PREDICTIVE PATTERNS ASSOCIATED WITH THE 1981 EARTHQUAKES IN CENTRAL GREECE

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SUMMARY

Detailed studies in an area of active faulting have revealed a wide range of recognition criteria for active tectonism on both long and short term bases. Although many of the large scale indicators of major tectonic activity are easily recognized, many smaller scale, more subtle observations and measurements allowed the identification of the effects of individual seismic events in the relatively recent past. The results of such studies reinforce the need to study all aspects of major earthquakes, in order to more properly assess seismic risk in areas of limited historical seismic data.

INTRODUCTION

Three earthquakes ranging from Ms 6.2 to 6.7 occurred in the eastern Gulf of Corinth in February and March of 1981 (Figure 1). The earthquakes and associated aftershocks caused widespread damage, generated over 25 kilometers of surface rupture, and were responsible for substantial coastal subsidence, ground deformation, liquefaction, and slope failure. The region provides an important study area for the identification of predictive patterns for major earthquakes. Predictive patterns identified in the Gulf of Corinth region can be divided into three categories: long term geological and morphological indicators, resulting from tens of thousands to millions of years of activity; shorter term patterns based on geological, morphological, biological, archeological, and seismic data reflecting activity in the past tens to thousands of years; and very short term precursory patterns based on transient ground deformation and biological precursors. This paper outlines many of the recognition criteria and predictive patterns identified during almost 6 months of intensive field investigations following the major shocks (Ref.1).

GEOLOGIC AND TECTONIC SETTING

The Gulf of Corinth occupies an east-west trending zone of crustal extension and rifting that has been seismically active throughout historic time. The morphology of the Gulf suggests asymmetric rifting, with a sharp, active southern boundary, and a more subdued, relatively stable northern boundary. The long term sinking of the central graben that forms the Gulf of

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Figure 1. Area of the 1981 earthquakes in the eastern Gulf of Corinth. Stars indicate locations and dates of the three main shocks. Ground ruptures are shown with hachures on the downthrown side. Dashed lines indicate prominent linear features identified as faults. Fence symbol along southern coast indicates area of up to 1 meter of subsidence during the 1981 events.

Figure 2. Landsat imagery of the same area as Figure (1).
Corinth is accompanied by uplift of the mountains along the southern boundary. This paired motion results in spectacular fault scarps along the southern shore of the Gulf, with relief measured in hundreds of meters from water bottom to the top of the mountains.

The extent of rift development varies along the length of the Gulf. The central and western part is the most mature zone, as indicated by the depth of water, sharpness of the southern faulted boundary, and the overall width. The eastern end is the least mature and most poorly developed part of the rift zone. It is in this area that the 1981 earthquakes occurred, in response to continued development of the rift and its extension eastward onto mainland Greece.

The geology of the eastern Gulf area is dominated by the intercalation of huge bodies of massive limestone in a pervasive, hydrothermally altered suite of extrusive igneous rocks, tentatively identified as altered sea-floor basalts. The massive limestones are presently cliff-formers in the semi-arid climate of central Greece, while the altered igneous rocks are easily eroded and form subdued topography, at least in areas where they are not undergoing rapid uplift. The limestones and altered igneous rocks are locally overlain by Neogene sedimentary rocks, generally representing marine terrace or valley fill deposits. The units are typically poorly consolidated siltstones, sandstones and conglomerates, and provide excellent marker horizons for the identification of faulting, tilting, and uplift.

LONG TERM INDICATORS OF TECTONIC ACTIVITY

Recognition criteria for long term, active tectonics are provided by morphological and geological data from around the entire Gulf of Corinth. As discussed above, the southern shore of the Gulf is fault bounded against a high range of mountains. Long term uplift of these mountains is indicated by extensive "badlands" type erosion of uplifted, poorly consolidated Neogene sediments. Marine terraces are found high in the mountains, and many of the young sedimentary units are tilted. In several areas stream courses have been diverted or abandoned as uplift and tilting reversed their gradients. In other areas, steep-walled canyons suggest long term changes in the base level of erosion.

Much of the southern coastline of the Gulf of Corinth is characterized by seaciffs with small, insignificant coves and beaches. Deep water also occurs immediately offshore in many areas. Such features are typical of emergent coastlines, and suggest that rates of fault movement equal or exceed rates of sedimentation, despite the rapid inflow of large volumes of material from the eroding mountains and uplifted Neogene sediments.

Landsat imagery of the area of the 1981 shocks is presented as Figure (2). The imagery of the area clearly shows the linear, east-west alignment of many of the ridges, valleys, and segments of the coastline. Field work revealed a number of east-west trending fault scarps corresponding with many
of the prominent linear features. The correspondence of the observed linear features to identified fault lines reinforces the value of remotely-sensed data in the identification of areas of long term, major tectonic activity.

SHORTER TERM INDICATORS OF TECTONIC ACTIVITY

In addition to the striking large scale morphological and geological features in the Gulf of Corinth area indicative of long term tectonic instability, a series of smaller scale, more subtle features suggest activity in the more recent past, on the order of tens to thousands of years. These indicators include geological, morphological, biological, and archeological data, as well as historical and instrumental seismic records.

Although the coastal areas near the southern rupture traces are actively subsiding (Figure 1), the Gerania Mountains immediately to the south have many of the geological and morphological characteristics indicative of rapid uplift. Evidence of recurrent tectonic activity is provided by study of the morphological and geological characteristics of the many alluvial fans developed from these rapidly eroding highlands. Many of the fans are oversteepened (9-10°), and consist of poorly sorted mixtures of angular boulder through silt-sized material. The internal texture of these fans is suggestive of catastrophic debris flows rather than steady erosion, reworking, and deposition. In addition, the source areas of the fan debris are remarkably limited in relation to the size of the fans. These combined observations suggest continued uplift, maintaining steep stream gradients and high erosional rates.

One of these fans, east the town of Schinos, is shown on Figure (3), as viewed looking east along the southern rupture trace. The rupture trace crosses this fan about two-thirds the way up the slope. Vertical offsets ranged from just a few centimeters to over a meter, with the lower part of the fan downdropped. Field work revealed that displacement during the 1981 earthquakes followed pre-existing fault scarps preserved on the older, vegetated parts of the fan. The highest of these scarps was nearly 5 meters high, and occurred on the part of the fan with the oldest, most mature tree growth. The observed relationship of the age of vegetation to the height of the scarps suggests re-use of the same scarps by each new rupture event, so that the age of the vegetation is indicative of the age of the earliest preserved movement.
Slope failures, including landslides and rockfalls, are common throughout the area. New failures associated with the 1981 events occurred in many of the same areas as older failures, suggesting earthquake mechanisms for the older failures as well. In many areas, huge limestone blocks shaken loose from the high cliffs rolled down the mountains, cutting wide swaths through the heavily forested slopes (Figure 4). Evidence of similar events in the relatively recent past was provided by the identification of older, boulder-cut swaths through the forests, noticeable because of different and/or clearly younger re-vegetation.

Within most of both the southern and northern rupture zones, the 1981 rupture traces re-occupied existing fault scars, as indicated by smooth, steep limestone faces or as remnant scars in soil materials. Limestone fault faces along the southern rupture zone typically dipped 45 to 60 degrees to the north, while limestone faces on the northern ruptures were near vertical. Figure (5) shows a typical rupture along the northern traces. Offset of over one meter occurred along a vertical limestone face at its boundary with valley fill soils. The face extends several meters above the photograph and was several kilometers long. In a few areas, weathering differences on these limestone faces above and parallel to the present soil horizon indicated remnant soil lines. The width of these zones suggest earlier offsets of similar magnitudes as the 1981 ruptures. Although dating of the old soil lines was not possible, their preservation suggests offsets in the relatively recent past.

Archeological remains also provide important evidence for young tectonic activity. Remains of Roman baths have been found 10 meters offshore of the southern coast near Schinos at a depth of 1.3 meters, suggesting several meters of subsidence in the past 2000 years or so. Since subsidence in this area was associated with the 1981 events, it appears likely that the previous subsidence was associated with earlier events.
In addition to these varied indicators of previous activity, the history of the eastern Gulf of Corinth region is rich with reports of large earthquakes accompanied by widespread damage, subsidence, rockfalls, slope failures, tsunami, and ground fissures. Major earthquakes occurred in 375 B.C., A.D. 77, A.D. 551, 1641, four times in the 1800's, and four times between 1914 and 1954 (Ref 2). Repeat times on this order of magnitude do not seem inconsistent with the vegetative evidence from the alluvial fans and boulder swaths, and the preservation of old soil lines on limestone fault scarps, even given that surface rupture may not occur at the same place during each event.

SHORT TERM PREDICTIVE PATTERNS

Precise leveling surveys, strain gauge installations, tiltmeter surveys, and a tide gauging station were all used in the area of the 1981 events to provide data on transient and permanent ground deformation.

![Diagram of Gulf of Corinth with tiltmeter stations labeled](image)

Figure 6. Location of tiltmeter stations. Labeled stations are referred to in text.

A series of 13 tiltmeter stations were deployed along and on either side of the main northern and southern rupture traces about 25 days after the first major shock (Figure 6). The stations were occupied approximately once a week for 120 days following installation. Readings during the first 30 days documented continued re-adjustment of the ground surface following the main shocks. Movements at most stations were relatively large, and in no consistent directions. The next 30 day period was marked by relative quiescence at virtually all the stations, with little net movement. Starting at about the 60th day, however, most tiltmeters began a systematic and consistent increase in movement in directions suggestive of inflation of the central rift. This movement continued until about the 90th day, followed at most stations by a return to relative quiescence. The exceptions occurred in the area of the southern ruptures, where three tiltmeters all reversed their direction of tilt on or about the 90th day. By the 120th day, most tilt stations had stabilized. Readings taken almost a year later indicated no appreciable additional movement.

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Figure (7) shows the magnitude of tilt at the three southern stations mentioned above for the period of study. The Strain Meter station was near the coast and was found to be sensitive to the daily ocean tides. Corrected tilt curves for low tide and mean tide readings are shown on the Figure.

Figure 7. Correlation of tilt at three southern stations with aftershocks greater than magnitude 4.0. Note the differences in scale for the three plots. Day 0 is March 20, 1981. Earthquake data is from the National Observatory of Athens Seismological Institute.

Note that the Monastery station was originally chosen as the control station away from the ground ruptures. Compared to all the other tilt stations, this point had little movement. However, when plotted at an expanded scale, the similarities to stations with large movements is remarkable.
Figure (7) also shows the time of occurrence of all earthquakes larger than magnitude 4.0 during the period. The data from the Monastery and Strain Meter stations may reflect ground deformation preceding the Ml 4.4 earthquake on day 50, but the data are not well constrained. The effects of the tectonic events prior to and following the 88th and 89th day earthquakes, however, are consistent at all three stations. The change from quiescence between 30 and 60 days to accelerated tilt after the 60 day mark certainly suggests tectonic strain. The tilt culminates at the time of these two earthquakes, when all three tiltmeters reverse their previous trend.

It must be noted that the actual shape of the tilt curves immediately prior to and following these two earthquakes is not known, due to the relatively wide sampling interval. It is very probable that rapidly increasing tilt occurred in the few days and hours immediately preceding the earthquakes, and a closer sampling interval and timely data reduction may well have allowed actual prediction of the events.

Numerous biological precursors were noted prior to the main shocks and major aftershocks. In the epicentral area, incidences of extreme distress of domesticated animals and birds were reported starting several days before the main shocks, and for several weeks during the period of major aftershocks.

CONCLUSIONS

Detailed studies in an area of active rifting documented numerous effects of both long and short term tectonic activity. Recognition criteria and predictive patterns were identified that reflect long term tectonic instability, as well as the effects of individual major earthquakes. Patterns were developed using data from varied disciplines, including geology, geomorphology, archeology, biology, and seismology. The results of these studies reinforce the need to study all aspects of major earthquakes, in order to better recognize and evaluate seismic risk in areas of limited historical seismic data.

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REFERENCES
