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# Seismic slip on a low angle normal fault in the Gulf of Corinth: Evidence from high-resolution cluster analysis of microearthquakes

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**Abstract.** The Gulf of Corinth in Western Greece is one of the most active extensional zones in the Aegean region. It is still an open question whether extension can be actively accommodated on low angle faulting or if those faults as seen in geological records have been rotated. Whilst numerous fault plane solutions obtained from a dense temporary network deployed in the western part of the gulf in July-August of 1991 showed one of the nodal planes as a subhorizontal plane, slip on the high-angle conjugate plane is equally probable from the focal mechanism data (Rigo et al. 1996). Since part of the activity occurred in spatial clusters with similar focal mechanisms, we used a high resolution cluster analysis to determine the most likely active plane. Exploiting the waveform similarity of these events, relative onset times of P and S waves could be determined at subsample accuracy (less than 0.01 s). The cluster analyzed here contains 12 events, among these 8 have a well constrained normal faulting fault plane solution with a shallow (12-20°) north dipping plane and a steeply south dipping plane. A master event relocation shows that the relocated 12 hypocenter centroids are aligned along the low angle plane showing clear evidence for active low angle normal faulting.

## Introduction

The generation of shallow dipping normal faults in regions of extensional stress is a puzzle still waiting to be solved conclusively. Although there is some evidence suggesting the possibility of active seismic slip on subhorizontal planes (e.g. Abers, 1991; Doser, 1987), conclusive seismological evidence is still lacking. Global compilations of fault plane solutions for normal faulting show the vast majority of the nodal planes in the range between 30° - 60° (Jackson, 1987; Jackson and White, 1989). Moreover, based on Coulomb's fracture criterion, normal faulting is mechanically impossible on shallow dipping planes under normal conditions ($\sigma^1$ vertical) (e.g. Jaeger and Cook, 1979; Buck, 1988).

Recently, however, a microseismic study in the Gulf of Corinth revealed a significant number of well constrained normal faulting mechanisms with shallow (10-20°) dipping nodal planes (Rigo, 1994; Rigo et al., 1996). This area is a very active asymmetric graben with quaternary slip rates of the order of 1 cm/yr (Armijo et al., 1996) and a present rate of opening of 1.5 cm/yr from GPS measurements (Briole et al., 1993; Rigo, 1994). The main active faults located at the southern edge of the Gulf strike E-W and dip north at 45-50° (Fig. 1). No clear activity could be associated with the main active faults observed at the surface (Fig. 1). Rather, the events are concentrated in a 2-5 km thick zone at 6-10 km depth. On the basis of microearthquake locations and fault plane solutions Rigo et al. (1996) suggested the existence of an active north dipping low angle detachment fault at a depth of about 10 km. This had already been suggested (King et al., 1985) on the basis of geometrical constraints in the eastern part of the Gulf. However, because of the ambiguity between fault plane and auxiliary plane in the fault plane solution determinations, Rigo et al. (1996) could not rule out that slip occurred on a series of steeply south dipping planes defining an overall shallow north dipping detachment zone.

In this study, we make use of the fact that a considerable part of the seismic activity in the Gulf of Corinth occurred in spatial clusters to demonstrate that a subhorizontal plane was seismically active. We do this by determining high precision relative locations for cluster events which are candidates for shallow dipping normal faults. While the conventional location accuracy (depth resolution less than 1 km) is insufficient to conclusively determine whether some of the events occur on the subhorizontal plane, the relative location accuracy reached for spatially clustered events has been shown in many cases to be sufficient to determine the active fault plane (depth resolution better than 100 m) (e.g. Fremont and Malone, 1987; Deichmann and Gracia-Fernandez, 1992; Got et al., 1994). The main prerequisite for the achievement of this kind of accuracy is sufficient waveform similarity for the individual cluster events. This allows the use of high resolution onset time determination techniques such as cross-spectral or cross-correlation methods (Nakamura, 1978; Poupinet et al., 1984; Ito, 1985; Scherbaum and Wendler, 1986; Deichmann and Gracia-Fernandez, 1992; Maurer and Deichmann, 1996). In general, waveform coherence requires proximity of the sources and similarity of the focal mechanisms and the source time functions. We used the complete waveform dataset from the 1991 seismological experiment to search for earthquake clusters with similar waveforms.

## Cluster detection

For the detection of earthquake clusters we used the method proposed by Maurer and Deichmann (1996). It is based on the evaluation of waveform coherence for all possible combinations of events in a dataset. As a quantitative measure of waveform similarity, the cross-correlation coefficients are computed for time windows containing the P and S

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wave portion of the seismograms. The length of the time window used was 1 s starting 10% before the wave onset time. These values are taken as the elements of a correlation matrix with the row and column indices corresponding to event numbers. This matrix is subsequently analyzed to identify rows with similar row patterns which indicate that the corresponding events show a similar amount of waveform similarity for the same station combinations.

In contrast to Maurer and Deichmann (1996) we did not restrict the analysis to single component records but used all components available. The highest correlation coefficient on either component was taken as a measure of waveform similarity. Only those waveforms which resulted in a correlation coefficient larger than 0.75 where treated as similar. We found that the high correlation coefficients for the S waves could only be found on the horizontal components. In total, we determined about 20 clusters based on waveform similarity. In this work we focus our interest onto one cluster, which corresponds to normal faulting events with one of the nodal planes showing dip angles below 25° (Fig. 1 and Fig. 2). To show the degree of waveform similarity obtained, the vertical component records for all cluster events for stations "kamb" and "anoz" are displayed in Fig. 3.

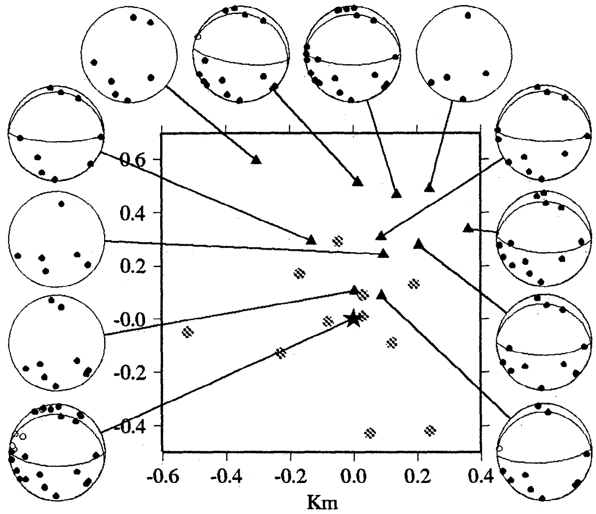


Figure 2. Locations of the cluster events before (circles) and after (triangles) relocation. The star indicates the location of the master event. Magnitudes range from 2.0 and 2.8. Lower hemisphere focal spheres with observed polarities are shown for all events. Well constrained nodal planes are plotted.

## Relocation

Since in the context of the current problem we are not interested in absolute locations, we can use a master event relocation technique, for which the relative location error is considerably reduced. We exploit the waveform similarity to determine the relative onset times at subsample accuracy (less than 0.01 s). This is done by using the phase of the cross-spectrum of the waveforms (Ito, 1985; Scherbaum and Wendler, 1986). In the first step of the analysis, the two phases are aligned by cross-correlation in a small time window (~ 0.2 s) centered around the predetermined onset time. Subsequently, the cross-spectrum is computed with the aligned traces and the relative onset times are determined from the slope of the phase of the cross spectrum by least squares fit. We added two constraints to the determination of the slope. Firstly, the regression line was only calculated for those frequencies for which the coherence of the phases was greater than 0.8 and the normalized cross spectrum amplitude was greater than 0.1. Secondly, we required the regression line to pass through the origin as expected for noise-free coherent signals. The error of the onset time was computed from the error of the slope determination at the highest usable frequency, thus providing an upper limit estimate. In cases where the slope of the phase corresponds to time differences larger than 1 sample (after pre-alignment by the cross correlation) we assumed that the onset time determination obtained from the cross-correlation could not be improved and the timing error was assumed to be 1 sample. This analysis was performed for the P and S wave onsets.

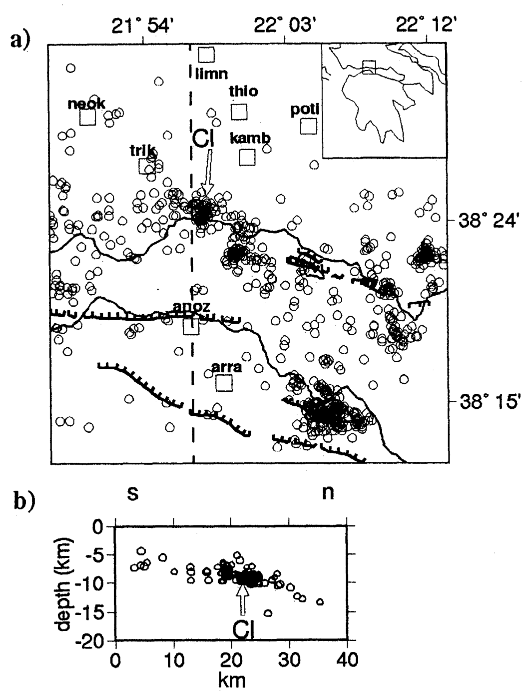


Figure 1. a) Microseismicity recorded during 2 months in 1991 by 55 digital stations (one station every 4-5 km recording at 100 or 200Hz) (Rigo, 1994). Only the stations used in this paper for the relocation are shown. Active normal faults are marked. Cl indicates the location of the studied cluster. The NS dashed line indicates the location of the cross section. b) vertical cross section through the studied cluster.

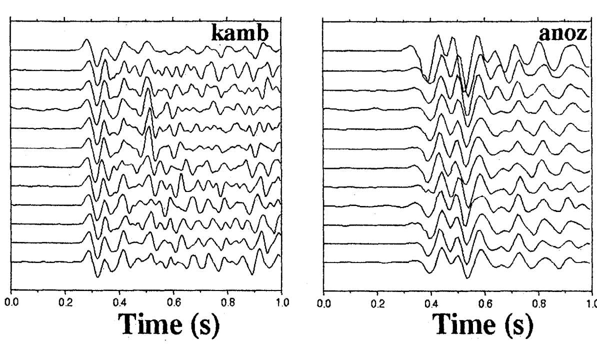


Figure 3. Waveforms of the vertical components recorded at stations "kamb" and "anoz" for the 12 events forming the cluster. The master event is shown at the top.

Relative relocation of the cluster events was performed based on homogeneity of velocity in the cluster region, with the rays for all the events to a particular station leaving the cluster region under the same slowness vector (e.g. Console and Di Giovambattista, 1987). This linearizes the location problem which was solved by singular value decomposition (Press et al. 1992). For the relocation we used 6-11 phase readings for each event (at least 4 P and 2 S wave phase readings). The distribution of the relocated events is shown in Fig. 4. In order to determine the location accuracy, we used a Monte Carlo technique to perturb the onset times and the velocity model, assuming that both are subject to error. It was assumed that the onset time errors follow a Gaussian distribution with the error of the phase slope as standard deviation. Furthermore, it was also assumed that the velocity of the cluster region was 6.0 ± 0.1 km (Rigo et al, 1996). 1000 synthetic data sets were computed in which the relative onset times and the velocity model according to these distributions were perturbed, and a subsequent relocation was performed. For each of the spatial coordinates the range containing 95% of the relocations was determined (95% being taken as the uncertainty measure). The corresponding error bars are shown in Fig. 4. According to this numerical experiment the relocated hypocenters are known within a few tens of meters.

## Determination of the active plane

To determine whether the relocated events are aligned along any of the two nodal planes obtained from the focal mechanisms, two different methods were used.

Firstly the best fitting plane for the final event locations using a least square fit was determined. To investigate the accuracy of the predetermined best fitting plane a Monte Carlo technique was employed. Randomly 1000 event combinations were selected according to the determined location errors. For each of these combinations the best fitting plane was computed and the pole of the plane was plotted in a stereographic projection. The obtained pole distribution is shown in Fig. 5 (gray circles). Superimposed with a black triangle is the pole of the best fitting plane for the final event locations. As one can see the plunge of the plane is determined with an accuracy of 10°. The shortest average distance between all used event combinations to the best fittings plane is about 43 m.

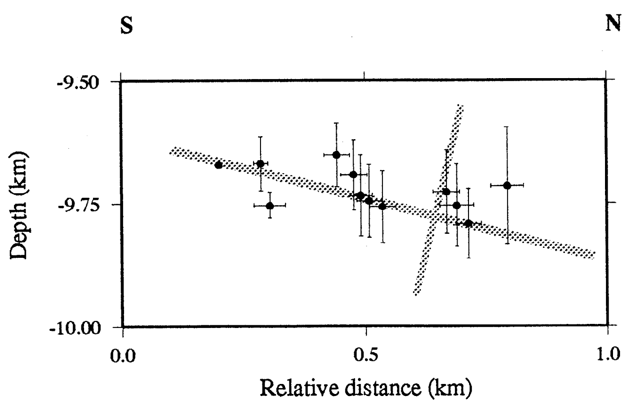


Figure 4. N-S cross section of the relocated events. The 95% error bars computed by the Monte Carlo technique are given for each event. The thick gray lines indicate the two nodal planes from a composite fault plane solution for all events.

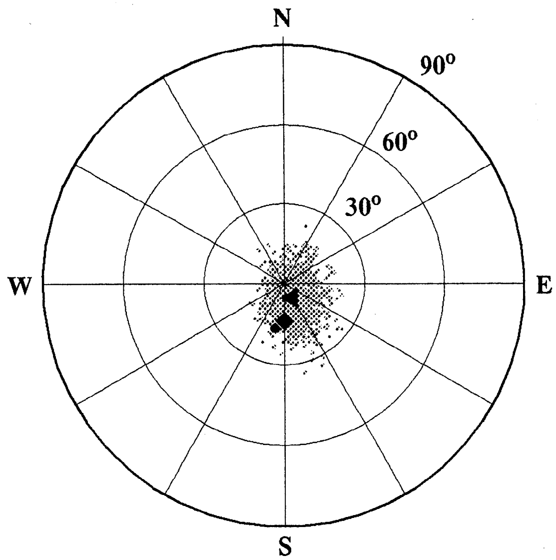


Figure 5. Pole distribution of best fitting planes computed from 1000 randomly selected event combinations according to the determined location errors (gray circles). Superimposed are with a black triangle the pole of best fitting plane for the final location, with a black square the maximum of the pole distribution determined by the three point method (Fehler et al., 1992), and with a black circle the pole of the shallow dipping plane determined from a composite fault plane solution.

As an independent approach, the three-point method proposed by Fehler et al. (1992) was also used to determine internal alignments in spatially distributed point sets. The philosophy behind this approach is that every combination of three points defines a plane which can be assigned a pole. If the poles of all these planes are plotted in a stereographic projection, preferred planes should show up by clustering of poles. The maximum of the pole distribution corresponds to the preferred plane in the cluster distribution and is indicated in Fig. 5 with a black square. Superimposed in Fig. 5 is also the pole of the shallow dipping nodal plane obtained from a composite fault plane solution for all selected events (black circle). All determined poles have a very small plunge and concentrate in an area of 10°.

## Discussion

The analysis presented above demonstrates that the hypocenters of the 12 events studied lie on a plane dipping 10° north. Uncertainties associated with the dip of the north dipping nodal plane in the fault plane solution are due to uncertainties in the assumed velocity structure. Although the mean velocity structure was well constrained by Rigo (1994), incidence angles can vary by about 10° when small perturbations in the velocity model are introduced. We thus estimate the uncertainty on the nodal plane dip to be 15°. The maximum possible dip for the north dipping plane would be less than 30°. Consequently, it cannot completely be ruled out that slip occurs on a series of either 25°-30° north dipping planes or on 60°-80° south dipping planes while the centroids of the 12 events would be aligned on a subhorizontal plane. This however is not likely to have happened: the rupture area of each event is of the order of 100 m by 100 m and there is no reason that all centroids would lie on the same plane. The coincidence of the internal alignment plane of the hypocenters with one of the nodal planes determined for these events is therefore interpreted as a clear example of seismic slip on a subhorizontal normal fault.

Mechanisms causing seismic slip on a low angle normal fault require either very low friction coefficients ($\mu$ of the order of 0.1), or non vertical $\sigma^1$. The latter could be due to stress refraction at interfaces with strong viscosity contrasts (Bradshaw and Zoback, 1988), or to stress perturbation near zones of stress concentration, or high pore pressures close to $\sigma^3$ and confined to the fault zone (Sibson, 1985; Rice, 1992). We do not have enough information at present to favor or reject one or the other of these mechanisms. However we postulate that the microseismicity recorded is restricted to a zone of creep at this depth, where the friction coefficient is likely to be low. Alternatively, fluid pressures may play an important role and independent information is urgently needed in order to choose between the different mechanisms.

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