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The Galaxidi Earthquake of 18 November 1992: A Possible Asperity within the Normal Fault System of the Gulf of Corinth (Greece)

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Abstract The Galaxidi earthquake that occurred in the Gulf of Corinth on 18 November 1992 was not followed by a noticeable aftershock sequence, a fact that was also observed for the 1965 Eratini event in the same area. The temporary network of 35 stations that we installed 5 days after the mainshock did not help to identify a cluster of activity related to the mainshock. In a section across the epicentral zone, the focal mechanism of the mainshock and the distribution of a few aftershocks define a plane dipping north, consistent with the nearby Helike fault. We propose that the Galaxidi earthquake was related to an asperity located between the Helike and Xilokastro faults.

Introduction

The Aegean is a rapidly deforming continental region. The Gulf of Corinth, located between continental Greece and Peloponnese, is a recent extensional structure not older than 2 m.y. that opens at about 1 cm/yr (Briole *et al.*, 1993) and accommodates a large part of the Aegean deformation (Armijo *et al.*, 1995). It is an asymmetric graben bounded to the south by 3 en-echelon E–W trending normal faults dipping north (Fig. 1). The geometry of the faults is not precisely known: the dip is about 50° at the surface, but microseismic activity suggests shallower dips at depth (Rigo *et al.*, 1996).

The Gulf of Corinth has experienced several large earthquakes that destroyed some of the ancient cities, such as Corinth, Delphi, and Patras in historical time (Papazachos and Papazachou, 1989). Since instrumental seismology started, six earthquakes of magnitude greater than 6 were located around the Gulf of Corinth, most of them at its eastern end near the city of Corinth. The focal mechanisms show a consistent pattern of E–W trending normal faulting, with one plane dipping shallowly toward the north. This pattern is consistent with microseismic observations obtained by dense temporary networks (Hatzfeld *et al.*, 1990; Rigo *et al.*, 1996).

On 18 November 1992, an earthquake of magnitude $M_S = 5.9$ occurred in the central part of the Gulf of Corinth, between the Helike and the Xilokastro normal faults. Surprisingly, it was not followed by a vigorous aftershock sequence. In this article, a study of the mainshock and of the aftershock sequence is presented, which improves upon previous work conducted by Kementzetzidou *et al.* (1993) and by Karakaisis *et al.* (1993).

The Mainshock

The mainshock occurred on 18 November 1992 at 21:10 GMT. The source parameters given by different agencies (NEIC, ATH, CSEM, ISC) vary significantly (Table 1). The location given by ISC is beneath the Gulf of Corinth at the eastern part of the Helike normal fault.

According to statistics, the number of aftershocks of magnitude greater than 4 following a magnitude 6 earthquake is 25 in Greece (Papazachos and Papazachou, 1989) and 6 in California (Kisslinger and Jones, 1991). Moreover, during the week following the 15 June 1995 Aigion earthquake of magnitude 6.2 located near Galaxidi, 12 aftershocks of magnitude greater than 3.5 were recorded. In contrast, no aftershocks of magnitude greater than 3.1 were recorded during the days following the mainshock of Galaxidi. This unusual lack of strong aftershocks was also observed for the 1965 Eratini earthquake that occurred in the same area (Ambraseys and Jackson, 1990).

Focal mechanisms computed by NEIC and HRVD using an automatic procedure both show normal faulting trending E–W with one plane dipping shallowly north. We collected broadband records from IRIS-DMC and GEOSCOPE stations and selected 20 *P* waves between epicentral distances of 30° and 85° and 11 *SH* waves between 40° and 70°. Despite the moderate magnitude of the earthquake, the number and quality of the records allow for a good inversion of the body waves. We use the program of McCaffrey and Abers (1988) to determine the depth, strike, dip, slip, and source time function composed of 10 elementary triangles of 1 sec each. The crustal velocity structure used is from Rigo *et al.* (1996)

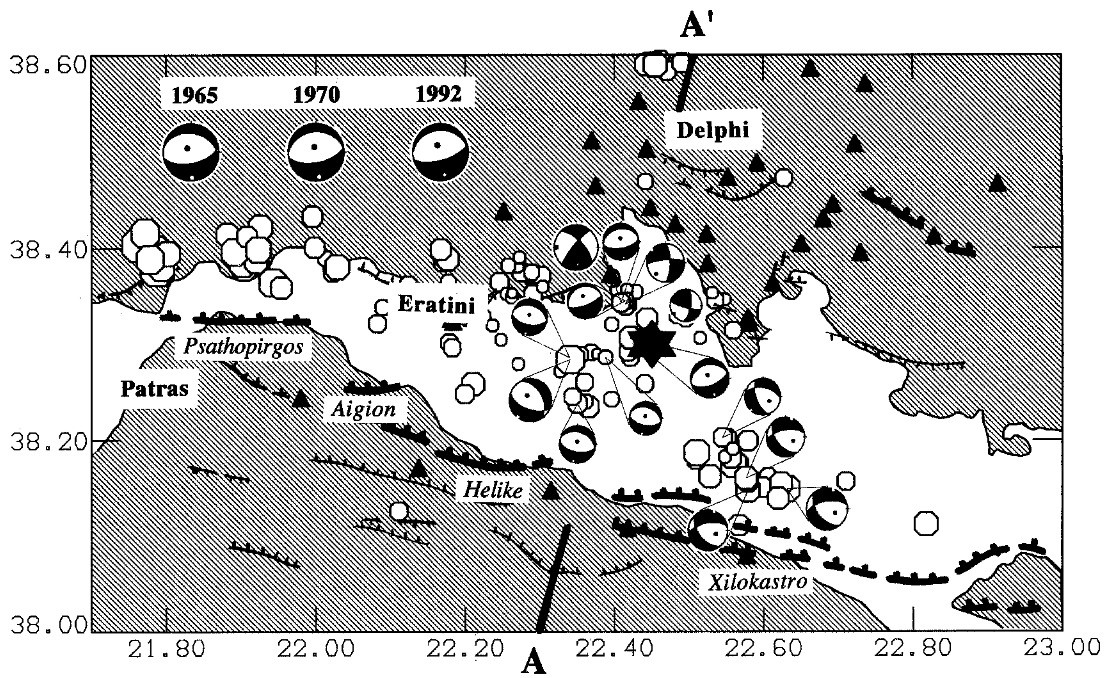

Figure 1. Seismicity map and available focal solutions for earthquakes recorded between 23 November and 2 December with the mobile network and located to better than 3 km by more than six stations. The big balloons are focal solutions for the 1965, 1970, and 1992 shocks that occurred in the same area. The black triangles are seismological stations. The star is the mainshock. The main active faults (Rigo *et al.,* 1996) and the cross section of Figure 3 are represented.

Table 1
Parameters of the Mainshock

Agency	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude	Scalar Moment (10 × 17 N-m)
NEIC	38.31	22.45	15	5.7 M_S	9.2
ATH	38.27	22.33	23	5.2 Ml	
CSEM	38.33	22.50	16		
HRVD	38.09	22.60	15		8.5
ISC	38.30	22.45	12	5.7 M_S	

Table 2
Velocity Structure

v (km/s)	Depth (km)
5.1	0
5.8	5.
6.5	17.
7.6	40.

(Table 2), but the choice of velocity model does not influence the results much.

The centroid depth is rather well constrained at 7.4 ± 1 km because of the short duration of the source, but the fault parameters ($\phi 1 = 270° \pm 7°, \delta 1 = 30° \pm 3°, \lambda 1 = 81° \pm 7°$) are less well constrained due to the poor azimuthal coverage toward the southeast. However, *P* waves at MBO and BNG, as *SH* waves at COL, HRV, and MBO, give some control on the solution. The seismic moment is $(4.1 \pm 0.5) \times 10^{17}$ N-m, and the source time function shows two distinct pulses of 2 sec each, for a total duration of 6 sec, which is not surprisingly long for an earthquake of such a magnitude. The solution is similar to those of the 1965 Eratini (Baker *et al.,* 1994) and 1970 Itea earthquakes (Liotier, 1989).

Aftershocks

Because the event was located in an area where seismicity (Rigo *et al.,* 1996), tectonics (Armijo *et al.,* 1995), and geodesy (Briole *et al.,* 1993) have been studied, we installed a network of 35 seismological stations that started to record on 23 November, 5 days after the mainshock. During the same time, geodetic measurements were conducted to look for coseismic displacements (Briole *et al.,* 1993). Most of the seismological stations were located on the northern part of the gulf (Fig. 2) where the earthquake was more strongly felt and remained until 4 December. We recorded about 255 events at more than five stations. We located them using the HYPO71 routine (Lee and Lahr, 1975) and a velocity structure (Table 2) determined by Rigo *et al.* (1996).

The events are spread almost uniformly within the gulf with no clear clustering. Of the 195 events that were located

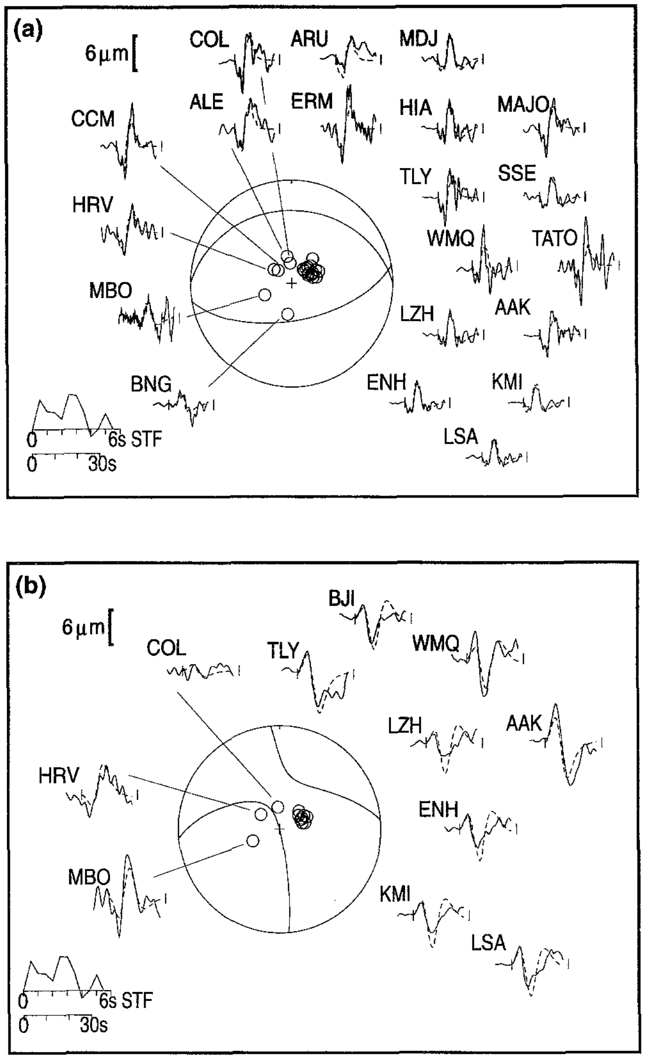

Figure 2. Focal solution, observed (continuous lines) and synthetic (dashed lines) displacement waveforms computed by the inversion. The upper figure is *P* waves, the lower figure is *SH* waves. The timescale as the source time function, STF, is on the left. Ticks delimit the portion of the seismogram that is used in the inversion.

with RMS residuals smaller than 0.3 sec and uncertainties in both epicenter and depth smaller than 3 km, 60 events that are located around the mainshock could represent aftershocks of the 18 November event (Fig. 2). This cluster defines an area that is about 25 km long and 15 km wide and trends WSW–ENE. The fault plane from aftershocks has a total surface area of 375 km^2, which is greater than the value of 50 km^2 that scaling laws predict for an earthquake of such a magnitude (Kiratzi *et al.,* 1985). A vertical cross section (Fig. 3) trending perpendicular to the Helike fault shows a deepening of the events toward the north with a dip of about 30°, consistent with the dip of the fault plane inferred from the focal mechanism. The projection of the seismic activity to the ground surface corresponds to the Helike fault.

We computed mechanisms for 14 events for which we have more than eight polarities (Figs. 2 and 4). Most of the mechanisms are E–W trending normal faults similar to the mainshock. A cluster located to the east, and probably not related to the aftershock sequence, shows a slight rotation in the *T* axes.

Discussion

The Galaxidi earthquake is an earthquake of moderate magnitude (M_S = 5.9) that occurred in the central part of the Gulf of Corinth, between the Helike and the Xilokastro normal faults. The mechanism of the mainshock and the pattern of aftershock seismicity are consistent with an E–W trending normal fault dipping northward at an angle of 30°. This shallow dip is seen, at that depth, in most of the Corinth gulf: toward the west near Aigio (Rigo *et al.,* 1996), as toward the east near Corinth (King *et al.,* 1985). It is shallower than the dip observed at the surface in tectonics and supports a listric shape for the active fault.

The fault area, as determined by the aftershocks, is greater than expected for such a magnitude earthquake and implies that the slip is only about 7 cm. This may explain why no surface breaks and so little deformation were observed at the surface (Briole *et al.,* 1993).

The aftershock sequence is unusually small because no aftershock of magnitude greater than 3.1 was recorded by the National Seismological Network. The events located 1 week after the main event are few, and it is difficult to even identify a cluster within the background seismic activity. This lack of aftershocks was also observed for the last strong Eratini (M_S = 6.4) event that occurred in the same area. But, in contrast, the earthquakes that occurred on both sides on other faults, around Corinth or Aigio, were followed by sequences of aftershocks (Ambraseys and Jackson, 1990). We suspect that it is not a coincidence.

There are two reasons, known to us, that could possibly explain a low aftershock sequence (Das and Aki, 1977).

The first is a total stress release during the mainshock at a regional scale. In this case, the whole fault behaves as an asperity, and there is no aftershock surrounding the main fault. This seems unlikely in our case, because the Aigion earthquake of magnitude M_S = 6.2 occurred in June 1995 only 2.5 yr after Galaxidi, and if stress can build up in such a short time, we should observe earthquakes more frequently in this region.

The second is a spatial change in the mechanical properties of the fault: A region of high strength is surrounded by regions of low strength, and the stress drop during the mainshock does not increase significantly stresses in the surrounding region that could induce aftershocks.

We think that the second hypothesis is a plausible explanation in the case of Galaxidi. The two events (Eratini in 1965 and Galaxidi in 1992) are located just between two important normal faults (Helike and Xilokastro) that strike

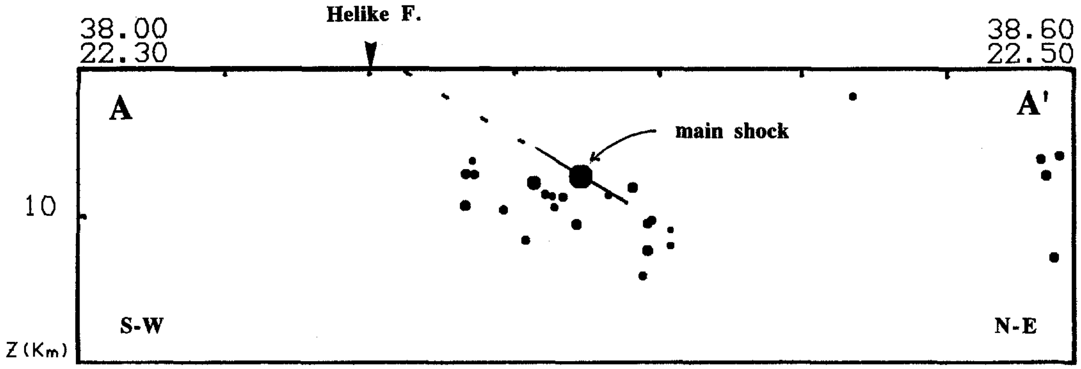

Figure 3. Section across the Gulf of Corinth almost perpendicular to the Helike fault of the events, with the same events as in Figure 1. The Helike fault, the mainshock, and the calculated dip of the mainshock fault plane are given.

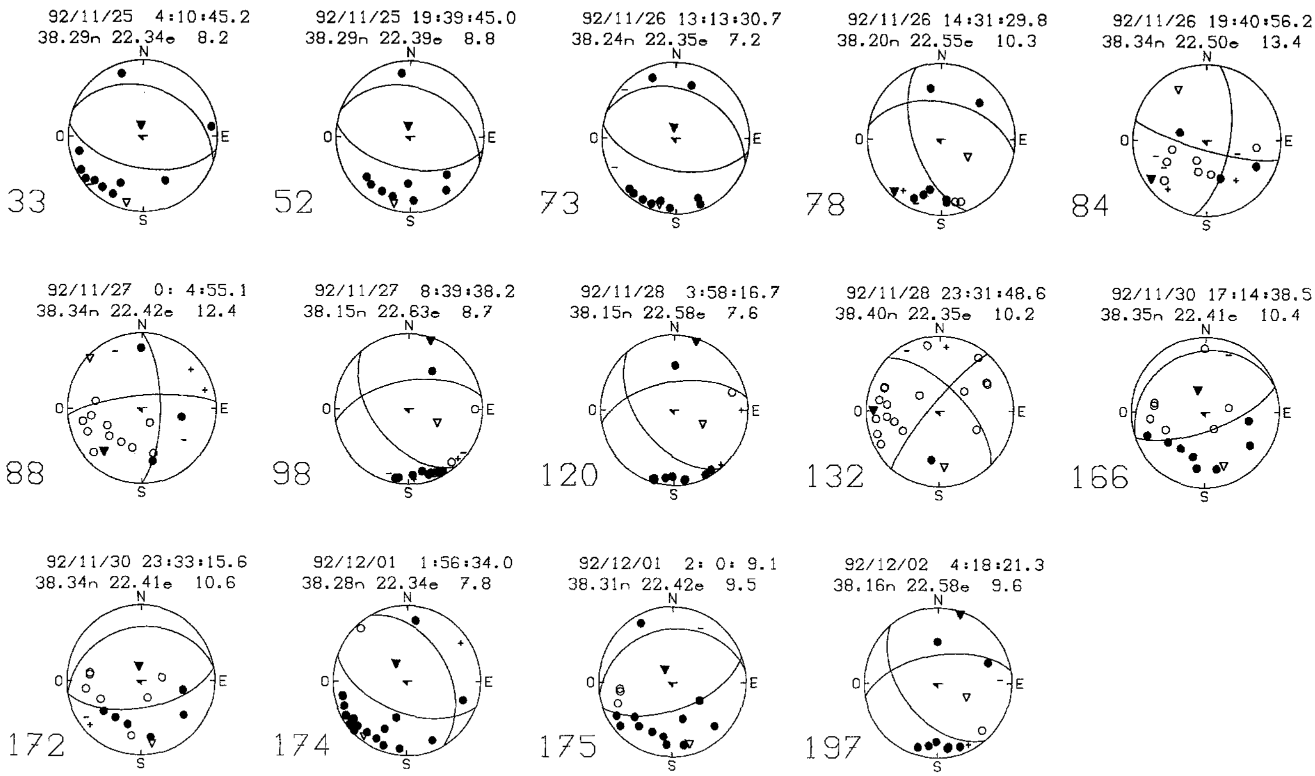

Figure 4. Lower hemisphere of focal sphere. Solid and open symbols are reliable compressional and dilatational first motion: + and − are less certain.

approximately E–W (Fig. 2). At the surface, the two faults are slightly offset by about 5 km, and it is reasonable to think that it is the same at depth (the shape of the fault planes looks similar). This offset behaves as a geometrical barrier (Aki, 1979) whose strength is greater than that of the surrounding faults. This barrier is conservative, in the sense that the slip vector does not change across the barrier.

Because displacement across the Gulf of Corinth is significant (greater than 1 cm/yr), this barrier, which is of small dimension, cannot remain unbroken for a long time and evolves as an asperity (Kanamori, 1981; Scholz, 1990). Moreover, because it is surrounded by "weaker" faults of lower strength (the Helike and Xilokastro faults), when an earthquake breaks the asperity, it does not generate aftershocks.

Conclusion

The Galaxidi earthquake of 18 November 1992 did not produce a "normal" aftershock sequence. On the other hand, the source time function and the scalar seismic moment are usual. The same observation was made also for the Eartini earthquake of 1965 located in the same area. These two events are located at the junction between the two important normal faults of Helike and Xilokastro, which are offset at the surface by about 5 km. We suggest to link these three observations together and propose that the junction between the two faults behaves as a barrier that evolves as an asperity whose strength is different from the two main surrounding faults.

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