Δελτίο της Ελληνικής Γεωλογικής Εταιρίας τομ. XXXII/1, 173-179, 1998
Πρακτικά 8ου Διεθνούς Συνεδρίου, Πάτρα Μάιος 1998

Bulletin of the Geological Society of Greece vol. XXXII/1, 173-179, 1998
Proceedings of the 8th International Congress, Patras, May 1998

MAPPING OF ACTIVE NORMAL FAULTS IN THE LOKRIS REGION (CENTRAL GREECE) USING SPOT DEM DATA.

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ABSTRACT

A DEM-based methodology is suggested for mapping active normal faults. The methodology makes use of processed 10-m resolution SPOT stereopairs to produce digital elevation models and is fast to implement. 100-m DEMs can provide the structural geologist with: (i) adequate resolution to visualise shapes of mountain ranges, (ii) raster background to extract footwall drainage patterns and (iii) maps to measure the spatial variation of surface slope. Then, fault segmentation criteria may be tested against the geomorphic evidence supplied by the DEM data and its derivatives. This methodology has been applied in the Lokris region (central Greece) where both the position and length (ci. 35 km) of two active fault segments (Kammena Vourla and Kallidromon) were extracted. This information can be used as a deterministic input into seismic hazard models for the area and to calculate maximum earthquake size.

KEY WORDS: Active Faulting, Digital Elevation Models, Stereomatching, SPOT, slope maps, GIS, Lokris

1. INTRODUCTION

Digital Elevation Models (DEMs) have been used extensively the last ten years in geological mapping through the development of digital cartography (e.g., Murphy, 1993, Riley and Moore, 1993, Wadge *et al.*, 1993; Wdowinski and Zilberman, 1997) and digital photogrammetry (Ganas *et al.*, 1996). Moreover, DEMs derived from the stereomatching of 10-m resolution SPOT stereopairs have been shown to match the quality of the digitised counterparts (e.g., Day and Muller, 1989; Bolstad and Stowe, 1994; Al-Rousan *et al.*, 1997) and this has offered to geologists the capability of extracting raster maps of surface topography of rift systems quickly (within 72hrs), and at high spatial resolutions (30-100 m).

This paper proposes a new use of SPOT DEMs in structural mapping. It is suggested that elevation and slope data can be used to infer active fault positions in continental rift systems because inside these areas the configuration of relief may be linked with systematic variations of fault displacement (Anders and Schlische, 1994). For example, in Central Greece (Figure 1; Roberts and Jackson, 1991; Roberts and Koukouvelas, 1996) as well as within the Basin and Range extensional province in southwestern USA (Stein *et al.*, 1988) the surface topography is controlled by long-term growth of normal faults, which rupture quasi-periodically in large earthquakes. It is shown here (see Figure 2a below) that areas of low topography marking the positions of segment boundaries can be recognised from space by the construction of DEMs of rift systems, and such data can be further analysed to extract the spatial variation of morphometric parameters of relief, in order to establish the extent of footwall areas of active faults. Under the assumption that most of seismic strain is released by slip along these major fault segments (Ambraseys and Jackson, 1990), the size (length, area) of the seismogenic sources may be extracted. In turn, this important parameter can be used in seismic hazard modelling studies or in empirical seismological relationships to calculate fault-specific surface magnitudes.

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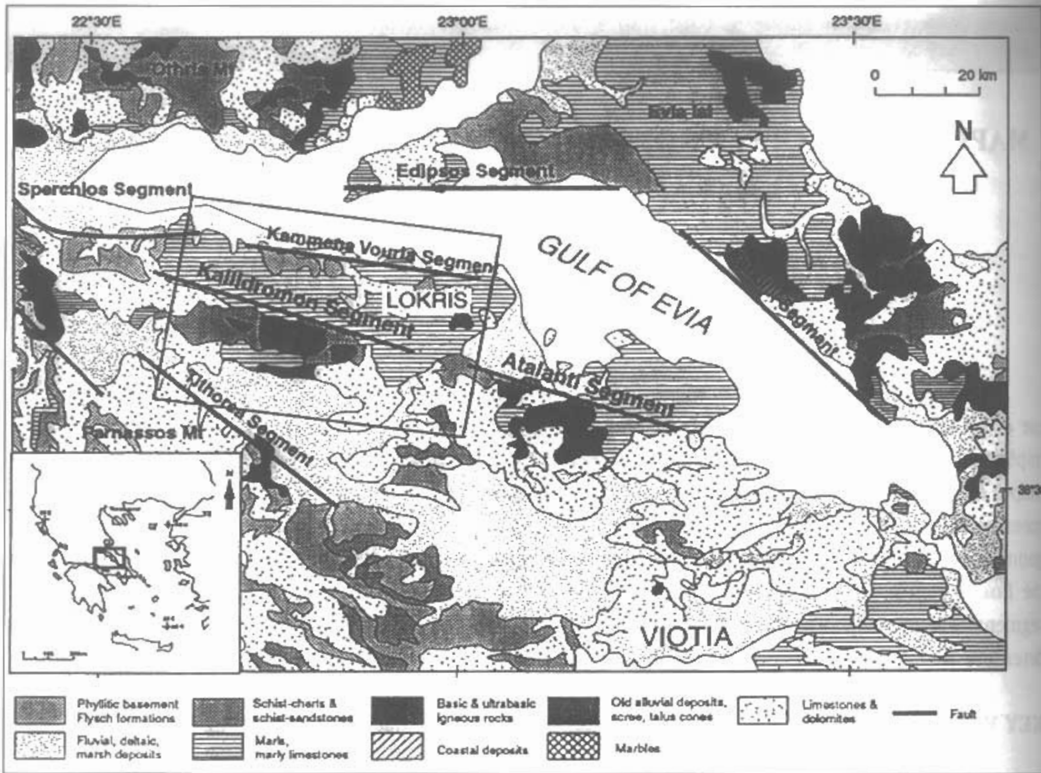

Figure 1: Geological map of Eastern Central Greece (after IGME, 1989) showing also positions of normal fault segments after Ganas and White, (1996) and Ganas *et al.*,(1996). The Gulf of Evia is an 80-km WNW-ESE marine basin formed as a result of Late Quaternary crustal extension. Inclined box shows boundaries of Figures 2a and 3.

Central Greece (Figure 1), is a well known extensional province (Mercier *et al.*, 1976; Roberts and Jackson, 1991; Ganas and White, 1996) where upper-crustal extension is accommodated by slip along large normal fault segments of planar geometry. This paper is based on analyses of DEM data and presents information on the length and position of two fault segments inside the Gulf of Evia rift, namely the Kammena Vourla and Kallidromon segments (Figure 1) located at Western Lokris. Given the seismic quiescence of the Lokris region this century (Ambraseys and Jackson, 1990), it is of particular importance to map the segmentation pattern inside this rift system and to make geologically based predictions on maximum earthquake size.

2. DESCRIPTION OF METHODOLOGY

A SPOT1 stereopair (processing level 1A) was used where the western half of the Gulf of Evia region is covered (path/row 89/272, B/H=0.75, view angle difference 41°). Both images were collected during a short time period (January 1989) and show excellent radiometric fidelity. Moreover, they are cloud free and do not show any noticeable atmospheric effects, nor any form of pushbroom striping. However, they do suffer from E-W, relief-induced shadowing at two areas and from local snow coverage at high altitudes. The shadowing problem is expected to influence stereomatcher output and consequently interpolation results may be erroneous at these areas. However, this is still tolerable in our methodology because it is the sun-facing footwall areas and not the hangingwall (shadow) areas that are of any concern.

The public domain UNIX-software *3D-Image Maker* by the University College London (©UCL, 1990) was used to construct a 100-m DEM. The basics of the procedure followed to generate the DEM are described in Ganas et al. (1996) and Ganas et al., paper submitted to EARSeL. The vertical accuracy of the

DEM (z-RMSe 16.21 m) was evaluated against 56 independent spot heights (± 1m) from the National Triangulation Network of the Greek Military Geographical Service (HAGS) which are plotted on the 1:50 000 topographic maps. This error is comparable to that obtained from previous workers (Day and Muller, 1989; Giles and Franklin, 1996; Devereux *et al.*, 1997). The vertical standard accuracy of 16 metres is adequate for this regional study, because average elevations over the region examined are 200-400 metres (HAGS, 1977, sheet "Stylis") and maximum elevations of mountain ranges reach 1700 metres (i.e. average z-error between 1-5% of topography).

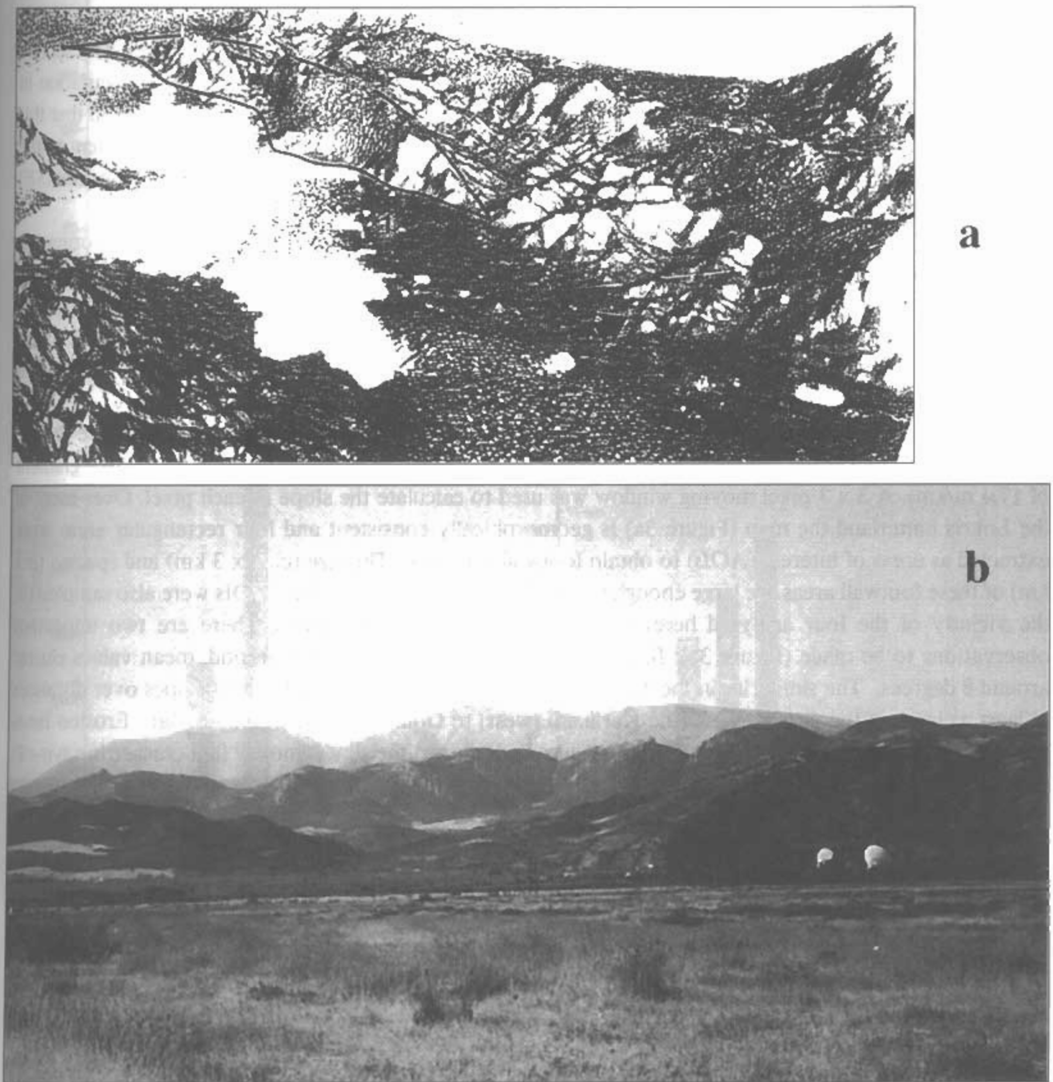

Figure 2: (a) Perspective view of the DEM of the western Lokris area, Central Greece. The view is towards the south and illumination is from the Northwest. The Gulf of Evia is at the foreground (white). The black sinuous line indicates the trace of the Kammena Vourla Fault Segment, while the semi-elliptical dashed line highlights the domal shape of the coastal mountain range. Numbers refer to half-graben positions with respect to the rift axis. Black arrow point to the viewing direction of figure 3b. (b). Field photograph of normal fault segments on the south side of the Gulf of Evia Rift, Central Greece. The low hill region in the foreground is the segment boundary between the Kammena Vourla and Sperchios Fault Segments (see Figure 1). Also shown in the background are the Kallidromon and Tithorea Fault Segments.

3. ANALYSIS AND INTERPRETATION OF DEM DATA

Firstly, a visualisation of the DEM in 3D image space is necessary to view the general relief configuration of the study area, in order to establish the size and orientation of mountain ranges. A panoramic view is shown in Figure 2a and a largely corresponding field photograph of the "ground truth" is shown in Figure 2b. A number of structural and geomorphic features can be seen (Figure 2a; compare with Figure 1) : The coastal Kammena Vourla Fault Segment shows the characteristic dome-shape footwall profile along its strike, as expected from isolated segmentation models (e.g., Anders and Schliesce, 1994). The sharp bend half-way along the trace of the fault by the Gulf of Evia coast (Figure 2a) is interpreted as an intra-segmental discontinuity because footwall topography is comparable on either side. The second segment to the south, the Kallidromon Fault Segment (Figure 1) does not show a systematic variation in footwall topography but an increase in footwall elevation towards the northwest. It is suggested that this asymmetry is due to the uplift of the northern part of the range by a younger normal fault segment to the north (the Sperchios Fault Segment; see Figure 1). The decreased elevation observed on the other end (SE) is consistent with the existence of a relay structure (Gawthorpe and Hurst, 1993).

Secondly, the raster elevation data were imported to ARC-GRID to extract quantitative information on the length and position of the active faults in the western Lokris area. A thematic elevation map grouped in 12 classes (with 100-m range) was produced. The map confirmed the interpretation suggested above, i.e. the footwall area of the coastal fault segment extends E-W for a distance of ci. 35 km. Drainage inside the Kallidromon half-graben (Figure 1) has been also reorganised in response to the varying footwall uplift of the Kammena Vourla fault during the Quaternary.

Thirdly, the DEM intensity image was processed in *Imagine 8.2* to produce a slope map. The surface slope was calculated as the change in elevation over a DEM pixel, in degrees (1 degree equals to a gradient of 17.4 m/km). A 3 x 3 pixel moving window was used to calculate the slope at each pixel. Over most of the Lokris hinterland the map (Figure 3a) is geomorphically consistent and four rectangular areas were extracted as areas of interest (*AOIs*) to obtain footwall statistics. The size (ci. 3 x 3 km) and spacing (≥ 1 km) of these footwall areas are large enough to avoid any sampling bias. Other AOIs were also sampled (in the vicinity of the four analysed here) which showed similar distributions. There are two important observations to be made (Figure 3b): first, all histograms are unimodal and second, mean values cluster around 8 degrees. The similarity in the distributions reflects a spatial dependence of slopes over distances at least as large as the distance from the Karia.aoi (west) to Goulemi.aoi (east; Figure 3a). Erosion rates may be assumed the same for all four areas because underlying lithology is mostly fluviolacustrine syn-rift (see key in Figure 1) and mean elevations are similar (HAGS, 1977). It is, therefore, suggested that these quantitative data record a finite deformation of the footwall area of the Kammena Vourla segment and strongly indicate that the size of the fault segment is comparable to the longitudinal distance of the sampling areas, that is between 30-35 km.

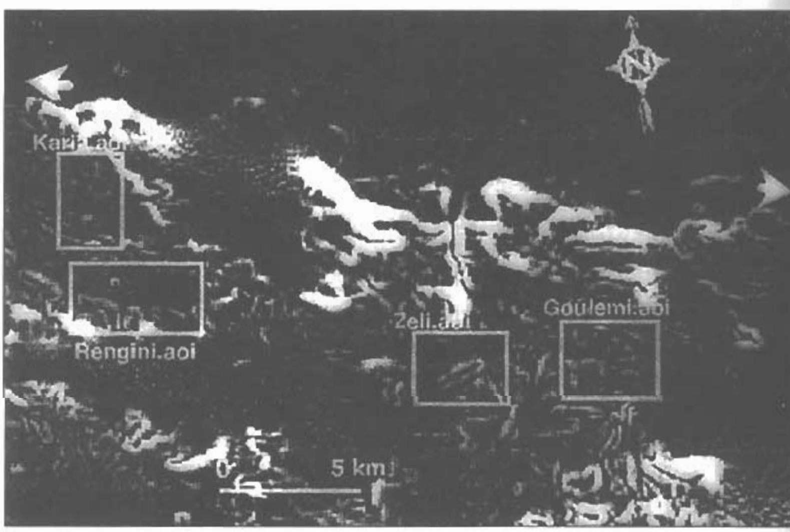

Figure 3a (next page)

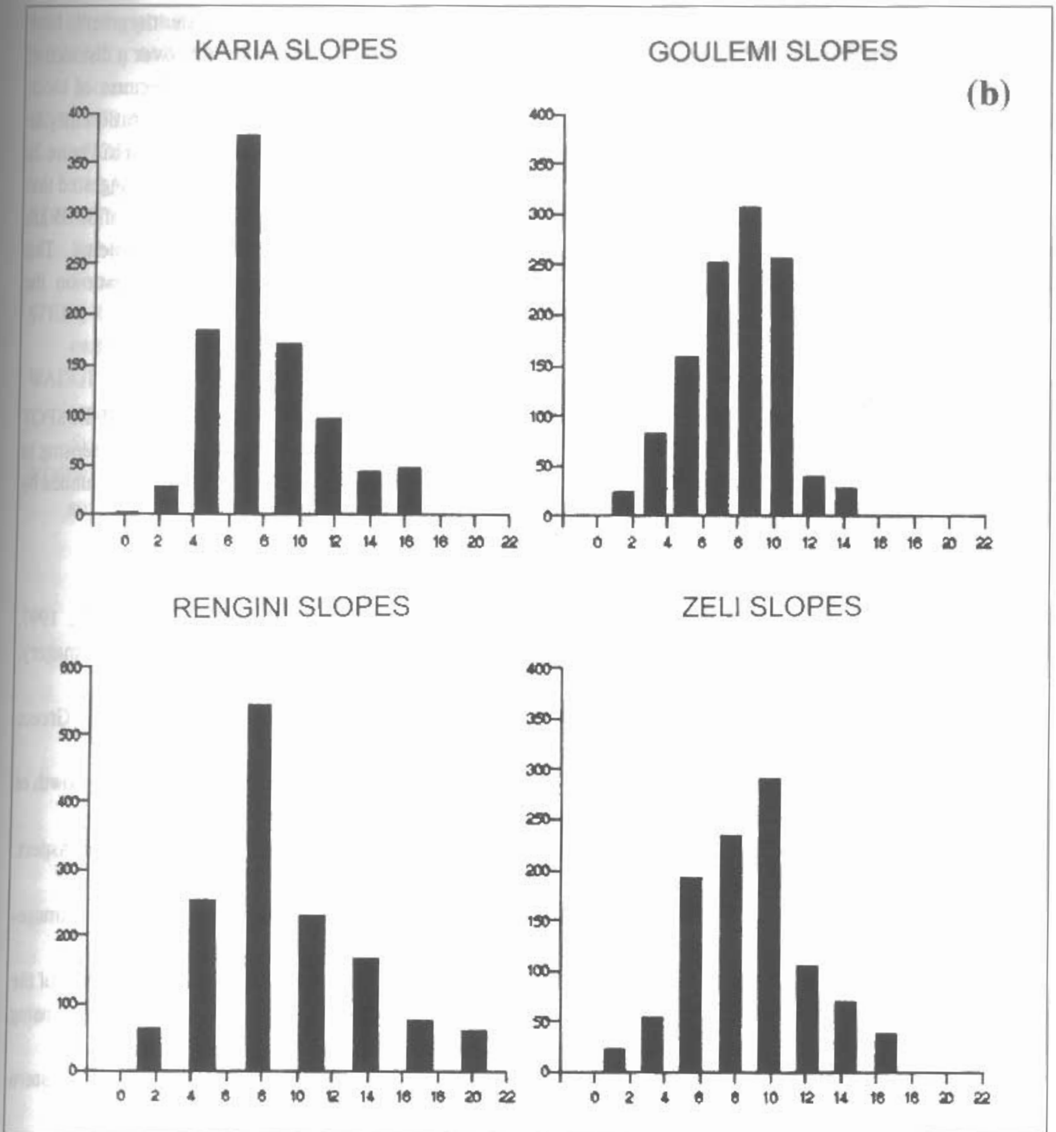

Figure 3: a) Image showing slope angle calculations for the region in figure 2. The image is in raster format and its intensity varies proportionally with slope angle, that is bright areas correspond to high slopes. Also shown are four rectangular areas at the footwall of the Kammena Vourla Fault Segment, selected for statistical analysis. Text refers to population centres of the area. b). The frequency distribution of slope angles at four areas in the footwall of the Kammena Vourla Fault Segment. Vertical axes numbers represent frequency of slope angle occurrence within each of the footwall area.

4. CONCLUSIONS

SPOT DEMs can be used in mapping active faults inside juvenile rift systems where footwall topography variations are linked to long-term fault growth rates. A remote sensing methodology is proposed involving image processing of SPOT panchromatic imagery and GIS analysis of the produced DEM. The results of the morphometric analysis in the Western Lokris region of Central Greece support a long (30-35 km) segment length model at least for two of the normal fault segments of the area, the Kammena Vourla and Kallidromon Fault Segments. Over this distance wavelength, footwall slopes exhibit a statistical homogeneity (Figure 3b), and elevation profiles (Figure 2a) along strike of fault segments have a dome-shape appearance. This is explained by a systematic variation in footwall uplift over a distance of approximately 35 km. As footwall uplift also varies across strike of fault segments, because of block tilting being greater closer to the fault plane (e.g., Stein *et al.*, 1988), a 3D ellipsoidal configuration may be expected to form in the hinterland of isolated fault segments. This configuration may be seen in Figure 2a where an oblique perspective view of the coastal Kammena Vourla segment is shown. It is suggested that dome-shaped strike-profiles and ellipsoidal configurations of footwall volumes over distances of 30-35 km may be used to extract the length and position of active faults in other continental rift systems. This information may also assist in probabilistic seismic hazard assessment studies, where data on the earthquake sources are missing or are incomplete.

ACKNOWLEDGEMENTS

I am grateful to Prof. Peter Muller (UCL) providing both the software *3D-Image Maker* and the SPOT imagery; Dr. Kevin White and Prof. Geoff Wadge for many discussions on the use of remote sensing in geology and Dr. Gerald Roberts for many discussions on fault segmentation. This research was funded by an IKY doctoral studentship and the University of Reading.

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