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Current seismic quiescence in Greece: Implications for seismic hazard

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Abstract

Based on previous observations of the phenomenon of precursory seismic quiescence before crustal main shocks and recent results that indicate an increase in the occurrence of main shocks in the next years, we focus this study on the detection of the seismic quiescence situation in Greece in the beginning of 1999. We use the declustered seismicity catalogue of the Institute of Geodynamics, National Observatory of Athens (NOA) from 1968–1998, to investigate the significance of seismic quiescence for the region 19°–29°E and 34°–42°N. We searched for seismicity rate changes at every node of the grid by a moving time window and we present the results for the beginning of 1999. The results map four (4) areas having a quiescence which duration ranges from 3.8 to 6 years in the beginning of 1999. Three of these areas have been devestated by catastrophic earthquakes 17–21 years ago and significant quiescence also preceded those main shocks. Based on these results, an estimate of the future seismic hazard of these areas is made.

Introduction

The seismicity rate has been used in a plethora of studies as a diagnostic tool for exploring the stress distribution in a particular area of the Earth's crust. For the area of Greece, Papazachos (1980) pioneered these studies by defining backround seismicity rates for nineteen different regions and indicated that a decrease in the seismicity rate occured before two main shocks in the South Peloponese (1947, M = 7.0) and the Ionian Islands (1953, M = 7.2) (see Figure 1) In the years to follow, a decrease in the seismicity rate in other areas of Greece has also been associated with earthquake occurrence by many investigators (Wyss and Baer, 1981a,b; Purcaru and Berckhemer, 1982; Papadopoulos, 1986; Papadimitriou, 1984; Papadimitriou and Papazachos, 1985a,b; Karakostas et al., 1986; Karakaisis et al., 1987; Papadopoulos and Voidomatis, 1987). Of these studies, the most well documented case of reported absence of seismicity prior to a main shock is that of the January 17, 1983, M = 6.2 main shock near the island of Kefalonia, in the western part of the Hellenic Arc, as presented by Papadimitriou and Papazachos (1985b). That study investigated the clustered catalogue of Comninakis and Papazachos (1982), which has a magnitude of completeness M_{comp} = 5, and indicated a 20 year 'quiescence' period prior to the 1983 main shock for earthquakes with M>5. Following this and based on the spatial distribution of the epicenters between 1952 and 1962 with M>4.5, around the island of Kefalonia, they indicated two gaps in seismicity prior to the 1983 main shock. The 1983 main shock occured in one of these gaps after that work had been submitted for publication and according to the authors '. . . it is the first proved prediction of the broader Aegean area.'.

Recently Papazachos et al. (1997a,b) based on previous patterns of the time distribution of main shocks (Mmin>6) in Greece, anticipate an increase of the seismic activity in the next years.

Since seismic quiescence has shown promising results in identifying precursory anomalies related to crustal main shocks (Wyss, 1997a, 1997b), it is the purpose of this study to provide additional information regarding the future seismic hazard of Greece, by investigating the seismic quiescence situation at

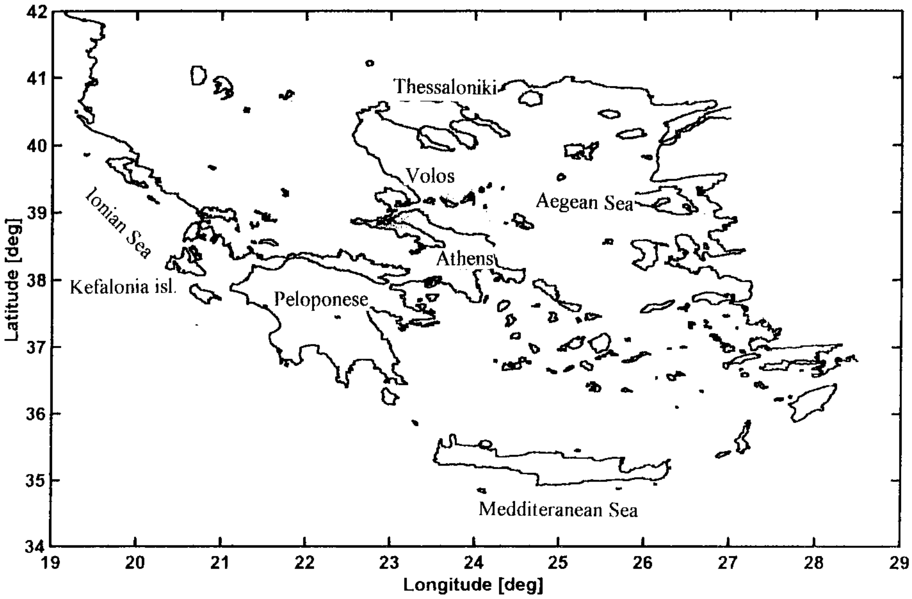

Figure 1. Map of Greece showing locations relevant to this investigation.

the beginning of 1999. For this reason we map the seismic quiescence in Greece, as defined by Wyss and Habermann (1988) using the gridding method of Wiemer and Wyss (1994) and the ZMAP analysis software (Wiemer et al., 1995). This methodology further investigates crustal quiescence prior to some of the strongest crustal main shocks that have occurred in Greece and gives us valuable information as to the validity and existance of the phenomenon.

Method and results

The Greek earthquake catalogue, issued by the Institute of Geodynamics (NOA), starting from 1964 contains more than 33000 regional events untill 1999. We have searched the catalogue for changes in reporting that could generate false alarms when one investigates seismicity rate changes. Using ZMAP and the GENAS analysis algorithm (Habermann, 1983), we found some reporting changes during the first four years untill 1968 but further on, the cumulative number of earthquakes as a function of time (Figure 2a) and the cumulative number of earthquakes as a function of magnitude (Figure 2b), well described by a straight line, show no significant changes of reporting as a function of time. Since this investigation deals with the rate of earthquake production and not of

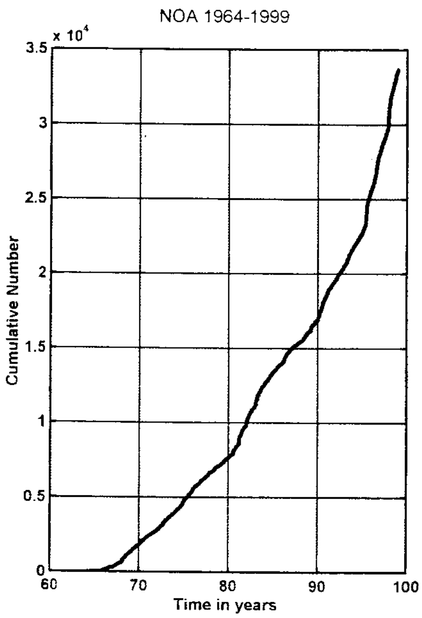

Figure 2a. Cumulative number of earthquakes versus time for the earthquake catalogue of NOA from 1964 untill 1999.

energy or moment release, the magnitude of completeness of the catalogue used to investigate quiescence is an important parameter because this varies spatially depending on the seismicity of the region under in-

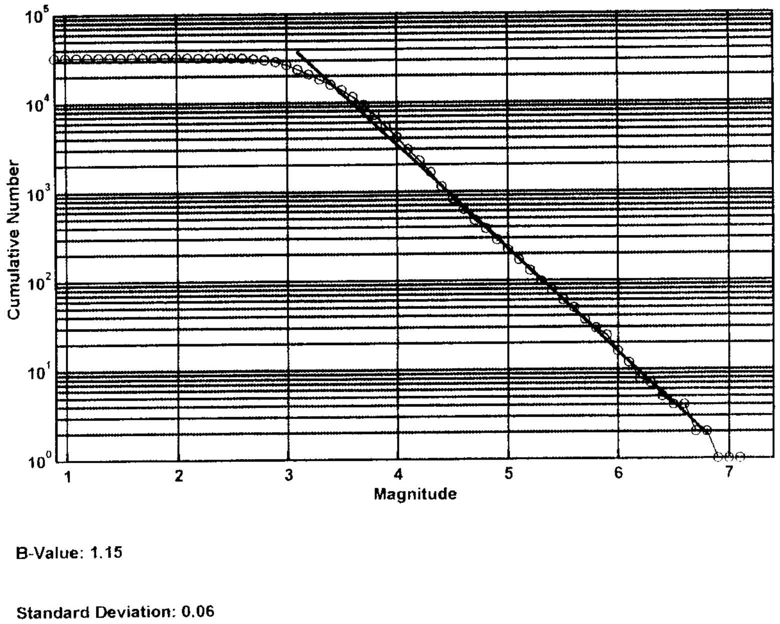

Figure 2b. Cumulative number of earthquakes versus magnitude for the earthquake catalogue of NOA from 1964 untill 1999.

vestigation and the detectability of the network. In this study we wish to consider the earthquake production for the entire Greek area at a specific time (beggining of 1999), so based on the results of Figures 2a and 2b and also by examining the spatial distribution of the frequency magnitude relation we conclude that NOA's catalogue is complete and homogeneous to MLOCAL = 3.3 for most of Greece. Of course when investigating seismic quiescence for specific areas of Greece, one should investigate the local seismicity catalogue of the area and determine its magnitude of completeness to be used in the subsequent investigation.

Seismic quiescence as originally proposed by Wyss and Habermann (1988) is investigated for crustal events and in Greece these have depths less than 50 kilometers, so we proceed to decluster the appropriate catalogue using Reasenberg's algorithm (1985) in order to remove aftershock sequences which can induce artificial quiescence in our observations. The cumulative number as a function of time for the Greek crustal declustered catalogue with M>3.3 (Figure 3) has a smoother slope when compared to the clustered catalogue and it shows that the declustering has removed aftershock sequences from Greek main shocks using Reasenberg's constants for California, similar to the case for the Italian eartquake catalogue as shown by Wyss et al. (1997c).

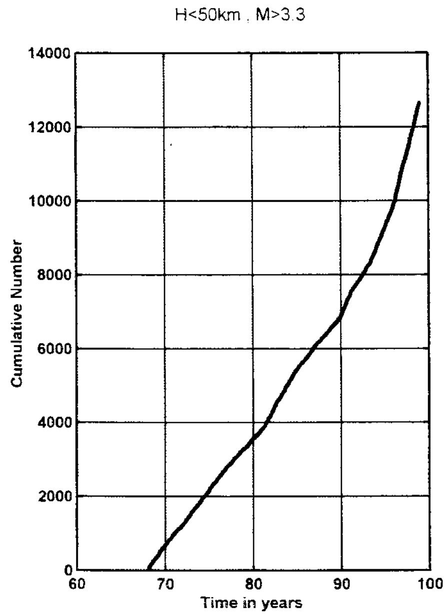

Figure 3. Cumulative number of earthquakes versus time for the declustered earthquake catalogue of NOA containing events with depths less than 50 kilometers and magnitudes greater than 3.3 from 1968 untill 1999.

Using ZMAP we measure the significance of seismicity rate changes at the nodes of a 0.05° grid spacing, because this is related to the accuracy of epicent-

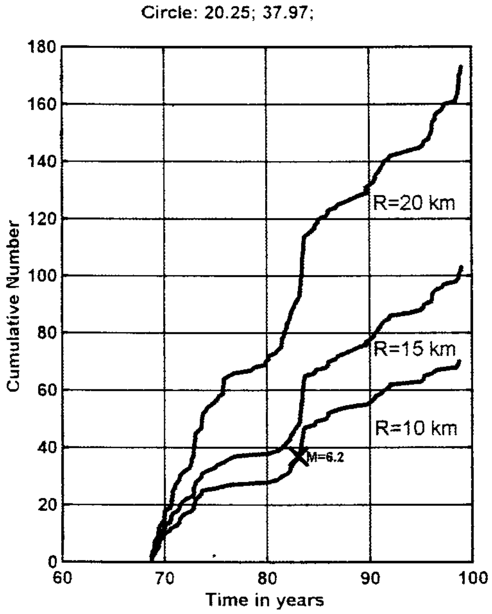

Figure 4. Cumulative number of earthquakes versus time for the area centered at the epicenter of the Kefalonia 1983 main shock for different radial distances.

ral determinations of the catalogue and it also provides a dense coverage in space. The gridding method has been described in detail elsewhere (Wiemer and Wyss, 1994) and we will briefly summarise the important points for the purpose of this study. At each node we took the nearest N earthquakes and searched for rate changes by a moving time window T_W, stepping forward through the time series by a sampling interval as described by Wiemer and Wyss (1994). The sampling interval is selected as a time step of one month in order to have a continuous and dense coverage in time and N and T_W values are usually selected accordingly in order to enhance the quiescence signal and this choice does not influence the results in any way.

As an example, in Figure 4 we show the cumulative nuber of earthquakes versus time for a circle with different radii (R = 10,15,20 km) centered at the epicenter of the Kefalonia main shock of magnitude M = 6.2 on 17-1-1983, since precursory quiescence has been indicated prior to this event by other investigators as mentioned earlier in our introduction. One can note a clear decrease in earthquake production for M>3.3 for all investigated radii prior to the main shock, however the duration of this quiescence as well as the rate of earthquake production, varies, depending on the size of the sampled volume.

Since we want to investigate the quiescence hypothesis which postulates that the quiet volume overlaps with the main shock source volume (Wyss and Habermann, 1988), we wish to keep N constant in order to satisfy statistical assumptions for evaluation. For this reason, we can see in Figure 4 that NOA's catalogue with a lower magnitude threshold of M>3.3 and a choice of N = 80 events will sample volumes with radii ranging between 10 and 15 kilometers in this case and these are reasonable dimensions for sampling seismogenetic volumes that generate large main shocks in Greece and whose dimensions have been recently investigated by Chouliaras and Stavrakakis (1997).

In order to rank the significance of quiescence, we used the standard deviate Z, generating the LTA(t) function (Wyss and Burford, 1985, 1987; Wiemer and Wyss, 1994).

$$Z=(R1-R2)/(S1/n1+S2/n2)^{1/2} \quad (1)$$

which measures the significance of the difference between the mean seismicity rate within window R1, and the backround rate R2, defined as the mean rate outside the window but within the same volume. S1 and S2 are the variances of the means and n1 and n2 are the corresponding number of bins with a measured seismicity rate. Thus at each node a z value is computed and these z-values are then ordered according to size. The computed z-values are then contoured and mapped, revealing the z-value distribution at the beginning of the window for which they are evaluated, since we want to define the onset of a significant rate change in the seismicity.

The duration of quiescence is the important parameter to be determined and its significance is maximised when T_W is equal to that value and for meaningfull results we demand that they do not depend on the choice of T_{wW}. Since we do not know how long quiescences may last we varied the window length from 1.5 to 5.5 years, because this is in the range of reported seismic quiescence prior to crustal main shocks (Wyss, 1997a,b).

Figures 5a to 5d show the Z-value distribution on January 1, 1999 for different values of T_W. The time window position for these figures is determined by adding the window length T_W value in years (indicated as iwl in the corresponding figures) to the time chosen as the beginning of the time cut, so that all figures show the Z-value distribution for the same time, the beginning of 1999, and further on all figures have the same Z-value limits for comparison purposes. From these results, four areas exhibiting seismic quiescence

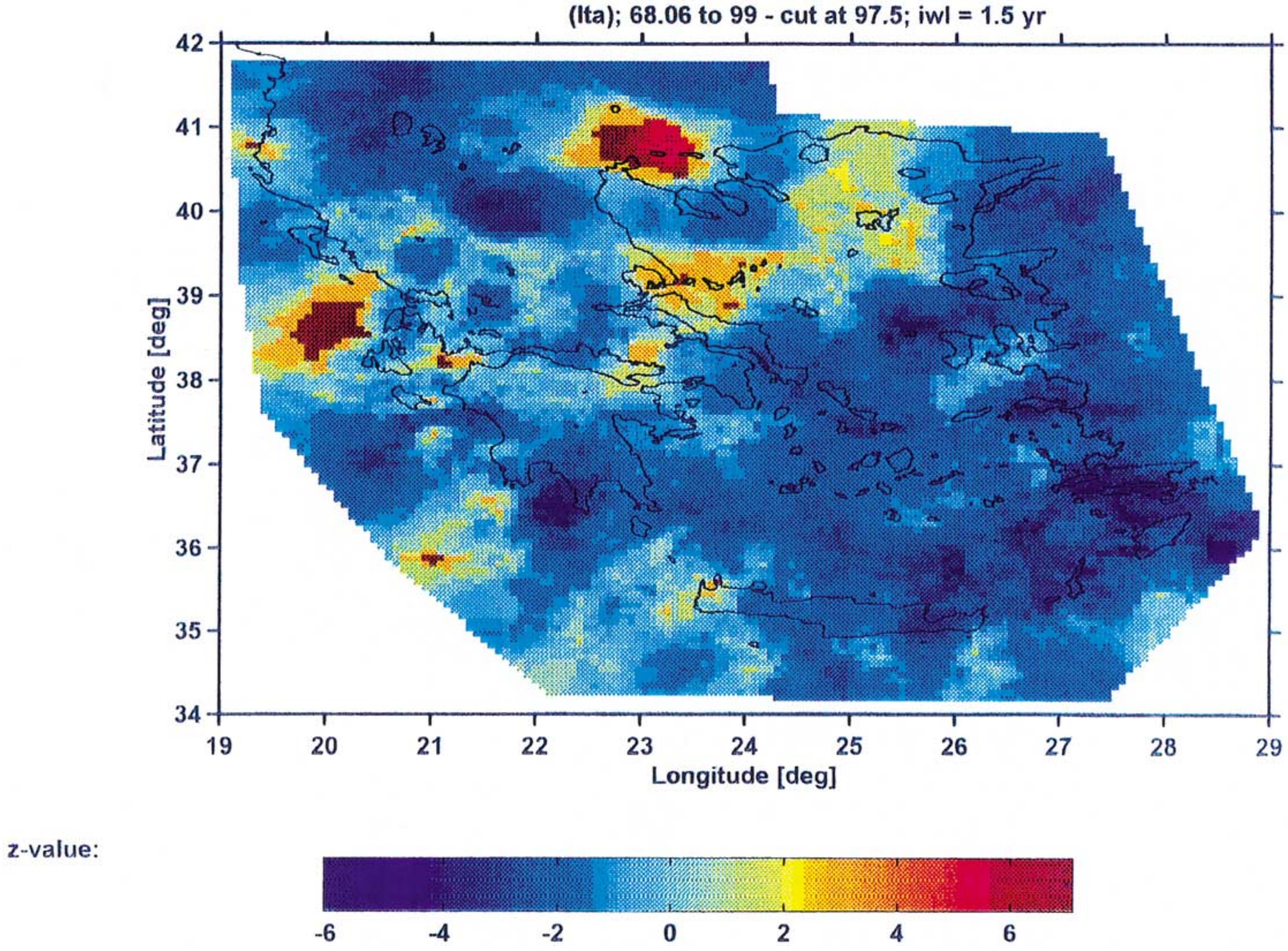

Figure 5a. Z-value distribution at the beginning of 1999 with T_W (iwl) = 1.5 years.

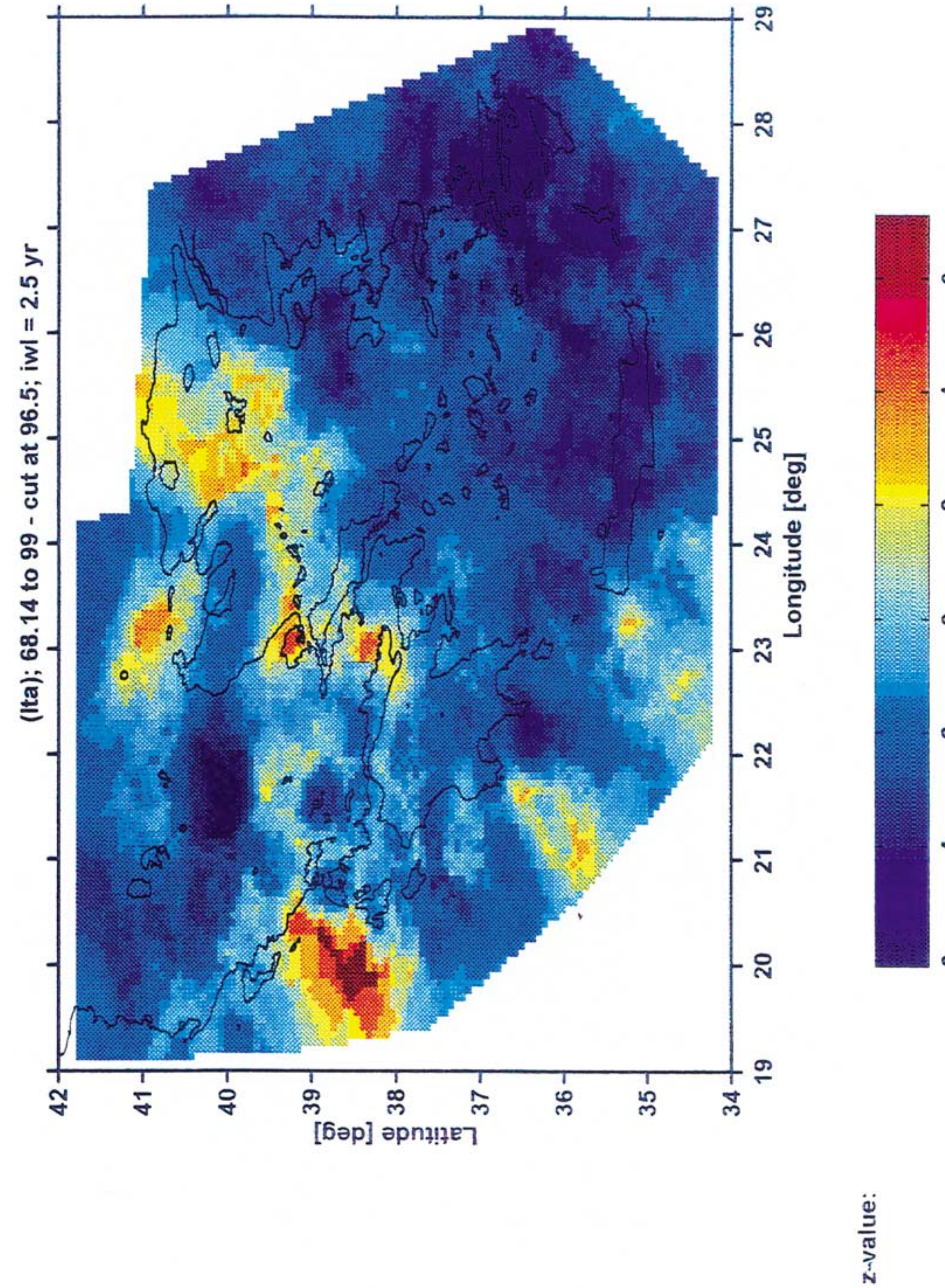

Figure 5b. Z-value distribution at the beginning of 1999 with Tw (iwl) = 2.5 years.

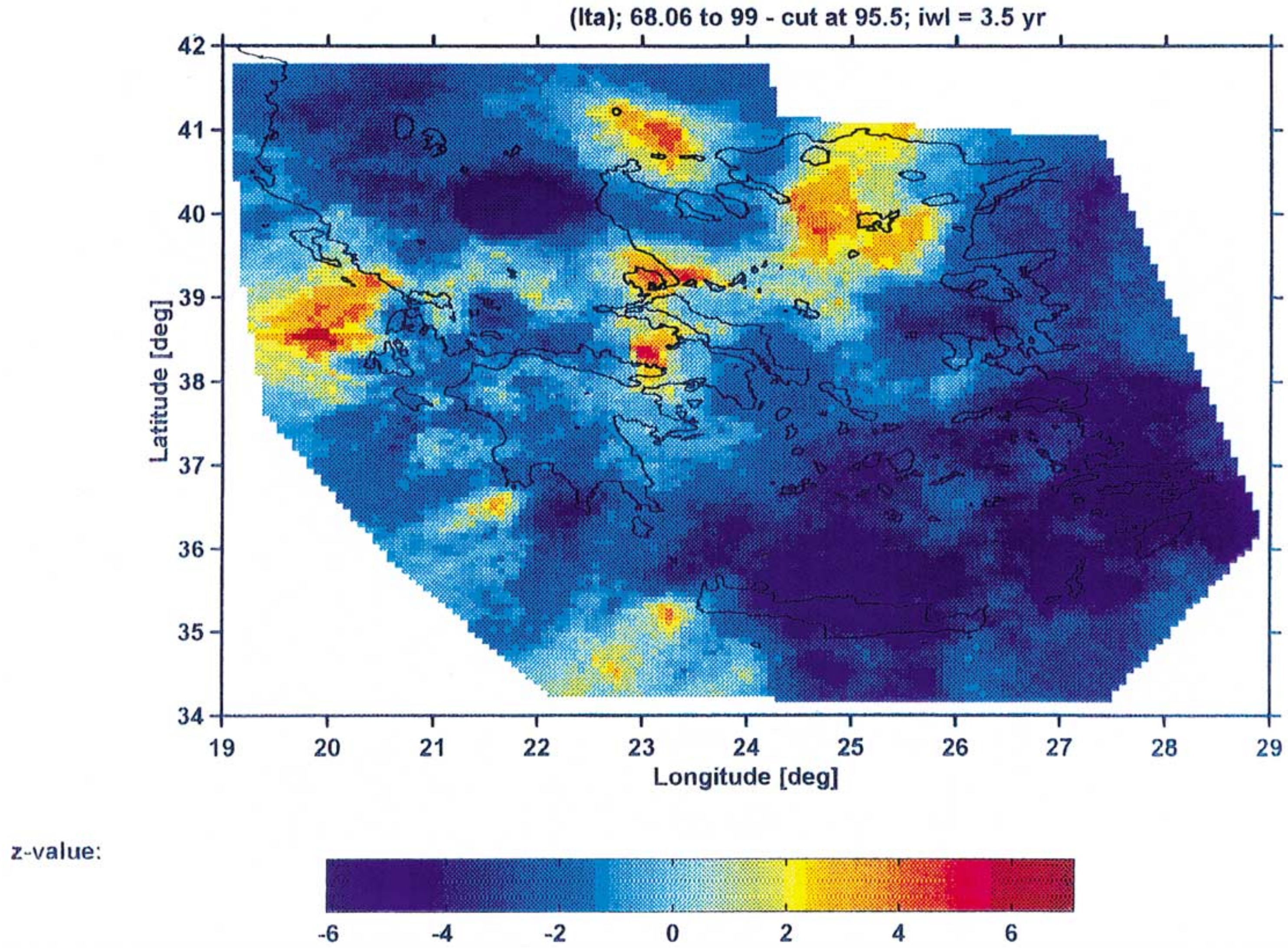

Figure 5c. Z-value distribution at the beginning of 1999 with T_W (iwl) = 3.5 years.

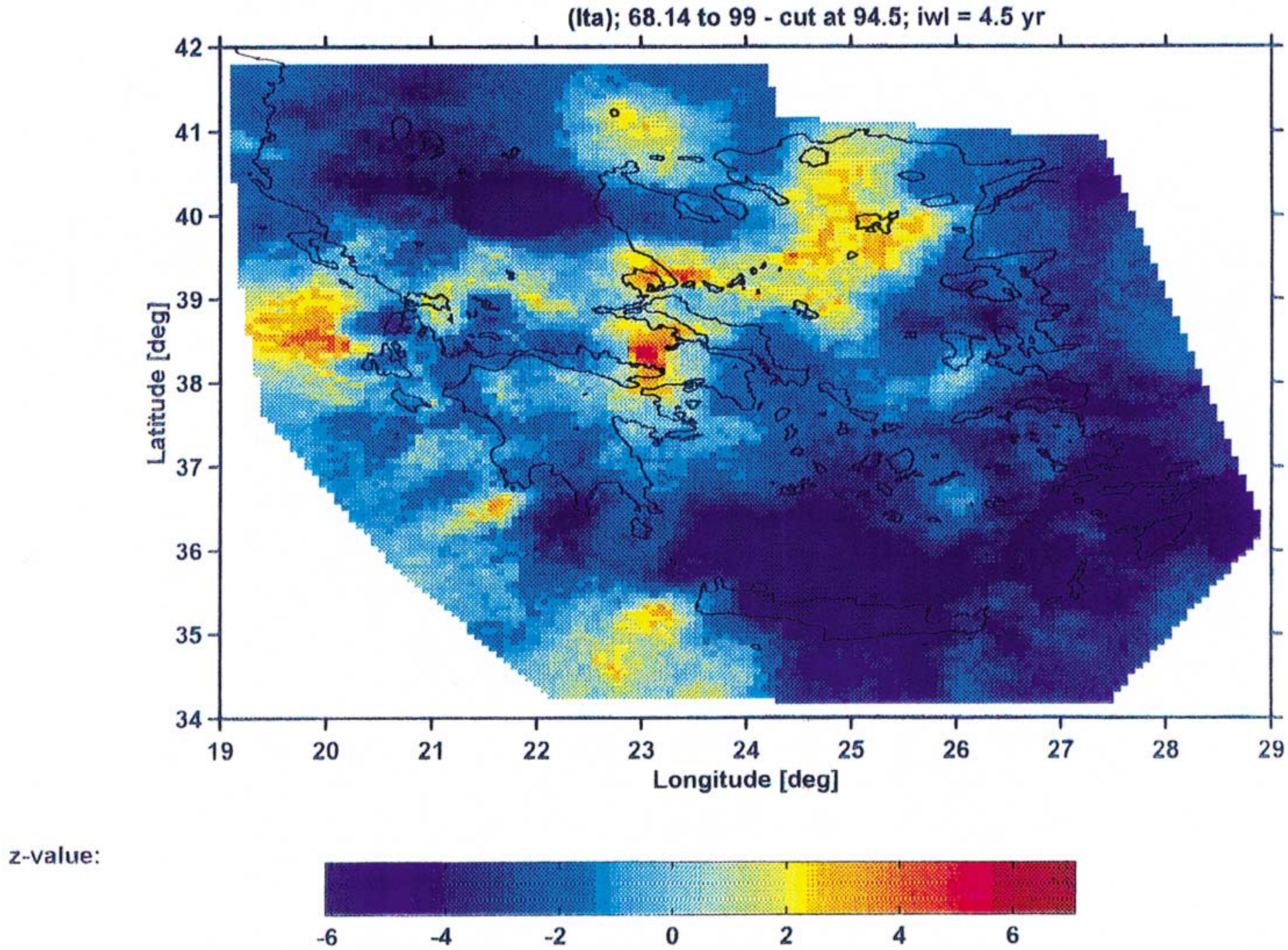

Figure 5d. Z-value distribution at the beginning of 1999 with T_W (iwl) = 4.5 years.

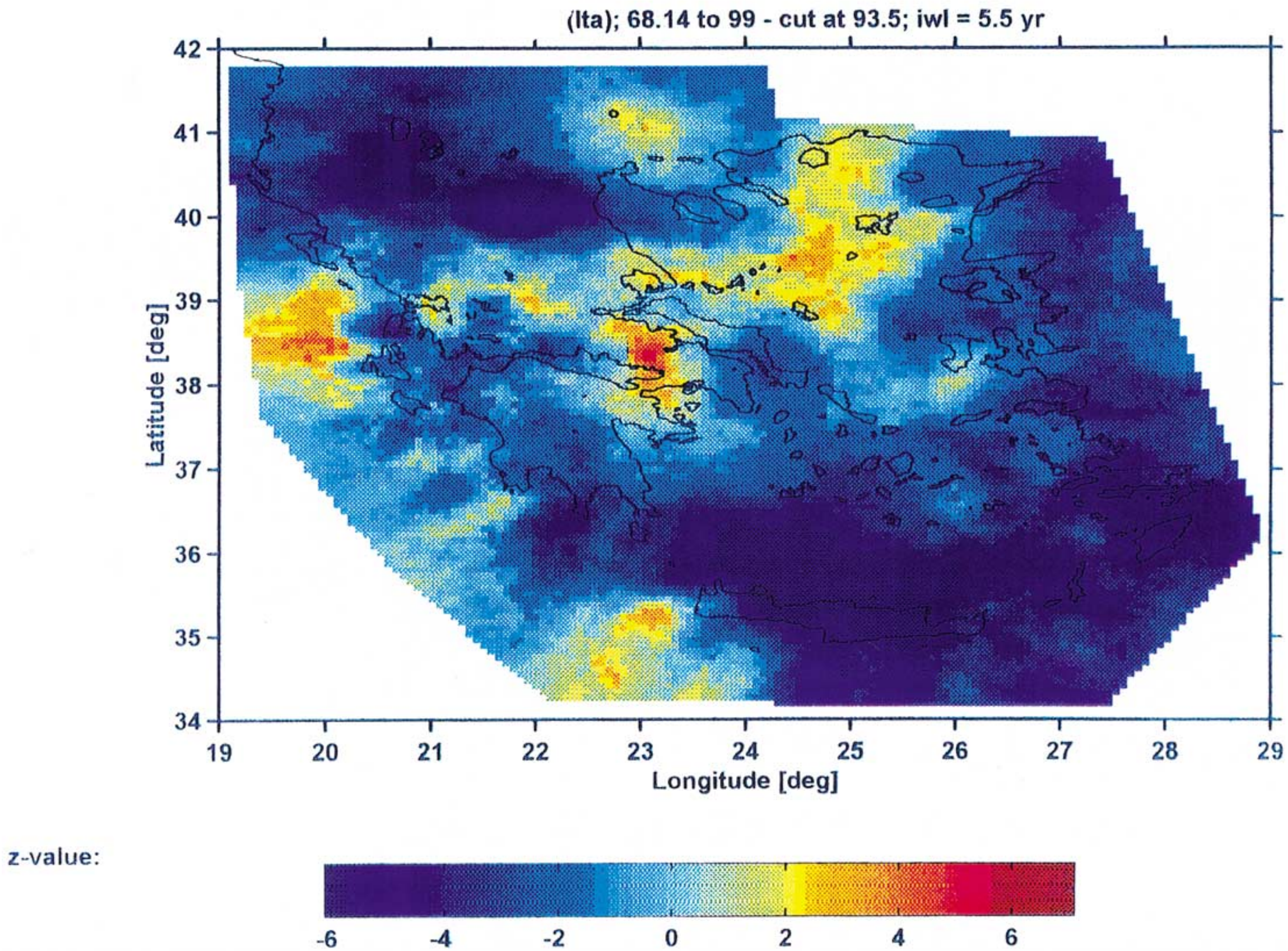

Figure 5e. Z-value distribution at the beginning of 1999 with T_W (iwl) = 4.5 years.

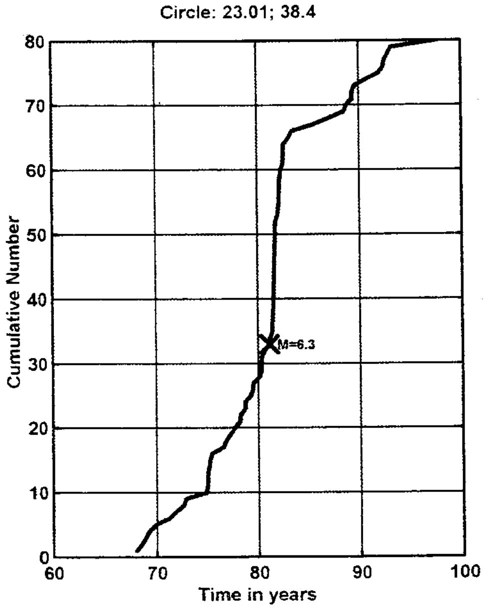

Figure 6a. Cumulative number of earthquakes versus time for the area centered at the anomaly on the eastern part of the gulf of Corinth.

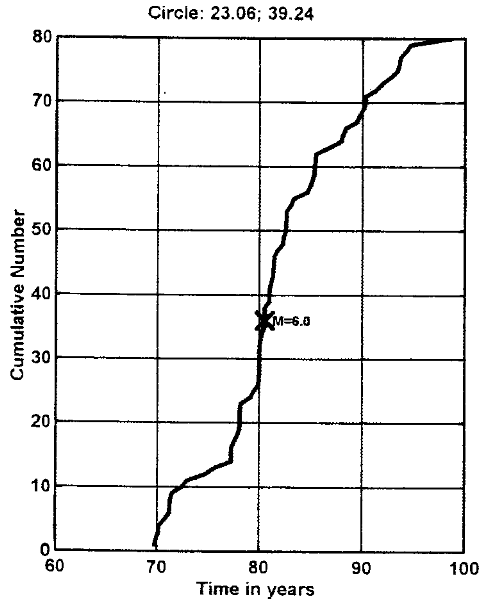

Figure 6b. Cumulative number of earthquakes versus time for the area centered at the anomaly near Volos.

are apparent: the area of the North-Eastern part of the Gulf of Corinth, the area to the east of Volos city, the area to the north of the city of Thessaloniki and the area to the north-west of Kefalonia island.

When examining the cumulative curves of circles centered at these anomalies in Figures 6a to 6d respectively, one notes a significant lack of production of earthquakes in the recent years for all four areas. The fact that these areas are very near permanent stations of the NOA seismic network that have not been disrupted in their operation, eliminates the possibility of artificial quiescence as the cause of the anomalies. In addition to that one can observe that these areas contain the largest main shocks that have occurred in Greece and which have also exhibited signs of quiescence prior to their occurrence, as we will show later in this section.

Figure 6a shows the cumulative number of earthquakes as a function of time for a circle centered at 38.4°N–23.0°E, whose radius has the dimensions needed to collect the nearest 80 events. For this anomaly the radius needed to collect 80 events has a size of 32 km and it is clearly seen that this area has stopped producing earthquakes since 1993 and it includes the source volume of the February 24, 1981 main shock in the gulf of Corinth at 38.14°N–23.25°E with M = 6.3.

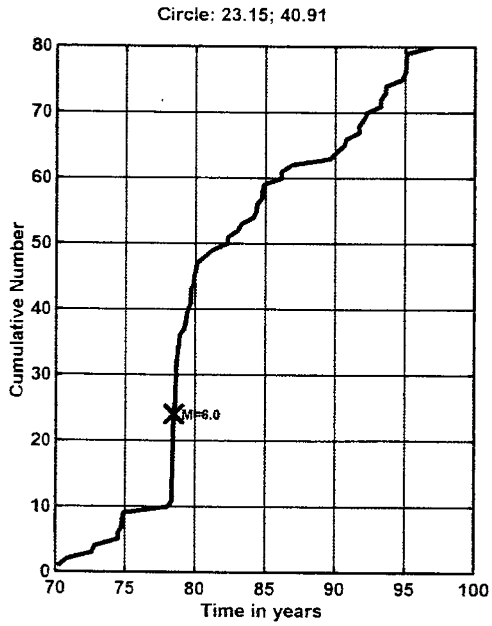

Figure 6c. Cumulative number of earthquakes versus time for the area centered at the anomaly near Thessaloniki.

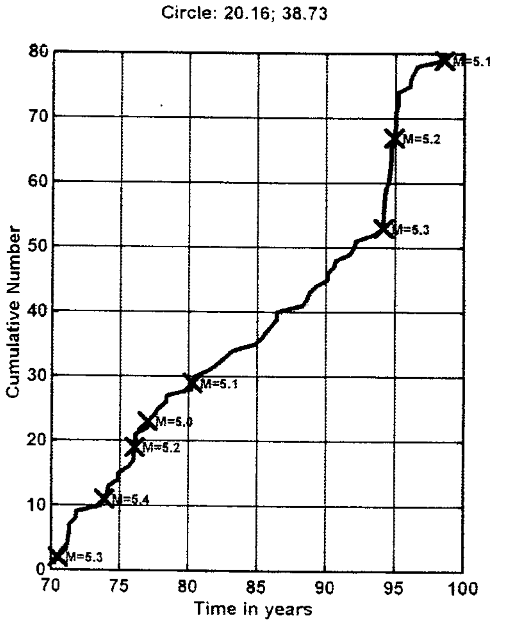

Figure 6d. Cumulative number of earthquakes versus time for the area centered at the anomaly near the north western part of Kefalonia island.

The second most significant anomaly in duration, is seen on Figure 6b, centered at 39.24°N–23.06°E and the radius for collecting 80 events is 29 km. This area has stopped producing earthquakes since 1994.7 and it includes the source volume of the July 9, 1980 Volos, main shock at 39.20°N–23.90°E with M = 6.0.

The third most significant anomaly is found centered at 40.91°N–23.15°E and Figure 6c shows that this area has also stopped producing earthquakes since 1995.2. The radius for collecting 80 events is 45 km and it includes the source volume of the June 20th, 1978, Thessaloniki main shock with M = 6.0. It is also important to note that this cumulative curve shows an absence of seismicity starting in 1975 and lasting for almost 3.5 years up to the time of the 1978 Thessaloniki, main shock.

The cumulative curve of the area to the north-west Kefalonia island centered at 38.73°N–20.16°E, as seen in Figure 6d, has a radius of 19 km in order to collect 80 events and one sees that the absence of seismicity which begins at 1996.4 results in a magnitude M = 5.1 earthquake that occured on July 16, 1998. This area has produced 8 shocks with magnitudes larger than M = 5.0 with the largest being a magnitude M = 5.4 on November 4th, 1973 and one can clearly see that prior to this event, the earthquake production had stopped since the end of 1971.9. The cumulative curve for this area also indicates that periods of quiescence also preceded other shocks from this area and in addition, this area does not appear to produce strong main shocks so that we can investigate the quiescence hypothesis as postulated.

The Z-value distribution of the three areas with significant quiescence, namely the area of the North-Eastern part of the Gulf of Corinth, the area to the east of Volos city and the area to the north of the city of Thessaloniki is shown in Figure 7, using a time window of 3.5 years. This choice of T_W (indicated as iwl in the respective figure), is in order to enhance the simultaneous mapping of all three quiescence anomalies in the beginning of 1999.

When we examine the epicentral position of the three largest main shocks that occured in these areas in the past (indicated by a cross in Figure 7), we note that in the cases of Volos and the gulf of Corinth, the 1980 and 1981 main shocks respectively, are on the outer limits of the recent quiescence anomalies, while the Thessaloniki 1978 main shock is within the recently observed anomalous area. This may explain why significant quiescence is seen clearly on the respective cumulative curve of Figure 6c before the 1978 main shock, while for the other two cases on Figures 6a and 6b, quiescence is not clearly observed for the 1980 and 1981 main shocks in Volos and the gulf of Corinth, respectively.

In Figures 8a-c we show the cumulative curves centered at the epicenters of the gulf of Corinth, Volos and Thessaloniki main shocks respectively, so that we can investigate their behaviour. One notices that the cumulative curves for the epicentral areas of the gulf of Corinth and Volos main shocks, on Figures 8a and 8b respectively, show periods of lack of earthquake production prior to the main shocks, however these periods do not end abruptly with the occurrence of he main shocks as is the case of the Thessaloniki main shock on Figure 8c. In the former two cases it is observed that a period of quiescence precedes the main shocks, however about one year prior to their occurence the seismic activity suddenly increases.

Further on, by directly comparing Figures 6a to 8a and also 6b to 8b we note that quiescence is best revealed at the epicentra) areas of the main shocks and it dissapears at larger distances, as was earlier demonstrated for the Kefalonia main shock on Figure 4. The radii for collecting 80 events in these three areas are between 29 and 45 kilometers and in this sense the areas sampled exceed the dimensions of the main

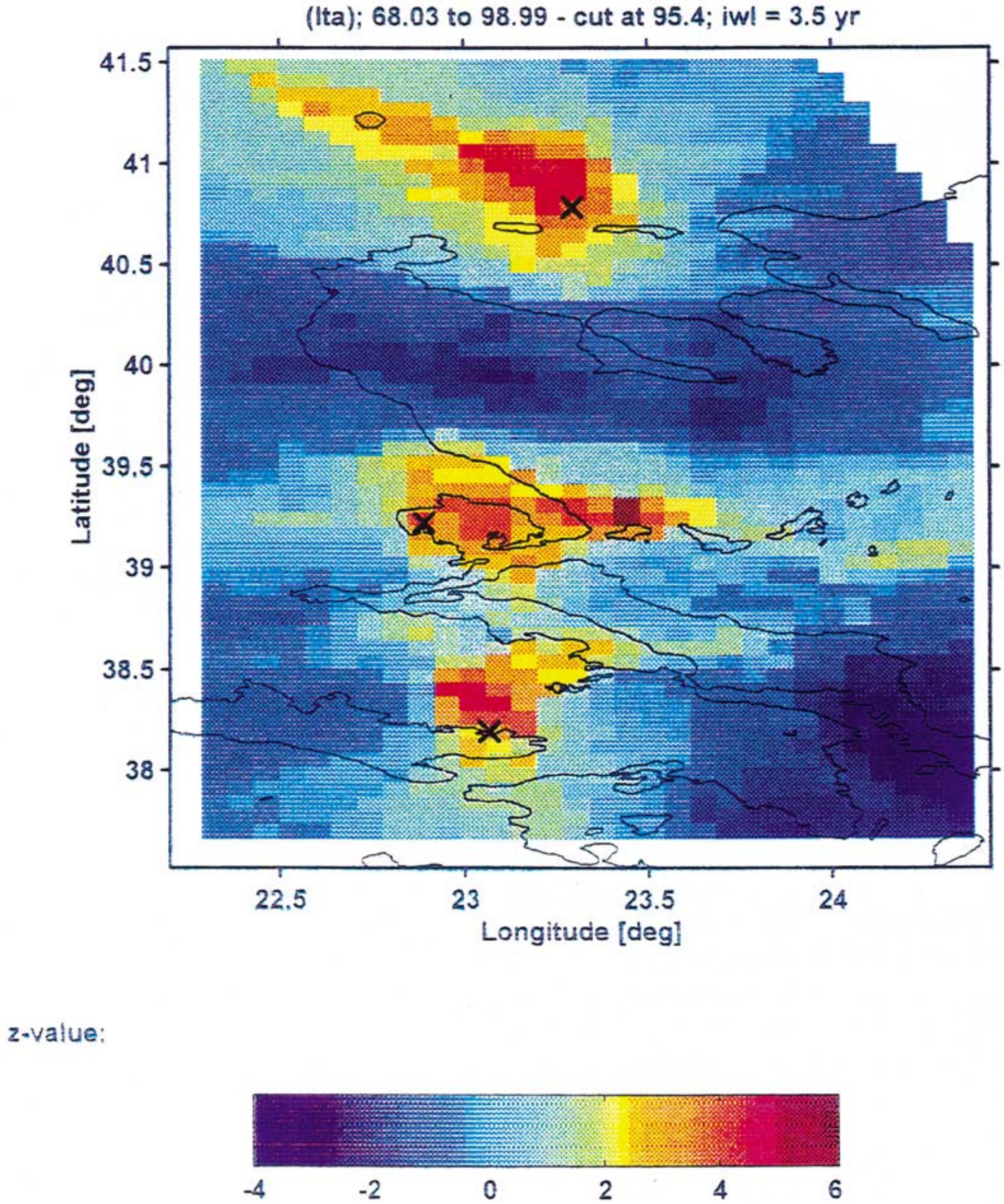

Figure 7. Z-value distribution at the beginning of 1999 with T_W (iwl) = 3.5 years, for the three areas with significant quiescence, namely, eastern part of the Gulf of Corinth, Volos and Thessaloniki.

shock seismogenetic volumes. In this sense, one cannot test the quiescence hypothesis as originally defined by Wyss and Habermann (1988). To perform such a task one will need to use an earthquake catalogue with a magnitude of completeness less than M = 3.3 in order to sample only the seismogenetic volume and not a broader region which may not be affected by the earthquake process.

Conclusions

In this study we have used the declustered earthquake catalogue of the Institute of Geodynamics of the Na-

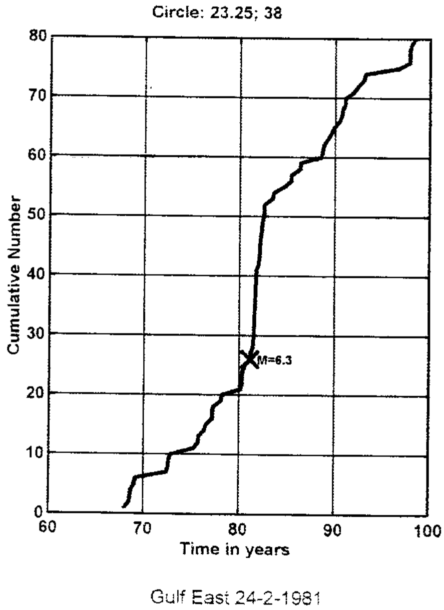

Figure 8a. Cumulative number of earthquakes versustime for the area centered at the anomaly at the epicenter of the 1981 main shock near the eastern part of the gulf of Corinth.

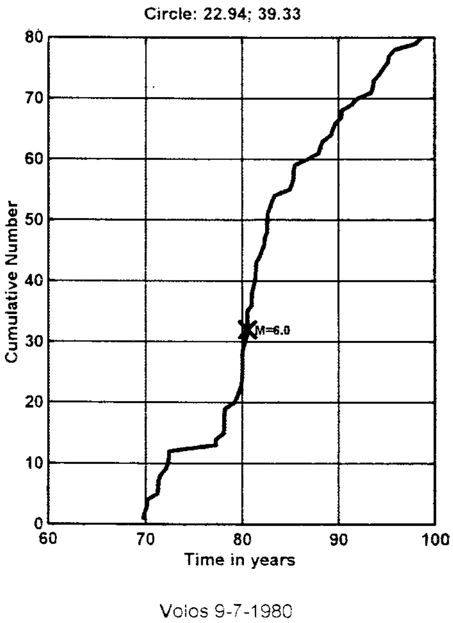

Figure 8b. Cumulative number of earthquakes versus time for the area centered at the anomaly epicenter of the 1980 main shock near Volos.

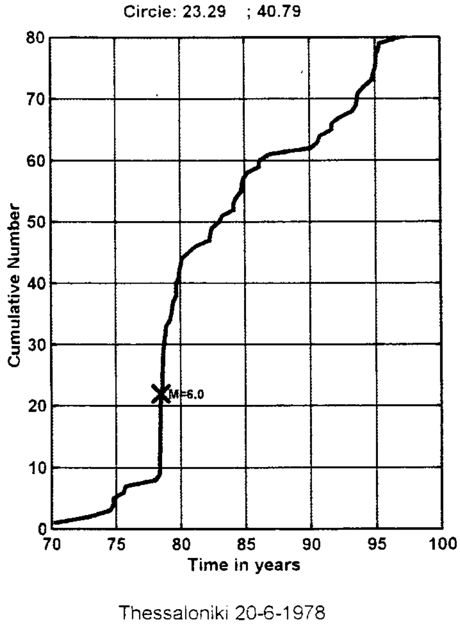

Figure 8c. Cumulative number of earthquakes versus time for the area centered at the anomaly near Thessaloniki.

tional Observatory of Athens from 1968 untill 1999, for crustal earthquakes with depth less than 50 km and M>3.3, to map the seismic quiescence pattern as defined by Wyss and Habermann (1988), in Greece. The methodology we use involves the gridding method of Wiemer and Wyss (1994) and the ZMAP analysis software (Wiemer et al., 1995), to investigate the significance of seismicity rate changes at the nodes of a grid spacing of 0.05° in the beginning of 1999 in Greece.

According to the hypothesis of Wyss and Habermann (1988) and the results of Wyss (1997a,b), the duration of seismic quiescence depends on the magnitude of the impending main shock and it should be observed within the seismogenetic volume. The results presented here show that the duration of quiescence as well as the rate of earthquake production varies and is dependant on the dimensions of the sampled volume, in accordance to the proposed hypothesis. In the case of the M = 6.2 main shock in Kefalonia island in 1983, a 6 year quiescence period has been identified within the seismogenetic volume. Further on, using the same methodology lead us to identify three other larger areas with an absence of seismicity not attributed to artificial causes, with durations of 3.8, 4.3 and 6 years, near the large cities of Thessaloniki, Volos and the eastern part of the Gulf of Corinth, respectively.

Since 3.5 years of seismic quiescence was also clearly observed in the greater area prior to the occurrence of the 1978 Thessaloniki main shock and shorter periods of decreased earthquake production were also observed prior to the Volos and Gulf of Corinth main shocks, in 1980 and 1981, respectively, the recently observed quiescence in the three aforementioned regions can be considered as significant.

These regions were struck with devastating earthquakes 17–21 years ago and the return periods of strong main shocks have been exceeded in all three cases, as shown in a recent study (Papazachos and Papaioannou, 1997). For this reason special attention should be given to these regions and monitoring of their microseismic activity by dense local arrays, as well as the monitoring of other geophysical parameters is suggested.

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