Geomorphology 228 (2015) 421–431

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Bedrock fault scarp history: Insight from t-LiDAR backscatter behaviour and analysis of structure changes

Thomas Wiatr [a], Ioannis Papanikolaou [b], Tomás Fernández-Steeger [c], Klaus Reicherter [a]

[a] RWTH Aachen University, Institute of Neotectonics and Natural Hazards, Lochnerstr. 4-20, 52064 Aachen, Germany
[b] Laboratory of Mineralogy & Geology, Department of Natural Resources Development and Agricultural Engineering, Agricultural University of Athens, 75 Iera Odos Str., 11855 Athens, Greece
[c] RWTH Aachen University, Department of Engineering Geology and Hydrogeology, Lochnerstr. 4-20, 52064 Aachen, Germany

ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form 16 June 2014
Accepted 24 September 2014
Available online 11 October 2014

Keywords:
Close range t-LiDAR
Fault plane morphology and alteration
Backscatter
Pisia fault
Corinth
1981

ABSTRACT

This paper provides a research approach and develops a methodology that helps natural weathered bedrock fault scarps to be understood in terms of their structural changes and backscatter behaviour when using terrestrial laser scanning (t-LiDAR). We tested our approach on the Pisia fault in Greece that ruptured during the 1981 Alkyonides earthquake sequence in Corinth Gulf. The method describes how to correlate fault geometry and structural variations with the backscatter signal of t-LiDAR data from naturally exhumed bedrock fault scarps. Using this method we are able to reconstruct the past slip history.

We used t-LiDAR for the analysis of the monochromatic laser beam's backscattered signal to define unsupervised classes of unknown objects on fault surface. Seven classes were created based on the dendrogram technique using the maximum likelihood method. These were used to determine their spatial distribution throughout the scarp height and to calculate the terrain ruggedness index (TRI) in the defined classes. The combination of these results shows that: (i) the ruggedness increases with the scarp height and (ii) the ruggedness and backscattering describe different fault plane conditions. We found evidence for past earthquakes on the Pisia fault at our study site with average displacements in the range of 30–60 cm with corresponding magnitudes of 6.4–6.6 $\pm$ 0.1 M_S. These results help to reconstruct the recent fault history and potential palaeo-events, and can also be used: i) to detect appropriate sample sites on the fault plane for absolute dating and ii) as an independent constraint on tracing slip events, assisting absolute dating techniques. This method can significantly reduce the sampling requirements and costs of cosmogenic absolute dating techniques. Overall, it might be a valuable tool for extracting data regarding the faulting history and slip events for defining seismic hazard parameters.

1. Introduction

Decoding coseismic palaeo-earthquakes on bedrock fault scarps is important for accurately estimating the seismic cycle, the slip characteristics and the seismic hazard potential of active fault zones. The long-term pattern of fault-slip is required in order to extend the history of earthquakes on a fault back many thousands of years, a time span that generally encompasses a large number of earthquake cycles (e.g. Yeats and Prentice, 1996). As a result, fault specific approaches are very important for seismic hazard assessment, because they provide quantitative assessments through measurement of geologically recorded slip on active faults, sample much greater periods of time than the historical earthquake records, offering a more reliable estimate of hazard (e.g. Michetti et al., 2005; Reicherter et al., 2009; Grützner et al., 2013). In addition, fault specific time-dependent probabilities, which incorporate the concept of the seismic cycle, follow the latest advances in extracting earthquake probabilities (e.g. Scholz, 2002; WGCEP, 2002; McCalpin, 2009). To calculate such a renewal probability, ideally one requires an earthquake catalogue containing several large events on each fault to deduce earthquake magnitudes, the mean inter-event time of similar events and the elapsed time since the last shock on each fault (Parsons et al., 2000). However, conditional probabilities depend strongly on the value of intrinsic variability of recurrence intervals, which is unknown and different for each fault (McCalpin and Slemmons, 1998; Ellsworth et al., 1999; Cowie et al., 2012). This intrinsic variability of recurrence intervals (known as the coefficient of variation COV or aperiodicity) is a measure of the irregularity of the length of the intervals between successive events, reflecting the complexities in the accumulation and release of strain (Nishenko and Buland, 1987; Ellsworth et al., 1999; Visini and Pace, 2014). Therefore, this value differs from fault to fault. As a result, the recognition of several surface faulting events on each fault offers a unique opportunity, to simply calculate not only the mean recurrence interval, but also its coefficient of variation (COV). Then, conditional probabilities can be calculated separately for every fault (e.g. McCalpin and Slemmons, 1998; Papanikolaou

E-mail address: t.wiatr@nug.rwth-aachen.de (T. Wiatr).

http://dx.doi.org/10.1016/j.geomorph.2014.09.021
0169-555X/

et al., 2013). As a result, fault bedrock scarps that are the cumulative result of many earthquakes, offer the possibility to extra such information, forming a valuable tool for seismic hazard assessment.

In general, fault scarps are dislocations of the ground surface, forming the primary geomorphic expression of active faulting and are commonly exposed in basement rocks (Stewart and Hancock, 1990, 1994). Exposed fault scarp segments result from shallow earthquakes generated at depths of around 10–15 km with magnitudes greater than 6 M_S (Stewart and Hancock, 1990). Fault planes associated with fault scarps bear lineations in the direction of fault slip (slickensides) which indicate the motion of fault movement; kinematic indicators range from metre-scale corrugations and gutters to centimetre-scale as well as micron-scale frictional striae (Stewart and Hancock, 1990, 1991).

Some features of the fault plane surfaces are proxy data of the kinematics (present-day stress field, palaeostress), slip rates (long term slip, individual events) and magnitudes of past events. This preserved information, along with absolute dating methods (e.g. cosmogenic nuclide dating), is used to decode previous earthquake activity (Zreda and Noller, 1998).

Our study was undertaken on a postglacial and naturally exposed scarp of the Pisia fault located at the eastern end of Corinth Gulf, in Greece, which ruptured during the 1981 Alkyonides earthquake sequence. This investigation is focused on the comparison of ruggedness changes and backscatter signal behaviour along the bedrock scarp height parallel to the slip direction using terrestrial laser scanning (t-LiDAR). The main goal of our research was to scan and analyse individual postglacial fault planes to determine which differences and changes can be traced on each of the surfaces; t-LiDAR data was used to analyse changes in surface structure and to determine characteristic features of the fault planes. Fault planes of naturally exhumed scarps are increasingly altered upwards by external influences and several geomorphic processes (i.e. weathering, karstification, bioerosion). Past coseismic events go back further in time with increasing scarp height and have, therefore, been exposed to weathering processes for a longer time (Giaccio et al., 2002). This time dependence is noticeable on the plane surface by different stages of weathering, bio-erosion, karstification, fractures, cracks, joints, vegetation and lichen growth. Moreover, there is a spatial dependence on the fault plane study location, which must be considered in the evaluation, along with the strike of the fault segment and the environmental conditions of data collection (Roberts, 1996; Roberts and Michetti, 2004). These temporal and spatial modifications are recorded using a ground based remote sensing technique (t-LiDAR) in which they are dimensionally preserved for subsequent analyses. We apply the t-LiDAR data in combination with high-resolution digital elevation models (HRDEM) and high-resolution digital backscatter signal model (HRDBSM) to analyse the structural changes on the fault plane. By using these independent methods, surface changes can be recognised along both the bedrock fault scarp height and along strike. Displacements and structural changes at different locations along the escarpment can then be correlated.

A fundamental hypothesis for this detailed analysis is the assumption that the ruggedness of a fault plane increases during the phases between rupturing earthquake events. In other words the longer the inter-event time or the recurrence interval, the higher the ruggedness. In this inter-seismic period, external processes (i.e. weathering) have the potential to increase the ruggedness of the fault plane. This means that the processes producing the ruggedness (weathering, erosion) affect the surface significantly more during the inactive phases than during the displacement. This imprint on the fault plane should be noticeable and could be used for relative dating between two long inter-seismic periods on an active bedrock fault system. If the interval height between these two stages (vertical displacement), the length of the fault system and the motion direction of the hanging-wall (slip vector) are known, the magnitude can be estimated with the empirical formulas of Wells and Coppersmith (1994) and these results can be cross-validated.

A small number of projects have been carried out to detect and characterise fault plane in term of roughness and t-LiDAR (e.g. Fardin et al., 2001; Renard et al., 2004; Rahman et al., 2006; Renard et al., 2006; Sagy et al., 2007; Candela et al., 2009; Brodsky et al., 2011; Candela et al., 2011; Candela and Renard, 2012; Renard et al., 2012), however, the use of t-LiDAR in neotectonic studies to analyse active faults is not well established and is still an emerging field. Fault plane analyses through descriptive approaches are more common and they support methods to quantify, design, develop and establish the terrestrial remote sensing technique in neotectonic and geological earthquake studies (Kokkalas et al., 2007; Kondo et al., 2008; Wilkinson et al., 2010; Karabacak et al., 2011; Wiatr et al., 2013). These studies have shown that the calculation of roughness on fracture surfaces depends on different surface materials and surface characteristics, and that these factors must be considered when estimating rock surface roughness (Feng et al., 2003). The fault's free face is exposed to weathering which leads to increased rock surface roughness with time, but the free face roughness has proved difficult to quantify (Stewart, 1996). Moreover, investigations of bedrock fault scarp surfaces with t-LiDAR have shown that fault planes are self-affine, anisotropic and fractal. The calculation of roughness with fractal geometry depends on: i) scaling and ii) slip orientation (parallel or perpendicular to the slip) (Candela et al., 2009; Candela and Renard, 2012). Additionally, the roughness parallel to the slip direction varies with slip displacement; roughness decreases with increasing slip, as the fault plane is polished at small scales and faults with low slip rates have a higher roughness at all scales (Sagy et al., 2007; Candela et al., 2009; Brodsky et al., 2011). The roughness and the geometry of fault surfaces are very important factors when considering the interpretation that the roughness is decreasing with increasing slip (Brodsky et al., 2011). These investigations were mostly performed on non-weathered fault surfaces.

The significant difference of our approach is that the investigation was carried out on a naturally exposed and weathered fault surface. The study site has a long faulting history with the last surface rupturing event in 1981. This paper does not address the scaling question of fault plane roughness and resolution. In our approach we use a close range t-LiDAR view in order to investigate the natural bedrock fault plane's surface characteristics and backscatter behaviour for subsequent analysis of the slip history and geometry.

An additional major difference of our approach with respect to previous publications (Candela et al., 2009; Brodsky et al., 2011; Wei et al., 2013) concerns the methodology for extracting and calculating ruggedness. These authors used line profiles, whereas we calculated the terrain ruggedness index (TRI) based on extensive areal data (cells, grid and the spatial distribution of changes). Therefore, our approach is favourable for determining the spatial distribution of ruggedness on a surface. Furthermore, two independent approaches with different dimensions were used in order to analyse the heterogeneity behaviour of a fault plane. Hence, established remote sensing approaches were adapted for this investigation. The starting point is the objective approach of unsupervised classification of the detected backscattered signal to create classes with significant differences in backscatter signal across the fault plane. The TRI is then used to evaluate the disparity of the fault plane topography in order to characterise differences in natural fault plane alteration all along the height of the fault surface within the scan window. Following these results, detailed analyses were performed using the unsupervised classification and TRI in boxes (10 cm high and 20 cm wide) along the height of the fault surface. Each box includes 4000 values of the calculated TRI and the detected backscatter signal.

There are two major goals (hypotheses) for this study and these were performed with the comparison and fusion of the results from unsupervised classification and TRI resulting from the t-LiDAR data.

Hypothesis (*i*): The ruggedness is increasing from base to top. Using t-LiDAR data with objective approaches we can prove that the ruggedness is increasing as a result of the external influences such as