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SEISMOTECTONIC STUDY OF CENTRAL GREECE AND HYPOCENTER RELOCATION USING A DOUBLE-DIFFERENCE ALGORITHM

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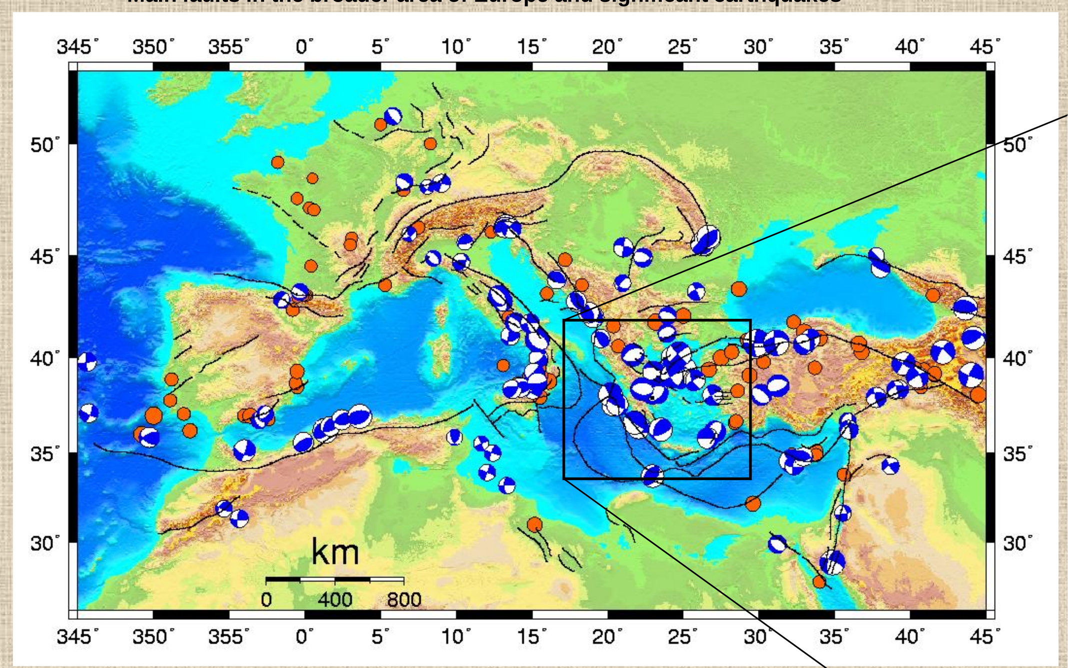
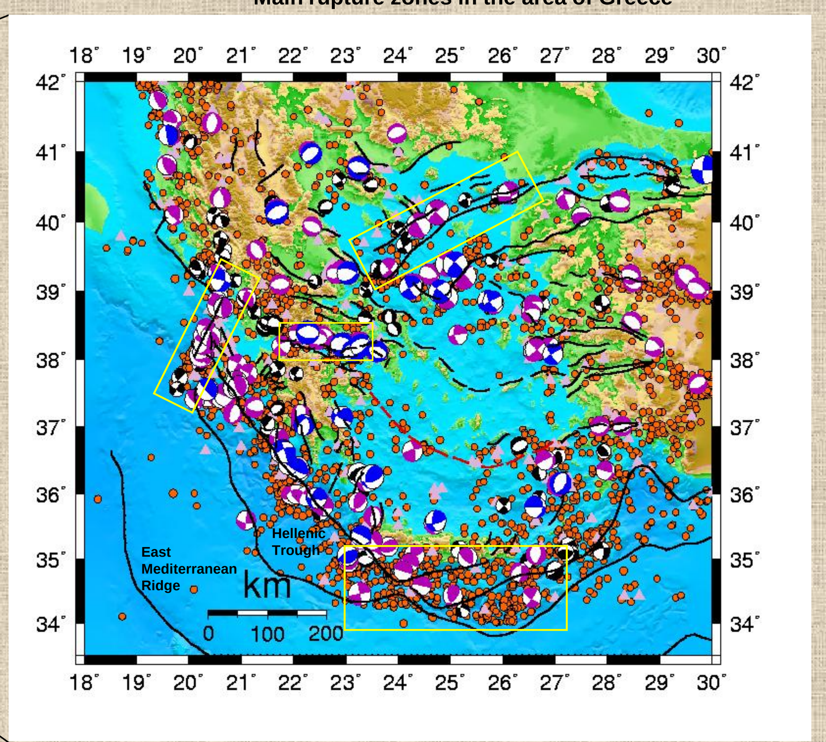
ABSTRACT

In this study phase data from the Cornet seismological network (local seismological network of the Geo-physics-Geothermics Department of the National and Kapodistrian University of Athens) and the permanent networks of the Geodynamic Institute of the National Observatory of Athens and of the Geophysics Department of Thessaloniki (Aristotle University), for a period of ten years (1996-2006), were merged. The data were jointly used to relocate the earthquakes that occurred in the Corinth Gulf (Central Greece) and surrounding areas. These data were initially processed with a single-event algorithm, where a re-weighting of body waves (P, S) and a re-determination of the one dimensional layered velocity structure were applied. Following, the hypocenters were relocated using a double-difference algorithm. Initially, errors were reduced from 1.5 sec, 15 and 25 km to 0.8 sec, 8 and 12 km (rms, erh, erz, respectively). Following, using a double-difference algorithm, RMS as well as the horizontal and vertical location errors (erh, erz) were minimized by one order of magnitude. After that process, the spatial distribution of the epicenters outlined some major local tectonic features in the study area. Focal mechanisms were also determined and are in agreement with corresponding local active fault characteristics. Moreover, the same methodology was applied to the aftershock sequence of large earthquakes and the results were successfully compared with those obtained by available local networks that were deployed in the study area. The results that came out using the algorithms that are described above in the aftershock sequences of Zakynthos (1997-1998) and Athens (1999-2000) earthquakes will be discussed in this case of study.

Main faults in the broader area of Europe and significant earthquakes



Main rupture zones in the area of Greece



1. Introduction

The creation of the Alpine mountain chain which is one of the most important geological features is caused by the collision between Europe and Africa (Fig.1a). Furthermore, an intense deformation observed in Greece and surrounding areas produces important seismicity concentrated in certain seismic zones, such as the Hellenic Arc, characterized by subduction, the North Aegean, dominated by dextral strike-slip faulting, and the Gulf of Corinth. This process generates high seismicity in the Eastern Mediterranean (Fig.1b).

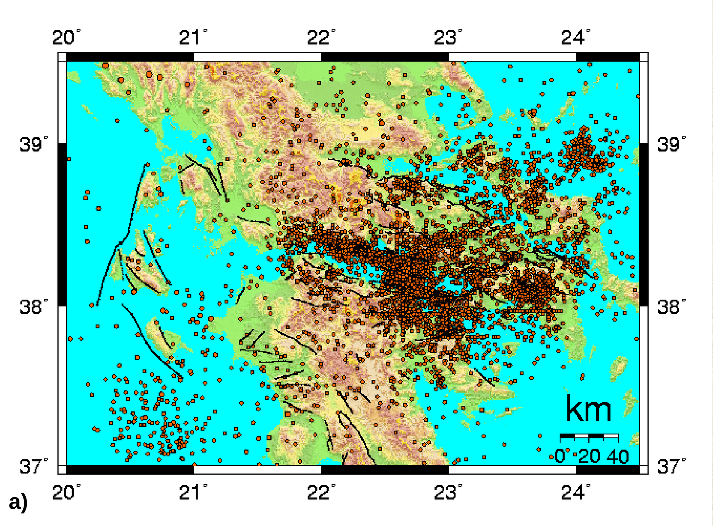
The deformation in the broader area of the southern Ionian islands is characterized by the subduction of a remnant oceanic crust, called Tethys, beneath eastern Europe and the creation of large tectonic features of NW-SE direction in this part of the trench. Large earthquakes in this region revealed reverse faulting with a direction approximately parallel to the Hellenic arc and depths that vary significantly for that part of the Eastern Mediterranean sea.

Two main fault systems, the Hellenic Trench and the North Aegean Trough, dominate the Eastern Mediterranean, while the majority of the seismicity is located along these tectonic zones. In the above figure focal mechanisms of large (M≥5.8), intermediate (4.5<M<5.8) and small earthquakes (M≤4.5) are presented with blue, purple and black color, respectively. Earthquakes with magnitude greater than 6 for the time period 1900-2008 are shown with purple triangles. Similar focal mechanism solutions are obvious in some regions as the Ionian sea, the North Aegean and the Corinth Gulf. On the contrary, in other areas, as south of Crete, different fault plane solutions appear. Three main types of focal mechanisms can be distinguished: a.) dextral strike-slip motion in the vicinity of the Cephallonia-Lefkas, NW Peloponnesus and North Aegean areas, b.) reverse faulting southern of the Ionian islands and along the Hellenic arc and c.) normal faulting in the back-arc region.

The Gulf of Corinth is considered to be one of the most active tectonic rifts around the world. The high level of seismicity, the quaternary local faulting and the 10 to 15 mm/year approximately N-S extension rate, imply that the Gulf of Corinth is a key place in Europe for the study of various physical processes related to the origin of earthquakes. Seismological and tectonic studies indicate that the morphology of the Gulf of Corinth is mainly due to repeated earthquakes that have occurred on 40° to 60° north-dipping normal faults. The Gulf is characterized by the long term subsidence of the northern coast and upward displacement of the main footwalls. Recent large events have focal depths of about 10 km and are characterized by normal faulting with an approximately E-W direction.

The area of Attica is mainly formatted by sediments of H3 terrain (platform of Internal Hellenides) and the direction of the main faults shows a transition of the E-W normal faults of the Corinth Gulf to the NW-SE normal faults of the Evoikos Gulf. The Athens Earthquake that occurred on 7 September 1999 and its aftershock sequence underlined an important fault that lies in the Thriassion plain.

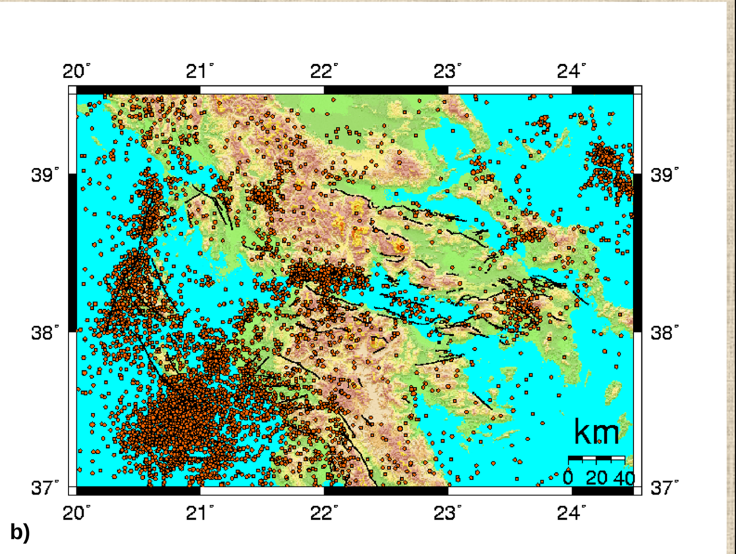
Fig.2 Located Seismicity 1996-2003 of a) CORNET b) GI-NOA (M > 3.3) and c) A.U.TH (M > 1.5) seismological networks



a)

2. Data sources

Data from three different seismological networks were used to form a joint catalogue that would supply better source parameters. The used earthquake catalogues were the ones of the Department of Geophysics of the National and Kapodistrian University of Athens (Cornet network), the Institute of Geodynamics of the National Observatory of Athens and the Department of Geophysics of the Aristotle University of Thessaloniki. Figure 2 shows the located seismicity of the three networks that are described above, while in Table 1 the statistics of the joint and the sub-catalogues are presented.



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Each seismological network has its benefits depending on the quantity, geometry and location of the stations. Cornet seismological network provides better locations for earthquakes that occurred in or near the Eastern Corinth Gulf. Using data from ATHU, NOA and AUTH networks better results are achieved for earthquakes that occurred in the study area, because of the larger number and better distribution of stations. Merging the data from these different sources, a better location of epicenters can be achieved, by reducing the spatial and time (RMS) errors.

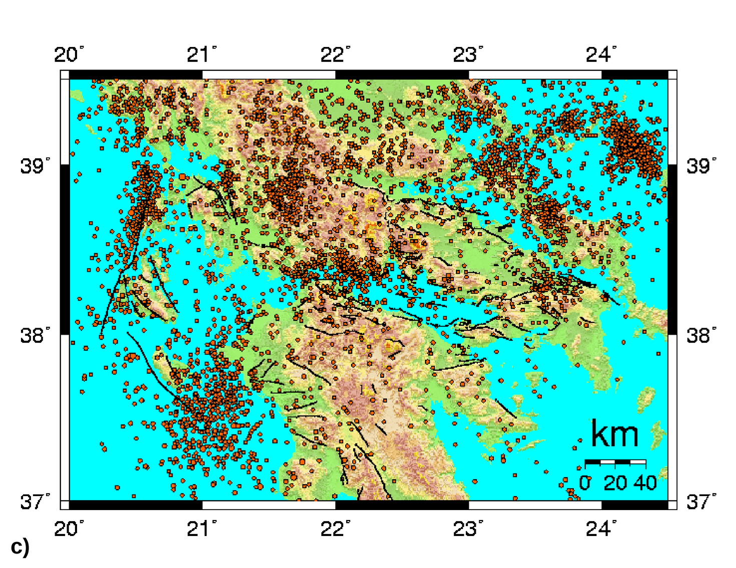

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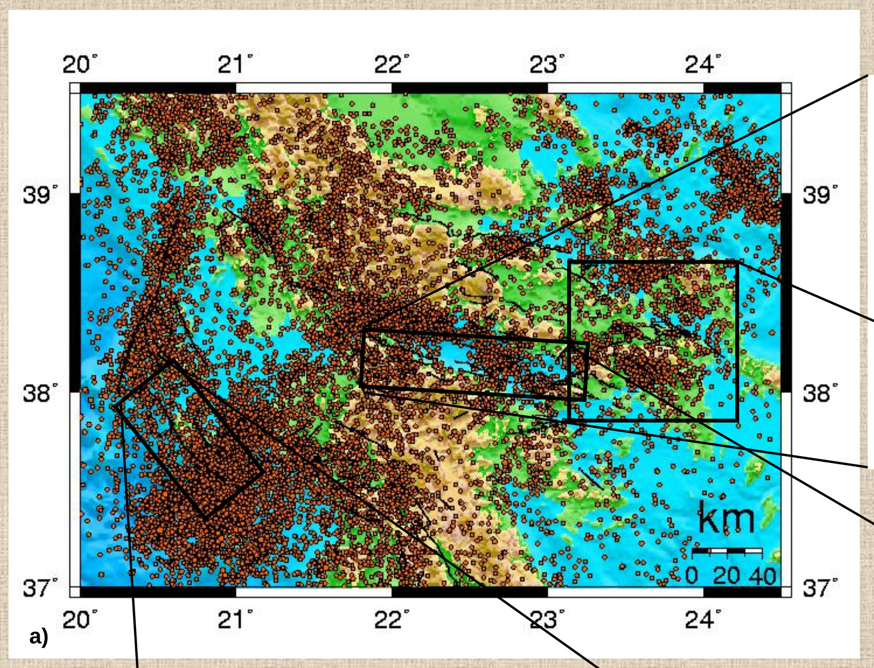
Table 1- Number of earthquakes per network per year

YEAR/CATALOGUE	JOINT CATALOGUE	CORNET	GI-NOA	THES (A.U.TH)
1996	2884	799	2559	2783
1997	5407	2087	3228	3219
1998	4380	788	2867	2086
1999	3942	710	1647	1438
2000	4115	742	2694	1488
2001	4136	751	3042	1873
2002	3239	472	2550	1121
2003	4035	382	3195	1709
2004	4987	-	3331	2662
2005	6481	-	5465	2139
2006	6383	-	5038	2797
Total	49989	6731	35616	23315

Fig.3 Located Seismicity (M > 2.5) 1996-2006 of a) Greece b) South Ionian sea (1997-1998) c) Corinth gulf and d) Attica and surrounding areas



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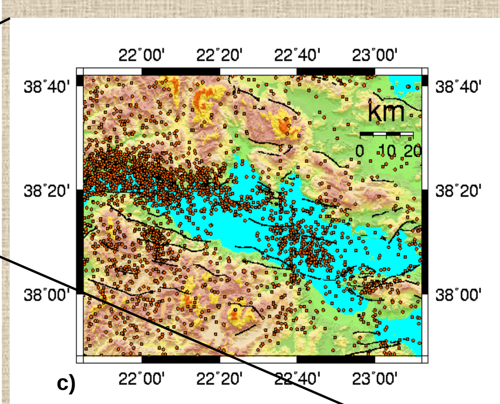

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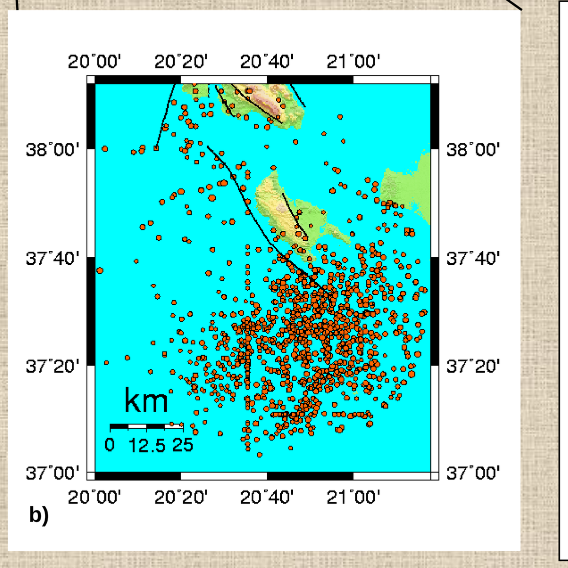


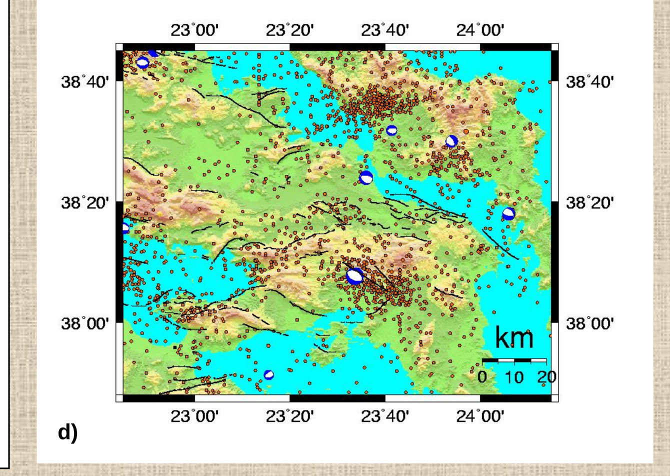
b)

3. Data processing

After the collection of data phases from the three institutes, data processing took place, in three main steps:

1. Merging phase data, of these three different catalogues, identifying the earthquakes that were recorded by stations of more than one network and completing the joint catalogue by adding the "single-network" events. This process was done manually by comparing the arrival times of the network stations that were mentioned previously. The events that didn't have time-difference greater than eighty (60) seconds were merged, as it would be done for records by a single network containing stations of two or more networks.
2. The result was an input file of phase arrivals for a single-event program as HYPO71. By re-weighting the P and the S phases and afterwards by changing the model of 1-D layered velocity structure in each region that was chosen, we achieved an improvement of time and spatial residuals. The results are shown in Fig.3 for the decade 1996-2006 (a. Hellenic peninsula b. South Ionian Sea c. Corinth Gulf and d. Attica).
3. The final catalogue obtained by this procedure was processed by the HYPODD double-difference algorithm (Waldhauser and Ellsworth, 2000), where, as it will be mentioned in a next paragraph, the residuals were minimized. As a result hypocenter locations were ameliorated and alignment of epicenters with main rupture zones of the studied areas was achieved. The merged input data file was divided in sub-areas, where the algorithm could give better results.

More than 40,000 earthquakes were recorded in Greece by permanent networks during the studied time period (1996-2006). The data were analyzed and processed by algorithms written in Fortran code (HYPO71, HYPODD) to reveal the main faults that were activated during this time of period. A re-weighting of P and S waves took place in a mode that RMS, as well as vertical and horizontal spatial errors would be reduced in desirable levels. Furthermore, we intervened in HYPO71 parameters, not only to change the velocity model, but also to manipulate the information that comes from each station for an event. Stations with systematical errors in certain distances are ignored to achieve better locations and match with rupture zones, as it can be seen in Fig.3d, where the seismicity of Attica is pictured. During this initial procedure the mean errors RMS, erh, erz were reduced from 1.5 sec, 15 and 25 km to 0.8 sec, 8 and 12 km, respectively. The earthquakes that were chosen per area should be recorded by more than three stations to be taken into account in the joint catalogue. This is the reason why in some cases the events that were recorded by one network are more than those referred in the joint catalogue.



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DOUBLE-DIFFERENCE ALGORITHM

HYPODD (Waldhauser and Ellsworth, 2000) minimizes residuals between observed and calculated travel time differences (or double-differences) for pairs of nearby earthquakes at each station that recorded both events, as it can be seen from equation (1) and Fig.4. In this way errors caused by unmodeled 1-D layered velocity structure are minimized without the use of station corrections. Inter-event distance and misfit weighting is applied after each iteration to catalogue data and to optimize data quality dynamically during relocation. Horizontal and vertical relative spatial errors are minimized by one order of magnitude.

Table 3- Number of events per year per network in Attica (1996-2006)

Year/catalogue	joint catalogue	CORnet	GI-NOA	THES
1996	41	184	19	13
1997	219	334	40	32
1998	143	102	45	17
1999	388	219	253	85
2000	175	98	114	32
2001	114	70	108	22
2002	123	41	98	29
2003	268	61	224	87
2004	152		193	43
2005	129		180	24
2006	34		163	19
Total	1786	1109	1437	403

As it can be seen from Fig.5, the relocated seismicity was concentrated in narrow zones near well-known rupture zones of the area, such as the Aigion, Helikl, Xylokastro and Psathopyrgos faults. An interesting match with some faults, south dipping, of the northern Corinth gulf (Nafpaktos area) is noticed. This shows that both north-dipping and south-dipping faults were activated during this time period with events of small to intermediate magnitude. All events are located in the seismogenic layer of the crust in depths that vary from 4-12 km. Mean time and spatial errors were minimized by one order of magnitude in a way that errors due to unmodeled velocity structure could reach the minimum possible values for RMS, erh and erz.

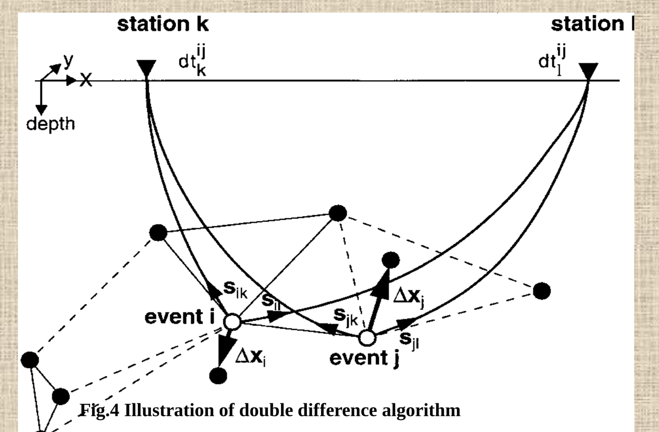


Fig.4 Illustration of double difference algorithm

$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \quad (1)$$

Fig.5 Relocated seismicity using HYPODD for 1996-2006 period in Corinth Gulf

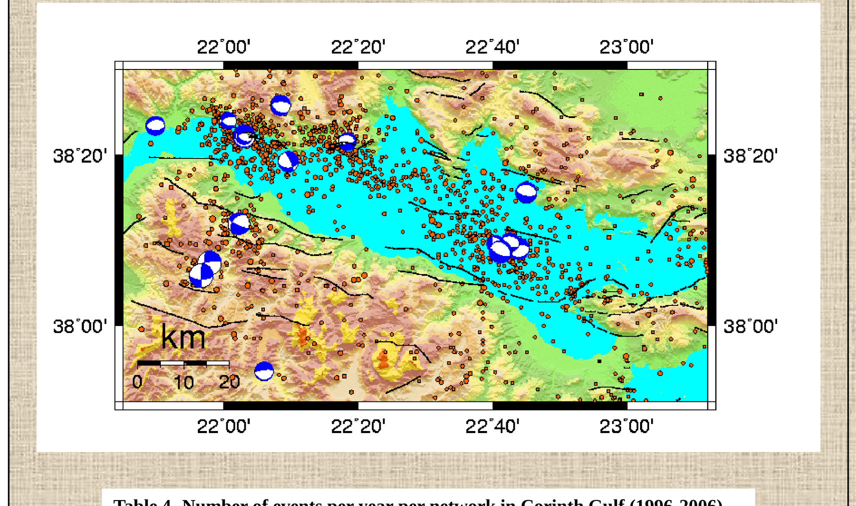


Table 2- Number of events per year per network in the South Ionian islands (1996-2006)

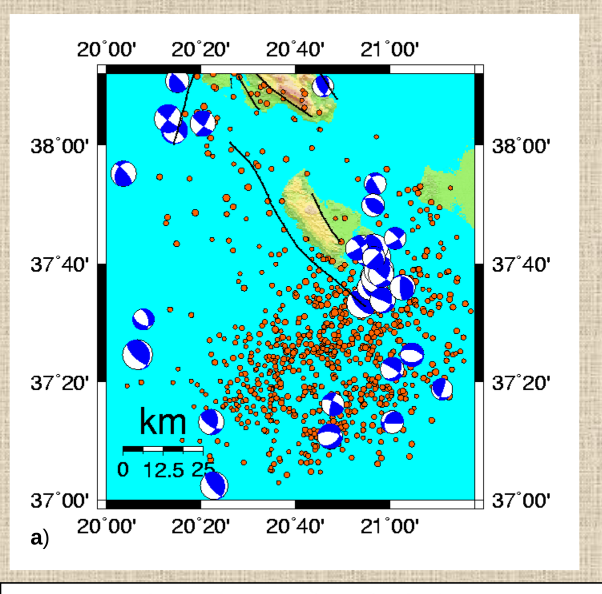
Year/catalogue	joint catalogue	CORnet	GI-NOA	THES
1996	59	5	167	49
1997	744	2	701	163
1998	836		729	88
1999	274	1	230	21
2000	175	1	168	35
2001	176	3	170	17
2002	410	7	394	34
2003	273	4	254	12
2004	185		254	16
2005	137		274	24
2006	775		880	78
Total	4044	23	4221	537

The chosen seismicity for certain areas was transformed into an input file for HYPODD. In that way we covered the seismicity of the Hellenic peninsula with ellipses that were following the main direction of the regional tectonic structures. The lack of waveform cross-correlation data forced us to test the algorithm's parameters to have better results. In Tables 2-5 the statistics of the chosen areas from the whole region of Greece for the decade 1996-2006 are shown. Two main events occurred during this period of time that generated significant aftershock sequences in these areas. On November 18, 1997 at 13:07 UTC, a strong earthquake M=6.6 occurred in shallow depth (h=10 km) south of Zakynthos island. The aftershock sequence continued also in 1998. This large sequence was processed with HYPODD, as well as the sequence of the Athens earthquake that occurred on September 7, 1999 at 11:56 UTC (M=6.0, h=8.5 km). The data from both aftershock sequences were recorded by the permanent networks that were described previously.

Table 4- Number of events per year per network in Corinth Gulf (1996-2006)

Year/catalogue	joint catalogue	CORnet	GI-NOA	THES
1996	63	292	45	31
1997	416	473	76	42
1998	335	230	73	25
1999	179	100	38	17
2000	248	120	77	63
2001	241	140	109	39
2002	75	150	60	14
2003	165	86	65	18
2004	126		104	31
2005	97		107	16
2006	61		113	12
Total	2006		867	308

RELOCATION OF IMPORTANT AFTERSHOCK SEQUENCES



a)

The epicenter of the Athens Earthquake was located in Thriassion basin at a depth of 8.5 km, obtained from the double-difference algorithm procedure. Out of 388 earthquakes of the aftershock sequence, 334 were relocated in a new location with time and spatial errors reduced at least by one order of magnitude.

The distribution of both epicenters in Fig.8d shows the activation of more than one faults during the aftershock sequence. It is clear that the majority of aftershocks is located on a rectangular area that includes the Parnitha's fault escarpment and its hanging wall that extents along Thriasion basin with main direction WNW-ESE, on the contrary with the initial located events that showed an important activity outside the fault area due to the large spatiotemporal errors. The focal mechanisms that were obtained during this study using first P-wave polarities, show that the fault plane has azimuth 102°, dip 48° and slip -95°. A smaller fault was activated on the north, in Phyli's basin, by earthquakes that reached in magnitude (Md) 4.2

In Table 5 we can see that the earthquakes that occurred within 13 minutes before the main shock were located along the Parnitha fault, in the same focal area, mainly at depths 11-14 km, clue that characterizes them as foreshocks.

More than 450 earthquakes were recorded from the three mentioned networks but about 400 events were recorded at least by three stations. The alignment with the Parnitha fault and the hypocenters distribution led to the conclusion that for a time period of one year (September 1999-October 2000) a major normal fault with length of about 15 km was activated. A secondary fault, south-dipping and normal also, of NW-SE direction generated earthquakes of maximum magnitude 4.2 (Md). In the time period 2000-2006 an important cluster to NW, where North Evoikos is located, was observed. During 2000 and afterwards about 400 earthquakes occurred in that region and can be matched with a NW-SE normal fault that is one of the tectonic features responsible for the formation of this graben. Out of 819 earthquakes that occurred during 2001-2006, 564 were successfully relocated. These are mainly shallow events with depths that do not exceed 15 km.

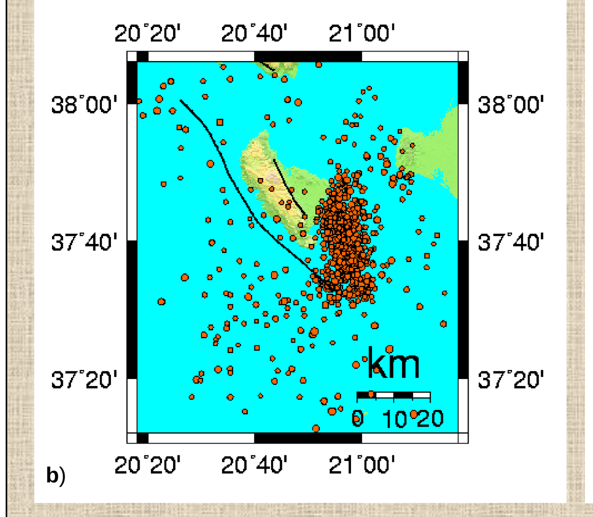
The results of the aftershock distribution of the Athens earthquake were successfully compared with those obtained by Papadimitriou et al. (2002), where a local network has been set up to record the aftershock sequence (3.500 events).

An example of relocation of an aftershock sequence is presented in Fig.7a, where more that 1000 earthquakes occurred in a time period of two years (1997-1998). In Fig 7b the seismicity was relocated for 2005-2006 where Zakynthos earthquake sequence (M=5.6, 2005) occurred, with aftershocks that in some cases reached the magnitude of 4.5. Depths vary in this example because of the main tectonic structure that dominates the area, the subduction zone.

During 1997-1998 the location of the epicenters and their depth distribution show that a fault with NNW orientation and with a length of more than 20 km was activated. 1224 earthquakes occurred during this time period, out of which 862 were relocated using the double-difference algorithm. This example can be judged as unsuccessful, due to the dispersion of the epicenters, even though the hypocenter distribution was improved and the relocation highlighted a double zone of slightly NE dipping hypocenters, fact that is consistent with the subduction in this area.

More than 1500 earthquakes occurred in the time period 2000-2006. As same occasion with the 1997's earthquake could be characterized the one that occurred on 18 October of 2005 (M=5.7) where a NW-SE, parallel to the arc, reverse fault was activated. Depths even for this period have significant variance, because of the subducted crust that causes the seismic deformation of this part of Greece. Focal mechanisms obtained from ATHU (http://www.geophysics.geol.uoa.gr) are also shown in the figures of relocated seismicity. 858 out of 912 earthquakes were relocated during 2005-2006 with three main clusters containing 776, 65 and 17 events with main direction of the clusters N345°, N320°, N280°, respectively. The concentration of earthquakes in the main cluster is in agreement with the focal parameters that were computed for the main event by the Department of Geophysics-Geothermics of the University of Athens (azimuth-312°, dip- 28°, slip-85°).

Fig.7 a) Relocated seismicity using HYPODD for 1997-1998 period, b) located seismicity for 2005-2006 period and c) relocated seismicity for 2005-2006 period



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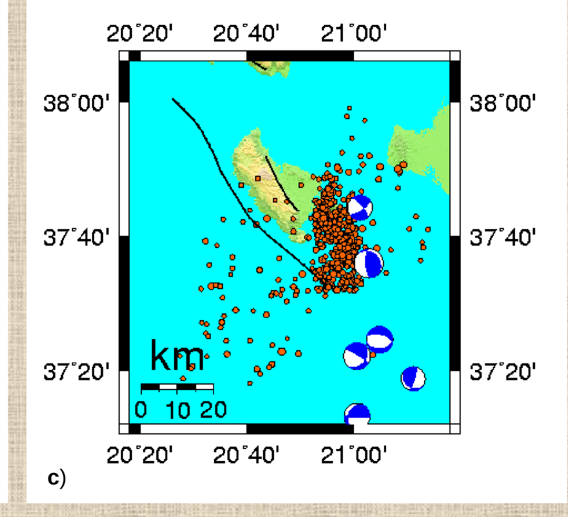

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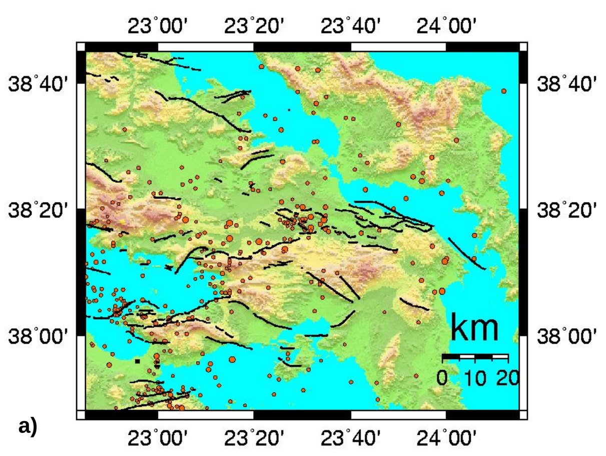
Fig.8 a) Relocated seismicity using HYPODD for 1996-1998 period and b) 2001-2006 c) located seismicity using HYPO71 for 1999-2000 and d) relocated seismicity of Athens aftershock sequence



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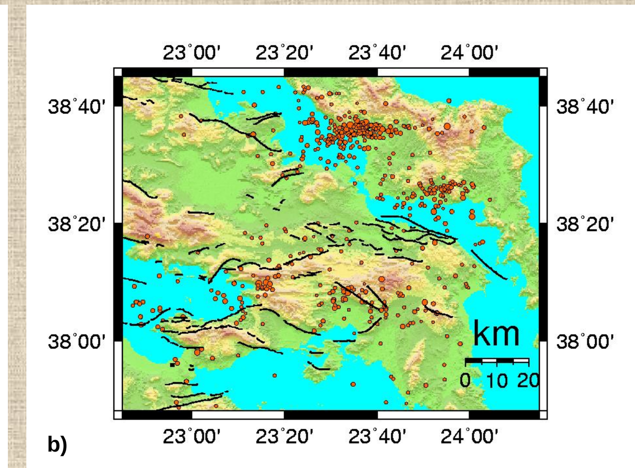

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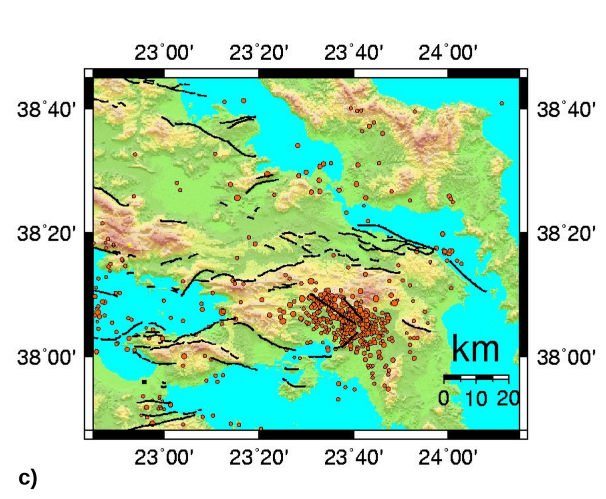

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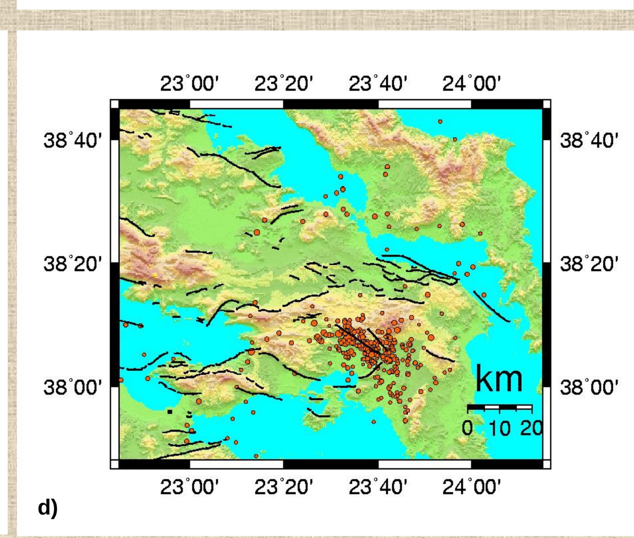

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Table 5-Location of preshocks, main event, biggest aftershock of the 7-9-1999 earthquake

Time (UTC)	Latitude (deg-minutes) φ	longitude (deg-minutes) λ	Depth (km)	Md
11.38'21.86''	38-10.27	23-34.82	7.60	3.2
11.40' 8.71''	38-07.19	23-34.56	8.01	2.6
11.43'34.75''	38-06.27	23-34.48	14.00	2.9
11.54'41.02''	38-08.87	23-35.53	13.57	3.2
11.56'51.47''	38-09.53	23-33.87	8.50	5.9
20.44'55.15''	38-07.85	23-37.07	11.09	4.7

CONCLUSIONS

In this study the importance of using data from more than one permanent seismological network, as well as the need of using different algorithms in data processing to obtain better results was revealed.

Phase data of the joint catalogue were used as an input file to HYPODD and by intervening in the parameters of the program we could achieve the optimization of the final result. As it can be seen by the presented images this algorithm has also its weaknesses. In order to obtain better results it is necessary to have good primary epicenter locations and a more dense coverage of stations in the epicentral area. Moreover, some relocated aftershock sequences, as the one of the Athens earthquake, clearly reveal the dimension of the activated fault area.

The results obtained by the double difference algorithm, in most cases, concentrated the seismicity (that was obtained from phase data of permanent networks) along main rupture zones of the Hellenic peninsula. Consequently they can be successfully compared to those obtained by available local networks that were deployed in the study area.

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