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Geodetic Estimate of Seismic Hazard in the Gulf of Korinthos

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Abstract. The recent 15 June 1995, $M_0 = 6.0 \times 10^{18}$ N m, Aigion earthquake in the western Gulf of Korinthos has focussed attention on the seismic hazard of the region. Although there have been few large earthquakes in the region during this century, the historical record suggests that there may have been many large earthquakes there in the interval 1750–1900. We present geodetic data that give estimates of the rate of extension of the Gulf of Korinthos during this century and which suggest that less than half of the elastic strain in the central and western Gulf of Korinthos has been released by earthquakes during this century. In contrast, the seismic and geodetic strains in the eastern Gulf of Korinthos are in agreement with each other. If the discrepancy between seismic and geodetic strains in the western Gulf of Korinthos that has accumulated during this century is removed in earthquakes, the moment release will be equivalent to several M_S>6.5 earthquakes.

Introduction

In the past, most seismic hazard assessments have had to rely on the record of seismicity in the region of interest. This record is patchy before the establishment of the WWSSN in the 1960s, and is extremely unreliable before the beginning of this century, except in a few places where record-keeping was exceptionally fine. In consequence, all such seismic hazard assessments run the risk of underestimating the long-term rate of earthquake activity and, because the interval between successive earthquakes on the same fault frequently exceeds a hundred years, seismic quiescence during this century is not a reliable indicator of future inactivity.

For this reason, the measurement of the accumulation of strain over a region ought to form a central part of seismic hazard assessment, but such measurements have only become widespread with the recent development of GPS. Greece is unusual in having both a reliable record of seismic activity over this century [*Ambraseys and Jackson*, 1990, 1997] and a reliable first-order triangulation network from the 1890s, which has been re-occupied by GPS [*Billiris et al.*, 1991; *Davies et al.*, 1997]. This means that Greece is one of the few regions where it is possible to relate, on the hundred-year time-scale, earthquake activity to the accumulated crustal strain. The Gulf of Korinthos is the most densely studied part of Greece, both seismically and geodetically. Comparison of geodetic and seismic strain reveals that elastic strain has accumulated in the western Gulf that has not been released by earthquakes in the last 100 years.

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Observations

Our geodetic estimates of the extension rate in the Gulf of Korinthos come from two sources. The first set of estimates is based upon strain measurements derived from the reoccupation, using GPS, of a 19^{th}-century first-order triangulation network [*Billiris et al.*, 1991; *Davies et al.*, 1997] (Figure 1). The second set comes from repeated occupations, with GPS, of a modern network established round the Gulf of Korinthos in 1988 [*Denys et al.*, 1995].

Figure 1 shows the relative motions across of monuments of the 1890s network that border the Gulf of Korinthos, and the principal strains derived from those motions for triangular regions spanning the Gulf.

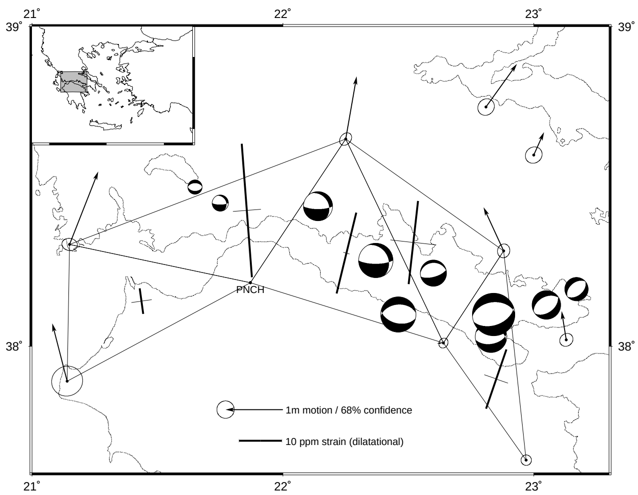

Figure 1. Relative motions of monuments surrounding the Gulf of Korinthos that form part of the 1890s triangulation network [*Davies et al.*, 1997]; motions are shown relative to the triangulation pillar on Panachaikon (PNCH). Cross symbols show the principal horizontal strains over triangles with vertices at these pillars; thick lines are extensional strain, with scale give by bar below. Focal mechanisms are for earthquakes during this century having $M_S \geq 5.8$, for which the catalogue is believed to be complete [*Ambraseys and Jackson*, 1990]. Centres of symbols are on the epicentres of the earthquakes; symbol area is proportional to scalar moment M_0. Inset shows location of plot.

The maximum extensional strains are all approximately along 020°, perpendicular to the strike of the Gulf and in agreement with the strain shown in the focal mechanisms of earthquakes [*Ambraseys and Jackson*, 1990]. Displacements have been computed [*Davies et al.*, 1997] by fixing a north-south baseline in the Peloponnisos to constant length, and adopting an orientation constraint based on the GPS-determined velocity field of *Kastens et al.* [1997]. The latter also allows confirmation of scale control. Within our reference frame, all sites on the southern coast of the Gulf of Korinthos (east of 21.5°E) exhibit negligible motion, whereas sites to the north of the Gulf show northward motion. We calculate the rate of opening of the Gulf by taking the component of each site displacement along 020°, and dividing the result by the interval (100 years) between the original triangulation (1890–1894) and its re-occupation in 1992. The rate of opening calculated from these observations varies from 11 mm yr^{-1} in the west of the Gulf to 4 mm yr^{-1} in the east (Figure 3).

These hundred-year estimates of extension rates refer to a network that extends several tens of kilometres to the north and south of the Gulf (Figure 1), and it is not clear from these measurements what fraction of the strain may have accumulated in the regions outside the Gulf itself. For this reason we make a second estimate of the rate of extension across the Gulf from the modern network, which includes sites very close to the coasts of the Gulf. This network as a whole was occupied in 1991 and 1993; monuments used in this study were also occupied in late June and/or October 1995, and in May 1996. All campaigns were carried out entirely with dual-frequency receivers, and processed using version 3.4 of the Bernese GPS processing software [*Rothacher et al.*, 1993]. Coordinate repeatability generally improves in precision at successive epochs, reflecting the improved satellite configuration and longer occupation times, and averages 7 mm.

Temporally-uniform site velocities are calculated by applying whole-network translations at each epoch, such that the deviation of each site's epoch-to-epoch displacement from that due to constant velocity over the interval 1991 – 1996 is minimised, in a least-squares sense. During the translation estimation, the velocities of the northern Peloponnisos sites are constrained to be zero. The fit of baseline length changes (Figure 2) shows that the relative GPS positions at each epoch change smoothly and so the data are compatible with this treatment. Coordinates obtained after 15 June 1995 have had a correction applied to remove the elastic co-seismic effects of the Aigion earthquake after the model of *Bernard et al.* [1997]; this only has significant effect on three sites.

Extension rates are calculated as the velocity component along 020°, as before. Despite the short timespan, the modern network shows extension rates across

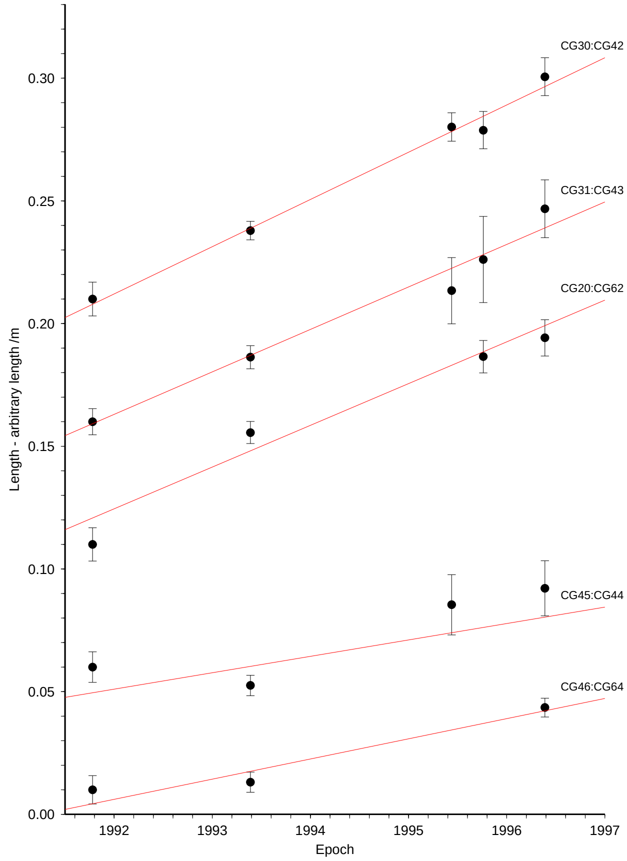

Figure 2. Baseline (geodesic) length changes between Central Greece Network sites around the Gulf of Korinthos, 1991 – 1996. Error bars are $\pm 1\sigma$. The best weighted linear fit to each set of baseline length observations is also shown.

the Gulf of Korinthos that are in remarkable agreement with the hundred-year estimates (Figure 3). This result is important in showing that short-term (a few years) measurements of strain may be representative of crustal strain over a period that is comparable with the repeat time of earthquakes.

The rates do not depend on whether sites are located close to the coast, or well to the north, so we conclude that the deformation is predominantly localised within the Gulf. We divide the Gulf into two sections on the basis of our geodetic measurements. Between 21.9°E and 22.5°E, the rate of opening is defined by nine measurements averaging 12.7 mm yr^{-1}. The rate of opening in the eastern Gulf of Korinthos, between 22.5°E and 23.1°E, is defined by eight measurements of baseline length changes averaging 6.4 mm yr^{-1}.

Comparison between geodetic and seismic strains

We use the moment tensor – strain tensor relationship of *Kostrov* [1974] to express the seismicity over the last century in the eastern and western Gulf of Korinthos in terms of the equivalent rate of extension. We divide the Gulf into two sections along its length as above, the length along strike of each section being 56 km. The vertical dimension of the region is given by the thickness of the seismogenic layer. All large crustal earthquakes in the region nucleated in the upper 10 – 15 km of the crust [*Taymaz et al.*, 1991], so we take values of 10 km and 15 km for this quantity.

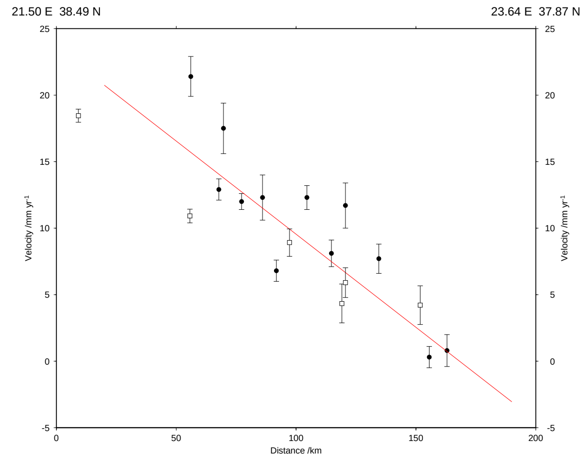

Figure 3. Rate of opening of the Gulf of Korinthos as a function of eastward distance along its length. Filled circles show measurements over the period 1991–1995, and open squares show measurements over the period 1892–1992. Error bars are $\pm 1\sigma$.

The shallow earthquakes of $M_S \geq 5.8$ that have occurred in the Gulf of Korinthos during this century are listed in *Ambraseys and Jackson* [1997]; this catalogue is thought to be complete, and the focal mechanisms of all earthquakes since 1970 have been constrained by waveform modelling [*Ambraseys and Jackson*, 1990; *Taymaz et al.*, 1991; *Jackson et al.*, 1992]. For earthquakes earlier than this time, the moments are less well determined, because of uncertainties in converting to M_0 from the $M_S$deduced from felt intensities. We have calculated scalar moments both from the local relation between M_0 and M_S[*Ekström and Dziewonski*, 1988], and from the global relation, which almost certainly overestimates the moments of earthquakes of this region [*Ekström and England*, 1989; *Jackson and McKenzie*, 1988a; *Ambraseys and Jackson*, 1990]. The differences between the two estimates of M_0 is always less than 30%. Even for the events constrained by waveform modelling, there is uncertainty in the moments. In order to estimate the maximum moment release for the earthquakes in the Gulf during this century, we use M_0 calculated from the global relation, for earthquakes before 1970; following *Ambraseys and Jackson* [1990], we allot a further 40% uncertainty to the moments of all earthquakes.

With these assumptions, the seismic estimates of rates of extension are 3±1 mm yr^{-1} across the western Gulf of Korinthos (Table 1), and 4±1 mm yr^{-1} in the east, for a 15 km thick seismogenic layer. These rates should be compared with the actual measured rates of 13±1 mm yr^{-1} in the west, and 6±1 mm yr^{-1} in the east. The rate of extension across the Xylokastro Fault (38.1°N, 22.5°E) is estimated to lie between 7 and 16 mm yr^{-1} [*Armijo et al.*, 1996].

Implications for seismic hazard

The total moment release by earthquakes of $M_S \geq 5.8$ during this century in the Gulf of Korinthos is $42 \pm 16 \times 10^{18}$ N m, if the global estimates of scalar moment are assumed, or $37 \pm 15 \times 10^{18}$ N m, if the local estimates are used (Table 1). Geodetic measurements show that the Gulf is opening at an average rate of 13 mm yr^{-1} in the west and 6 mm yr^{-1} in the east (Figure 3). If all this strain had been released in earthquakes during this century, then the moment release would have been between 70 and 100×10^{18} N m. In the eastern Gulf of Korinthos the seismic moment release during this century matches, to within observational uncertainties, the rate that would be expected from the geodetic strain. The principal discrepancy between geodetic and seismic strain is in the Gulf west of 22.5°E. In this region, the cumulative seismic moment for this century is at most 50% of the moment expected from the observed rate of opening, and may be as low as 20% of that figure (Table 1).

We cannot be certain that all the deficit will be expressed in earthquakes. Aseismic strain is well documented in other parts of the Mediterranean region [*Jackson and McKenzie*, 1988b]. However, the observation that the seismic and geodetic strains in the eastern Gulf of Korinthos are in agreement suggests that it would be wise to estimate the seismic hazard in the central and western Gulf of Korinthos by determining the amount of seismic activity that would be required to remove completely the discrepancy between geodetic and seismic strain. The deficit in seismic moment (Table 1) could be as high as 50×10^{18} N m: equivalent to five earthquakes of the magnitude of the 24 Feb 1981 M_S=6.9 earthquake, which is the largest earthquake of the region this century. When the lowest estimate of geodetic strain is compared with the highest estimate of seismic strain, we still find that the discrepancy is about 20×10^{18} N m.

The strain need not be released in large earthquakes, but could be released by many small earthquakes. For the regional moment – frequency distribution, events of $M_S \leq 5.8$ may add an extra 85% to the seismic extension rates [*J. Haines, pers. comm.*, 1997]. In this case, seismic strain release marginally outpaces geodetic strain accumulation in the eastern Gulf, but a deficit remains in the west. There have, however, been three earthquakes of moment greater than 5×10^{18} N m in the region during this century, and the historical record indicates that $M_S \geq 6.0$ earthquakes are common in this part of the Gulf, and may have been more frequent in earlier centuries than they have been in this one [*Papazachos and Papazachos*, 1989; *Mouyaris et al.*, 1992; *Ambraseys and Jackson*, 1997]. It would be prudent to assume that large earthquakes may occur in the western Gulf of Korinthos in the medium term.

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References

Ambraseys, N., and J. Jackson, Seismicity and associated strain of central Greece between 1890 and 1988, *Geophys. J. Int.*, *101*, 663–708, 1990.

Ambraseys, N., and J. Jackson, Seismicity and strain in central Greece since 1694, *J. Earthquake Engineering, in press*, 1997.

Armijo, R., B. Meyer, G. King, A. Rigo, and D. Papanastassiou, Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean, *Geophys. J. Int.*, *126*, 11–53, 1996.

Bernard, P., et al., The $M_s = 6.2$, June 15, 1995 Aigion earthquake (Greece): Results of a multidisciplinary study, *J. Seismol., in press*, 1997.

Billiris, H., et al., Geodetic determination of tectonic deformation in central Greece from 1900 to 1988, *Nature*, *350*, 124–129, 1991.

Davies, R., P. England, B. Parsons, H. Billiris, D. Paradissis, and G. Veis, Geodetic strain of Greece in the interval 1892–1992, *J. Geophys. Res., in press*, 1997.

Denys, P., et al., GPS networks for determining the accumulation of current crustal strain in Central Greece, in *Proc. of the 1st International Symposium on Deformations in Turkey*, pp. 748–758, Ankara, TMMOB–HKMO, 1995.

Table 1. Comparison between seismic and geodetic extension rates for regions west and east of 22.5°E.

	ΣM_0 [a]	ΣM_0 [b]	$\Sigma M_0^{\max}$ [c]	M_e [d]	u_{15} [e]	u_{10} [e]	u_g [f]	M_g [g]
West	15	18	25	16±6	3±1.2	4.5±1.8	12.7±1.0	70 (47)
East	22	24	29	21±8	4±1.6	6.0±2.4	6.4±1.0	35 (24)

[a] Summed scalar moment release according to local M_s–M_0 relationship.
[b] Summed scalar moment release according to global M_s–M_0 relationship.
[c] Maximum scalar moment release calculated by adding 40% to moment release calculated from global relation.
[d] Extensional eigenvalue of tensor formed by summing moment tensors of earthquakes. Uncertainty represents 40% of M_e (see text).
[e] Extension rates calculated from M_e, with 15 km and 10 km-thick seismogenic layers respectively.
[f] Measured geodetic extension rate (averaged from Figure 3).
[g] Summed moment release during this century expected if all measured extension rate had been released in earthquakes, for 15 km and 10 km (in parentheses) seismogenic layer thickness.

All moments are in units of 10^{18} N m.

Ekström, G., and A. Dziewonski, Evidence of bias in the estimation of earthquake size, *Nature*, *332*, 319–323, 1988.

Ekström, G., and P. England, Seismic strain rates in regions of distributed deformation, *J. Geophys. Res.*, *94*(B8), 10,231–10,257, 1989.

Jackson, J., and D. McKenzie, Rates of active deformation in the Aegean Sea and surrounding regions, *Basin Research*, *1*, 121–128, 1988a.

Jackson, J., and D. McKenzie, The relationship between plate motions and seismic moment tensors and the rate of active deformation in the Mediterranean and Middle East, *Geophys. J. R. Astron. Soc.*, *93*, 45–73, 1988b.

Jackson, J., J. Haines, and W. Holt, The horizontal velocity field in the deforming Aegean Sea region determined from the moment tensors of earthquakes, *J. Geophys. Res.*, *97*(B12), 17,657–17,684, 1992.

Kastens, K., L. Gilbert, K. Hurst, G. Veis, D. Paradissis, H. Billiris, W. Schlö, and H. Seeger, GPS evidence for arc-parallel extension along the Hellenic Arc, Greece, *Tectonophys., in press*, 1997.

Kostrov, B., Seismic moment and energy of earthquakes, and seismic flow of rock, *Izv. Acad. Sci. USSR Phys. Solid Earth*, *97*, 23–44, 1974.

Mouyaris, N., D. Papastamatiou, and C. Vita-Finzi, The Helice fault?, *Terra Nova*, *4*, 124–129, 1992.

Papazachos, B., and C. Papazachos, *The Earthquakes of Greece*, Ziti Publications, Thessaloniki, 1989, (In Greek).

Rothacher, M., G. Beutler, W. Gurtner, E. Brockmann, and L. Mervart, *Bernese GPS Software Version 3.4 Documentation*, Astronomical Institute, University of Berne, 1993.

Taymaz, T., J. Jackson, and D. McKenzie, Active tectonics of the north and central Aegean Sea, *Geophys. J. Int.*, *106*, 433–490, 1991.

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