INTRODUCTION

Crete is the largest Greek island with an area of ~ 8300 km² and approx. 900 km coastline. The development of a multidirectional tectonic regime on Crete is interpreted as a result of the Hellenic subduction zone in the south and the westward extrusion of the Anatolian plate in the north. The island is formed as a horst structure in the Hellenic fore arc zone, which is also influenced by the roll back of the African plate. Rapid uplift of ~ 1.2 mm/yr can be observed on the entire island (Meulenkamp et al., 1994). Crete has been uplifted since the Middle Miocene from 1 up to 2 km depending on the influence of different tectonic blocks. The island of Crete lies on top of the active subduction zone for about 30 ma years, implying that it experiences high strain rates and constant deformation processes (Papanikolaou, 1993). Crete is characterised by a complex geological and tectonic structure that results from: i) the successive thrusting of the alpine geotectonic units on top of each other (Bonneau, 1984), ii) the activity of major detachment faults (Fasoulas et al., 1994, Papanikolaou and Vassilakis, 2010, Zachariasse et al., 2011), iii) by the intense neotectonic and active faulting (Monaco and Tortorici, 2004, Peterek and Schwarz, 2004, Caputo et al., 2010). Crete is located in a high seismicity area. Over the last 40 years the active Hellenic subduction zone produced earthquakes in a depth range from 18 to 162 km with magnitudes of M > 4.9 up to 6.1 (Benetatos et al., 2004). Hypocentral depths of earthquakes showed that the north dipping Wadati-Benioff seismic zone close to the low angle subduction along the convex side of the Hellenic arc trench is located in a depth of around 60 to 90 km near Crete (Papazachos et al., 2000). But this region has also experienced strong thrusting paleoearthquakes with magnitudes up to M > 7.5 - 8.0 and hence one of the most intense seismic activity area of the Aegean region (Papazachos & Papazachou, 1997).

Decoding paleoearthquakes in fault bedrock scarps is important for seismic hazard assessment. Shallow earthquakes greater than M ≥ 6 can produce an imprint in the landscape named fault scarps (Stewart & Hancock, 1990). Bedrock fault scarps are indicators of large surface faulting events and may provide not only slip rates, but also information on slip per events when they are analysed with cosmogenic isotope dating (Benedetti et al., 2003). Fault scarps are preserved in the landscape when the slip rate is greater than the erosion rate. Therefore, these are regarded as postglacial scarps that were formed since the last glaciation (Benedetti et al., 2002). The Neogene fault plane solutions and the seismic activities indicate large earthquakes and a rapid uplift with complex tectonic settings of Crete (Dewey & Sengör, 1979; Papazachos et al., 1987). This paper is focused on the N-S striking fault zone in the Heraklion basin to the south of Knossos (Fig.1). This basin is characterized by block tectonics and the Yiouchtas Mt. represent a neotectonic horst structure which is subdivides the Heraklion Basin in a western and an eastern subbasin (Papanikolaou and Nomikou 1998). Major aims of the investigation were to find quantitative and qualitative data for the reconstruction of surfaces and to analyze the tectonic geomorphology and paleoseismicity of active faults with terrestrial laser scanning (TLS) to reconstruct fault history and activity along surface rupturing scarps.

The varying scale of structural heterogeneity and discontinuous geometry of the exhumed foot wall slip plane along a fault zone and the complexity of the surface features like the subslip-plane breccia sheet, brecciated colluvium or frictional water-wear striaions on the rupture plane, makes it difficult to recognize the paleoevents on the fresh fault scarp.
above the level of exhumation (Stewart & Hancock, 1991; Roberts, 1996). Even, more the detail geometrical characterisation of the slip surface depends on the view direction to the strike-slip direction (parallel or perpendicular), the calculation approaches and the scaling size of the analysis, because the anisotropy properties and fractal dimensions of fault morphology are decisive (Mandelbrot, 1985; Fardin et al., 2001, 2004; Rahman et al., 2006; Renard et al., 2006; Sagy et al., 2007, 2009; Candela et al., 2009). Additionally, several time-dependent and overlapping processes influence the condition of the free face fault plane that become degraded. These processes involve weathering, pedogenesis of the unbrecciated colluvium, vegetation, karstification and erosion of the colluviums and the fault outcrop.

PRIMARY RESULTS OF THE LiDAR INVESTIGATION ON THE NORMAL FAULT ZONE NEAR ANEMOSPILIA “CAVES OF THE WIND” (1900-1700 BC MM II/III) IN THE HERAKLION BASIN

In the northern part of the Mount Juktas about 7 km south of Knossos, the legendary area and tomb of Cretan Zeus is situated, which is considered to be one of the earliest Minoan temples: Anemospilia (Fig.1).

The three small rooms, each of them opened into a corridor, were described and discovered by Sakellarakis during the 1979 expedition. They assumed that the temple was destroyed by a sequence of large earthquakes around 1700 BC and based this conclusion on pottery and artefacts (Nur, 2008). Furthermore, they found a skeleton with broken legs under an ash layer implying that the earthquake was strong enough to damage the massive temple and was followed by a fire. Five different close range LiDAR scans were made in the middle of the N-S striking normal fault 2 km south of the Anemospilia temple (Fig.2). The free natural fault plane in the interesting area is around 6 m high and the scanned area is around 30 m wide. The whole outcrop is by this location around 70 m continuous wide. Our primary goal in this study was to use the TLS for fault tectonomorphology reconstruction. The TLS data have a point to point range between 3 and 7 mm. The examples in this paper (Fig.3/4) had around 2.8 and 3.8 million numbers of shots (points) and the average range between LiDAR and defined scan window was 10 m. This allowed a spatial reconstruction of the scan sequence without gaps and ensured a good data quality and spatial resolution for the interpolation between the points and for the analysis of the plane morphology. The detailed structural analysis of rock surfaces has shown that the surface conditions are changing from base to top (Fig.4). The hillshades in figure 3b and 4b illustrates the plane morphology with different karstic features and degradation in the upper part of the scarp plane (variance of rougher surface conditions in section III, IV, V, VI in Fig.3).

Fig. 2: Photo of the east dipping continuous normal fault zone western Archanes and eastern Mount Yiouchtas within the ancient Minoan site Anemospilia in the northern part of Mount Juktas (a). b) Zoom in photo of the fault plane.

Parts I and II of this section have no significant karstification. The sections are dominated by striation, slickensides and small fractures (compare Fig.4). The combination of the plane morphology with the detected backscattered signal of the LiDAR is shown in figure 3d/3e and 4d. By using this technique, a different point of view allowed that the detected near infrared laser signal can be used for the classification of different functions of weathering, morphological and erosion features on the fault plane.
and also reveals the exhumation history. The signal intensity can be used to identify vegetation (including lichen) and its influence on the fault plane. The results show the influence of the colluvium on the base of the scarp (Fig. 3e), which can be detected by a change of the backscattered intensity. Furthermore, it is possible to distinguish between the different parts of the fault plane, which are characterised and dominated by 1) degradation; 2) karstification; 3) slickensides; and 4) the influence of the colluvium. Following Giaccio (2002) and the model of natural free normal bedrock scarp, we identified different weathering micromorphologies depending on the scarp height (Fig. 4e). The different sections with determinates features on the fault plane represent the time-dependent fault scarp evolution (Stewart, 1996).

The time- and height-dependent features of bedrock fault scarps are shown figure 4e. The boxes illustrate examples of the fault plane morphology from bottom to top (young to old; brown, red, green, yellow). Conspicuous is the increasing roughness from young to old (brown to yellow) and the specific surface features in different heights. The reason could be the different bio-karstic, bio-erosional, physical and biochemical processes which depend on time (Giaccio et al., 2002). The brown box shows the striation in the lower part of the fault. The red box illustrates small fractures and a rougher surface than in the brown box. The green box the gradation of the karstification and the yellow box show the rillen karst in an advanced stage. Close range LiDAR investigation on postglacial natural normal fault scarps has shown that reconstruction of the spatial distribution of different plane evolution indicators is possible.

These fundamental phenomena can be realized by and imaged with a high resolution digital elevation model (HRDEM) in combination with the backscattered laser impulse. The primary interpretations of the fault surface conditions and their interaction are described in figure 3. Based on the LiDAR results and the field survey we created a principal model of fault scarp alteration for the East Yiouchtas fault, following the general model of Giaccio et al. 2002 (Fig. 5).
The investigation with LiDAR and the field survey has shown that the eastern Yiouchtas fault is active with several events in the post-glacial time period.

References


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