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EARTHQUAKE RELOCATION IN THE WESTERN TERMINATION OF THE NORTH AEGEAN TROUGH

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Abstract

The area of North Aegean Trough exhibits complex tectonic characteristics as a consequence of the presence of complicated active structures. Exploitation of accurately determined earthquake data considerably contributes in the investigation of these structures and such accuracy is seeking through certain procedures. The determination of focal parameters of earthquakes that occurred in this area during 1964–2003 was performed by collecting all the available data for P and S arrivals. After selecting the best solutions from an initial hypocentral location, 739 earthquakes were found that fulfilled certain criteria for the accuracy and used for further processing. The study area was divided in 16 sub regions and by the use of the HYPOINVERSE computer program, the travel time curves were constructed, and were used to define the velocity models for each one of them. For each sub region the time delays were calculated and used as time corrections in the arrival times of the seismic waves. The V_p/V_s ratio, necessary for S–wave velocity models, was calculated with two different methods and was found equal to 1.76. The velocity models and the time delays were used to relocate the events of the whole data set. The relocation resulted in significant improvement of the accuracy in the focal parameters determination.

Key words: *velocity models, residuals, relocation.*

Περίληψη

Η περιοχή της Τάφρου του Βορείου Αιγαίου παρουσιάζει πολύπλοκα τεκτονικά χαρακτηριστικά, ως συνέπεια της παρουσίας σύνθετων ενεργών δομών. Η αξιοποίηση των εστιακών παραμέτρων σεισμών, οι οποίες έχουν καθορισθεί με όσο το δυνατόν μεγαλύτερη ακρίβεια, συμβάλλει σημαντικά στη μελέτη τέτοιων δομών και τέτοια ακρίβεια επιδιώκεται με την εφαρμογή συγκεκριμένων διαδικασιών. Ο υπολογισμός των εστιακών παραμέτρων σεισμών οι οποίοι έγιναν σ΄ αυτή την περιοχή κατά την περίοδο 1964–2003 πραγματοποιήθηκε με τη συλλογή και χρήση όλων των διαθέσιμων δεδομένων των αφίξεων των επιμήκων και εγκαρσίων κυμάτων των σεισμών αυτών. Μετά από την επιλογή των ακριβέστερα υπολογισμένων εστιών που προέκυψαν από μία πρωταρχική επεξεργασία, 739 σεισμοί βρέθηκαν να πληρούν συγκεκριμένα κριτήρια και χρησιμοποιήθηκαν στην περαιτέρω επεξεργασία. Η περιοχή μελέτης διακρίθηκε σε 16 υποπεριοχές και με την εφαρμογή του

προγράμματος H/Y HYPOINVERSE, κατασκευάστηκαν οι καμπύλες χρόνων διαδρομής και χρησιμοποιήθηκαν για τον προσδιορισμό μοντέλου ταχυτήτων σε κάθε υποπεριοχή. Για κάθε υποπεριοχή υπολογίσθηκαν χρονικά υπόλοιπα και χρησιμοποιήθηκαν ως χρονικές διορθώσεις στο χρόνο άφιξης των σεισμικών κυμάτων. Ο λόγος V_p/V_s, ο οποίος απαιτείται για τον προσδιορισμό μοντέλου ταχυτήτων για τα εγκάρσια κύματα, υπολογίσθηκε με δύο διαφορετικές τεχνικές και βρέθηκε και στις δύο περιπτώσεις ίσος με 1.76. Τα μοντέλα ταχυτήτων και τα χρονικά υπόλοιπα χρησιμοποιήθηκαν για τον επαναπροσδιορισμό των εστιακών συντεταγμένων όλων των σεισμών του δείγματος. Η διαδικασία αυτή είχε ως αποτέλεσμα τη σημαντική βελτίωση καθορισμού των εστιακών συντεταγμένων.
Λέξεις κλειδιά: *μοντέλα ταχυτήτων, χρονικές διορθώσεις, επαναπροσδιορισμός επικέντρων.*

1. Introduction

The study area belongs to the back arc Aegean region, which is a part of a broader region whose tectonic characteristics are formed from the movements of big tectonic plates (Eurasian, Arabian, African) as well as from the movement of smaller ones (Anatolian, Aegean) in the Eastern Mediterranean area (Fig. 1). The Aegean region is one of the most rapidly deforming regions in the continental domain (Jackson 1994, Papazachos and Kiratzi 1996). The collision of the Arabian and Eurasian plates in the Caucasus area forces the small Anatolian microplate to move westward towards the Aegean region at about 2.0 – 2.5 cm·yr^{-1} (Mc Kenzie 1972, Taymaz *et al.* 1991) along the North Anatolian Fault (NAF). This clockwise movement of the NAF continues along the North Aegean Trough (NAT), as well as in additional parallel branches to the south. Recent studies (Faccenna *et al.* 2006) suggest that the formation of the North Anatolian Fault is a result of the subduction and the rollback of the Hellenic trench. The North Anatolian Fault is divided in three branches (Taymaz *et al.* 1991), from which the northern one, along the North Aegean Trough, is characterized by intense seismicity that is related with the presence of the basins of Saros and Sporades with depths of 1400 m and 1500 m, respectively. The depth of the Sporades basin is the largest in the Aegean area, excluding the Cretan sea where the depth reaches 2000 m.

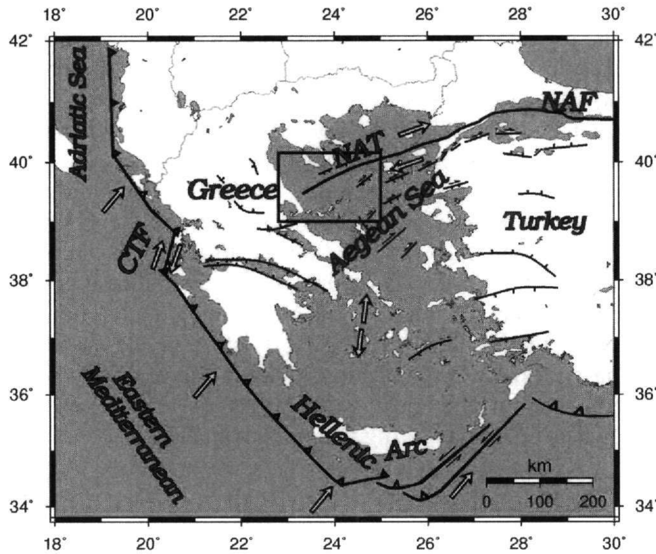

Figure 1 – Main seismotectonic properties of the Aegean and surrounding regions. The study area is indicated by the rectangle

In the Aegean region, in addition to the westward movement of the Anatolian plate, movement in N–S direction caused by internal deformation is being added. All these movements result to the SW movement of the Aegean at 3.5 cm·yr^{-1} towards the convergent oceanic plate of the Eastern Mediterranean, which moves to the north at 1 cm·yr^{-1} (Mc Kenzie 1972, Dewey and Sengor 1989). The Aegean region is one of the best examples of continental extensional tectonics, where the elongation of the continental lithosphere has caused the crust thinning. It is characterized by high seismicity with its topography ruled to a large extend by normal faulting (Oral *et al.* 1995). The movement of the Aegean in the SW direction has been established by seismological and geodetic data. The extensional field in the Aegean area has been recognized by geodetic observations (Mercier *et al.* 1989), as well as from recent studies using SLR (Satellite Laser Ranging) and GPS (Global Positioning System) measurements.

Numerous geodynamical models have been proposed to explain the deformation and the kinematics of the North Aegean. Some models imply one (Mc Kenzie 1972) or two (Le Pichon *et al.* 1995) small rigid lithospheric plates that move relative to Eurasia. Others include crustal blocks of smaller size (e.g. Mc Kenzie and Jackson 1983, Taymaz *et al.* 1991) that interact over a viscoplastic substratum (e.g. England *et al.* 1985).

The purpose of the present study is to redefine, as better as possible, the focal parameters of earthquakes that occurred at the western termination of the North Aegean Trough (depicted by a rectangle in Fig. 1). Seismicity studies for the area were previously performed by using data from temporary seismological stations (Hatzfeld *et al.* 1999, Barakou *et al.* 2001) as well as using data from the regional seismological network (Karakostas 1988). Detailed investigations on the seismic sequences that took place in the study area were also performed, like the 1980 Pagashitikos gulf seismic sequence (Papazachos *et al.* 1983), the 1981 – 1982 North Aegean seismic sequence (Papazachos *et al.* 1984), the 1983 North Aegean seismic sequence (Rocca *et al.* 1985) and the 2001 Skyros Island seismic sequence (Karakostas *et al.* 2003) by the use of the HYPO71 computer program for earthquake location. In the present study, the regionally and locally recorded earthquake data were processed by the use of the HYPOINVERSE computer program (Klein 2002). The located events will be used to establish the properties of the active structures in our study area, which deserves particular attention since it comprises the continuation and translation of dextral strike slip faulting on NE striking faults along the NAT, to sinistral strike slip and normal faulting on NW striking faults close to the eastern coastline, and finally to pure normal faulting on almost E–W striking faults in the mainland of Greece. Our target is feasible since it concerns one of the most active parts of the Aegean back arc region with several strong earthquakes of $M \geq 6.0$ during the instrumental era.

2. Data collection – Preliminary Processing

The data used for this study cover the time period from 1964 until 2003. In general, the accuracy in the determination of the focal coordinates depends on the number of the available phases (recordings of both P– and S– arrivals) and the density of the seismological network. For this reason our aim was to find and collect all the available data, in order to obtain as more phases as possible. The main source of our collection was the electronic database (http://www.isc.ac.uk/) of the International Seismological Centre (ISC). In addition, unpublished but available to us data from local networks maintained by the P. P. C. (Public Power Corporation) were also used in the present study.

During the first years of the period that our data cover, the number of seismological stations in Greece and the neighboring countries was not sufficient. Therefore, it was decided to use the arrival times at seismological stations with epicentral distances as far as 10^{o}. Thus, the recordings at 772 seismological stations located in southeastern Europe were used. The sites of all these seismological stations have been plotted on the map of Figure 2. Gray circles have been used to denote the locations of seismological stations, which were in operation before 1981, open diamonds stations from temporarily operating local networks, while black triangles for the seismological stations, which started operating since 1981. It is obvious that the permanent seismological network became denser around the study area, after the installation of the telemetry network of the Department of Geophysics in 1981, and the gradual increase of the stations during the next years.

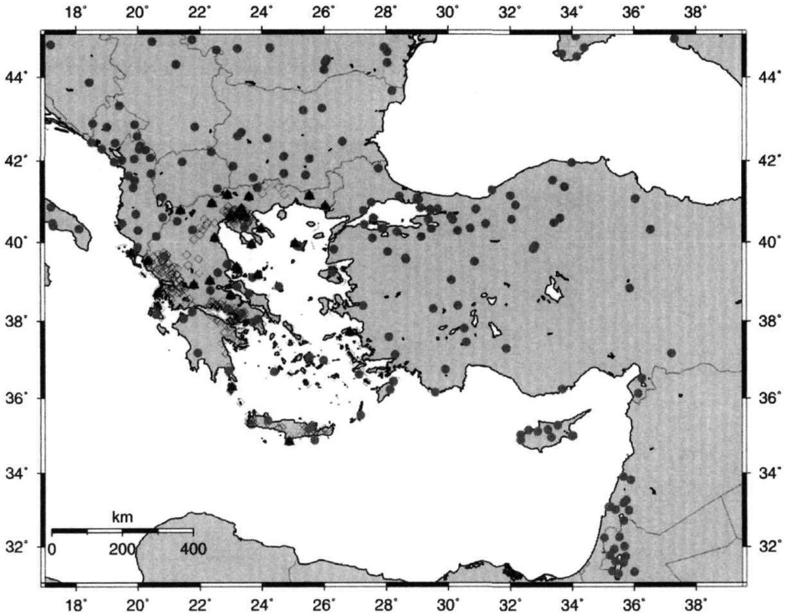

Figure 2 – The sites of the seismological stations from where recordings are used in the present study. Gray circles, and black triangles are used to denote stations in operation before and after 1981, respectively, while open diamonds depict temporary stations

Both accurate phase pickings and a valid velocity model are the basic prerequisites for an accurate determination of the focal coordinates of the earthquakes. Aim of the present work is, based on modern software, as it is the HYPOINVERSE (Klein 2002), to apply a procedure that gives in more detail the velocity structure of the Earth's crust and as a consequence to improve the accuracy of the relocated data. The main problem is that we should start our procedure using only the best of our data set, that is, earthquakes with a sufficient number of recordings with epicentral distances as short as possible, with epicentral coordinates in fact independent from the velocity models that already have been proposed for the area. As such data the earthquakes which occurred after 1980 were considered, for which more than 8 P– and S– arrivals were available, with the closest station in a distance less than 100 km, the maximum angle between the epicenter and two successive stations (GAP) less than 180°, and errors in the origin time (RMS) in the epicenter (ERH) and in focal depth (ERZ) determination, less than 0.5 sec, 5.0 km and 5.0 km, respectively, independently of the velocity model used for the location. For this area four different models proposed by Panagiotopoulos (1984), Hatzfeld *et al.* (1999), Barakou *et al.* (2001) and Sachpazi (2003) were applied. Thus, from 5021 earthquakes, which is the total collected number (Fig. 3), only 731 fulfill the above criteria and were used as the initial data set to define a more detailed crustal model for the area. These criteria were chosen based on the results of previously studied seismic sequences (e. g. Karakostas *et al.* 2003) using data from the permanent seismological network. Data of such quality can significantly contribute to the identification of the seismotectonic properties of the associated active structures, and in particular in our study area where these structures are submarine.

3. Definition of the velocity models

For the earthquake location the HYPOINVERSE (Klein 2002) Fortran program was used. The main feature of HYPOINVERSE is that it has the ability to use different velocity models for different regions that are defined within inner and outer circles (Fig. 4). For earthquakes that are placed in the transition zones, outer circles, a combined velocity model is used that is weighted in accordance to the distance of their epicenters from the two regions. On the basis of the spatial distribution of the selected earthquakes, the region under study was divided in 16 sub regions (Fig. 4) in a way that most of the earthquakes would belong in one of the inner or outer circles. In our data sample only a few earthquakes found not belonging to any of these sub regions.

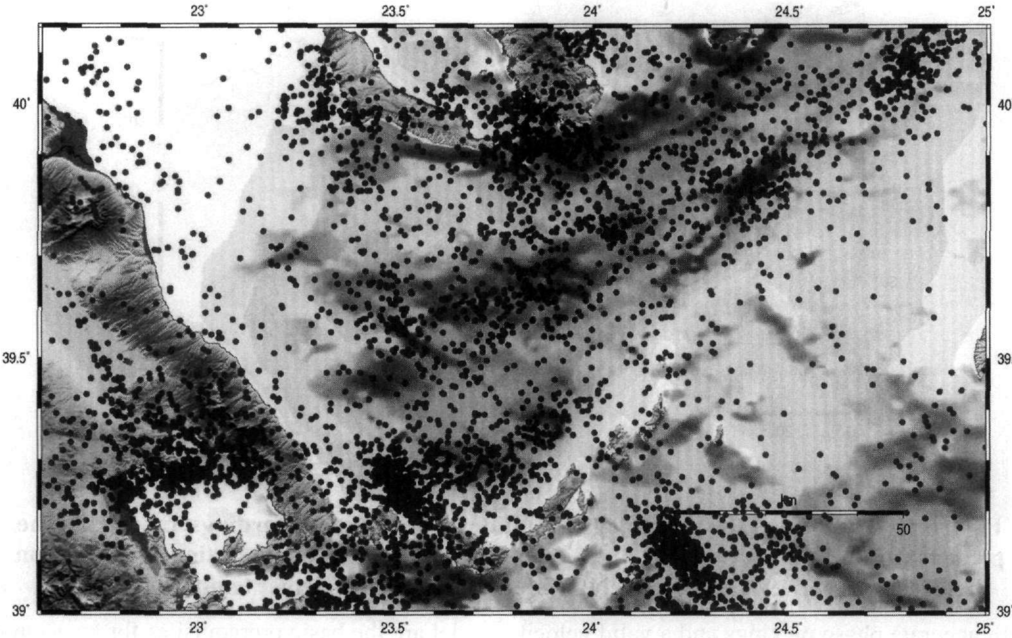

Figure 3 – Spatial distribution of all the earthquakes collected for the study area after a preliminary location by the use of the HYPOINVERSE computer program

In order to determine the velocity models for each one of the 16 sub regions, the phases of P– and S– waves of the 739 selected earthquakes were used. Following the theory of refraction, the travel time curves for each one of the regions were constructed. It is well known that a change in the slope of the travel time curve reveals change in the velocity of the waves that traveling in different layers inside the earth. The definition of the points where the travel time curves change their slope must be done very carefully because quite small slope changes produce high changes in the velocity of seismic waves. Therefore, every travel time curve was examined thoroughly before extracting any result. At this point, it must be noticed that travel time curves could not be constructed for two of the subregions (A2 and A10) due to the unavailability of a satisfactory number of events. For these two regions, models from adjacent regions were used. By estimating the slope of the different parts of every travel time curve, the estimation of the velocity of the waves, as they propagate into the different layers of the crust, is made possible.

Afterwards, using the equations of the refraction theory, we can calculate the thickness of each layer. The thickness of the first layer is given by:

Equation 1 – Estimation of the first layer thickness

$$h_o = \frac{\tau_1}{2\sqrt{\frac{1}{u_o^2} - \frac{1}{u_1^2}}}$$

where, τ_1 is the interception of the travel time curve on the t axis and u_o, u_1 the respective velocities of the first two layers.

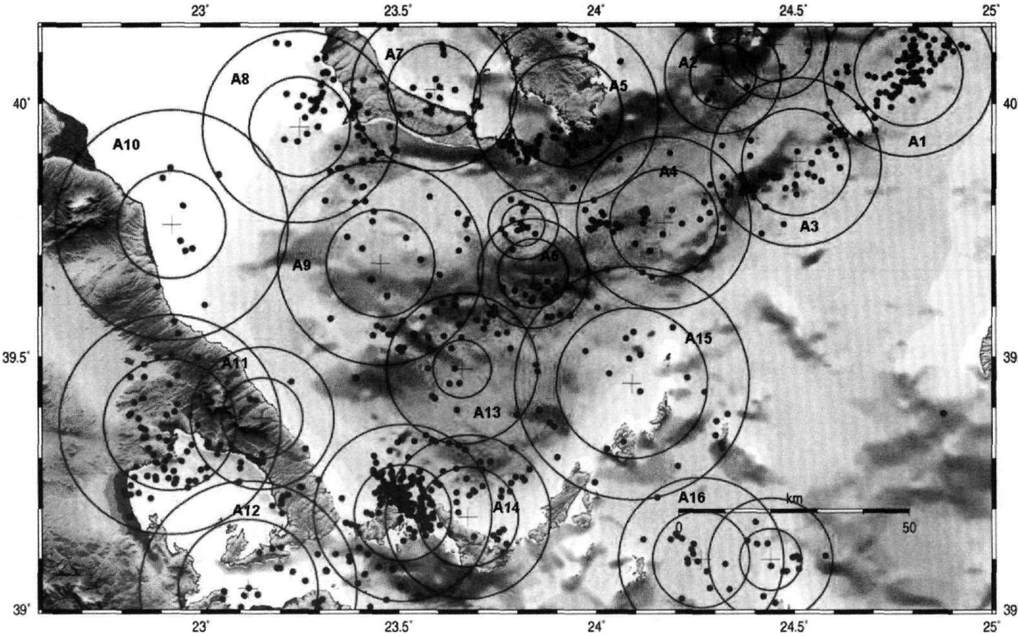

Figure 4 – Spatial distribution of the selected earthquakes and the 16 smaller regions including most of the seismicity of the area

The thickness of *n* successive layers can be found by starting with the top layer, whose thickness is h_o and continuing downward using the iterative formula:

Equation 2 – Estimation of the thickness of n successive layers

$$h_{n-1} = \frac{\tau_n - 2\sum_{j=0}^{n-2} h_j \sqrt{\left(\frac{1}{u_j^{\;2}} - \frac{1}{u_n^{\;2}}\right)}}{2\sqrt{\left(\frac{1}{u_{n-1}^{\;2}} - \frac{1}{u_n^{\;2}}\right)}}$$

With the procedure described above, we managed to acquire different velocity models for each one of the 16 small sub regions. Overall, we came up with models that are composed of three layers over a half space. The velocity of the first layer for all models ranges from 4.82 – 5.0 km/sec, with its thickness ranging from 1.5 – 4.5 km. The maximum velocity, which is observed in the upper mantle, ranges from 7.78 – 7.93 km/sec, while the Moho depth ranges from 26 – 30 km in the North Aegean region and from 32 – 34 km in the western part of our study area close to the eastern coasts of the Greek mainland.

The 16 sub regions were grouped into four zones according to their location. The first includes regions A16 – A14 – A12 that form a line in the southernmost part of the study area. The second section includes regions A15 – A13 – A11 that form a line in the central part of the study area. The third section follows the trend of the NAF into the North Aegean Trough (NAT) (A1 – A3 – A4 – A6 –A9 – A13) while the fourth section is composed by the three regions (A5 –A7 –A8) that are in the northern part of the study area. From these sections, two regions (A2 and A10) have been excluded because, as mentioned earlier, these are regions with a few earthquakes only and for this reason their models were derived from the velocity models of nearby regions.

The velocity models that derived from the study of the travel time curves include information only for the P waves. The velocity of the S waves is taken into account by the use of the ratio $\left(\frac{V_P}{V_s}\right)$.

This means that we consider that the velocity of the S waves is changing with the depth in an analogous way that the P waves velocity changes.

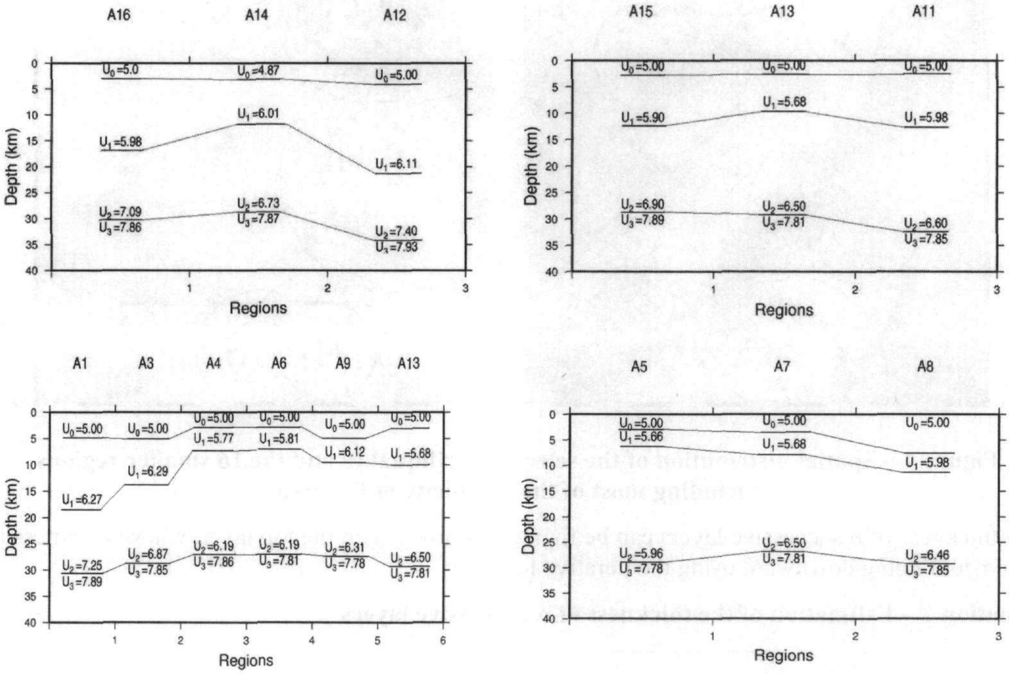

Figure 5 – Schematic view of the velocity models of each subregion

We used the Wadati method for 80 of the selected earthquakes to calculate the ratio that was found equal to 1.76. This method has the advantage that can be used without taking into account the earthquake origin time but it cannot be applied easily for a large data set. In addition, it has the disadvantage that large errors for S waves may be taken into account. In the present study, we used one more method to calculate the ratio. This one is based on the travel times of P and S waves and it has the advantage of being able to use large set of data. The ratio $\left(\frac{V_P}{V_s}\right)$ is considered equal to the ratio $\left(\frac{t_s}{t_P}\right)$, where t_s and t_p are the travel times for S and P waves, respectively. The calculation of the ratio with this procedure gave a value equal to 1.76, an indication that both procedures followed here gave robust results.

4. Time Delays

With the term '*time delay*' the difference between the theoretical travel times of the seismic waves from their observed ones is appointed. It is easily concluded that high values of the time delays imply that the theoretical crustal model diverges from the real structure, whereas small values show good agreement between them. The calculation of the time delays in the present study was performed after the determination of the different velocity models for each one of the 16 sub regions. The reason that this procedure was selected is that the seismic waves that arrive to each seismological station travel through the earth's crust following different paths. Thus, in the calculation of the time delays for small regions, only seismic rays following almost the same path are used. By this way, in addition to the velocity model, which gives the vertical velocity changes, the horizontal velocity changes are also taken into account.

In order to ensure credibility in the calculations of these values, a minimum of three observations for each seismological station was set while the value of the calculation standard deviation was considered as well. We mapped the number of observations for each seismological station in connection with the values of the standard deviation of the time delays. It was observed that the standard deviation values were stabilized when the number of observations was equal or larger than ten.

Since the velocity models for each sub region are not exactly the same and the distances of each seismological station from every sub region are different, the calculated time delays are also different. In some cases, this could be explained due to the different type of the arrival phase (e. g. Pg– or Pn–, etc).

The geographical distribution of the time delays of each seismological station shows that positive values (up to 2.5sec) were found for stations located in western Greece, which agrees with the thicker crust in this area. This means that the seismic waves propagate into the thicker crust with lower velocity than the theoretical model suggests and thus they arrive at the seismological stations later than expected. On the contrary, negative values of time delays are found in the North Aegean area attributed to the thinner crust in this area, meaning that in this case the seismic waves arrive earlier at the seismological stations than the theoretical model predicts. Negative values were found in the northern part of the Balkan Peninsula as well as in the eastern coasts of Italy, which must be regarded with caution since the number of the recordings at the seismological stations is limited in these distant areas. In addition, negative values are calculated for the NW part of Turkey, probably due to the fact that seismic waves on their way to the seismological stations propagate through the North Aegean region. Both negative and positive values were calculated in the area of Crete, with a tendency of the absolute values to be higher in the western part of the island. Relevant work was conducted by Taymaz (1996) who studied the average S–P travel time residuals fro 29 earthquakes that occurred in the Aegean Sea and Hellenic trench and found positive residuals for the earthquakes in the Aegean and negative for the ones near Crete.

In general, the values of time delays show consistency with what is known about the thickness of the crust in different parts of the study area. It must be pointed out that not only the discrimination of the time delays in positive and negative values is of interest, but also their relative differences. The values of time delays should not show big divergences, because it is due to large differences between the velocity models of each region.

5. Final processing – Determination of the focal parameters

The final stage of the processing concerns the relocation for all the earthquakes using the results derived from the previous procedures, as these were described in the above sections. Thus, the velocity models for each region, as well as the values of time delays of the seismological stations were used. For earthquakes that are not included in any of the 16 sub regions, a regional model proposed by Panagiotopoulos (1984) has been used.

Following a procedure of step–by–step subtraction of the phases with high time residuals, and keeping eventually only the phases with residuals less than 2.0 sec, 4546 earthquakes were relocated. The epicenters of these earthquakes are plotted on the map of Figure 6, using different symbols to depict different magnitude ranges. Big black circles denote earthquakes with $M \geq 5.0$, while smaller open ones earthquakes with $4.0 \leq M \leq 4.9$. The smallest circles denote earthquakes of smaller magnitude – the bigger dark gray for events with 3.5≤M≤3.9 – and the smaller light gray ones events with M<3.5.

The vast majority of the events are aligned along the North Aegean Trough, continued in the North Sporades basin and the area of North Paghasitikos gulf. Clusters of epicenters also depict an active structure south of Halkidiki Peninsula and near Skyros Island. This is partially due to the seismic sequences that took place during the study period (1965 in Sporades basin, 1980 seismic sequence in north Paghasitikos gulf, 1982 and 1983 seismic sequences along the NAT, 2001 Skyros seismic sequence), while it is evident that additional active structures exhibit intense seismicity. This enables the detailed investigation of their seismotectonic properties, a topic that will be handled in a future investigation.

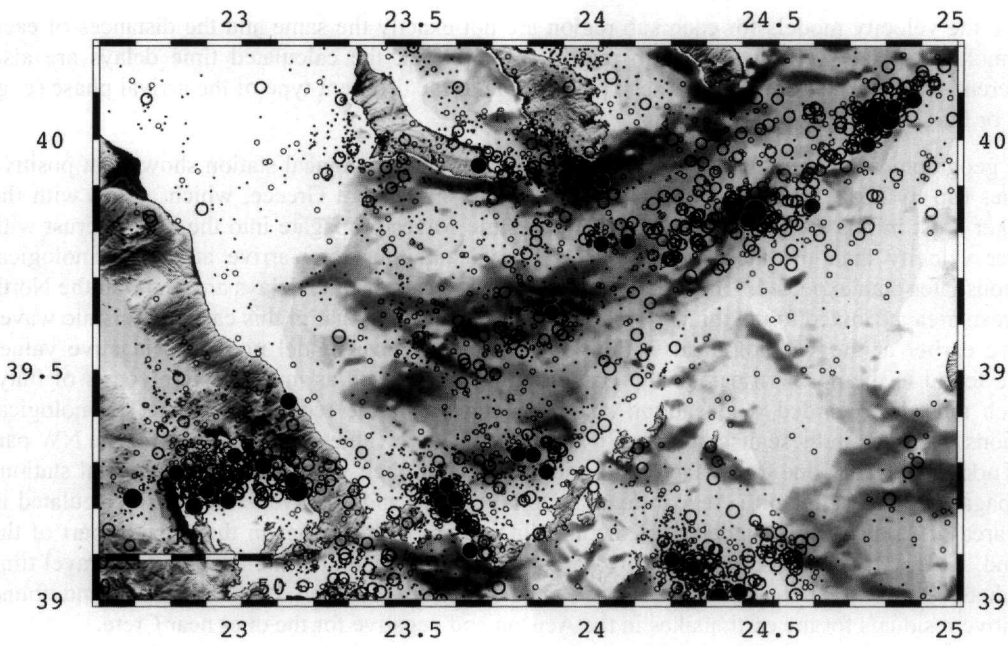

Figure 6 – Spatial distribution of the earthquakes that occurred during 1964–2003 after the final processing using the velocity models derived from the travel time curves and the values of time delays for each seismological station

Comparing the locations derived from the final processing with the ones from the initial determination of the focal parameters, it is found that a significant improvement of the time errors (RMS) was achieved. In particular, after the initial processing only 60% of the earthquakes exhibit RMS values smaller than 0.8 sec, while after the final processing this proportion reaches 100 % with over 90 % of them with RMS < 0.5 sec.

Improvement is evident as well as for the hypocentral uncertainties of the epicenter (ERH) and the focal depth (ERZ). These are much smaller than they were after the initial processing with the large majority of values to be less than 5 and 8 km, respectively.

Overall, the procedure of constructing velocity models for each one of the 16 sub regions, as well as the calculation of the time delays for each one of the seismological stations, significantly contributed to the better determination of the focal parameters and in particular to the decrease of the uncertainties of the hypocentral determination (Fig. 7).

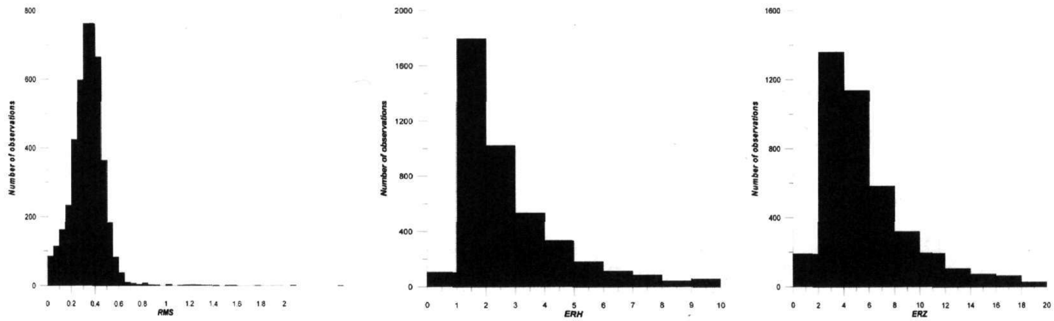

Figure 7 – Histograms of the root–mean square of the time errors, RMS (in seconds) (left part of the figure), the horizontal, ERH (in km) (central part of the figure), and vertical, ERZ (in km) (right part of the figure), uncertainties of the hypocentral determination

After the final determination of the epicentres and the foci parameters of the earthquakes, a new catalogue of earthquakes was compiled by adding all the available magnitudes as they have been calculated by the Geophysics Department of University of Thessaloniki (Papazachos *et al.* 2005).

6. Discussion

We collected all the available data for the time period 1964–2003 in order to relocate the earthquakes that occurred in the western part of northern Aegean and the eastern part of the Greek mainland in Central Greece. Using velocity models that were already proposed for the area we performed an initial determination of the focal parameters of the earthquakes. By setting criteria for the earthquake analysis, we managed to select the best earthquakes in order to continue the processing.

The use of the HYPOINVERSE computer program for the location proved to be a suitable choice in order to derive velocity models, using the travel time curves for each one of the sub regions in which the study area was divided. Three layers on a half space constitute the velocity models, and though they have differences they seem to be in a good agreement with the pre-existing proposed models. The possibility to calculate the time delays for each one of the seismological stations and use of them as corrections of the arrival time of P– and S– waves, improved much more the locations.

The relocation performed in the present study by certain procedures proved to be effective for more accurate hypocentral determination. This latter is a contribution to delineate the associated active structures and investigate their seismotectonic properties, which consist input parameters for seismic hazard assessment in a study area.

7. Acknowledgments

The GMT system (Wessel and Smith, 1998) was used to plot the figures. The comments of T.Taymaz and an anonymous reviewer are kindly acknowledged. This study was supported by the research project between Greece and USA EPAN–M.4.3.6.1 funded by the General Secretariat of Research and Technology of Greece. Geophysics Department contribution 688.

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