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Slip vector analysis with high resolution t-LiDAR scanning

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ABSTRACT

A palaeostress analysis of an active bedrock normal fault scarp based on kinematic indicators is reconstructed using terrestrial laser scanning (TLS). For this purpose, three key elements are necessary for a defined region: (i) the orientation of the fault plane, (ii) the orientation of the slickenside lineation or other kinematic indicators, and (iii) the sense of motion of the hanging wall. The paper specifies a workflow in order to obtain stress data from point cloud data using terrestrial laser scanning (TLS) in an active tectonic environment.

The entire analysis was performed on a continuous limestone bedrock normal fault scarp on the island of Crete, Greece, at four different locations along the WNW–ESE striking Spili Fault. At each location we collected data with the terrestrial light detection and ranging system (t-LiDAR). We then validated the calculated three-dimensional stress results at three of the locations by comparison with conventional methods using data obtained manually with a compass clinometer. Numerous kinematic indicators for normal faulting were discovered on the fault plane surface using t-LiDAR data. When comparing all reconstructed stress data obtained from t-LiDAR to that obtained through manual compass measurements, the degree of fault plane orientation divergence is ±005/03 for dip direction and dip. The degree of slickenside lineation divergence is ±003/03 for dip direction and dip. Therefore, the percentage threshold error of the individual vector angle at each investigation site is lower than 3% for the dip direction and dip for planes, and lower than 6% for the strike. The maximum mean variation of the complete calculated stress tensors is ±005/03.

1. Introduction

Palaeostress analysis is used to reconstruct stress field variations for a defined region throughout different geological periods. In particular, the analysis of neotectonic fault segments and their stress field orientations is essential for the investigation of present-day geodynamics, fault kinematics, recent seismic events, potential reactivations of fault segments, and for the evaluation of the fault activity. Furthermore, natural fault scarps and exhumed fault plane segments are indicators of shallow earthquake activity with earthquakes that cut the entire seismogenic layer, involving magnitudes greater than $M_S > 6$ (Stewart and Hancock, 1990).

Study of normal faults has shown that slip-directions vary with throw and distance, converging towards the fault hanging walls (Roberts, 1996; Maniatis and Hampel, 2008; Michetti et al., 2000). Indeed, the hanging wall of normal faults is stretched along strike because hanging wall subsidence is greater than footwall uplift and fault throw is greatest at fault centres whereas it decreases to zero at the fault tips (Ma and Kusznir, 1995; Roberts, 1996). Fault lengths should therefore be reflected in the length-scale of the converging patterns of fault slip; as a result they have also been used as an indicator for defining fault lengths (Papanikolaou and Roberts, 2007; Roberts and Michetti, 2004).

For palaeostress reconstruction, we need to obtain some key elements in order to define the fault character, its geometry and the sense and direction of motion. Fault segments have to be characterised and described for deciphering the fault evolution in a specific area. Therefore, the fault plane orientation, the orientation of slickenside lineation and the shear sense of motion, i.e. the movement of the hanging wall, have to be determined. The varying scales of structural heterogeneity, discontinuous geometry along the exhumed footwall slip plane, and the complexity of the surface features like subslip-plane breccia sheets, brecciated colluvium or frictional water-wear striations on the rupture plane, make it difficult to recognise palaeoevent indicators on natural fault scarps above the level of exhumation (Roberts, 1996; Stewart and Hancock, 1991). Nevertheless, several authors have published, described and classified tectonic normal fault structures, slickensides and other important kinematic indicators, at different scales, in order to identify the shear sense on active normal faults (Doblas, 1998; Doblas et al., 1997; Hancock and Barka, 1987). For our study we used an artificially exhumed slip plane, a fresh fault scarp above the level of exhumation, a degraded fault scarp and an unbrecciated Quaternary colluvium for metre scale descriptions to determine the fault kinematics (Hancock and Barka, 1987). In

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addition, at the tens of centimetre scale, eleven major groups of slickenside kinematic criteria on the exhumed fault plane were used (see Doblas, 1998).

Some recent studies on active fault planes using terrestrial laser scanning (TLS) have indicated that the investigative technique is applicable for morphotectonic analysis (Candela et al., 2009; Jones et al., 2009; Sagy et al., 2007). Using TLS allows data to be collected in dangerous, steep and inaccessible outcrops (Nguyen et al., 2011). Moreover, virtual geometric measurements (Kokkalas et al., 2007) and statistic calculations (Candela et al., 2009; Sagy et al., 2007) of natural fault scarps can also be obtained.

This paper presents a remote sensing solution for slip vector reconstruction in an active tectonic regime using a t-LiDAR system. The test site was on the Spili Fault, which is an active normal fault in limestone bedrock located on the island of Crete in the Aegean region. All measurements of the fault plane, slickenside lineations and slickenside kinematics were performed through analysis of terrestrial remote sensing data and accompanied also with a conventional compass and clinometer so that a comparison can be made. Extension direction analysis was carried out for both data sets and the results were compared.

1.1. Location

The island of Crete (Greece) is located north of the Hellenic trench and south of the volcanic arc in the external Hellenides and is associated with the Oligocene/Miocene high pressure/low temperature belt (Fassoulas et al., 1994). 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 (Fassoulas et al., 1994; Papanikolaou and Vassilakis, 2010; Zachariasse et al., 2011), and iii) the intense neotectonic and active faulting (Caputo et al., 2010; Monaco and Tortorici, 2004; Peterek and Schwarze, 2004).

Crete has undergone uplift of around 2.5 km since the Early Tortonian (Miocene) in several different phases (Meulenkamp et al., 1994). The most recent phase of uplift as evidenced by the uplifted Messinian deposits (Krijgsman, 1996) began at around 6 Ma and continue up to the present day. This is evidenced by the sudden uplift of max. 9 m in AD 365 caused by an earthquake on the plate boundary with an estimated magnitude of $M > 8$ (Fassoulas, 1999; Meulenkamp et al., 1988; Scheffers and Scheffers, 2007; Stiros, 2001).

Crete has a complex pattern of fault zones due to the island's tectonic evolution. There are two major groups of active normal fault strike directions located on the island (Fig. 1a); many of the associated fault scarps are very impressive and late Quaternary in age. The first group is the WNW–ESE trending faults with north and south dipping fault plane segments, which are principally located in the central southern Crete. Caputo et al. (2010) define four active major normal fault segments within this group including the Sfakia Fault, the Asomatos Fault, the Agia Galini Fault and the Spili Fault; these four fault segments have a cumulative length of around 55 km. The second group is the NNE–SSW trending normal fault segments. These faults are distributed throughout the entire island. The major faults and fault zones of this group are the Phalasarna Fault, Gramvousa Fault, Rodopos Fault Zone, Asterussia Fault, Eastern Psiloritis Fault Zone, Giouchtas Fault, Kastelli Fault, Ierapetra Fault Zone and Sitia Fault Zone (from west to east).

1.2. The Spili Fault

The Spili Fault is located in the southern part central Crete. This fault belongs to the group of WNW–ESE trending normal faults dipping to the south (see Fig. 1b). The fault extends over the southern slope of the Kedros ridge (around 1600 m a.s.l.) and has a total length of 20 to 25 km (Monaco and Tortorici, 2004; Mouslopoulou et al., 2011). The elevation of the Spili Fault varies from west to east. The altitude in the western segment ranges from around 400 m to 900 m a.s.l., the middle segment from around 800 to 600 m a.s.l., and the eastern segment slopes down to around 200 m a.s.l. (see Fig. 1c). The footwall primarily consists of Mesozoic carbonates of the Pindos limestone unit and is partly comprised of the Tripoli limestone unit. The hanging wall comprises formations of alluvial and colluvial deposits.

The Spili Fault has a clear exposed postglacial fault scarp with a maximum height of 8–10 m. The fault scarp is predominantly a free face; however, in localities it is also partly exposed by selective erosion and anthropogenic intervention. All main characteristics across the scarp can be observed such as the artificially exhumed slip planes, the fresh fault scarp above level of exhumations, the free face, the degraded fault scarp and the unbrecciated colluvials. On the fault plane there are various slickenside kinematic indicators such as lineations, plucking markings, tension fractures, hybrid fractures and asymmetric cavities with congruous steps (Fig. 2). Towards the tips of the fault the lineations are continuously inclined pointing towards the hanging wall centre of the fault. Our investigations were carried out at four locations along the exposed fault. At location 1, which is also the sample area from Mouslopoulou et al. (2011) (Fig. 2.1a–d), there is an impressive fault plane containing tension gashes, slickenside lineations, pluck holes and spall marks (Fig. 2.1b). Furthermore, two types of fault gouge are present (Fig. 2.1c), and the eastern part of the fault segment separates into four sub-slip fault planes (Fig. 2.1d). At location 2, the fault plane has been artificially excavated revealing a colluvial wedge. Above the excavated fault plane, the surface is weathered and is increasingly vegetated (see Fig. 2.2e). Locations 3 and 4 are situated near a canyon close to the village Kria Vrisi. The exhumed fault scarp has tension gashes and karstic features (Fig. 2.3f, 4). Some areas on the fault plane contain no kinematic indicators as erosion has completely erased them. However, calcite fibres are present which are located up to 40 cm above the underlying colluvium. Moreover, lineations, breccia sheets, polished fault plane surfaces and corrugated slip planes can also be observed.

V-shaped canyons and wind gaps are also present on the footwall mountain ridge in the north. Moreover, earthquake archaeological effects are described at the archaeological site of Phaistos, located around 20 km south-east of the Spili Fault; the site dates back to Minoan era between 4000 and 1350 B.P. (Monaco and Tortorici, 2004). These factors all indicate that the Spili Fault is active.

2. Data acquisition

Our investigation on the Spili Fault was carried out at four locations along the exposed fault escarpment (Fig. 1b). These areas comprise the middle segment of the fault and cover a distance of 10 km. The individual locations have exposed fault planes up to several metres in height. The locations also contain a variety of useful kinematic features (subslip-plane breccia sheet, corrugated slip plane, brecciated colluvium, polished surfaces, degraded fault scarps and slickensides), which can be used to calculate palaeostress. The variation in scarp height can be explained by erosion, variable deposition on the drainage network, anthropogenic intervention and also by the along strike variability of slip along strike of the fault. The kinematic indicators used for palaeostress analysis come in diverse units of scale. The scale of indicators ranges from microscopic, to tens of millimetres, all the way up to metres (Doblas et al., 1997; Hancock and Barka, 1987). Kinematic indicators of microscopic scale could not be measured in the field. This is due to the resolution constraints of the t-LiDAR instrument. However, all other indicators on the fault plane were measured such as corrugations, fractures and calcite fibres.

To reconstruct the palaeostress regime, the orientation of both the fault plane and kinematic indicators must be analysed. For that reason, four measurements on the exhumed fault plane need to be carried out in the field: (i) the dip direction of the fault plane must be measured to determine the spatial orientation; (ii) the dip angle of the fault plane;