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DEEP TECTONIC STRUCTURE OF NORTHWESTERN ATTICA,GREECE: GEODYNAMIC PATTERN OF ATHENS EARTHQUAKE

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ABSTRACT

The study of Athens 09.07.1999 earthquake (M_S =5.9), which occurred in the area of the NW Attica peninsula within the Thriasio neotectonic basin, shed light to the complicated active tectonic structure of Attica. The geological, gravity and magnetic data, as well as the results of InSAR analysis were jointly considered for a better understanding of the block tectonics and kinematics of the meisoseismal area, as well as block geodynamic related to the seismic event. The deep tectonic structure is characterized by existence of small (up to 20km) dimensions uplifted and subsided blocks of Paleozoic basement that defined the characteristic tectonic pattern of the area. The largest values of co-seismic subsidence, derived from InSAR analysis, are observed within the subsided blocks of epicentral area. This evidence, together with the results of field microtectonic observations, implies that this ensemble of blocks, during the seismic event, moved in accordance with block kinematics and under the approximately N-S tension, which is characteristic for Attica on its neotectonic history ranging from Mid Pleistocene to date.

KEY WORDS: earthquake, potential fields, InSAR, block tectonics and kinematics, geodynamic, northwestern Attica, Greece

1. INTRODUCTION

On September 7 1999, a devastating earthquake struck the districts of Athens in northwestern Attica and was followed by an aftershock sequence with magnitude range of M_S£ 4.7. The determined parameters of the main shock are: Lat. 38.1°N, Lon. 23.6°E; M_S=5.9; depth interval 9-20 km. The focal mechanism solution suggested a WNW-ESE trending normal fault (114°-123°) with slight left-lateral component, dipping to SSW about 45°-55°, with subhorizontal extensional axis T oriented NNE (about 208°). According to the Brune model (Stavrakakis et al., 2000) the seismogenic fault length is about 19 km and the average co-seismic displacement on the fault plane 9 cm.

Our recent studies (Foundoulis et al., 2000a, 2000b) have shown that the geodynamics of the earthquake is defined by a stress tensor, which can be approximated by a tensional rotation ellipsoid. Axes σ_2 and σ_3 are both tensional and equal to each other in absolute value, whilst the axis T of the main shock source mechanism coincides with the axis σ_2 but not with the axis σ_3 as could be expected. This geodynamic situation implies the prevailing of vertical movements during the main shock and suggests that several blocks of the affected area had moved along the pre-existed bordering faults following one of the tensional axes, σ_2 or σ_3.

In this study, the results of gravity and aeromagnetic data analysis, as well as the results of InSAR analysis have been jointly considered for a better understanding of the block geometry, kinematics as well as the block geodynamics related to the Athens earthquake.

2. TECTONIC AND GEOPHYSICAL CHARACTERISTICS OF NORTHWESTERN ATTICA

Two main tectonic units may be distinguished in the area (Fig. 1):

(i) The Pelagonian geotectonic zone of non-metamorphic formations situated westward of Kifissos river valley (Mts. Parnitha and Aegaleo), that constitutes the alpine basement of the majority of the meizoseismal area,

(ii) The Attico-cycladic zone consisting mainly of metamorphic rocks (Mts. Penteli and Imittos).

The Pelagonian zone upthrusts the Attico-cycladic zone(G. Katsikatsos et al., 1986); the tectonic contact between the two units is usually covered by post-alpine sediments. Thrust strike is consistent nearly with the direction of Kifissos river valley (see Fig. 1).

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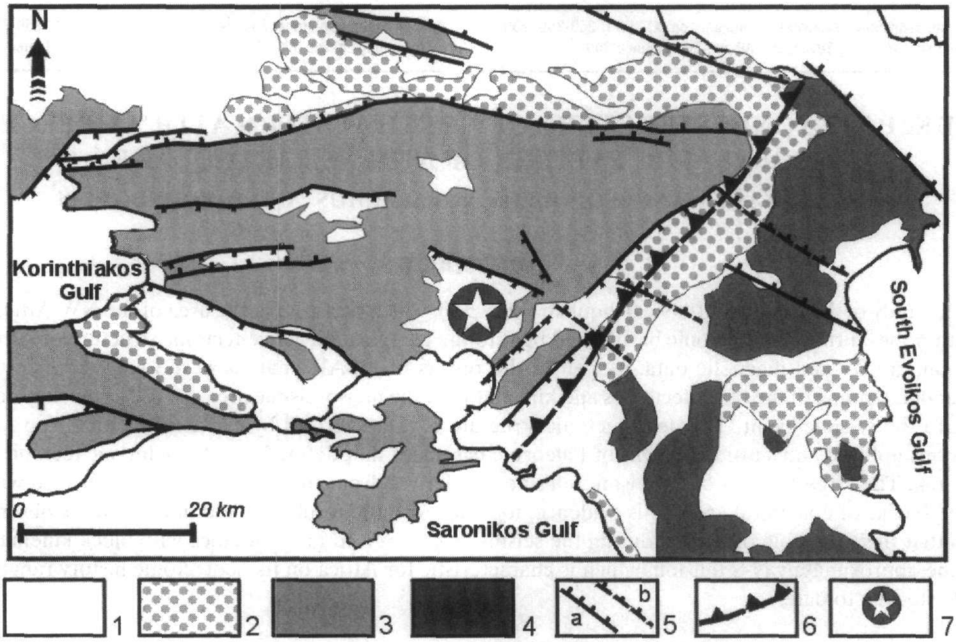

Fig.1: Simplified neotectonic map of the area affected by Athens earthquake (after Papanikolaou et al., 1999; Mariolakos & Foundoulis, 2000).
1:Quaternary deposits, 2: Neogene deposits, 3: Pelagonian zone (mainly Mesozoic carbonates), 4: Attico-cycladic zone (mainly Mesozoic metamorfics), 5: Active neotectonic faults (a - detected, b - probable) 6: Upthrust - major tectonic contact separating the two zones, 7: Epicenter of Athens earthquake 07-09-1999, M_S=5.9.

Several neotectonic basins, filled with lacustrine-continental deposits, have been created by the fragmentation of the area because of the post-alpine extension: the Thriassio basin, Kifissos basin etc.

Three extensional tectonic regimes have occurred during the Tertiary structural evolution (J. Mercier et al., 1989). The tensional directions of these regimes are striking (1) WNW-ESE, (2) NE-SW and (3) N-S; they were active during the Upper Miocene, Pliocene - Lower Pleistocene and Mid Pleistocene to date, respectively. Active tension of the crust approximately in the N-S direction, has been calculated also using repeated G.P.S. measurements (Le Pichon et al., 1995; Kahle et al., 1998). Such situation may account for the fact that various tectonic phases, from alpine napping to opening of neotectonic basins, have led to complicated fracturing of the area.

Physical properties of rocks outcropping in meizoseismal and adjacent areas are shown in Table 1 according to: Stefouli & Angelopoulos, 1990; Engineering Geological Map of Greece, 1993; Tsokas et al., 1998.

Based on the data of the Table 1, the following assumptions on the heterogeneities creating gravity and magnetic anomalies in NW Attica may be made. Density of the Mesozoic metamorphic rocks amounts to 2.9 g/cm^3 which predetermines the existence of densitive discontinuity between non-metamorpic and metamorphic formations. The Paleozoic metamorphic rocks that constitute the pre-alpine basement of the Parnitha tectonic structure, due to their density characteristics, appear to occupy the intermediate position between the non-metamorphic and metamorphic carbonates. So the gravity field peculiarities have to be defined inside the Parnitha mountain range mostly by the structure of pre-alpine Paleozoic basement and in the area of Penteli and Imittos mountains mostly by Mesozoic metamorphic formations. As regards the magnetic anomalies, most of them have to be related to Neogene-Quaternary deposits, excepting some of them, which should be connected to Bauxite lenses, or FeNi ore bodies.

3. DEEP BLOCK STRUCTURE OF NORTHWESTERN ATTICA

Qualitative interpretation and zoning of magnetic and gravity fields allow to understand some features of the deep tectonic structure of the study area and to determine "blind" faults zones. Zoning of the gravity and magnetic field and related tectonic zoning are based on the relation between the peculiarities of field pattern

Table 1. Physical properties of rocks and minerals of Attica and adjacent areas

Type of rocks	Bulk density, g/cm^3	Susceptibility, $1x10^{-6}$ CGS	Remanent magnetization, $1x10^{-6}$ CGS
Neogene-Quaternary deposits (sandstone & conglomerates)	1.8-2.2	300	-
Mesozoic non-metamorphic carbonates	2.5-2.7	0-25	10-40
Mesozoic metamorphic carbonates	2.7-2.9	-	-
Paleozoic metamorphic rocks	2.6-2.8	-	-
Ophiolites	2.5-3.2	800	500±200
Bauxite	3.2	850	150
FeNi ore	3.3-3.8	2.000-15.000	140-1020

over the geological or structural heterogeneity (object) or on theoretical anomalies over "simple" bodies (Khesin et al, 1983).

Various "blind" fault zones may be determined in potential fields from their different linear features related to their origin and development. Some principal peculiarities of magnetic and gravity fields over faults of different types are shown in Table 2 (Khesin et al., 1983).

Owing to fault segmentation it is possible to find different linear features (indications) in gravity and magnetic field along the fault zone. An arrangement of indications along the same direction allows the tracing of the fault. Some fault segments cannot be detected with confidence by slight indication only in one potential field, but they may be delineated by comparison of indications observed in the gravity and the magnetic field.

For determining the zoning and detecting the deep tectonic structure of the Attica, the observed gravity field and upward continued to 2.0 km magnetic field were used as basic data (Fig.2a and 2b). The aeromagnetic field on the level of 2km apart from flight line is free from small heterogeneity and more comparable with observed gravity field.

Table 2. Magnetic and gravity fields over faults

TYPES OF FRACTURE	GEOLOGICAL CHARACTERISTICS	REFLECTION IN FIELDS
Faults with vertical displacements	Abrupt change in position of boundary separating a section into individual structural-facial complexes Crush zone due to differentiated movement of conjugated blocks along the fault	Elongated zone of high field gradients Abrupt closure or contraction of isolines. Chain of linearly elongated magnetic and gravity minima coinciding in plane
Faults with horizontal displacement	Horizontal rock displacement and offset determined by comparing age as well as structural and facial features of rocks on both sides of a fault	Rupture and echelon displacement of zones with linearly elongated anomalies Offset (breaking off) of anomalies belonging to the elongated anomalous zone Flexure type bending (abruptly inflecting) of isolines or of intense extending steps axis
Synsedimentary faults	Abrupt change in lithological composition, facies and deposit thickness of the same unit on both sides of a fault	Change of sign or pattern of the same sign field at a fault

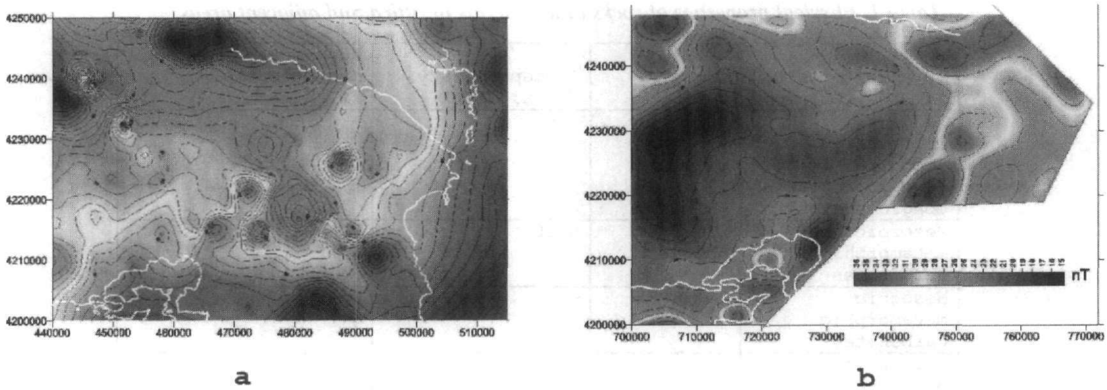

Fig. 2: Gravity and magnetic maps of northwestern Attica
a - Bouguer gravity map, ϱ=2.67 g/cm3, topo correction 100m-167km (IGME, A. Angelopoulos and V. Noutsis, 2000)
b - Aeromagnetic map, H=300 amsl, spacing 800m (IGME, A. Angelopoulos, 1978) upward continued to 2.0 km

The results are shown on Fig 3, wherefrom some characteristic features may be obtained. The Parnitha tectonic structure composed of carbonates of low magnetization and relatively low density may be recognized as an area of the relatively low values of magnetic field, which coincides, with the area of the moderate field values on the gravity map. The northern border of Parnitha structure, where Thiva basin lies along the system of active normal faults with prominent vertical movement (see Fig.1), is shown by high gravity gradient zone pointing to considerable vertical displacement of density unconformity. This zone coincides with the "chain-like positive" magnetic anomalies that point to the development of Neogene-Quaternary conglomerates close to the area of denudation. The same sign and pattern of the magnetic field characterize the southern border of the Parnitha, which coincide with Kifissos Neogene basin. In the gravity field this border is not appearing so clearly as the northern border, due to the upthrusting of the Pelagonian zone on the Attico-cycladic zone.

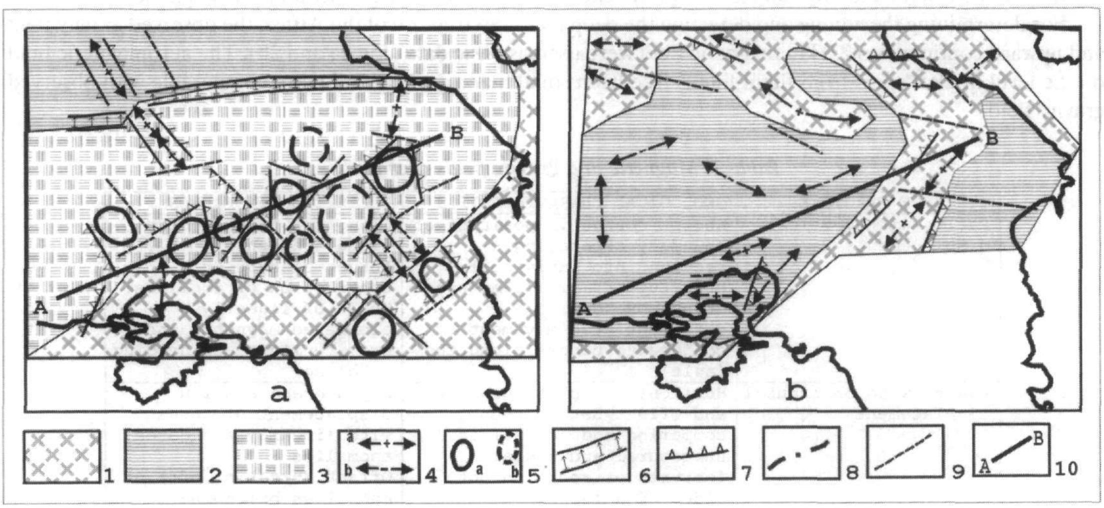

Fig. 3: Results of the geophysical zoning of Attica area on the Bouguer gravity map (a) and on the map of upward continued aeromagnetic field (b)
1: Relatively high field values, 2: Relatively low field values, 3: Area of moderate field values with "mosaic" anomalies, 4: Axes of elongated anomalies (a - "positive", b - "negative"), 5: Isometric anomalies (a - "positive", b - "negative"), 6: High field gradients, 7: Moderate field gradients, 8: Changes of field sign or pattern, 9: Axes of abrupt closure or contracting of isolines within anomalous zone, 10: Location of geological-geophysical cross-section.

4. RESULTS OF SAR INTERFEROMETRY: SUBSIDENCE IN THE EARTHQUAKE EPICENTER

NPA Group Associates Ltd.(R.Capes, M. Haynes & G. Cooksley) has conducted ERS Interferometric analysis with collaboration and financial support of E.P.P.O in order to study the surface deformations related to the Athens earthquake. A differential interferogram is by definition processed in conjunction with a digital elevation model (DEM), such that the effect of topography are subtracted from the output phase image.

This differential interferogram covers the epicentral area of the Athens earthquake (Fig. 4). It is relatively noisy as a consequence of topography that is inadequately modeled by the DEM, but nevertheless reveals a clear subsidence signature centered on earthquake epicenter. From the known geology of the region, the most plausible interpretation of the differential signature is in terms of a vertical, as opposed to horizontal displacement; the sense of the differential phase is decreasing towards the epicenter, implying a subsidence associated with the earthquake. Each fringe represents 28mm of displacement (~30 mm of vertical subsidence), suggesting a total displacement of 84 mm (~90 mm of vertical subsidence) at the epicenter, falling off over a 10km radius.

Fringe features extend beyond this region to both the north and to the south towards Athens that represent an extended region of subsidence.

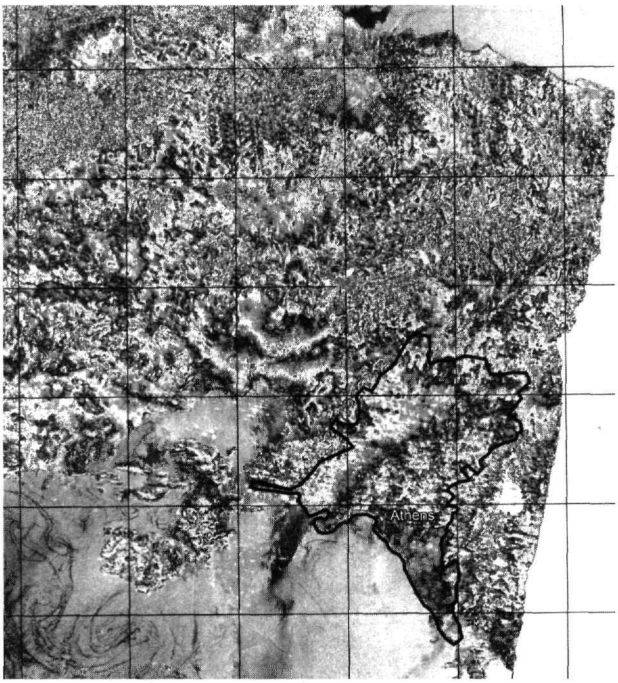

Fig. 4: Results of InSAR analysis of Athens earthquake (7 September 1999).
ERS-2 scene dates: 15-Jul-99 & 23-Sep-99; Temporal separation: 70 days; Ground displacement accuracy: X,Y: 30m, Z: 2cm; Background image: Radar amplitude image (23-Sep-99).

5. CONCLUSIVE REMARKS

The results of gravity and magnetic fields interpretation as well as the InSar analysis are given on Fig. 5, where the main deep block structure in the Athens earthquake epicentral area is shown.

Due to the complicated tectonic regime during the alpine and post-alpine evolution, the fault zones experienced complicated segmentation that led to the creation of mosaic tectonic block of small dimensions, most of them having isometric or subisometric shape. The length of faults or fault segments bordering these blocks does not exceed 15-20 km, but the arrangement of these segments in one direction predetermines the existence of elongated fault zones in NW Attica with two prevailing orientations: NE and NW.

Beside the deep-seated seismogenic fault (Fig.6), the fault segments bordering the subsided block on the SE flank of Parnitha structure in the Thracomacedones area appear to be also deep-seated faults, cutting the zone of major thrust. According to fault kinematics, a number of uplifted and subsided tectonic blocks may be de-

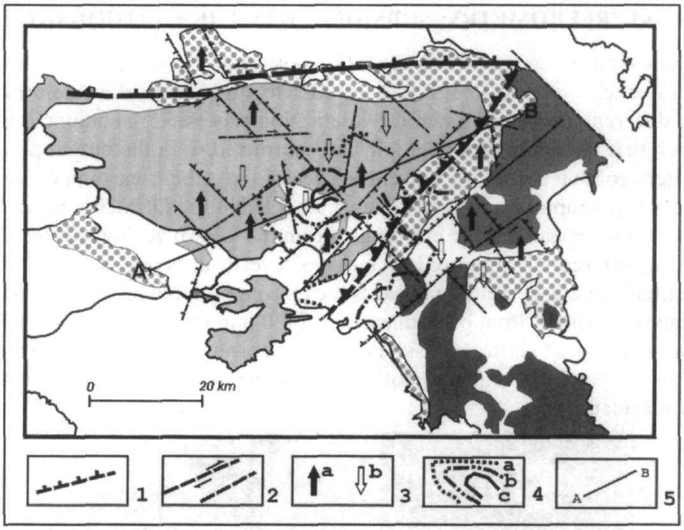

Fig. 5: Scheme of the NW Attica deep block tectonics and kinematics
<u>Deep faults:</u> 1: Normal faults(a - major, b - secondary), 2:Other faults: a - strike-slip, b - of uncertain kinematics, 3: Block movement: a - uplifted block, b - subsided block, 4: Smoothed out InSAR fringes, showing subsidence in the area of Athens earthquake: a - 28mm, b - 56mm, c - 84mm, 5: Location of the geological-geophysical profile. For other explanation see Fig. 1.

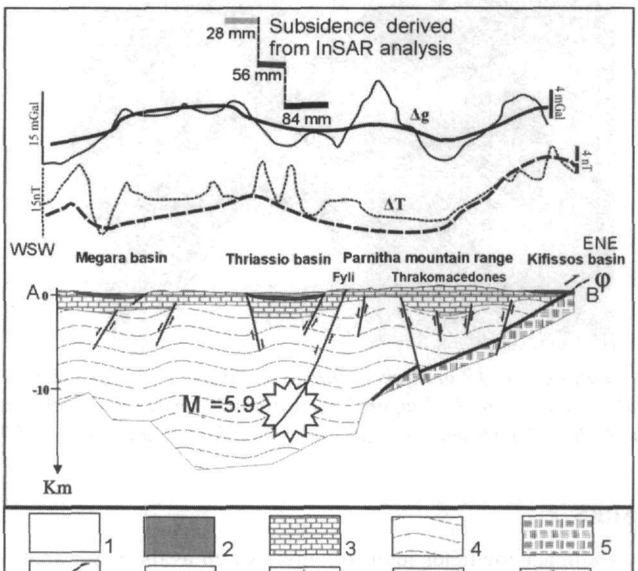

Fig. 6: Schematic geological - geophysical cross-section of northwestern Attica
1: Quaternary deposits, 2: Neogene deposits; <u>Pelagonian zone:</u> 3: Mesozoic non-metamorphic formations, 4: Paleozoic formations; <u>Attico-cycladic zone:</u> 5: Mesozoic metamorphic formations; 6: Upthrust (major tectonic contact separating two zones), 7: Faults (arrows show sense of motion), 8: Location of the Athens earthquake hypocenter; <u>Curves of geophysical fields:</u> 9: Bouguer gravity field (a- observed, b - continued up to 3.6km), 10: magnetic field (a -observed, b - continued up to 2km)

tected in the meizoseismal area of the Athens earthquake. This ensemble of blocks defines the characteristic tectonic pattern of the area.

Considering block geometry and kinematics together with the co-seismic displacements derived from InSAR analysis, it results that the largest values of co-seismic subsidence (from 56 mm to 84 mm) are observed inside the subsided blocks of pre-alpine basement, the fringes closing to the block borders. It is remarkable, that the maximum value of co-seismic surface subsidence according to InSAR analysis (~9 cm) is the same with the value of co-seismic displacement on fault plane derived from the seismic data analysis (Stavrakakis et al., 2000).

All the above mentioned together with the results of field microtectonic observations (Foundoulis et al., 2000a, 2000b), implies that during the seismic event, the ensemble of blocks of meizoseismal area moved in accordance with their kinematics and under approximately N-S tension. This geodynamic situation is characteristic for Attica on its neotectonic history ranging from Mid- Pleistocene to date.

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