relief orientation, and its average elevation either positive or negative. Additionally, each neotectonic block may present a different tectono-stratigraphy referring to the Alpine formations and/or the post-Alpine sediments and eventual volcanic formations. The general dip of the strata and of the volcanic products may indicate the nature of vertical and/or tilt motions during or after the deposition of each geological formation.

The neotectonic blocks are distinguished in tectonic horsts, tectonic grabens and transitional blocks on the basis of their general character of uplift, or subsidence or tilt. The neotectonic blocks characterised as tectonic horsts show a relative uplift towards all surrounding blocks. Similarly, the neotectonic blocks characterised as tectonic grabens show a relative subsidence towards all neighboring blocks whereas the neotectonic blocks characterised as transitional show mixed relative motion with uplift from one side and subsidence on the other. The neotectonic blocks will be described in the following according to the above distinction.

3.1 Tectonic horsts

Kos Island constitutes a synthetic tectonic mega-

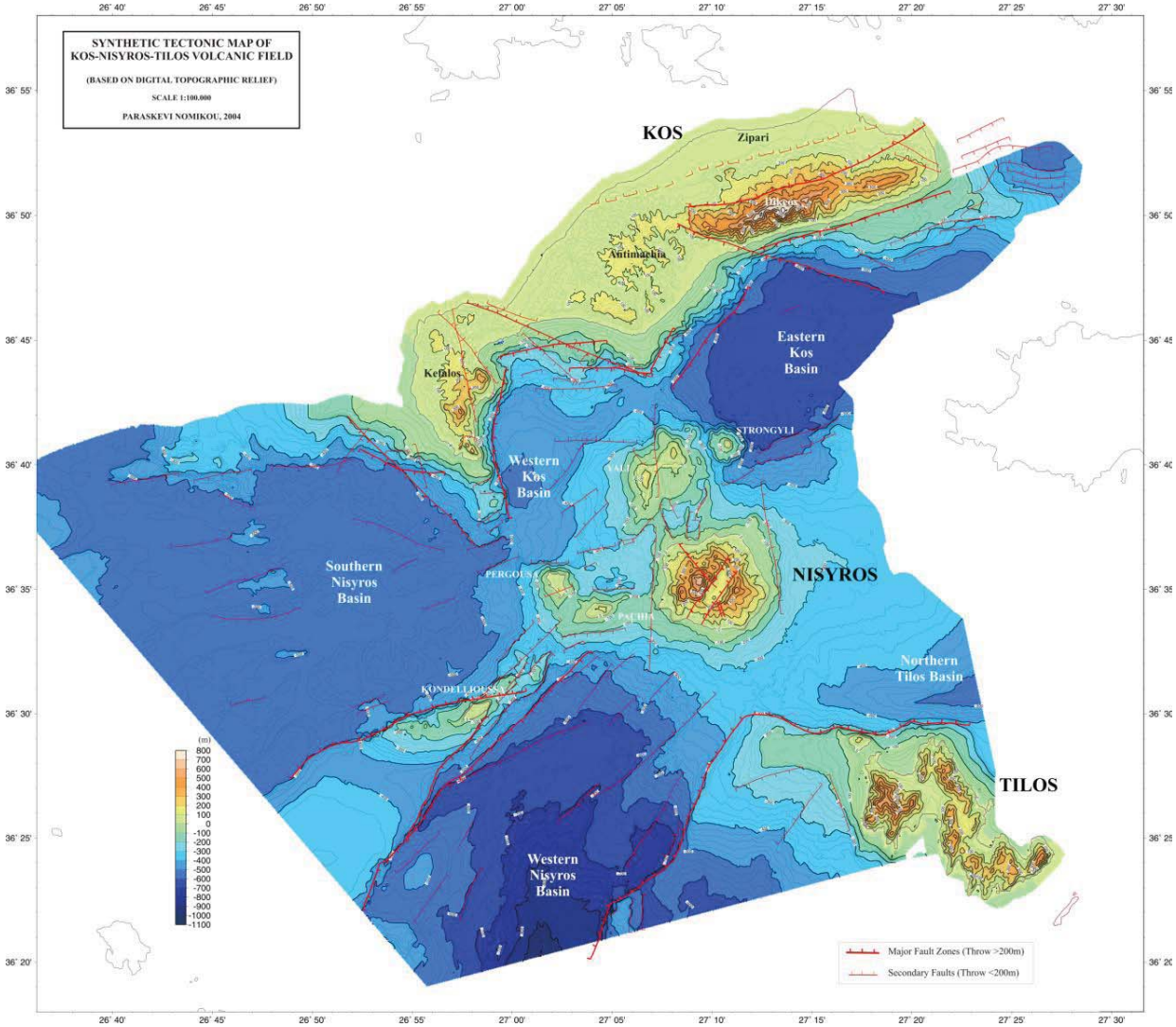

Fig. 3. Synthetic Tectonic map of Kos-Nisyros-Tilos Volcanic field based on data obtained from multi-beam bathymetric surveys and combined with onshore hypsometric data.

horst of ENE-WSW direction including three successive multi-blocks: Kefalos multi-block (1) in the west divided in Kefalos Peninsula (1a), Western Kefalos (1b) and Southern Kefalos (1c), Antimachia block (2) in the middle and Dikeos multi-block (3) in the east divided in Dikeos mt. (3a) and Zipari block (3b) (Fig. 4). All these blocks constitute the Kos mega-horst bordering from the north the successive grabens/basins of blocks 4, 5 and 6. However, the tectonic horsts showing relative uplift from all surrounding blocks are only blocks 1a of Kefalos peninsula and 3a of Dikeos mt.

The tectonic horst of Kefalos Peninsula (1a) is made of Alpine metamorphic formations belonging to the lower tectonic unit covered by molassic sediments of lower Miocene age and small tectonic klippen of Tripolis nappe. Pliocene and Pleistocene sediments and volcanic rocks occur above the Alpine formations with extended outcrops mainly at the southern part of the peninsula. The post-Alpine sedimentary sequences are dipping to the west and thus, the kinematic character includes uplift together with westward tilt. The marginal faults of the block comprise: (i) the WNW-ESE fault separating Kefalos Peninsula from Antimachia block both onshore and offshore, (ii) the N-S fault separating Kefalos Peninsula from the Western Kos Basin, (iii) the NW-SE fault separating Kefalos Peninsula from the Western Kefalos block at the western margin of Kefalos and (iv) the E-W fault separating Kelalos Peninsula from the Southern Kefalos block along the southern margin.

The Dikeos block (3a) shows very intense relief with higher elevations up to 900 m at Christos summit and is made mainly of Alpine rocks, including the three lower tectonic units (Palaeozoic of Dikeos Unit, Mesozoic of Zia/Tripoolis Unit and Upper Cretaceous–Eocene of Eastern Kos/melange Unit) together with the Late Miocene intrusion of a monzonitic pluton. Considering that the depth of crystallization of the monzonite was at least 3-5 km a strong uplift of several km has occurred since the Late Miocene. The horst is bordered by ENE-WSW major fault zones both towards the Eastern Kos Basin (6b) in the south and towards the Zipari block (3b) in the north.

The Kondelliousa horst (7) is made of Mesozoic limestones cropping out on the island covered by post-Alpine sediments occurring on the submarine plateau developed westwards. The sediments are tilted to the SW and thus, the general kinematic character is uplift together with south-westward tilt. The Kondellioussa horst is bordered by two marginal faults trending NE-SW and ENE- WSW which have produced a subsidence of more than 1.3 km both towards the Western Nisyros Basin to the north and towards the Southern Nisyros Basin to the south. This subsidence is estimated by the depth of the two basins (about 600 m for Western Nisyros and more than 1000 m for Southern Nisyros) together with the 600 m minimum thickness of the sediments detected through the air-gun lithoseismic survey.

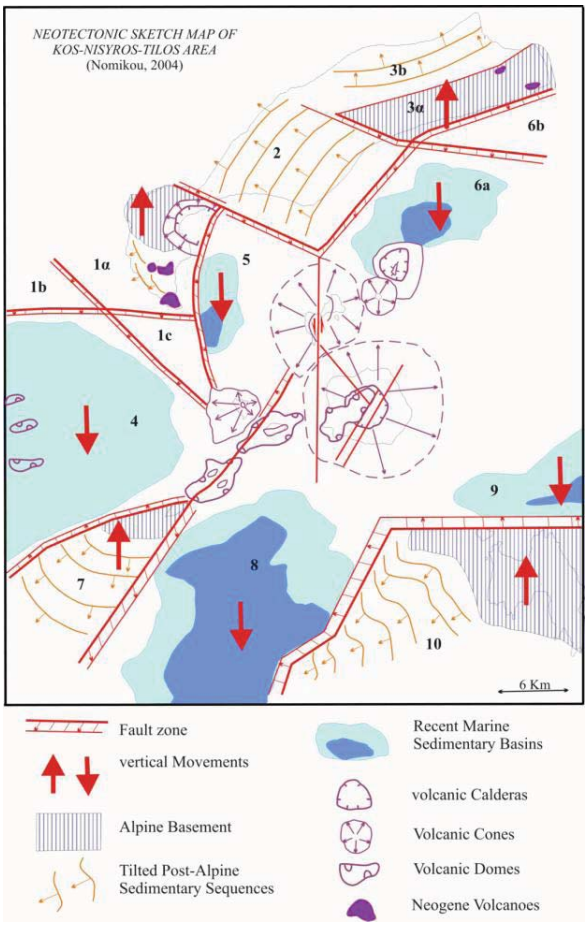

Fig. 4. Neotectonic Sketch Map of the Kos-Nisyros-Tilos area. The neotectonic blocks are shown together with their general kinematic character of uplift, subsidence or tilt as well as the volcanic structures. The main outcrops of the Alpine formations are shown at the uplifted blocks whereas the basinal areas of actual marine basins are shown at the subsided blocks and the general dip of the sedimentary sequences is shown at the tilted blocks.

The Tilos horst (10) is made of Alpine formations covered by post-Alpine sediments occurring on the submarine plateau developed towards the southwest of Northern Tilos Island. The sediments of this plateau look very similar at the lithoseismic profiles with those occurring over the neighbouring plateau of Kondellioussa and show the same tilt towards the SW. The tectonic margins of Tilos horst are made by a NE-SW oriented fault towards the Southern Nisyros Basin and another fault of E-W direction towards the Northen Tilos Basin. Both faults are producing an asymmetry of the basins with the deepest subhorizontal parts reaching the margins of Tilos Horst. The fault throw is more than 1 km as the depths of the basins (about 600 m in Northern Tilos and more than 1000 m in Southern Nisyros) and the minimum thickness of the sediments (more than 600 m detected on the air-gun profiles) imply.

3.2 Tectonic grabens

Five submarine basins can be distinguished within the regional graben of Kos - Tilos area (Nomikou & Papanikolaou, in press). The intermediate horst of Kondellioussa (10) and its northeastward volcanic prologation of Nisyros and surrounding islets separate three basins (4,5 and 6a-6b) along the northern sub-graben and another two basins (8,9) along the southern sub-graben.

The Eastern Kos Basin (6) comprises a main block of a tectonic graben (6a) with an average sea-bottom depth of 630m and a minor block of a more shallow subsided area (6b) towards the northeast between Eastern Kos and the Peninsula of Knidos in the opposite coast of Minor Asia. The tectonic boundary between the two blocks of Eastern Kos Basin is a WNW-ESE oriented fault which is the

submarine prolongation of the fault separating the Antimachia plateau from the Dikeos mountain on Kos Island. The fault throw is more than 300 m as this is indicated by the difference in the depth of the two submarine blocks (about 630 m for block 6a and about 300-350 m for block 6b). The tectonic boundary of both blocks of Eastern Kos Basin towards the north is the major ENE-WSW fault which contols all the southern costal area of Kos Island. The throw of this fault is more than 700 m in the sector between blocks 6a and 2 (Marine Pleistocene sediments at 100 m of elevation on Antimachia plateau and 600 m depth plus more than 600 m thick sediments in the Eastern Kos Basin) and more than 1700 m in the sector between blocks 6b and 3a (Alpine rocks at 900 m of elewvation on Dikeos mt and more than 400 m of sediments bellow the 350 m deep sea bottom of eastern Kos block).

The Western Kos Basin (5) comprises a volcano-sedimentary sequence of more than 500 m thickness below its average depth of 520m. The basin is separated from the Eastern Kos Basin by a relatively shallow rise between Yali and Kos with a depth of 400m. Its western boundary towards the Kefalos Peninsula is an N-S fault producing an asymmetry of the basin with the maximum depth occurring near the western margin. The fault throw is more than 1300 m comparing the 300 m of elevation of the Kefalos Peninsula with the 520 m of depth of the basin and the more than 500 m of volcano-sedimentary thickness below the sea bottom. The southern part of the basin is bounded by the volcanic structures forming the islands of Pergoussa, Pachia, Nisyros and Yali.

The Western Nisyros Basin (4) is bordered between the Kondelioussa tectonic block (7) towards the south and the Western Kefalos platform (1b) towards the north. Its average depth is 550 m and the volcano-sedimentary thickness below its sea bottom exceeds 600 m. The basinal area of Western Nisyros Basin is characterized by a complex sea-bottom morphology with a number of flat-floored elongate basins of E-W direction alternating with parallel ridges which according to the air-gun profiles represent volcanic intrusions. The northern tectonic boundary of the basin is formed by two intersecting faults of E-W and NW-SE direction separating the tectonic graben of block 4 from the intermediate marginal blocks 1b and 1c of the Kefalos Peninsula. The most important marginal fault occurs in the southern part of the basin with a ENE-WSW direction separating it from the tectonic horst of Kondeliousa(7).

The Southern Nisyros Basin (8) constitutes the northern end of the large Karpathos Basin extending towards the south-southwest which reaches great depths of more than 2000m. It is a characteristic tectonic graben bordered by NE-SW trending marginal fault zones which separate it from the tectonic horst of Kondelioussa (7) in the west and the tectonic horst of Tilos (10) in the east. Towards the north-east a peculiar morphology is observed, result of a large deposit of volcanic debris avalanches derived from Nisyros Island (Tibaldi et al, 2008).

The Northern Tilos Basin (9) forms an assymmetric graben of E-W direction with depths around 600 m. It is separated from the Southern Nisyros Basin (8) in the west through a shallow rise with less than 400 m depth observed between Tilos and Nisyros islands. It is bounded to the south by an E-W marginal fault zone with throw more than 1400m separating it from the Tilos tectonic horst (10). The northern boundary is formed by a rise of about 400 depth developed between Nisyros and Knidos Peninsula with an ENE-WSW direction.

3.3 Transitional Tectonic Blocks

The Antimachia tectonic block (2) comprises outcrops only of Neogene and Quaternary sediments observed bellow the widespread Upper Pleistocene volcanic breccia and pumice of the “Kos Ignimbrite” which forms the planar surface of the Antimachia plateau. It is characterized as tectonic graben between the adjacent tectonic horsts of Kefalos (1a) and Dikeos (3a). However, it presents an important uplift relatively to the submarine tectonic grabens of Western Kos Basin (5) and Eastern Kos Basin (6a). This relative uplift is confirmed by the occurrence of marine Pleistocene sediments on the Antimachia plateau at altitudes around 100-120 m. The lack of outcrops of Alpine formations as well as of Miocene continental deposits (known from the adjacent horsts of Kefalos and Dikeos) implies a relative subsidence of more than 1000 m with respect to Dikeos and more than 600 m with respect to Kefalos. The tectonic throw between Antimachia block and Zipari block is only a few hundreds of m. The post-Alpine sedimentary formations below the Kos Ignimbrite are tilted to

the NW by 10 -15 degrees around an ENE-WSW axis.

The tectonic block of Zipari (3b) comprises thick alluvial sediments observed all along the northern coast of Kos and Neogene continental sediments tilted towards the north. Small outcrops of Alpine rocks belonging to the Prophitis Ilias/Pindos tectonic unit occur in the hills of Zipari block. Thus, there is strong subsidence in relation to the tectonic horst of Dikeos (3a) and a relative uplift in relation to the tectonic block of Antimachia (2).

The two marginal tectonic blocks of Kefalos (1b and 1c) are subsided areas of the Kefalos Peninsula horst but they are uplifted blocks in relation to the Western Nisyros Basin (4). The tectonic block of Kos-Knidos channel (6c) also presents subsidence in relation to the tectonic horst of Dikeos (3a) and uplift in relation to the tectonic graben of the Eastern Kos Basin (6a).

4. Conclusive remarks and discussion

The neotectonic structure of the Kos-Nisyros-Tilos area is a complex tectonic graben between the Kos tectonic horst in the north and the Tilos tectonic horst in the south. The complexity is produced by the occurrence of the intermediate Kondellioussa horst which towards the northeast is substituted by large volumes of recent volcanic rocks dividing the basins on both sides of Nisyros and continues up to the Knidos Peninsula in the coastal area of Minor Asia. The volcanic relief is developed both offshore and onshore and starts from 670 m of depth up to 700 m of elevation. Thus, the overall volcanic relief is of the order of 1400 m as this is shown on the Shaded relief – topographic map given in Fig. 5.

The vertical motions between the neotectonic blocks as estimated from the throws of the mar-

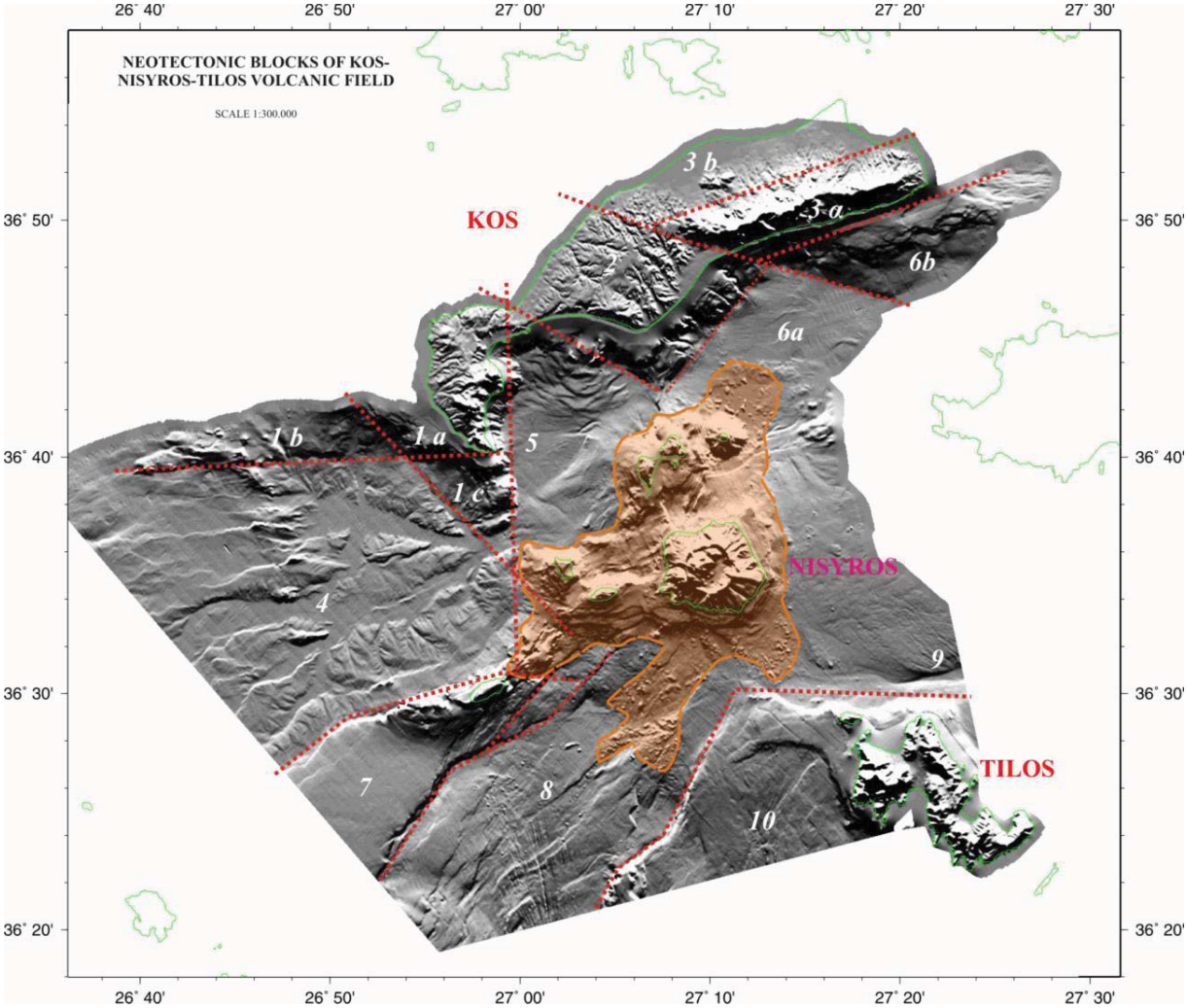

Fig. 5. Shaded relief map of the Kos-Yali-Nisyros volcanic field showing the Neotectonic Blocks and the intermediate volcanic relief.

ginal faults are about 1 – 2 km. This general subsidence observed at the regional Kos – Tilos Graben is equilibrated by the positive relief produced by the volcanic extrusions penetrating through the average depth of 600 m observed over all the marine basins surrounding the Nisyros volcanic field.

References

Allen SR., Stadelbauer E., Keller J., 1999. Stratigraphy of the Kos Plateau Tuff: Product of a major Quaternary explosive rhyolitic eruption in the Eastern Aegean, Greece. Int J Earth Sci 88:132–156.

Fytikas M., Guliani O., Innocenti F., Marinelli G., Mazzuoli R., 1976. Geochronological data on recent magmatism of the Aegean sea. Tectonophysics 31, 29–34.

Geotermica Italiana, 1983. Nisyros 1 geothermal well, PPC-EEC report, 160 pp.

Geotermica Italiana, 1984. Nisyros 2 geothermal well, PPC-EEC report, 44 pp.

Jackson J., 1994. Active tectonics of the Aegean region. Ann Rev Earth Planet Sci 22: 239–271.

Keller J., 1969. Origin of rhyolites by anatectic melting of granite and crustal rocks. The example of rhyolitic pumice from the island of Kos (Aegean Sea). Bull Volcanol 33:942–959.

Le Pichon X. and Angelier J., 1979. The Hellenic arc and trench system: a key to the evolution of the Eastern Mediterranean. Tectonophysics 60:1–42.

Liritsis I., Michael C., Galloway R., 1996. A significant Aegean volcanic eruption during the Second Millennium B.C. revealed by thermoluminescence dating. Geoarchaeology: An International Journal 11 (4), 361–371.

McKenzie D.P., 1972. Active tectonics of the Mediterranean Region. Geophys J R Astron Soc 30:109–185.

Nomikou P., 2004. Geodynamic of Dodecanise islands: Kos and Nisyros volcanic field. PhD Thesis. Department of Geology, University of Athens.

Papanikolaou D., 1993. Geotectonic evolution of the Aegean. Bull Geol Soc Greece 18(1): 33–48.

Papanikolaou D. and Nomikou P., 1998a. Morphotectonics of Kos Island, Dodekanese, Greece. 15th Congress of the Carpatho-Balcan Geological Association, Vienna, Abstracts p.454.

Papanikolaou D. and Nomikou P., 1998. The Palaeozoic of Kos: "A low grade metamorphic unit of the basement of the External Hellenides Terrane." I.G.C.P. Project 276 Newsletter, No 6, p.155-166.

Papanikolaou D. and Nomikou P., 2001. Tectonic structure and volcanic centres at the eastern edge of the Aegean Volcanic Arc around Nisyros island. Proceedings of the 9th International Congress, Athens, September 2001. Bulletin of the Geological Society of Greece XXXIV (1), 289–296.

Pe-Piper G., and Piper D.J.W., 2002. The Igneous Rocks of Greece. The anatomy of an orogen. Gebr. Borntr¨ager, Berlin, Stuttgart, pp 1–57.

Roussos N., 1985. Geological Map of Greece, Sheet Tilos 1:50.000. (I.G.M.E.), Athens.

Smith P.E., York D., Chen Y., Evensen N.M., 1996. Single crystal 40Ar/39Ar dating of a late Quaternary paroxysm on Kos, Greece; concordance of terrestrial and marine ages. Geophys Res Lett 23 (21):3047–3050.

Tibaldi A., Pasquarè F.A., Papanikolaou D., Nomikou P., 2008. Discovery of a huge sector collapse at the Nisyros volcano, Greece, by on-land and offshore geological-structural data. Journal of Volcanology and Geothermal Research 177 (2008) 485-499.

Triantafillys M., 1994. Geological Map of Greece, Sheet Kefalos 1:50.000. (I.G.M.E.), Athens.

Triantafillys M. and Mavridis A., 1994. Geological Map of Greece, Sheet Eastern Kos 1:50.000. (I.G.M.E.), Athens.

Willmann R., 1983. Neogen und jungtertiare Entwicklung der Insel Kos (Agais, Griechenland). Geologische Rundshau, 72, 3, 815-860.