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SHORT NOTES

A rough guide to limestone fault scarps

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Abstract—The surface roughness of limestone fault scarps in central Greece is examined with the aim of relating variations in rock weathering to palaeoseismic activity. The study employs a micro-roughness meter (MRM) and a carpenter's profile gauge to collect field measurements of scarp roughness, presenting the results in terms of roughness indices which permit comparison between different height levels of a scarp. The study confirms the increasing degradation of scarps with height, thereby inferring the time-dependent evolution of fault-scarp roughness. In addition, roughness indices are found to discriminate between fault surfaces exposed during the 1981 Corinth earthquakes and those emergent prior to this event. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Bedrock fault scarps are long-lived expressions of repeated surface faulting in many active tectonic terrains. Although such scarps potentially preserve a valuable 'palaeoseismic' record, interpreting this is difficult. The morphology of bedrock scarps does not evolve in the same predictable, time-dependent fashion as equivalent scarps in sediments and, as a result, bedrock scarps are not considered sensitive indicators of the timing and magnitude of past faulting events (Mayer 1984, Stewart 1993). In limestone bedrocks, however, portions of the same fault surface exposed in different surface faulting events may be discriminated by contrasting degrees of subaerial weathering and biogenic colonisation. Limestone fault surfaces reactivated during the 1915 Pleasant Valley (Nevada) earthquake, for example, displayed an absence of karstic pitting and lichen development, both of which were well developed on pre-1915 fault surfaces (Wallace 1984). Wallace (1984, p. 23), speculated that the degree of surface pitting "should provide a measure of the length of time that that surface has been exposed and, thus, a time constraint as to the date of a large displacement event prior to 1915". More commonly, however, sharp weathering contrasts on limestone fault surfaces have been used to delimit recent slip increments (e.g. Taymaz & Price 1992, Papanastassiou *et al.* 1993, Wu & Bruhn 1994).

This paper outlines a new approach to quantifying the varying degrees of weathering exhibited by active fault surfaces based on field-based measurement of their surface roughness. The paper is limited to the investigation of recently reactivated limestone fault scarps in the eastern Gulf of Corinth, central Greece, where the fresh appearance and pedogenic staining of fault planes exposed during the 1981 Corinth earthquakes (Ms 6.7–6.4) (Jackson *et al.* 1982) readily distinguish them from pre-1981 fault surfaces.

FIELD DETERMINATION OF FAULT-SCARP ROUGHNESS

Although faults generally emerge from the ground as smooth, polished planes, high-resolution laboratory and field studies show that at outcrop scale they possess an inherent roughness which can, in turn, be accentuated by weathering (Brown & Scholz 1985, Power *et al.* 1987, 1988). Such detailed studies rely on high-cost profiling instruments which are time-consuming to set up in the field and require considerable computing power for subsequent data analysis, with the result that only a limited number of roughness profiles can be recorded. Since detecting variations in the degree of weathering requires a large sample rather than extreme precision (McCarroll & Nesje, in press), simpler, manual determinations of rock surface roughness can be used as the basis of discriminating fault surfaces with different weathering histories. In this study, the traditional 'carpenter's profile gauge' method of recording the topography of limestone surfaces is combined with a more sensitive, specially built 'micro-roughness meter' (MRM) to record the roughness characteristics of exposed limestone fault surfaces.

The MRM, described by McCarroll (1992), comprises a robust but lightweight, triangular alloy frame set on adjustable tripod legs (Fig. 1a). Within this frame, which constitutes the reference surface from which the depth to the rock surface will be determined, is a graduated steel bar along which a measuring unit traverses. A thin steel

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stylus passing through the centre of this unit can be adjusted such that its tip is lowered to the rock surface. Within the measuring unit, this vertical motion of the stylus is transferred horizontally to a dial gauge (1 cm travel, 0.001 mm graduations) from which the distance from the alloy frame, the datum line, to the rock surface can be read off (measurements made to the nearest 0.01 mm). Relative heights of points on the rock surface are recorded at evenly spaced points along a transect.

Microkarren relief in the form of 0.1–1.0 cm sized solution pits and rills can develop on exposed limestone surfaces within a few decades and, over longer timespans, evolve into centimetre- to decimetre-scale hollows and channels (Ford & Williams 1989). Although McCarroll & Nesje (in press) recommend a 2 cm measurement interval for weathering studies, in general, a sampling interval of 5 mm used in previous fault-roughness studies (e.g. Power *et al.* 1987,1988) was adopted here to detect the scale of karstic features expected from 10^1–10^3 years of fault exposure. Set against the recognition that such a sampling interval—effectively disregards weathering features with wavelengths <1.0 cm (that is, double the sample interval the Nyquist cutoff) (Brown & Scholz 1985), the 5 mm sampling interval facilitates the speedy collection of roughness data from a large number of profiles at a site. Measurements were taken along horizontal transects, 20 cm in length, thereby aligned essentially perpendicular to the direction of slip on the normal faults studied.

The MRM is particularly convenient in that it can measure varying degrees of rock roughness, although it is ideally suited to measuring rock surfaces whose irregularity does not exceed the 1 cm travel distance of the dial gauge. For surfaces which exceeded the degree of irregularity which could easily be accommodated by adjustments to the MRM (see McCarroll 1992), recourse was made to the less accurate but very convenient 'carpenter's profile gauge' (Dunkerley 1979, Goudie *et al.* 1989). Roughness values determined for transects measured by both the MRM and profile gauge display a statistically significant rank correlation at the 0.05 significance level (Fig. 2), confirming the contention of McCarroll & Nesje (1993) that roughness data collected by either method can be directly compared. The profile gauge, with an array of metal needles or plastic slats which are free to move parallel to each other, is pressed against a surface such that the sliding needles/slats adopt the form of the rock surface. In this study, a 13 cm long profile gauge was used, thereby necessitating that two profile gauge impressions were taken along adjacent transects to allow a direct comparison with the longer MRM transects. The gauge profiles were traced directly onto 1 mm graph paper in the field for later analysis.

ROUGHNESS INDICES

The values recorded by the MRM represent height differences between the rock and the MRM datum and, therefore, can be used to construct detailed rock-surface profiles. These profiles can be directly compared with those imprinted on the profile gauge, and serve as useful visual impressions of surface roughness. As well as showing millimetre-scale irregularities produced by surface weathering, however, such profiles may express larger-order perturbations resulting from a suite of kinematic structures which commonly adorn tectonic slip planes (Hancock & Barka 1987, Stewart & Hancock 1991). As a result, a grooved or corrugated fault surface may exhibit an apparent roughness even when at the micro-scale it is unweathered. In order to 'filter out' such centimetre- to decimetre-scale tectonic irregularities, the degree of weathering is instead considered in terms of simple roughness indices.

Roughness indices are based on a recognition that the difference between adjacent measured 'height' values (the distance between which is constant along a transect) provides a measure of the 'slope' between the two points (McCarroll 1992, McCarroll & Nesje 1993). Although the magnitude of these surface gradient or 'slope' values is affected by any angular discrepancy between the rock surface and datum, the spread of values and the difference between adjacent values are not. Thus, following McCarroll (1992), two simple indices of rock-surface roughness based on 'slope' values can be determined (Fig. 3): (1) the standard deviation of the 'slope' values, and (2) the mean absolute difference between adjacent 'slope' values. These indices can be calculated at different sampling intervals and over different transect lengths to derive a suite of measures that can assess roughness at varying scales of observation (McCarroll & Nesje, in press).

In order for roughness indices to be useful as a palaeoseismological tool, they must demonstrate two criteria. Firstly, the indices must show that limestone fault scarps do indeed become increasingly degraded upscarp (i.e. along a transect of increasing age), and secondly that where surfaces are known to have been exposed in different earthquake slip increments, roughness indices must distinguish between them. The following sections examine the utility of fault-scarp roughness assessments with respect to field measurements conducted along the Kaparelli and Pisia–Psatha Faults, two active normal faults located on the northern and southern flanks, respectively, of the Gulf of Alkonides, central Greece (Roberts *et al.* 1993).

DO FAULT SCARPS BECOME INCREASINGLY 'ROUGH' UPSCARP?

A 3.0–4.0 m high limestone fault scarp at Kaparelli discontinously displays a 0.5 m high basal strip of fresh bedrock exposed during the Ms 6.4 Corinth earthquake of 4 March 1981 (Jackson *et al.* 1982). Roughness measurements were taken along two ~100 m-long sections of the Kaparelli Fault where reactivated limestone scarps are best developed. At each of the 14 measurement stations, roughness transects were spaced

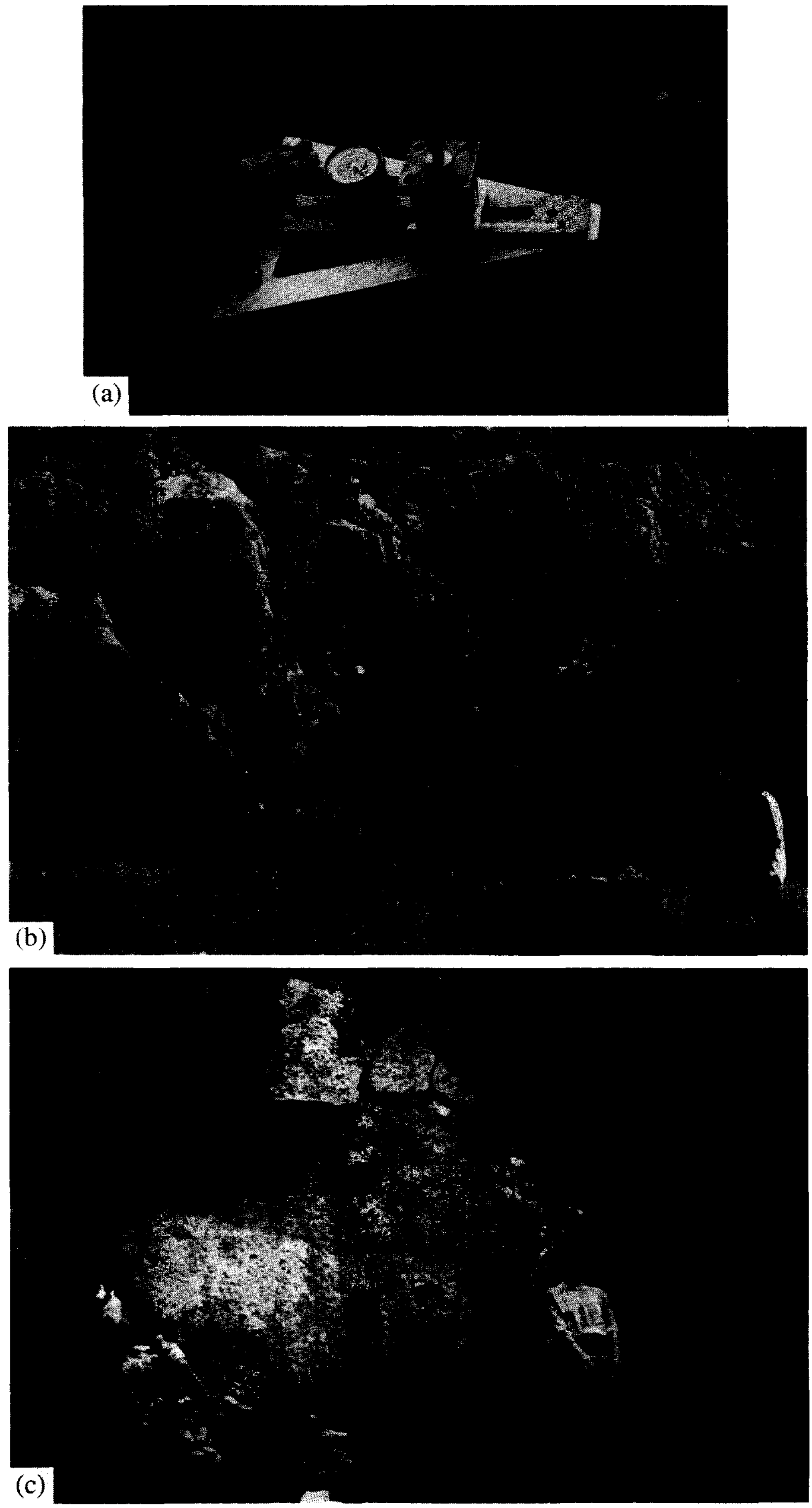

Fig. 1. (a) View of the MRM, a robust, portable instrument which allows precise field measurement of rock-surface profiles from point measurements on horizontal transects. See text for details. (b) A 4 m-high limestone fault scarp at Kaparelli, central Greece, which was reactivated during an earthquake in 1981, exposing a 0.5 m-high white basal strip. The photograph shows the scarp form at measurement station K14, the roughness attributes of which are plotted in Fig. 4 and in particular illustrates the occurrence of large-scale karstic features (rillenkarren) towards the crest of the scarp. (c) A 3 m-high limestone fault scarp, located immediately east of Pisia (central Greece) on the Pisia–Psatha Fault, displaying lichen banding interpreted as the product of episodic fault slip. The lower lighter band of the fault scarp was exposed during the 1981 Corinth earthquakes and displays a smooth, micro-pitted surface devoid of lichen; higher levels of the scarp appear to be increasingly degraded.

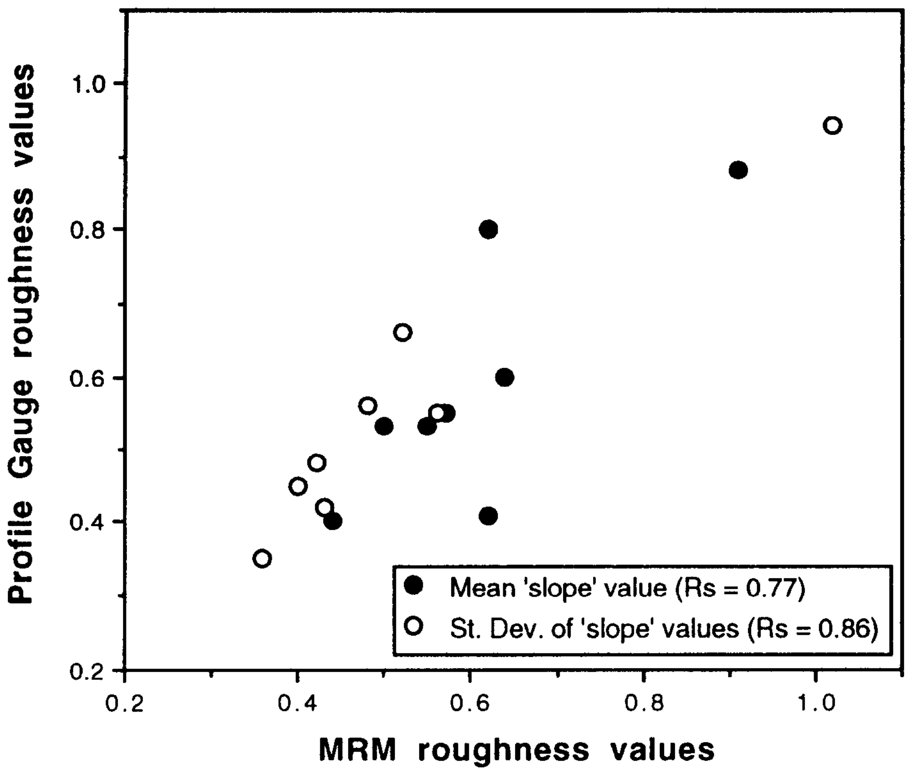

Fig. 2. Comparison of roughness index values determined for transects measured by both the profile gauge and the MRM along the Kaparelli and Pisia Faults. Spearman rank correlation coefficients (Rs) for the two roughness indices (see Fig. 3) used in the study are 0.77 (mean 'slope' value) and 0.86 (standard deviation of 'slope' values) demonstrating a significant correlation between roughness datasets collected by the two measurement techniques at the 0.05 significance level.

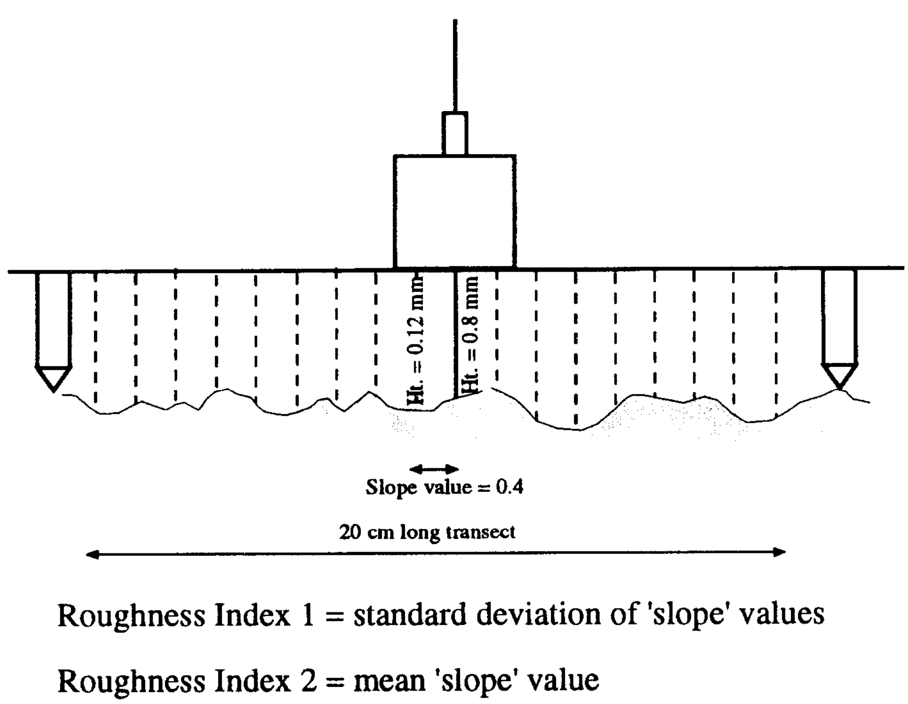

Fig. 3. Derivation of roughness indices from 'slope' values obtained from point measurements along MRM and profile gauge transects. 'Slope' refers to the height difference between two adjacent points and the indices used correspond to the standard deviation and mean of the 'slope' population along a transect.

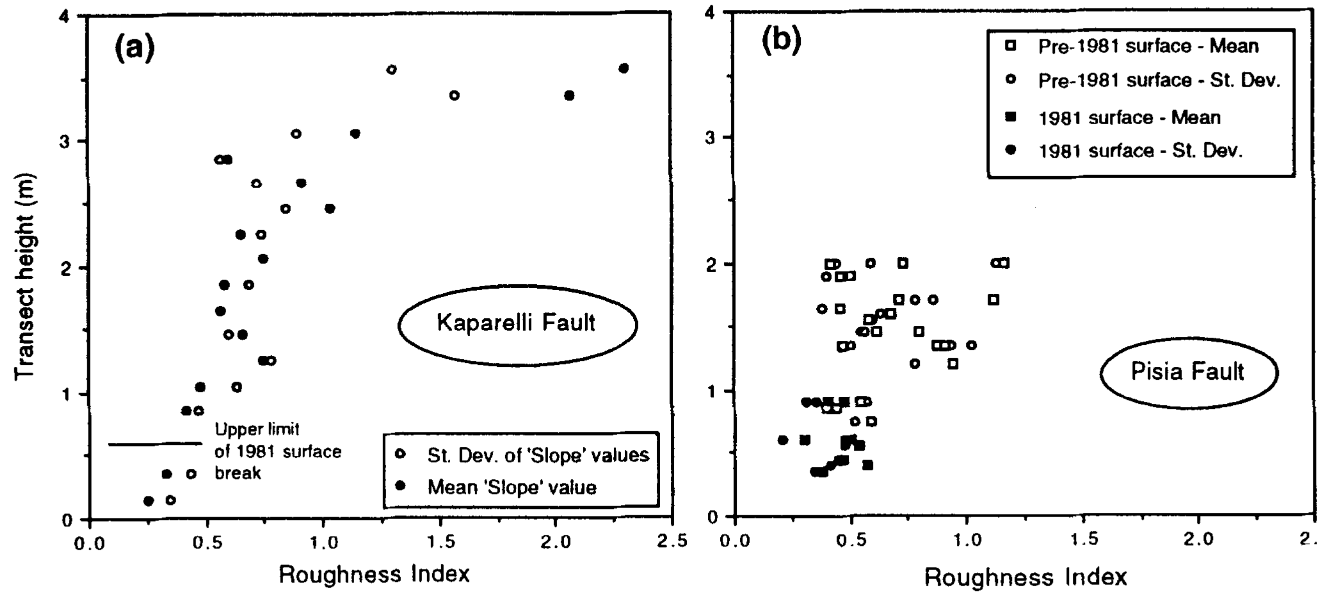

Fig. 4. (a) Plots of roughness indices (mean 'slope' value and standard deviation of 'slope' values) against transect height for a station (Station K14) along the Kaparelli Fault scarp. The plot is representative of results derived from 14 stations which all confirm increasing surface roughness upscarp. The absence of distinct discontinuities in the broadly 'linear' weathering trend indicates that discrete palaeoseismic increments cannot be distinguished. (b) Weathering plot combining surface roughness data for nine measurement stations along the Pisia Fault to highlight the contrast in roughness index values (mean 'slope' value and standard deviation of 'slope' values) for the 1981 and pre-1981 fault surfaces.

at vertical intervals of 0.2 m, thereby recording up to 20 transects per station. Plots of transect roughness (defined in terms of indices of standard deviation and mean of 'slope' values) against transect height defined for all stations show a comparable pattern, illustrated by reference to one 'representative' station, K14 (Fig. 4a). The results confirm a positive correlation between transect roughness and transect height for the Kaparelli scarp, consistent with higher (older) levels of the scarp experiencing more weathering. An increasing spread of roughness values towards the top of the scarp, evident from K14 and other stations, probably reflects the superimposition of larger karstic forms near the scarp crest (Fig. 1b). It remains unclear whether the broadly 'linear' roughness trend shown for the main section of the scarp extends to the subsurface portion of the fault, since the roughness of excavated parts of the scarp was not measured.

Although the weathering plot shown in Fig. 4 (a) conforms to that expected of an incrementally emerging and degrading scarp, the absence of a step-like increase in degree of weathering upscarp, or of at least distinct offsets in the 'linear' weathering trend, suggests that individual palaeoseismic uplift events cannot be identified. This may reflect the insensitivity of scarp roughness to discriminate minor (centimetre–decimetre) slip increments, but alternatively it may point to a more complex exhumation history for the scarp. In the study area, for example, the Kaperelli fault bounds the northern edge of a well-cultivated alluvial plain and locally the scarp forms the backwall to small olive-tree plantations, leading to the possibility that artificial removal and/or accumulation of sediment against the fault prior to movement in 1981 has obscured abrupt changes in degree of weathering related to past tectonic emergence.

CAN FAULT ROUGHNESS DISTINGUISH DIFFERENT FAULTING EVENTS?

Limestone fault scarps developed along the Pisia–Psatha Fault display a sharply defined lichen zonation at several sites (Fig. 1c). This zonation, characterised by a sequence of 1 m-thick bands of increasing diversity and intensity of lichen coverage, together with the scarp's location on moderately steep, forested slopes away from obvious anthropogenic modification, suggests the scarp has emerged incrementally by repeated palaeoseismic slip events. The lowest 1.0 m of the scarp was exposed in the 1981 Corinth earthquakes (Jackson *et al.* 1982), and displays a smooth, micro-pitted surface devoid of lichen, while higher levels of the scarp appear to be increasingly degraded. Comparisons of roughness values derived from measurement of the 1981 and pre-1981 surfaces (Fig. 4b) show some degree of overlap but generally indicate higher roughness values and a greater spread of roughness values in the pre-1981 surface population relative to the 1981 surfaces. Furthermore, there is a comparatively abrupt change in the roughness range approximately coincident with the +1.0 m level which separates the two populations. Although a number of pre-1981 roughness values plot within the narrow range of the 1981 surfaces, they occur at the base of the previously emergent fault surfaces and may represent anomalously smooth parts of the older scarp surfaces protected from subaerial weathering by colluvial build-up on the pre-1981 ground surface.

CONCLUSIONS

The recognition from the Kaparelli Fault that progressively higher (older) levels of a scarp exhibit increasing roughness lends confidence to the contention that bedrock scarps may indeed exhibit time-dependent morphological changes related to scarp degradation. At the Kaparelli site, however, it appears that any palaeoseismic signal of incremental emergence has been obscured, possibly by exhumation and burial of the scarp due to adjacent land-use changes. Along the Pisia–Psatha Fault, however, portions of the fault surface exposed in an earthquake in 1981 can be differentiated from portions emergent prior to that event, suggesting that recent faulting events can be discriminated on the basis of surface-roughness measurements.

Although the study demonstrates that field-based assessments of surface roughness provide a potentially valuable tool in reconstructing the palaeoseismic history of a limestone fault scarp, the utility of this method must be refined through a more detailed appreciation of the weathering processes operating at the microscale. Ultimately, while lithological and climatic controls on fault-scarp degradation and uncertainties over past exhumation/burial histories will limit the sensitivity and wider applicability of this technique, roughness indices may be useful in distinguishing limestone scarps of widely differing ages, akin to the application of morphologic dating to colluvial and alluvial scarps.

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