Imaging Near-surface Tectonic Structures Using GPR: Western Eliki Fault, Gulf of Corinth, Greece

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Abstract - We present ground-penetrating radar data from the footwall region of the Western Eliki Fault, a normal fault on the southern shores of the Gulf of Corinth, Greece. The fault bounds the southern edge of the Eliki Plain, the site of repeated destructive earthquakes, most notably in 373 BC, 1861 AD and 1995 AD. A number of linear scarps, suggestive of recent tectonic disturbance, were identified from aerial photographs cutting an alluvial fan apron, the Nikolaiika Fan, at the eastern end of the Western Eliki Fault. In the field, the Nikolaiika Fan scarps are 0.5-1.0 m high morphological steps. These steps generally coincide with, and are indistinguishable from, the risers of agricultural terraces. To assess the likelihood of a tectonic origin, GPR common offset surveys were collected on three roads crossing the fan surface and running perpendicular to the scarps. Surveys were conducted using a pulseEKKO 100 with 50, 100 and 200 MHz antennae. GPR profiles reveal offset reflections, possible warping of reflections between offsets and regions of scattering beneath suspected fault zones, indicating that a number of surficial scarps are the surface expressions of faulting. Offsets are visible throughout the GPR profiles in sediments deposited in the last few thousand years, confirming late Holocene activity on the Western Eliki Fault. The profiles indicate that fault activity may not be confined to the main escarpment footwall, suggesting activity in the uppermost hanging-wall sediments.

Keywords – Eliki, Gulf of Corinth, earthquakes, faults.

I. INTRODUCTION

Recent ground-penetrating radar (GPR) investigations have proven effective in palaeoseismic studies, both in terms of mapping concealed faults offsetting recent sedimentary infill and identifying buried sedimentary expressions of past seismic activity [1,2,3]. GPR is most commonly used to locate fault traces and establish a 3-D picture of the surficial fault geometry prior to palaeoseismic trenching [4]. The subsequent fault trenches then provide cut-faces for comparison with and calibration of the GPR data as well as directly revealing fault relations in near-surface stratigraphy. Occasionally, GPR profiles can image buried faults sufficiently well to resolve their near-surface geometries and estimate palaeoseismic fault displacements [3,5]. Alternatively, the profiles may record only the sedimentary responses to fault activity: sand wedges injected into sediments along fault planes [3]; colluvial wedges formed by burial of a surface fault scarp; or seismically-induced liquefaction phenomena [6].

II. FIELDSITE

The western region of the Gulf of Corinth, Greece is one of the most earthquake-prone zones in Europe [7]. Two of the active normal faults that border the western gulf’s southern shores have ruptured in recent historical earthquakes; the Eliki Fault in 1861 and the Aegion Fault in 1995 [8]. The Eliki Fault comprises two independent fault segments, the Eastern and Western Eliki Faults [9] (Figure 1). The recent rupture history of the Eastern Eliki Fault is reasonably well constrained. Radiometric dating of raised shoreline features along the Eastern Eliki Fault suggest that the coastline experienced two, meter-scale uplift events [10], attributed to the 373 BC earthquake [11], the most violent seismic event in Greek history that destroyed the ancient city of Helike, and to a previously unknown earthquake during the interval 440 - 870 AD recently confirmed by paleoseismology [12].

Figure 1: The southwestern shore of the Gulf of Corinth, Greece, showing the traces of the western and eastern Eliki Fault segments, WEF and EEF, respectively. Only the EEF ruptured in the 1861 earthquake. The GPR surveys were conducted on the Nikolaiika Fan (NF), in the immediate hanging-wall of the eastern end of the WEF. The Helike archaeological site is located at the base of the Kartourla Fan (KF).

GPR has been used to identify potential sites for palaeoseismic trenches along the Eastern Eliki Fault [13, 14]. The
GPR profiles showed the position of the basement fault scarp, highlighted the presence of multiple fault strands and confirmed the presence of recent sediments in the footwall of the fault. The profiles also revealed a prominent liquefaction feature (sand blow) thought to have been formed during an earthquake in 1861.

Nothing comparable is known about the rupture history of the Western Eliki Fault. Although the western fault segment was demonstrably not ruptured in AD 1861, its involvement in the 373 BC earthquake is supported only by its proximity to the likely site of ancient Helike. In order to identify the location of active fault traces, investigate the nature and geometry of the fault zone and identify any recent seismic activity, ground penetrating radar (GPR) surveys were undertaken. The location of the field site is the Nikolaiika Fan, beneath the limestone normal fault scarp of the Western Eliki Fault (Figure 1). Evidence of recent surface faulting occurs in aerial photographs of the Nikolaiika and Katourla Fans in the form of a series of low-relief scarps that trend parallel to the main fault escarpment and affect Quaternary sediments in the upper part of the coastal plain. In the field these morphological steps often coincide with agricultural terrace risers (Figure 2) and so, in some cases may be of anthropogenic rather than tectonic origin. GPR studies have been conducted to ascertain whether these surficial scarps relate to concealed near-surface faults.

III. METHODOLOGY

GPR lines were collected on the Nikolaiika Fan in July 2001 using a pulseEKKO 100 GPR system with 50, 100 and 200 MHz antennae. Two types of surveys were undertaken: common offset (CO) surveys in stop-and-collect mode, collecting a trace every 0.10 m for 100 and 200 MHz surveys and every 0.25 m for 50 MHz lines; and common midpoint surveys (CMP). Velocity estimates could not be made from the CMP surveys as most sub-surface reflections were dipping, producing erroneous velocity estimates. Analysis of hyperbolic reflections also failed to produce velocity estimates. Depth scales have been added using a velocity of 0.07 m ns-1 [15]. Elevations along the GPR lines were recorded by leveling survey from sea-level to allow topographic correction of the GPR lines. Data profiles were processed using GRADIX 1.10 software (Interpex Ltd.). The processing sequence included drift correction, time zero correction, dewow and bandpass filtering, background removal, depth correction and elevation statics and AGC gains.

The overall quality of GPR data from the Nikolaiika Fan is poor. Data has been degraded by off-line reflections such as wire supports for vines, metal water pipes installed for irrigation and olive tree plantations, with frequent near-surface scatters indicating root systems and the boles of cleared trees. Many soils are irrigated so saturated silts and clays are common in the near surface, leading to poor GPR penetration and resolution. Often the most accessible flat sites for surveys are the roads, though roads in the area are often constructed from steel reinforced concrete blocks preventing GPR profiling. Despite these problems, careful site selection has allowed collection of usable GPR data. Field sketching of possible off-line reflections has also assisted with profile interpretation.

IV. RESULTS AND DISCUSSION

Fault planes can be recognised on the GPR profiles in three ways (Figure 3):

1. Offsets are visible in some GPR reflections.

2. Concave and convex reflections are imaged between prominent offsets. These reflections may representing warping of sediment horizons between faults, though we would expect such responses to be difficult to image in unconsolidated sediments.

3. Regions of scattering with no coherent reflections are found, possibly representing steeply dipping fault planes or areas where layering in unconsolidated sediments have been disturbed by seismic activity.
Stratigraphic relations from GPR profiles indicate that there has been tectonic disturbance of the surficial strata across much of the Nikolaiika Fan. Some faults have a surface expression, with scarp faces of 0.5-1.0 m in height visible in the fields near the survey sites. Not all faults mapped by the GPR are visible at the surface. Likewise, not all visible surface scarps show a subsurface expression in the GPR. It is possible that some surface scarps represent man-made terracing, though it is likely that GPR has been unable to image all faults, particularly near vertical failure planes.

Elsewhere along the Eliki Fault slope-derived sediments in the uppermost few meters typically span a period of a few millennia [12], and similarly, on the higher flanks of the coastal plain Hellenistic and Roman sites are covered by 1-3 meters of slope-derived and river-derived sediment [16]. The main fault structures mapped using GPR are visible throughout the profiles in sediments deposited in the last few thousand years, confirming late Holocene activity on the Western Eliki Fault. In a limited number of cases the offsets appear to be lower in the GPR profiles and apparently undisturbed strata cover these offsets. This indicates that, either:

- The near-surface expression of these faults has not been imaged by the GPR,
- The faults have been buried, and are, therefore, older structure,
- The faults have not yet propagated fully to the ground surface.

The GPR profile passing the terraces in Figure 2b is shown in Figure 4. Noise from off-line reflections, most noticeably a telegraph pole and the overhead wires from it, degrade the profile. Two sets of structure can be imaged in the near surface. The first set, from 20–40 m produce a number of offset reflections suggesting faulting that does not appear to be correlated to surface scarps. Possible warping of reflections and incoherent noise below the fault zone suggesting loss of structure in unconsolidated sediments can be seen. The second set of faults from 55 m can be correlated to visible scarps seen in the fields adjacent to the road (marked S on Figure 2b).
A key question is whether these fault zones are tectonic structures (i.e. they root into the main fault with depth) or whether they are simply surficial deformation phenomena (i.e. they relate to either differential sediment compaction or gravitational instability of the fan sediments). Unfortunately, the GPR data is too coarse with depth to resolve whether or not the high-angle splays shallow into low-angle slip surfaces. However, comparable high-angle fault splays are exposed in shallow (<3-4 m deep) fault trenches on the Eastern Eliki Fault [9, 12,14], where they cut the uppermost sediments in the immediate hanging-wall of the main bedrock fault. In these instances, the splay faults are interpreted as tectonic splays that root downwards into the main bedrock fault. In these instances, the splay faults are interpreted as tectonic splays that root downwards into the main bedrock fault plane and which consequently are expressions of primary surface faulting rather than syntectonic depositional accommodation structures. In short, they are interpreted as primary tectonic structures.

Our expectation is that the GPR profiles are revealing a similar tendency along the Western Eliki Fault, that is, that the youngest (active) slip plane has migrated with time into the hanging-wall sediment pile. Such a tendency is well documented amongst active normal faults, in the Aegion region and elsewhere, and is termed ‘intrafault-zone hanging-wall collapse’ [17]. The implication that this has for seismic hazard is important. Surface rupture zones lie beneath the higher portions of the coastal plain, under the main infrastructure (towns and roads) of this area.

V. CONCLUSIONS
Preliminary GPR investigations on the Nikolaika Fan demonstrate recent tectonic disturbance on the Western Eliki Fault. The GPR profiles reveal offset reflections, possible warping of reflections between offsets and regions of scattering, indicating that a number of surficial scarp found in the study area are the surface expressions of faulting. These scarp act as the risers for agricultural terraces, but are mostly tectonic in origin rather than anthropogenic. These surface displacements indicate that fault activity may not be confined to the main escarpment footwall, suggesting activity in the uppermost hanging-wall sediments. These observations have implications for the mapping of seismic hazard in the higher portions of the Eliki coastal plain, in what is one of the most earthquake prone zones in Europe.

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REFERENCES


