4.5.3. GPS-RECORDED EARTHQUAKES IN GREECE

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4.5.3.1. Introduction

Since 1990, when the first GPS campaigns were made, several strong (magnitude >6) earthquakes occurred in Greece. However, only three of them are covered by GPS data describing the associated surface deformation. For one of these earthquakes crustal deformation was inferred from a comparison between triangulation data and GPS data, while for the other two, seismic surface deformation was deduced from comparison of homogeneous or non-homogeneous data from successive GPS surveys.

The first earthquake was the 1995 Kozani-Grevena (Northern Greece) earthquake of magnitude 6.6, the second was the 1995 Aigion, Gulf of Corinth (central Greece) earthquake of magnitude 6.2, while the last one was the 1997 Strophades Islands (Ionian Sea) earthquake of magnitude 6.5 (for location see Fig. 4.5.3.1.). A characteristic of all three events is that geodetic data permitted to constrain their focal mechanisms, resolve ambiguities concerning their kinematics and help understanding their structural significance.

Fig. 4.5.3.1. Location map. 1, 2 and 3 correspond to the epicentres of the 1995 Kozani-Grevena, Northern Greece, 1995 Aigion (Gulf of Corinth) and 1997 Strophades Islets (Ionian Sea) earthquakes discussed in the text.

4.5.3.2. The 1995 Kozani-Grevena earthquake

The major importance of the Ms6.6, 13 May 1995 Kozani-Grevena earthquake is that it affected an area in Northern Greece which was assumed earthquake free and, and it was widely regarded as a surprise earthquake. Yet, archeological and historical data revealed that it was the last in a sequence of strong shocks, with recurrence intervals longer than in other parts of the region. For this reason memories of older events tend to faint, the areas gives the impression of an aseismic zone and buildings were unfortunately of limited structural strength and 1995 seismic damage was extensive, though for some reasons the main shocks caused no death toll (Stiros, 1998).

A main problem was this earthquake was that it was not associated with significant surface rupture, and seismological data could not unambiguously describe its mechanism; geodetic data were used to solve this ambiguity.

About 90 triangulation points of the National Geodetic Network covering the wider meizoseismal zone and measured during the period 1984-1986 were occupied by GPS shortly after this earthquake. Coordinates of the triangulation stations, assumed of an accuracy of a few centimeters, transformed to the GGRS87 reference frame, were subsequently compared with those of the GPS network, assumed accurate to 1cm. This permitted to compute surface displacement vectors for about 80 stations (Fig. 4.5.3.2 a), excluding some stations showing large, unexplained near-field or far-field displacements. A subsequent elastic dislocation analysis revealed a possible simple, linear, blind causative fault (Fig. 4.5.3.2 a, b) which helped to constrain the focal mechanism (Clarke et al., 1997). Still, there has been a debate for the modeling of this fault, for based on Synthetic Aperture Radar data a more complicated, shorter seismic fault was computed (Meyer et al., 1996).

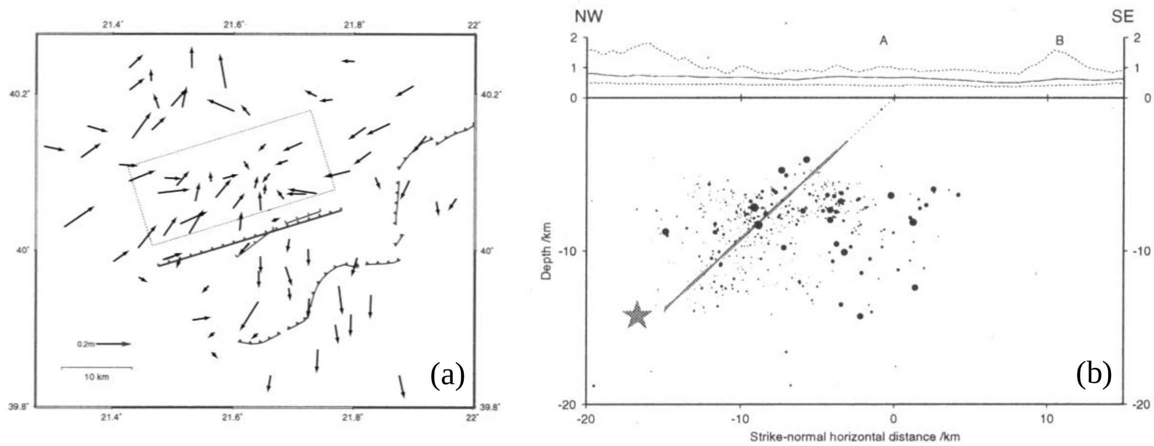

Fig. 4.5.3.2. a: Displacement vectors deduced from a comparison between coordinates of a triangulation and a GPS network, describing surface seismic displacements in the meizoseismal area of the 1995 Kozani-Grevena earthquake. Simplified after Clarke et al. (1997). b: Vertical cross-section plot of earthquakes of the seismic sequence (dots, with diameter proportional to their magnitude; the main shock is shown by a star) and of the calculated normal fault which is deduced to have reactivated during the 1995 seismic sequence. Topography is shown on top. After Clarke et al. (1997).

4.5.3.3. The 1995 Aigion earthquake

The destructive 15 June 1995 Aigion earthquake of magnitude Ms=6.2 in the Gulf of Corinth, was the first earthquake in Greece which occurred in a zone in which a GPS network had already been established and measured in 1991, 1993 and 1994, as well as shortly after the earthquake. The available data, however, were somewhat inhomogeneous, with networks covering mostly different stations in each survey, and corresponding data were processed with different software.

For this reason, the earthquake displacement field was not computed on the basis of a comparison of observed coordinates of different surveys, but inferred from the comparison of observed coordinates of 14 stations just after the earthquake and of their predicted pre-seismic coordinates. The latter were estimated on the basis of the following assumptions: the comparison of the 1991 and 1993 pre-seismic surveys revealed that GPS stations in the southern and northern parts of the Gulf of Corinth seem to testify to rather rigid blocks, with the southern block rather stable and the northern block shifting northwards with a rate of 14mm/yr. Taking account of this rate, corrected coordinates of the stations prior to the earthquake were computed, and their difference from the observed post-seismic coordinates permitted to estimate a seismic dislocation signal, about 10cm opening in the central part of the Gulf (Fig. 4.5.3.3, Bernard et al., 1997).

Elastic dislocation modeling subsequently permitted to estimate a blind, gently (35^{o}) north-dipping normal fault offshore (Fig. 4.5.3.3). Geodetic data did not provide evidence of significant vertical tectonic dislocation, in agreement with field data.

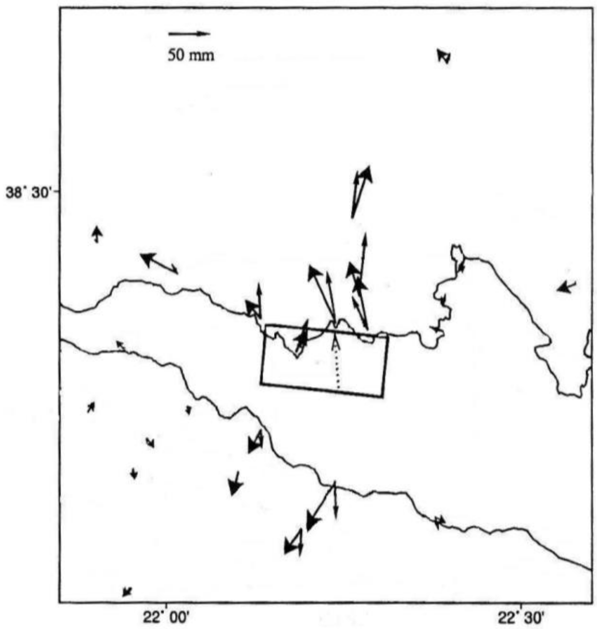

Fig. 4.5.3.3. Estimated displacements of GPS stations during the 1995, Aigion, Gulf of Corinth earthquake. Large and small arrows indicate computed and predicted displacements based on the elastic dislocation analysis. A parallelogram indicates the projection of the inferred seismic fault, and a dashed arrow its slip vector. After Bernard et al. (1997), simplified.

4.5.3.4. 1997 Strophades earthquake

The November 18, 1997, M_w 6.5 earthquake at the occurred in the vicinity of the Strophades Islets, representing a >1000-2000m high active diapir (mostly salt) associated with shortening along the western margin of the Hellenic arc. These islets, indeed, have been regarded as a model for the unusual type of deformation of the nearby (about 100km to the north) 1953 Cephalonia earthquake of magnitude 7.2 (Stiros et al., 1994). This earthquake was therefore especially important for it permitted to record the response of a diaper to an earthquake.

Between 1993 and 1998 a large number of GPS stations in Western Greece had been established and measured during seven repeated campaigns. Each campaign was analyzed separately using the Bernese 4.0 software and IGS orbit data and trajectories were plotted relative to Eurasia. These trajectories indicate that stations along the Ionian Sea front, and especially along the coast of Western Peloponnese, have a rather systematic pattern, with slip vectors trending SW and their amplitude is increasing southward, as if Western Greece coast is rotating clockwise around pole in Albania (Fig. 4.5.3.4, Cocard et al., 1999).

While the trend of slip of all survey stations remained practically constant during all surveys, both as far as their slip orientation and amplitude are concerned (Fig. 4.5.3.4), a main exception was noticed. Between September 1997 and December 1997, the station in Strophades Islets deviated from its longer-term slip trend, approximately 25mm/yr towards SW, and a southward slip of 12cm was recorded (Fig . 4.5.3.4).

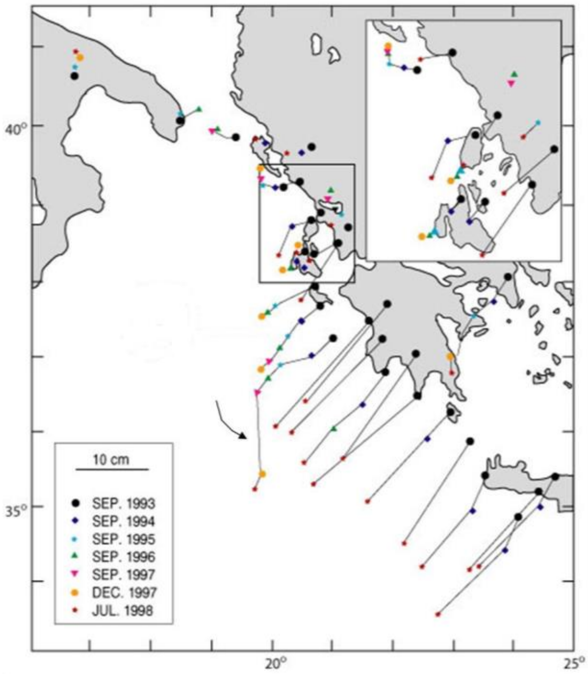

Fig. 4.5.3.4. Trajectories of GPS-derived horizontal slip for the period 1993-1998 relative to Eurasia. Observed displacements are several orders of magnitude higher than the corresponding errors. The deviation of station at Strophades Isles from the trend characterizing all stations, marked by an arrow, is assigned to the 1997 earthquake. After Cocard et al. (1999).

This offset is likely to reflect real displacements and was assigned to the 1997.11.18 Strophades earthquake, the only significant tectonic event which occurred in the area between the October and December 1997 GPS surveys. In addition, there is evidence for about 10cm uplift as well (Stiros, 2005).

A particularity of the 1997 earthquake is that the sense of seismic movement was similar to those before and after the earthquake, in contrast to what is expected in normal earthquakes (Shimazaki, Nakata, 1980). This is due to the fact that the 1997 deformation did not reflect elastic deformation, but rather plastic response of evaporites to crustal shortening of the geologic basement (Stiros, 2005). Therefore the 1997 Strophades earthquake represents a case of unusual earthquake cycle and probably the first known case of geodetically recorded response of a salt dome to an earthquake.

4.5.3.5. Conclusions

The number of earthquakes recorded by GPS in Greece is certainly small, especially given the frequency of earthquakes in this region – only along the Hellenic Arc occur one magnitude 5 earthquake per year and one magnitude 8 earthquake per 60 years (Papazachos, Papazachou, 1997). This is clearly due to the very limited number of permanent GPS stations in Greece. Still, even in these three cases, GPS data permitted to shed much light to mechanism of these earthquakes or the modeling of the seismic surface deformation.

4.5.3.6. Acknowledgements

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4.5.3.7. References

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