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A New Observation of Dynamically Triggered Regional Seismicity: Earthquakes in Greece Following the August, 1999 Izmit, Turkey Earthquake

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Abstract. The M_w=7.4 Izmit, Turkey earthquake triggered widespread regional seismicity in Greece over a study region extending from 400 km to nearly 1000 km away from the epicenter. Small events began immediately after the passage of the mainshock surface waves suggesting that the transient stresses of the seismic waves were the trigger. The increase in cataloged earthquakes in ordinary continental crust is a new observation and is statistically significant at the 95% level. Unlike the previous example of distant triggering during the Landers earthquake, the activated seismicity occurred entirely in non-volcanic areas. The Greek sites were triggered by waves with amplitudes at least a factor of 3 lower than the observed triggering threshold for Imperial Valley. We speculate that dynamic triggering on a regional-scale results in countrywide episodes of increased seismicity, or "superswarms", in regions with low triggering thresholds such as Greece.

Observation

The M_w=7.4 Izmit earthquake on August 17, 1999 at 00:01:39.80 UT was followed immediately by small earthquakes occurring throughout much of continental Greece. The number of earthquakes per day recorded by the network of the Department of Geophysics of the University of Thessaloniki from January 1, 1999 through October 9, 1999 are shown in Figure 1. A peak is visible on the day of the Izmit event (Julian day 229). The seismicity discussed in this figure and throughout this study includes only the events west of longitude 25°, i.e., at least 400 km from the Izmit epicenter at 40.702°N 29.987°E. A cursory inspection of the daily seismicity maps before and after day 229 strongly suggests a link between the activity in Greece and the Turkish event (Figure 2).

The triggering of events from the Izmit mainshock occurred immediately after the passage of the surface waves. Figure 3 shows several local, high-frequency events directly after the surface waves. Although it is possible that the occurrence of these local earthquakes was coincidental, the timing strongly suggests that the large amplitude dynamic strain of the surface waves is responsible for triggering regional seismicity. The local events shown here are not in standard catalogs since the surface waves obscure their arrivals. This masking of early events by the mainshock coda results in an apparent delay of approximately a half hour before the onset of triggered seismicity in the Thessaloniki catalog.

This observation of regionally triggered seismicity is significant for the following reasons: (1) It is the first fully documented observation of regional triggering over a large area by seismic waves in non-volcanic continental crust. (2) The threshold for triggering is at least a factor of 3 lower than in volcanic regions of California. (3) The observation demonstrates interactions between earthquakes over large distances and suggests that regions with low triggering thresholds are prone to episodes of widespread increased seismicity.

Catalog

We use the catalog of the Thessaloniki network for this study. The network consists of 16 Teledyne S-13 stations with natural frequencies of 1 Hz located in northern Greece (Figure 4). All stations were operational throughout 1999 except station LKD which was activated on July 10, 1999 and located at 38.707°N 20.651°E. There was no change in the automated cataloging procedures after the Izmit event; therefore we can eliminate extraordinary alertness of the seismological staff following a large event as a cause of the apparently elevated seismicity. The Thessaloniki catalog exhibits the standard Gutenberg-Richter magnitude-frequency relationship above M=3.5 and is depleted in events below this magnitude. Following standard practices, we take M=3.5 as the threshold for completeness of the catalog. As can be seen from Figures 1 and 2, the peak in seismicity post-Izmit is still evident even if we limit ourselves to the formally complete section of the catalog. Including the smaller events in Figures 1a and 2 provides a larger sampling and makes the phenomenon even clearer.

Statistical Significance

We fit a log-normal probability distribution function to the catalog for the first 228 days of 1999 in order to determine the statistical significance of the peak on day 229. We then used the best-fitting log mean and log variance for the

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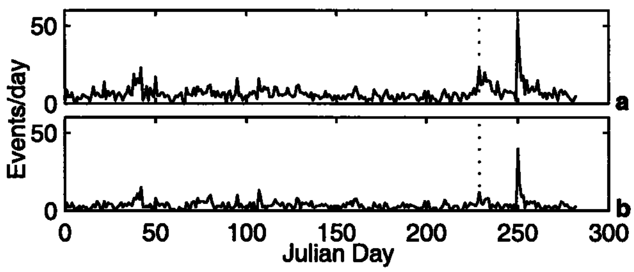

Figure 1. Number of earthquakes per day recorded by Thessaloniki network west of longitude 25°. (a) Events of $M \geq 2$. (b) Events of $M \geq 3.5$. The dotted line indicates the date of the Izmit earthquake. The peak on day 250 is caused by the Athens M_w=5.8 event and its aftershocks.

catalog of $M \geq 3.5$ events to calculate the probability that the twelve events occurring on day 229 was a coincidence unrelated to the Izmit earthquake. With this distribution the probability that 12 or more events would occur on a given day is ~3%. The statistical calculation was repeated for larger catalogs including all events from 1988 to 1998 or all events with $M \geq 2$. Even in the least favorable case, the hypothesis that the increase in seismicity on day 229 was coincidental can be rejected at the 95% level. Furthermore, the other days in 1999 with a similar number of events were during locally confined (<250 km^2) earthquake sequences. The activity on day 229 was unique in the 1999 catalog in that it had a large number of events spatially dispersed over 4×10^5 km^2.

Spatial distribution

It has been previously suggested that dynamically triggered seismicity occurs preferentially in geothermal and magmatic areas [*Hill et al.*, 1993]. Continental Greece has no recent magmatism, but there is a possible correlation between triggered seismicity and geothermal areas. *Anderson et al.* [1994] has suggested that such apparent correlations are artifacts of the fact that an increase in events is most easily measured in the regions which are most seismically active. Such active areas are commonly geothermal. To distinguish between these possibilities we have relocated the events listed in the Thessaloniki catalog using the combined phase picks of the Thessaloniki network and the Geodynamical Institute of the National Observatory of Athens. Location errors for the combined network were estimated by comparing the network locations of the September 7, 1999 M_w=5.9 Athens aftershock sequence with high-quality locations obtained from a local, temporary array. The mean difference between the network and temporary array locations is 8 km horizontally and 5 km in depth.

The map in Figure 4 shows the relocated triggered events and the level of background seismicity. The Council of National Seismic System (CNSS) composite catalog of events with $M \geq 4$ during the interval 1961–1998 is used as a measure of the normal regional seismicity. This catalog has relatively uniform spatial coverage for nearly 40 years and is complete according to a standard test of the magnitude-frequency distribution.

We do not attempt a systematic statistical study of the spatial correlation of the triggered events with either geological features or background activity since the data are too sparsely distributed. We focus instead on the two most striking groups of the sequence: (a) the cluster of events near Arta and (b) the cluster near Pirgos. Both areas have grabens and documented thermal springs [*Waring*, 1965]. The springs indicate geothermal activity in that hot, aqueous fluids are present, although the heat flow is not necessarily elevated relative to the surrounding region. The Arta cluster occurred in a region which generally has a relatively low level of seismicity as shown by the white background in Figure 4. Contrary to the hypothesis of *Anderson et al* [1994], the largest number of observed triggered events are not in the most seismically active areas. Triggered activity outside the clusters may also be located at geothermal sites since hot springs occur over much of Greece [*Waring*, 1965]. All triggered events are at crustal depths.

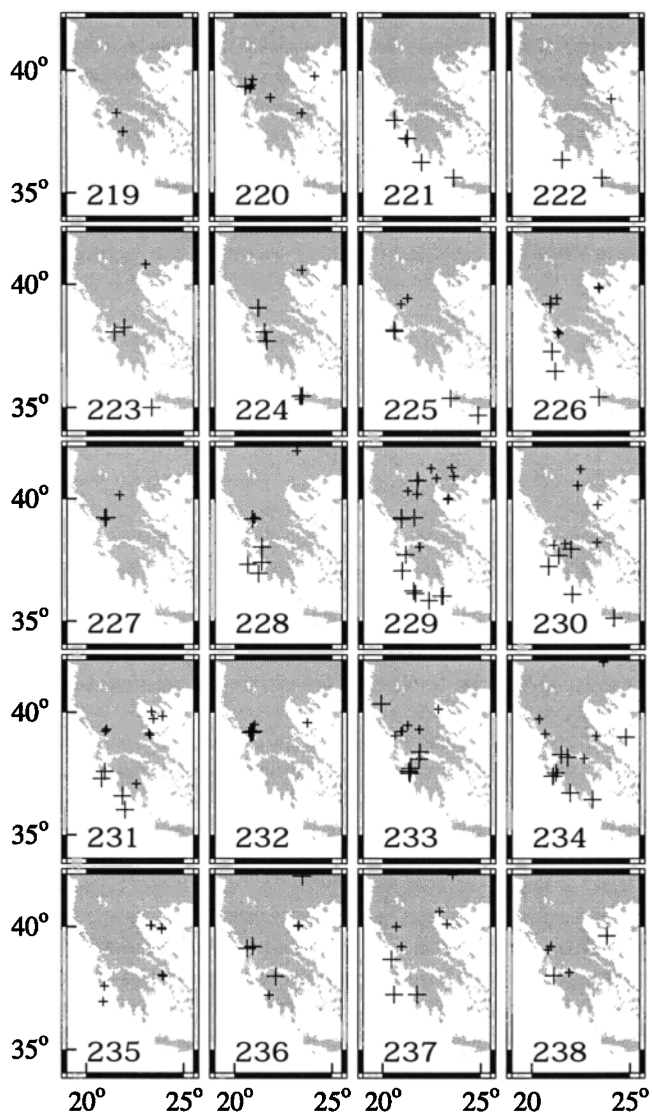

Figure 2. Map of events recorded by the Thessaloniki network west of 25° during the days surrounding the Izmit earthquake (Julian day 229). The large crosses are events with $M \geq 3.5$ and the small crosses indicate $3.5 > M \geq 2$.

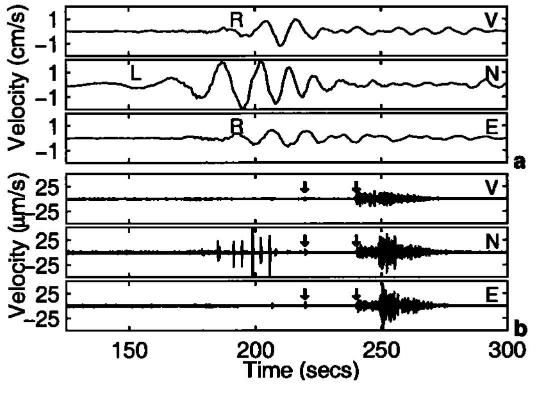

Figure 3. The waveforms of the mainshock and local events occurring immediately after it. (a) Records from a temporary deployment of a Guralp CMG40-T at 40.5952°N 23.0023°E (station 7905). The three components are as labeled. (b) The same records band-passed 5-20 Hz. Note the difference in scales. The two events marked by arrows are located at 40.580°N 22.860°E and 39.930°N 23.367°E with origin times of 00:05:13.4 UT and 00:05:26.1 UT and magnitudes $M_L \approx 1$ and 3.8, respectively. The glitches on the north component result from band-passing the clipped signal. The origin time of the plot is the origin time of the Izmit mainshock. The Love (L) and Rayleigh (R) arrivals are labeled.

Table 1. Observed amplitudes and energies

Event	Station	Δ km	Amplitude cm/s (MPa)	En. Density J/m^2
Landers	SSW[1]	139	6.6 (0.60)	3.5×10^5
Hector Mine	SSW	158	9.0 (0.82)	1.3×10^6
Izmit	7905	589	1.9 (0.18)	7.8×10^4

Distance Δ is measured from the epicenters to the stations. Amplitude is reported in terms of both velocity and dynamic stress. The velocity amplitude is half the maximum peak-peak value of the horizontal velocity. The stress amplitude is the velocity amplitude multiplied by μ/β where μ is the shear modulus (3×10^{10}Pa) and β is the shear velocity (3300 m/s). Energy density is the integral over time of the velocity squared multiplied by β and the rock density (2750 kg/m^3) [*Kanamori et al.*, 1993]. Station SSW is in Imperial Valley. Station 7905 in Greece is described in Figure 3.

[1]SSW was not operational in 1992. The amplitude and energy density here are calculated by applying empirical corrections derived from the local broadband network to the velocity traces of the nearest station (PFO, Δ=63 km) to account for geometric spreading, radiation pattern, directivity and site amplification.

Comparison with Southern California

We compare the Izmit triggered seismicity to the two other well-documented examples of regionally triggered seismicity in order to establish the relative sensitivity of triggered regions. The June 28, 1992 M_w=7.3 Landers earthquake [*Hill et al.*, 1993] and the October 16, 1999 M_w=7.1 Hector Mine earthquake both triggered widespread microseismicity in southern California [*Scientists from the U.S. Geol. Surv. et al.*, 2000]. Like Izmit, both events were large strike-slip earthquakes and they triggered seismicity in areas under regional extension with geothermal activity. Since it is established that both the Landers and Hector Mine earthquakes had the ability to trigger distant events, we infer that any area that was triggered during one of the events but not the other experienced shaking above its local triggering threshold during only one of these events. Imperial Valley, California was triggered during Hector Mine and not Landers. Therefore the recorded ground motion during Hector Mine provides an upper bound to the triggering threshold in Imperial Valley and the record of Landers provides a lower bound. It is assumed that there was no change in the triggering threshold during the seven years between Landers and Hector Mine.

The strength of the triggering waves can be measured by either the amplitude of the transient stress, which scales as the particle velocity, or by the energy density delivered by the waves. Table 1 lists both of these metrics. It shows that triggering in Greece occurred at amplitudes and energies lower than Imperial Valley. The record in Figure 3 measures shaking within 20 km of at least one $M_L \approx 1$ event. Four nearby stations situated on a variety of rock types show similar records which suggests that local site response effects are negligible for the long-period waves considered here. The record is a good measure of the shaking at the triggered site and yields the values in Table 1. Since the site is closer to the Izmit mainshock than most of the other Greek triggered sites, the values measured here are upper bounds on the triggering threshold for susceptible regions in Greece. Whether amplitude or energy is taken as a measure of the strength of the triggering wave, the threshold is more than a factor of three lower at the triggered sites in Greece than in Imperial Valley.

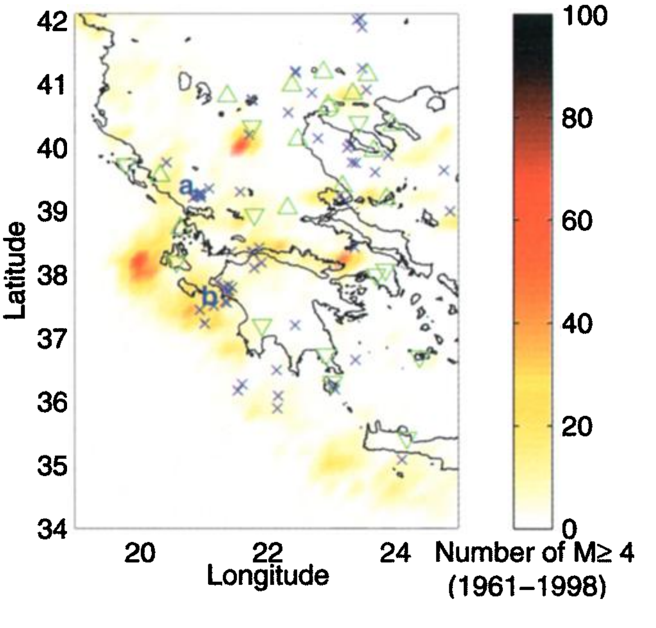

Figure 4. Plot of relocated events with $M \geq 2$ from 8/17/99–8/22/99 inclusive (crosses) and background activity (colorbar). The background seismicity is binned into 0.2°×0.2° cells and then smoothed by linear interpolation between cells. Seismic network stations are plotted in green. Thessaloniki stations are upward pointing triangles, Athens stations are downward pointing triangles and station 7905 is a circle. Groups of events are labelled (a) Arta cluster (b) Pirgos cluster.

Triggering mechanisms

Although static stress changes may be an important trigger for nearfield aftershocks, the static stress changes at more than a fault length from the source are negligible even compared to tidal stresses. The observation of events immediately after the largest amplitude shaking (Figure 3) is consistent with the dynamic stress triggering the earthquakes. A physical mechanism is required to transform the transient stresses of the seismic waves into sustained stresses on the fault capable of producing an earthquake hours or days later and a number of possible mechanisms have been suggested [*Hill et al.*, 1993; *Linde et al.*, 1994; *Sturtevant et al.*, 1996; *Gomberg et al.*, 1998]. Most of these studies have focussed on fluid mechanical processes since geothermal activity commonly occurs in the extensional areas where triggering is observed.

A previously undiscussed process for dynamic triggering is subcritical crack growth accelerated by seismic waves. At crack tips in wet rocks, chemical reactions are accelerated by the high stresses and cracks slowly grow [*Das and Scholz*, 1981]. Large cracks grow faster than smaller ones due to the increased stress intensity at the tip. If the cracks are in a near-critical state prior to the seismic shaking, the large amplitude seismic waves temporarily increase the rate of stress corrosion. This transient stress increases the average size of the crack population and accelerates critical failure. As stress corrosion is most effective in hot, wet rocks, this model predicts that geothermal areas are likely to have a high occurrence of triggered events.

Regional Superswarms

Observable interactions between distant earthquakes as shown in this paper suggest that seismicity can be coupled over broad regions. We call such regional-scale episodes of elevated seismicity "superswarms." Superswarms can last up to a few months and are distinguished from common mainshock-aftershock sequences by the large areas involved. Candidates for superswarms include the October 1994 to January 1995 sequence of large (M>7.0) earthquakes in Japan and the September 1999 Athens event following the August 1999 Izmit earthquake. Areas prone to superswarms have low triggering thresholds, as was observed for Greece. Such regions can be identified globally by using modern broadband instruments to record the amplitude and energy of triggering waves. A systematic evaluation of regional sensitivity using the methods shown in Figure 3 and Table 1 would be a logical extension of this work and a valuable test of the hypothesis.

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