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Fault structure and deformation rates at the Lastros-Sfaka Graben, Crete

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ABSTRACT

The Lastros and Sfaka faults have an antithetic relationship and form a ca. 2 km wide graben within the Ierapetra fault zone in eastern Crete. Both faults have impressive bedrock fault scarps many metres in height which form prominent features within the landscape. t-LiDAR investigations undertaken on the Lastros fault are used to accurately determine vertical displacements along a ca. 1.3 km long scanned segment. Analyses show that previous estimations of post glacial slip rate are too high because there are many areas along strike where the scarp is exhumed by natural erosion and/or anthropogenic activity. In areas not affected by erosion there is mean scarp height of 9.4 m. This leads to a slip rate of 0.69 ± 0.15 mm/a using 15 ± 3 ka for scarp exhumation. Using empirical calculations the expected earthquake magnitudes and displacement per event are discussed based on our observations. Trenching investigations on the Sfaka fault identify different generations of fissure fills. Retrodeformation analyses and ^{14}C dating of the fill material indicate at least four events dating back to 16,055 ± 215 cal BP, with the last event having occurred soon after 6102 ± 113 cal BP. The Lastros fault is likely the controlling fault in the graben, and ruptures on the Lastros fault will sympathetically affect the Sfaka fault, which merges with the Lastros fault at a depth of 2.4 km. The extracted dates from the Sfaka fault fissure fills therefore either represent activity on the Lastros fault, assuming they formed coseismically, or accommodation events. Cross sections show that the finite throw is limited to around 300 m, and the derived slip rate for the Lastros fault therefore indicates that both faults are relatively young having initiated 435 ± 120 ka.

1. Introduction

The island of Crete is located within the active extensional regime of the Aegean (Fig. 1a). Many of the associated normal faults throughout the island have bedrock scarps which form prominent features within the mountainous landscape. These normal faults comprise footwall limestone bedrock scarps which are mainly juxtaposed against hanging-wall Quaternary colluvial and/or marine sediments. The faults are easy to recognise as they offset smooth mountain slopes and have steeply dipping preserved fault scarps that are many metres in height. The preserved fault scarps were generated coseismically and result from cumulative earthquake events on the individual fault plane. In the Mediterranean the common theory (Benedetti et al., 2002) is that during glacial conditions the erosion rate of these bedrock fault scarps, and sediment deposition on the hanging-wall, were faster than the fault's slip-rate. This resulted in the bedrock fault scarp being covered and not visible in the landscape. In postglacial times, however, the climatic conditions reduced erosion rates allowing fault scarps caused by recurrent earthquakes to be preserved (Benedetti et al., 2002; Papanikolaou et al., 2005; Reicherter et al., 2011). Scarp preservation is response to the progressive variation of several natural phenomena and their role and intensity in shaping the Earth surface. These include: i) the annual amount of precipitation, and rainfall event duration and intensity; ii) vegetation type and density; iii) mean annual temperature and daily/seasonal variations. These parameters, in turn, strongly influence and govern the overall rate of erosion, the rate and size of clastic production in the footwall block, and the transport energy. Accordingly, it is likely that the growth of a cumulative fault scarp with a relatively stationary velocity (i.e. constant slip-rate) began at 15 ± 3 ka, which is some ka after the last glacial maximum. This ±3 ka age uncertainty is due to the fact that even though the major glacial retreat in the Mediterranean began at ca. 18 ka, some small magnitude glacial re-advances followed by retreat phases have been recorded between 12 ka and 18 ka (Allen et al., 1999; Giraudi and Frezzotti, 1997; Papanikolaou et al., 2013). There are over 20 known bedrock normal faults/fault segments (Caputo et al., 2010) located throughout Crete (Fig. 1b) which are considered to be capable and have large exposed bedrock fault scarps. These faults range from 4 to 25 km in length, some of which stand

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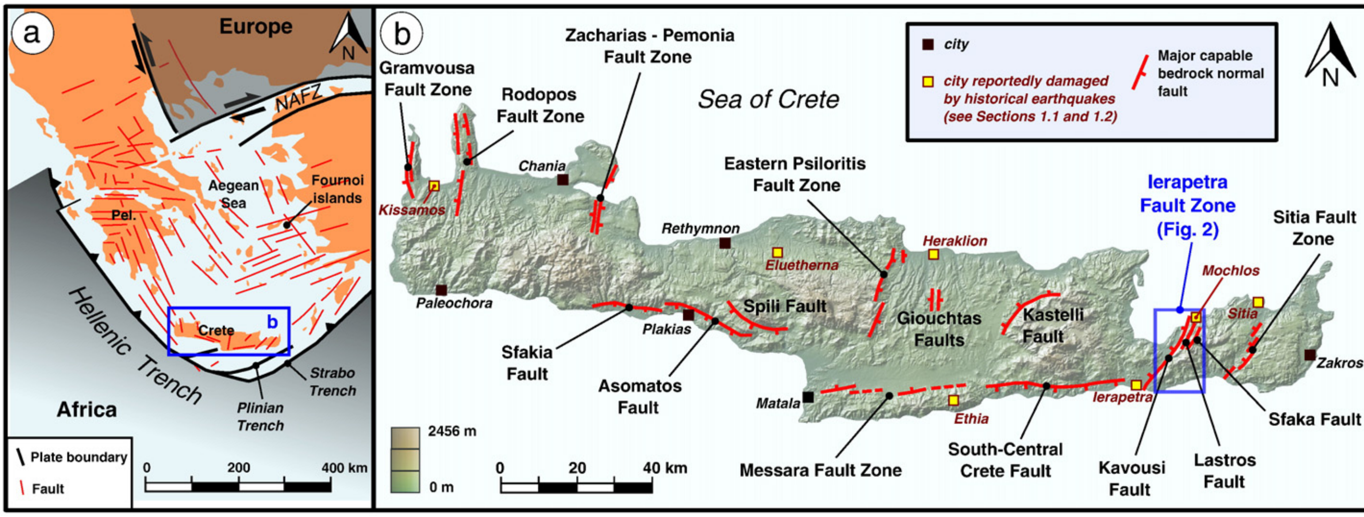

Fig. 1. a) Simplified tectonic map of the Aegean showing plate boundaries and faults, NAFZ = North Anatolian Fault Zone; Pel. = Peloponnese (modified after Papanikolaou et al., 2007); b) relief map of Crete showing the locations of the major capable bedrock faults throughout the island (fault locations from Caputo et al., 2010; Gallen et al., 2014) and cities reported to have been damaged by earthquakes (see main text).

alone and some of which form segmented parts of more complex fault zones; all faults/fault segments have the potential to generate moderate to large earthquakes $M_w > 5.5$ (Wells and Coppersmith, 1994) and are associated with shallow crustal earthquakes of ~10–15 km depth.

This paper presents the results of a multi-disciplinary investigation on the Lastros-Sfaka Graben located within the Ierapetra fault zone (IFZ), eastern Crete (Figs. 1b, 2). The Lastros-Sfaka Graben is approximately 2 km wide and consists of two opposing faults, the Lastros fault and the Sfaka fault (Figs. 1b, 2), both of which strike approximately NNE–SSW and have prominent fault scarps. Methods including geological mapping, terrestrial Light Detection And Ranging (t-LiDAR), trenching (road cuts) and laboratory analyses were carried out at these faults. The results allow us to infer slip rates based on scarp heights and also bracket the dates of the most recent earthquakes, providing an insight into the neotectonic evolution of this part of the island.

1.1. Geological and tectonic setting

The orogenic belt of the Hellenides dominates the structure of the Aegean and has long been recognised to comprise numerous distinct sedimentary facies belts known as "isotopic zones" which have an approximate N-S orientation. It is now understood that these linear isotopic zones are thrust sheets developed as a result of oceanic closure. The island of Crete forms part of the external Hellenides (Aubouin, 1959) and comprises a number of these thrust sheets which have been successively imbricated by other sedimentary and metamorphic units (van Hinsbergen et al., 2005; Papanikolaou and Vassilakis, 2010). In the IFZ in eastern Crete the stratigraphically lowest Mani unit, also known as the Plattenkalk unit (Fig. 2), is the so called autochthon basement comprising crystalline limestone. This unit was imbricated by the Western Crete unit (Fig. 2) which comprises mainly Permo-Triassic phyllites and Middle to Late Triassic evaporites. The Tripolis unit (Fig. 2) was then imbricated and comprises a thick sequence of flysch, limestone, dolomite, andesite, diabase and phyllites, all of which are preserved in eastern Crete. These rocks form the volcano-sedimentary base to the shallower carbonate rocks of the Tripolis carbonate platform, exposed in both Crete and the Peloponnese (Papanikolaou and Vassilakis, 2010). The deformation history of these units within Crete can be summarised as: (i) compressional deformation producing arc-parallel east–west-trending south-directed thrust faults in Oligocene to Early Miocene time (e.g. Bonneau, 1984); (ii) extensional deformation along arc-parallel, east–west-trending detachment faults in the Middle Miocene, with hanging-wall motion to the north and south (Fassoulas et al., 1994; Papanikolaou and Vassilakis, 2010; Zachariasse et al., 2011); and (iii) Late Miocene–Quaternary transtensional deformation along high-angle normal and oblique normal faults that disrupt the older arc-parallel structures (Papanikolaou and Vassilakis, 2010; Peterek and Schwarze, 2004). The Hellenic Arc and trench system is located to the south of Crete (Fig. 1a) and the Late Miocene–Quaternary extension is attributed to crustal back arc extension, interpreted as a response to the southward slab-rollback of the Hellenic margin, the southwestward expulsion of the Aegean microplate and the anticlockwise rotation of the African lithosphere relative to Eurasia (Meulenkamp et al., 1988; Reilinger et al., 2006). The southward slab-rollback is the predominant mechanism; from the Middle Miocene the central and southern Aegean domain began to extend rapidly in a north-south direction implying the rapid migration of the Crete trench relative to northern Greece (Angelier et al., 1982; Royden and Papanikolaou, 2011). Extension is occurring orientated both arc-perpendicular and arc-parallel, which has led to a complex pattern of normal faulting throughout the region (Fig. 1a) which affects the entire pile of tectonic units (Fig. 2). Crete has normal faults roughly oriented both NNE–SSW and ESE–WNW (Fig. 1b). Mountrakis et al. (2012) state that for northwestern Crete the ESE-WNW trending faults are older and now inactive as they do not affect Quaternary deposits and are overprinted by N-S trending faults. Moreover, focal mechanisms for recent normal faulting earthquakes throughout the whole of the island (Heidbach et al., 2008) also show predominantly E-W extension, indicating that the NNE–SSW trending faults may pose a higher hazard.

The study area is the Lastros-Sfaka Graben located in eastern Crete (Figs. 1b, 2, 3). The Lastros-Sfaka Graben forms part of the IFZ which consists of a roughly 25 km long zone of fault segments most of which dip WNW (Fig. 2). The westernmost and longest is the Ierapetra fault which likely traverses the whole width of the island. The Lastros fault dips to the ESE and forms the ESE boundary of the Kapsos ridge (Figs. 2, 3b). The easternmost Sfaka fault has an antithetic relationship with the Lastros fault dipping WNW. The footwall mountains of both the Lastros and Sfaka faults comprise crystalline limestone of the Mani unit (Papanikolaou and Vassilakis, 2010). In the south of the graben the hanging-wall of these faults comprises limestone of the Mani unit and Permian-Triassic phyllites of the Western Crete unit overlain by Quaternary colluvial deposits, whereas in the north the hanging-wall mainly comprises Permian-Triassic phyllites of the Tripolis unit overlain by Quaternary colluvium. In many places on both faults this young colluvium has become cemented. A detailed description of the Lastros and Sfaka faults is provided in Sections 2 and 3 respectively.