A seismotectonic study for the Heraklion basin in Crete (Southern Hellenic Arc, Greece)

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Abstract—In the context of the present work the spatial distribution of the seismic activity around Crete Island in the Southern Hellenic Arc for the period 2003-2007 is studied. Especially in the period July-October 2007 about 600 events of low and moderate magnitudes have been indicated. Most of these events are located near coast and onshore of Crete. Additionally, we studied the relation of the earthquake epicenters with specific fault zones for the Heraklion basin.

GIS techniques were used for mapping the distribution of earthquake epicenters on the various topographic and geological features of the area. Maps were created through interpolation algorithms. Spatial tools and statistical analysis were exploited to examine the correlation between earthquake loci and faulting orientations.

The distribution of the epicenters indicates that the near coast and onshore seismicity is closely associated to the Crete tectonics. Especially for Heraklion prefecture the epicenter distribution is related to E-W, NE-SW and NW-SE striking faults.

Keywords—Earthquake, Geotectonic structure, Normal faulting, GIS

I. Introduction

THE Hellenic Arc represents the most seismically active area of Europe due to the interaction between Eurasia and Africa plates. Main geotectonic feature of the area is the Hellenic Trench, where the eastern Mediterranean oceanic lithosphere (frontal part of the African plate) is subducted under the Aegean overriding plate. Earthquakes with magnitudes of up to 8.0 have been reported in the literature since the early historic times [1] [2] pointing out the great seismogenetic potential of the area. According to [3], an ocean-continent interaction occurs on a curved subduction zone, which is characterised by a shallow branch (20.0-100.0 km) of the Wadati-Benioff zone, intersecting the outer side of the sedimentary arc (Western Peloponnesus-west of Kythira-south coast of Crete, east coast of Rhodes) and dips at low angle (~30°) to the north and northeast. Subduction at the Hellenic subduction zone appears to have been operated continuously since the late Cretaceous [4] [5].

The Hellenic Arc can be at present subdivided into three zones with different kinematic behaviour: In the northwestern part of the Aegean region, the boundary between the Aegean and African plates (e.g Ionian Sea) is of continent-continent type now due to the collision of the Hellenides with the Apulian platform [6] [7] [8]. The boundary between these regions of contrasting subduction style is presently formed by the right-lateral Kefallonia Transform Fault Zone [9]. The southern part of the Hellenic arc south of, and including Crete and Rhodos has since the early Pliocene been associated with left-lateral strike slip along the Pliny and Strabo trenches [10]. In between these two regions, active northeast directed subduction is accommodated along the Hellenic Trench and deformation in the overriding plate on the Peloponnesos, and in the Kythira-Antikythira strait [11] is associated with a complex pattern of arc-parallel and arc-normal extension and strong compression perpendicular to the Hellenic Trench (Fig 1a) [12]. Beneath this area, the subduction zone dips gently to the northeast, changing to a steeper dip farther northeast beneath the Argolikos Gulf [13].

Scope of this work is to study the spatial distribution of the near coast and onshore earthquakes occurred in the period 2003-2007 and to associate the earthquake loci with specific geotectonic features. Innovative GIS techniques were used in order to implement the pre-mentioned scope. The Heraklion basin, as a well studied region, was selected in order to combine the distribution of the near coast and onshore seismicity with the orientation of specific fault zones.

II. Geological Setting of Crete

The island of Crete (Fig.1a) represents an emergent high in the fore-arc of the Hellenic Subduction Zone, indicating the transition between African and Eurasian plates. A variety of intensive studies in the last decades figured out the geodynamic attributes of the wide area of Southern Hellenic Arc [6]. Additionally [6] and [14] concluded that the north-dipping Wadati-Benioff seismic zone is extending beneath Crete to a depth of about 200 Km. Nowadays the Hellenic arc

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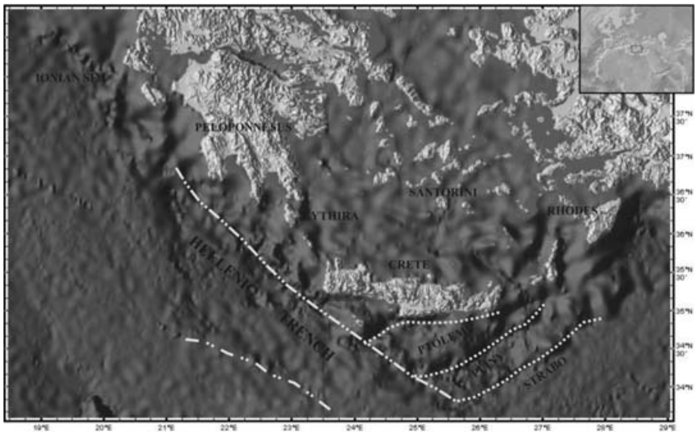
is associated with moderate arc-parallel extension and strong compression perpendicular or oblique to it.



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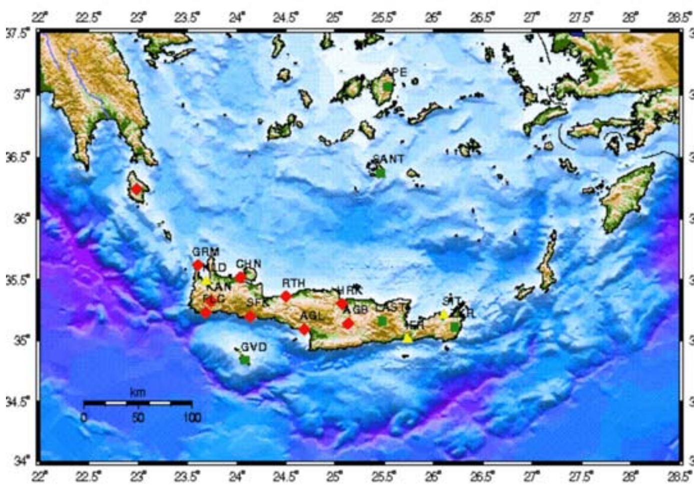


(b)

Figure 1 The study area (a) and the seismic network (b) of the laboratory of Geophysics and Seismology of the Technological Educational Institute of Crete

According to tomographic studies the seismicity of the wide area around Crete corresponds to a lithospheric slab extending through the transition zone and into the lower mantle below Europe. The Mediterranean Ridge (MR) complex consists of accumulated sediments of the subducted African plate. Between Crete and the MR are located a series of E-NE trending depressions or troughs (e.g. Hellenic, Ptolemy, Pliny, Strabo, Fig. 1a).

North of the Crete Island, the tomography drops off into the thinned continental crust of the Cretan sea [15]. The volcanic arc is positioned about 100 Km north of Crete, represented by the island of Santorini. GPS and seismic studies [16] show that Crete and the South Aegean are moving together as a coherent block. The divergent motion between the Aegean block and mainland Europe is indicated by an extension zone, with Crete and Aegean diverging from mainland Europe at a rate of about 3 cm/yr [17] while Africa is moving northward relative to Europe at a rate of about 1 cm/yr [18].

According to previous geologic and tectonic studies [6] [19] three successive fault groups-generations could be distinguished on Crete Island and especially in Heraklion basin (Fig. 2). The first group represents E-W trending faults, kilometer-scale, mainly cutting the basement rocks or bound basement rocks and Miocene sediments. The second group consists of large and moderate-scale N-S striking faults, cutting the previous mentioned group. The third group comprises Kilometer-scale faults striking NE-SW and NW-SE which appear to be the youngest faults occurring on Crete Island. The largest earthquakes occurred on and around Crete [3] indicate E-W extension along N-S striking faults onshore Crete. Fault plane solutions in the western part of Crete Island found T-axes nearly horizontal and oriented mostly E-W in the upper crust [20] [21]. [22] studied large to moderate earthquakes along the Hellenic Arc and noticed that fault plane solutions for half of the 15 studied events show approximately E-W compression, sub-parallel to the trend of the eastern Hellenic Trench. N-S compression dominates the offshore regions south of Central and Western Crete, while normal and thrust faulting is the predominant mechanism south of Eastern Crete.

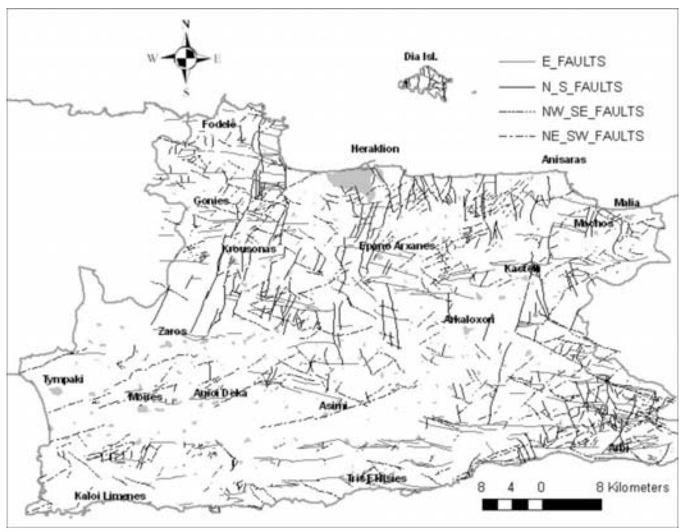


Figure 2 Faults of the Heraklion Prefecture (according to the geological map of Greece, 1:50000, I.G.M.E.)

III. METHODOLOGY

Topology of the seismic network The new telemetric seismic network (Fig. 1b) has been installed since the end of 2003 on the island of Crete and the broader area of South Aegean and is continuously operated by the Laboratory of Geophysics and Seismology of the Technological Educational Institute of Crete in order to provide modern instrumental coverage of seismicity in the southern Greece, as well as some more insight into the stress and deformation fields, tectonics, structure and dynamics of the Hellenic Arc. Network's geometry as well as site selection has been chosen carefully, since the primary goal is to locate seismic events, fact which assures the most accurate determination of seismic parameters. Furthermore, plenty of studies are conducted, concerning mainly the crust structure of the area which will lead to a representative velocity model, the stress-field and the focal depth distribution. The South Aegean Seismic Network (SASN) is now in extensive operation and the associated database has increased in both quantity and quality during the period 2003-2008. Due to the technical development of the network, there has also been a good knowledge of software applications for seismic data acquisition, communication and processing.

Due to the technical development of the network, there has also been a good knowledge of software applications for seismic data acquisition, communication and processing. Today the network consists of 10 operational stations (nine short period and one broad-band station) which are equipped of three-component sensors, third generation high resolution 24-bits digitizers, Reftek type 130-1.

Telemetry is digital in terms of conventional TCP/IP networking using dedicated ADSL-VPN connections. Data are transmitted to the central processing unit, situated at the Laboratory of Geophysics and Seismology building in Chania, Crete, where the data packets stored in two data servers and one real time processing server running Seismic Network Data Processor (SNDP) software. In addition backup connections with satellite links are prepared for installation.

Velocity model The presented velocity model was implemented using velocity analysis data from seismic reflection experiments in the study area (Hellenic Petroleum Co.) many years ago. Western Geophysical Company of America, which towed a high pressure airgun tuned array, produced the seismic signals. Common depth point (CDP) velocity data was used in order to construct 2D and 3D velocity models for the upper 15.0-20.0 km of the larger study area. Bathymetry data (www.geomapapp.org) was also processed and included in the construction of the present velocity model. The detection of the velocity layers is based on velocity jumps. Previous velocity models [19] [26] were also used in order to correlate our models and to extend them to a depth of 40 km.

Root mean square (RMS) velocities were converted to interval velocities according to Dix equation. The 1D velocity models were initially used for the construction of 2D models. Thereinafter, a 3D database was created using topographic data, previously available information about velocity distribution and interval velocities for the upper 20.0 km of the Cretan crust. Special emphasis has been given to the upper 15.0-20.0 km of the cover that comprises a seismogenic layer of generally small to moderate earthquakes.

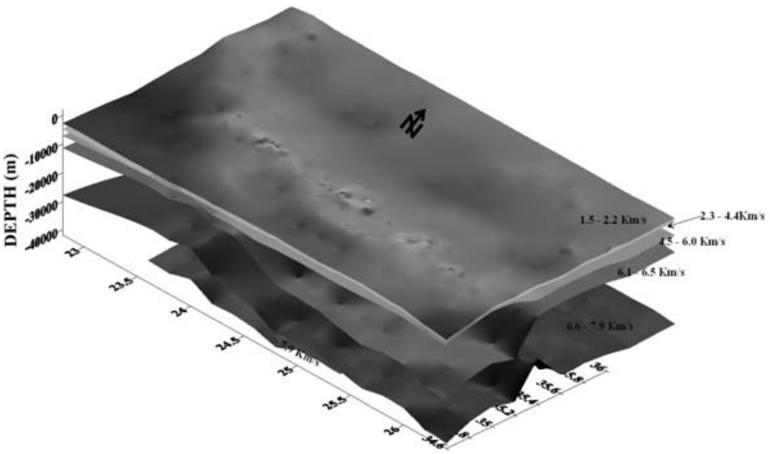
The 3D velocity sections (Fig. 3a, b) provide a generalized image of the onshore and offshore Cretan crust.

The 3D model was constructed in order to have a general assumption of the Cretan crust velocity distribution [23], [24], [25], due to the high range of the velocities which characterize the crust structure of north western, southern and northern part of Crete Island. The layer thicknesses change not only in E-W direction but also in N-S. We divided the Cretan crust in five units. The upper layer, showing a velocity range between 1.5–2.2 km/s, corresponds to the seawater layer and the upper series of the post-Alpine sediments. The second layer has a velocity between 2.3 and 4.4 km/s and could represent the lower post-Alpine sequences and part of the upper Alpine successions. It is followed by a layer showing a velocity range of 4.5–6.0 km/s, which is attributed to the lower successions of the Alpine sediments, mainly consisting of carbonates. The next layer corresponds to a velocity between 6.1 and 6.5 km/s and could be the lowermost part of the carbonate_ succession and the Palaeozoic metamorphosed sequence. The layer corresponding to 6.6-7.9 km/s may represent the lowermost part of the Cretan crust.

Earthquake dataset The earthquakes of magnitude $M \geq 2.5$ which occurred in the broader area of Crete, during the period 2003-2007 have been selected in the context of the present work. These data are based on the recordings at two permanent seismological networks in Greece (National Observatory of Athens - Institute of Geodynamics NOA, and the SASN) as well as the Eastern Mediterranean Seismological Centre (EMSC). The stations (Fig. 1b) of SASN that used in the present work are mostly distributed in the region of Crete as well the neighboring islands. Furthermore the earthquake epicenters (Fig. 3c), recorded by the SASN in the period 2006-2007, are distributed offshore and onshore Crete. The density map of the earthquake epicenters (Fig. 3d) shows an intense near coast and onshore seismicity that gave rise to study the relation between the spatial distribution of the faults and the earthquake epicenters for the area of the Heraklion prefecture contacting more intense earthquake analyses for two distinct periods, namely July-August 2007 and September-October 2007.

GIS techniques and mapping Density maps were created for each one of the NOA, EMSC and SASN seismic activity datasets corresponding to the periods of 2003-2006, and 2006-2007 respectively. A kernel density algorithm using a quadratic formula where the highest value corresponds to the center location falling to zero at the search radius distance was preferred in the calculations of the density maps for creating smoother distribution surfaces. A circular search area of approximately 10Km was used around the location of each seismic epicenter. The resulting density surfaces having a resolution of about 1km indicate the spread of the seismic epicenters over the areas surrounding the island of Crete. Similar density maps were created for the micro-seismicity of the region for two distinct periods, namely July-August 2007 and September-October 2007.

In order to correlate the seismic risk of the prefecture of Heraklion in terms of the activated inland faults of the region, the IGME (Institute for Geological and Mineral Exploration) geological maps of the region were digitized and the described faults were classified in four main categories depending on their alignment, namely E-W, N-E, NW-SE and NE-SW. A buffer distance of 500m was used around each epicenter for the seismic incidences corresponding to the NOA, SASN and micro-seismicity (whole period of July-October 2007), each of which was approached independently. Similarly, buffer zones of 250m were created around each one of the fault classes. Boolean algebra was then used to combine the above surfaces and generate areas that overlapped. In this way, it was possible to correlate the seismic activity of the area with specific faults (or even sections of faults) and examine the attributes of specific seismic zones.



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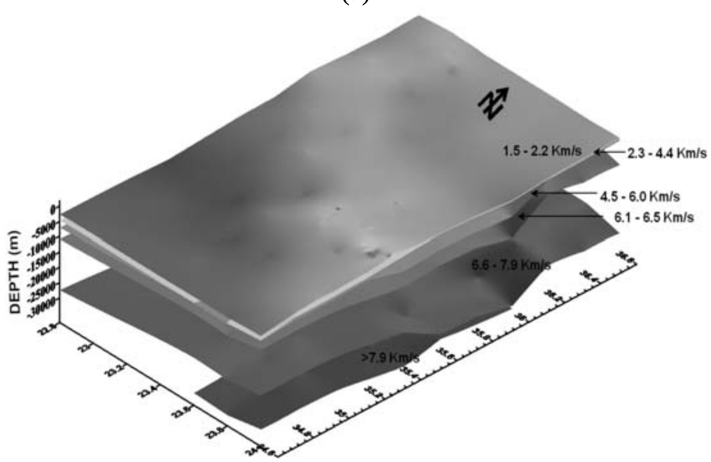

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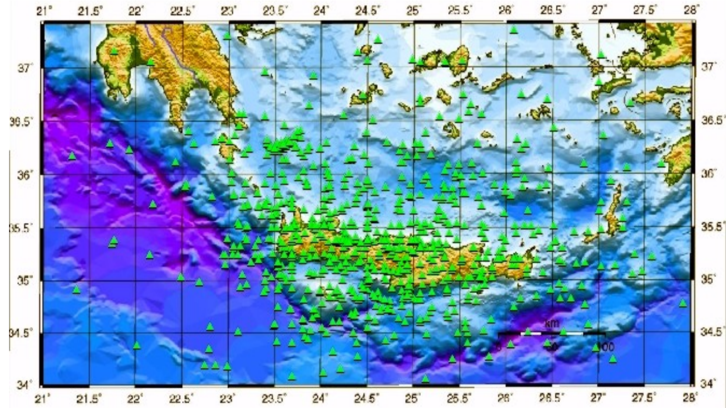

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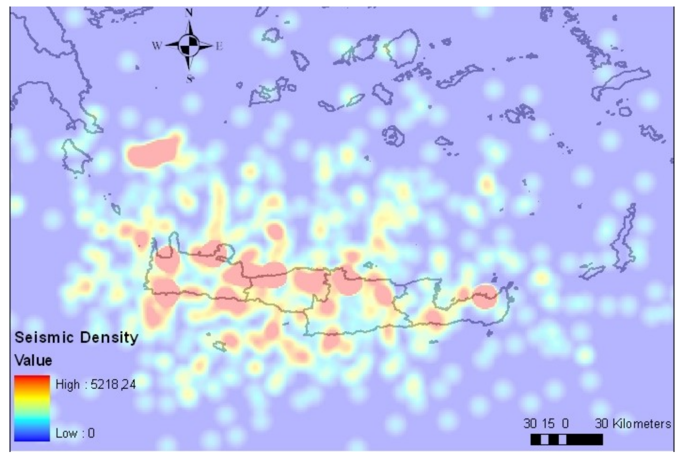

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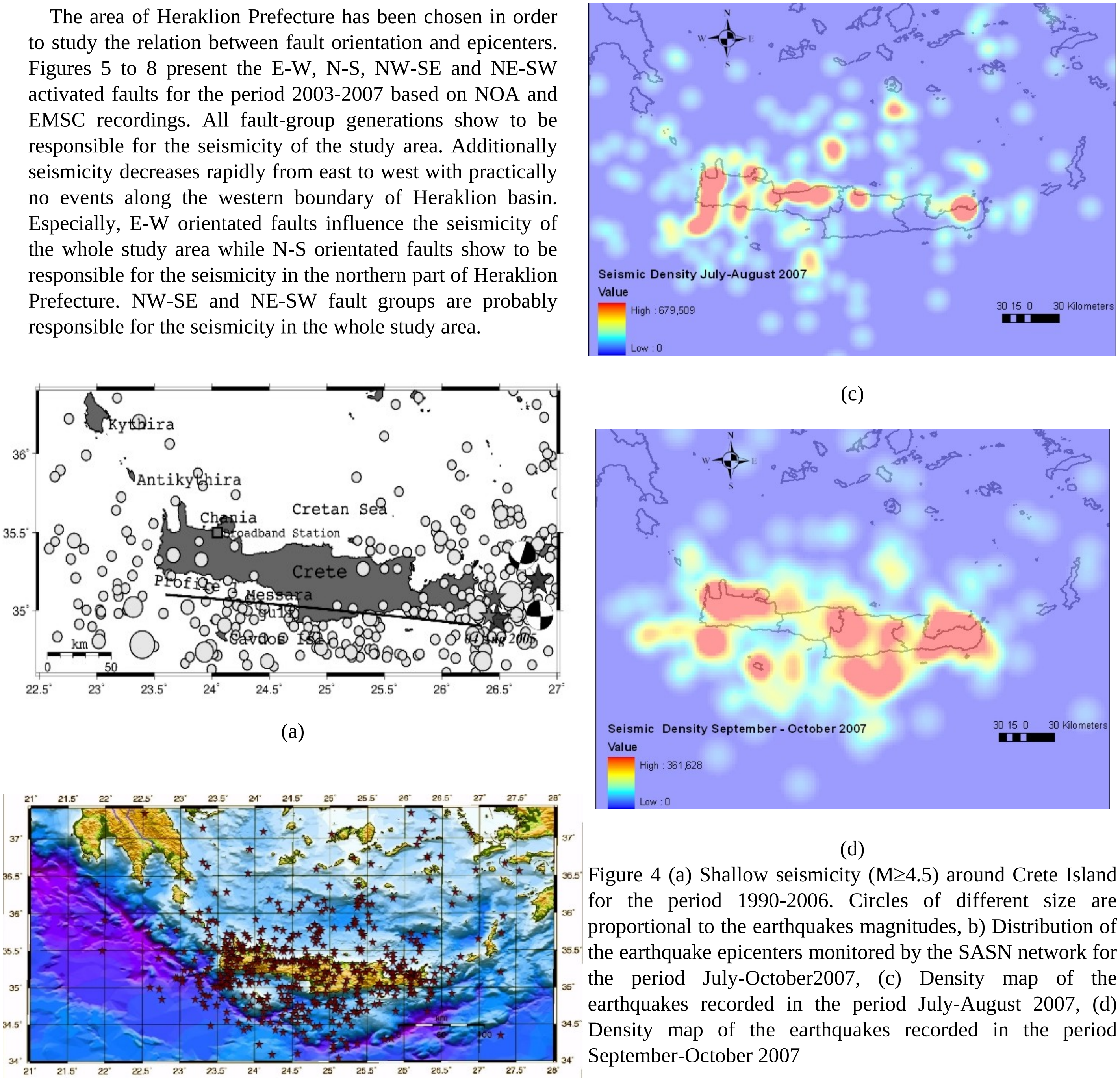
Figure 3 a) 3D velocity section of the Cretan crust in the E-W direction, b) 3D velocity section of the Cretan crust showing better the geodynamic structure in the N-S direction, c) Distribution of the earthquakes epicenters monitored by the SASN network for the period 2006-2007, d) density map of the earthquake epicenters

IV. RESULTS

Figure 4a, b show the shallow seismicity (M≥4.5) around Crete Island for the period 1990-2006 [24] and the spatial distribution of the earthquake epicenters recorded in the period July-October 2007. Figures 4c and 4d present the density maps of the earthquakes for two distinct periods, namely July-August 2007 and September-October 2007 respectively. In the period July-August 2007 an intense seismicity is observed in western Crete. An N-S orientation of the epicenters is clearly seen in the westernmost part of Crete while an E-W orientation of the epicenters is present at the northeastern part of Crete. The seismicity pattern of the period September-October shows an intense onshore seismicity in the whole island with no specific orientations.

The area of Heraklion Prefecture has been chosen in order to study the relation between fault orientation and epicenters. Figures 5 to 8 present the E-W, N-S, NW-SE and NE-SW activated faults for the period 2003-2007 based on NOA and EMSC recordings. All fault-group generations show to be responsible for the seismicity of the study area. Additionally seismicity decreases rapidly from east to west with practically no events along the western boundary of Heraklion basin. Especially, E-W orientated faults influence the seismicity of the whole study area while N-S orientated faults show to be responsible for the seismicity in the northern part of Heraklion Prefecture. NW-SE and NE-SW fault groups are probably responsible for the seismicity in the whole study area.



(a)

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Figure 4 (a) Shallow seismicity (M≥4.5) around Crete Island for the period 1990-2006. Circles of different size are proportional to the earthquakes magnitudes, b) Distribution of the earthquake epicenters monitored by the SASN network for the period July-October2007, (c) Density map of the earthquakes recorded in the period July-August 2007, (d) Density map of the earthquakes recorded in the period September-October 2007

The maps of Figures 9 and 10 present the general seismicity pattern in relation to all fault-group generations for the periods 2003-2007 and July-October 2007 respectively. At this point we must refer that for the period July-October 2007 the recordings of the SASN were used and intensively analyzed. Both maps indicate that E-W, NW-SE and NE-SW fault orientations can generally be considered responsible for the seismicity of the study area.

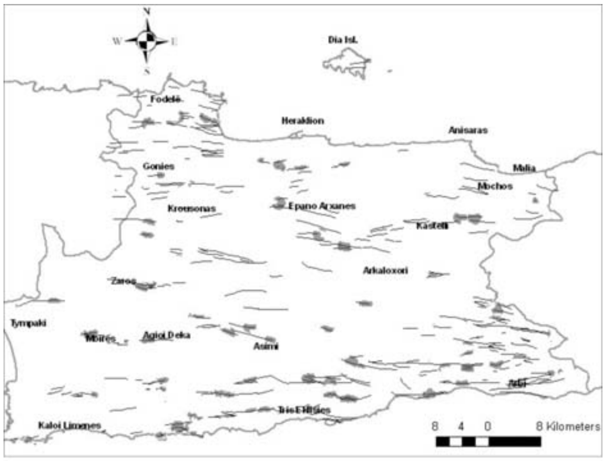

Figure 5 E-W Activated faults (according to the geological map of Greece, 1:50000, I.G.M.E.) of the Heraklion Prefecture for the period 2003-2007

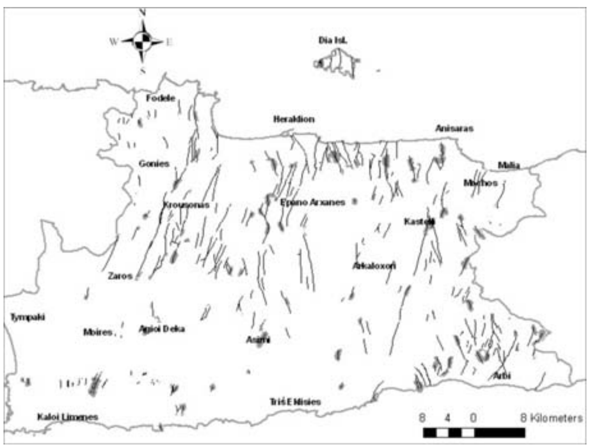

Figure 6 N-S Activated faults (according to the geological map of Greece, 1:50000, I.G.M.E.) of the Heraklion Prefecture for the period 2003-2007

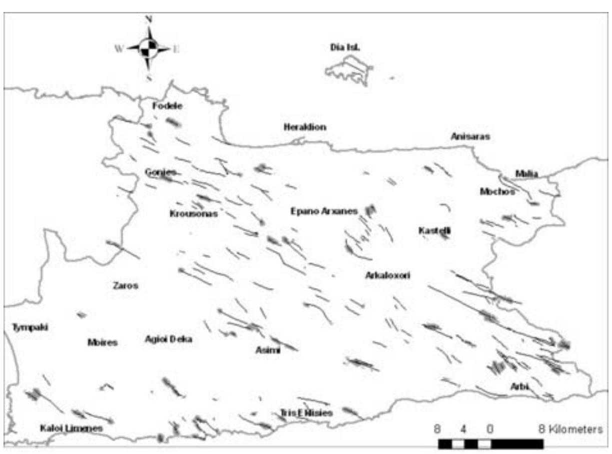

Figure 7 NW-SE Activated faults (according to the geological map of Greece, 1:50000, I.G.M.E.) of the Heraklion Prefecture for the period 2003-2007

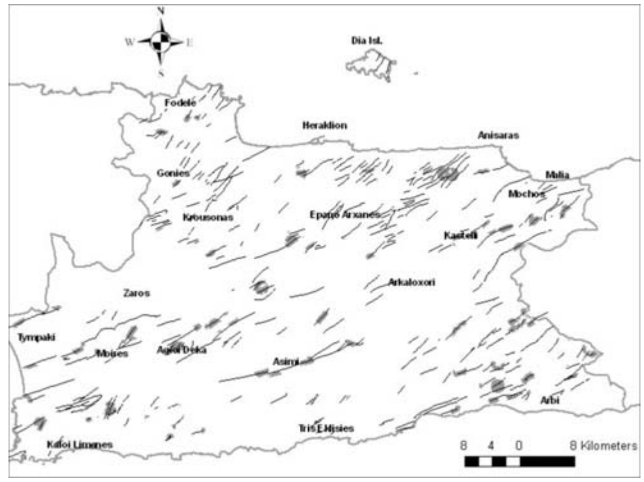

Figure 8 NE-SW Activated faults (according to the geological map of Greece, 1:50000, I.G.M.E.) of the Heraklion Prefecture for the period 2003-2007

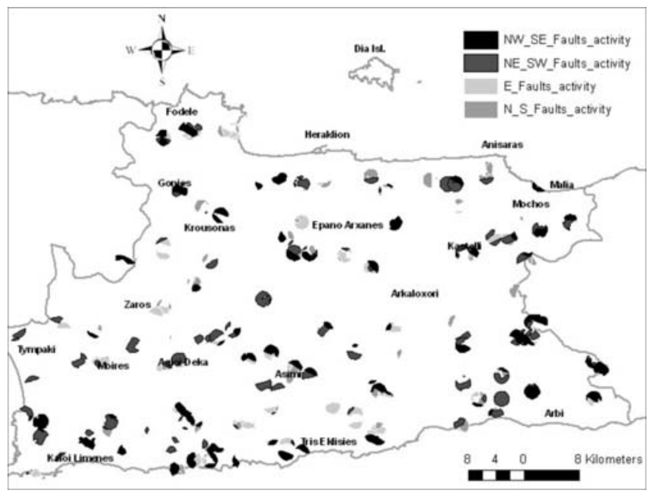

Figure 9 Activated faults of the Heraklion Prefecture for the period 2003-2007

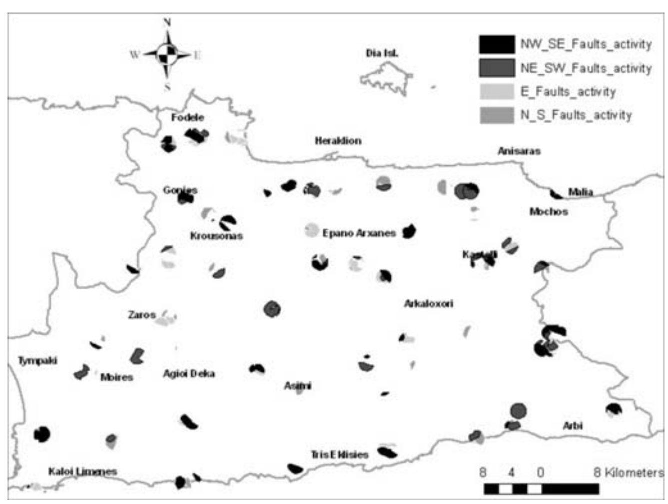

Figure 10 Activated faults of the Heraklion Prefecture for the period July-October 2007

V. DISCUSSION AND CONCLUSIONS

In the context of the present work the earthquake data from the catalogs of NOA and EMSC as well as recordings of the SASN network were processed in order to study the near coast and onshore spatial distribution of the seismicity in Crete. Additionally the relation between fault-group generations and epicenters was investigated for the area of Heraklion Prefecture located in central Crete. Significant seismic activity, possibly of low magnitude, characterizes the near coast and onshore part of Crete. The westernmost part of Crete is characterized by an N-S orientation of the earthquake epicenters while in the rest of the island an E-W trend in the orientation of the epicenters is observed. Especially for the area of the Heraklion basin the seismic activity is concentrated along the eastern margin of the Heraklion Prefecture and in Messara graben to the south. Seismicity decreases rapidly from east to west. These observations are in agreement with the results presented by [13] and [21]. The intense seismic activity in the southern coastline of the Heraklion basin is probably associated with the offshore graben structure defined by E-W trending faults [25].

The overview of the near coast and onshore seismicity in Crete indicates a complex seismotectonic regime. This could be the result of both extensional and compressional stress fields in the area [22], resulting from the convergence of the European and African plates as well as from the extension within the Aegean basin.

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