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Key Points:

- Displacement and fault length constrain earthquake and fault growth processes on orthogonal fault sets
- Millennial displacement rates are a factor of 4 higher than million-year rates, with the greatest disparity for short (<10 km) faults
- Paleoearthquakes on Crete three times more frequent than historical earthquakes for the last 100 years, possibly due to multi-fault ruptures.

Supporting Information:

- Supporting Information S1
- Table S1

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Displacement Accumulation and Sampling of Paleoearthquakes on Active Normal Faults of Crete in the Eastern Mediterranean

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Abstract Active normal faults on the Mediterranean island of Crete form prominent limestone scarps together with basin and range topography. These faults mainly strike E-ESE and N-NNE in southern and northern Crete, respectively, with fault sets commonly intersecting and northerly trending faults being a factor of 3 more abundant. Lengths, displacements, and displacement rates have been analyzed for 84 active faults sampled over 2 ± 0.5 Ma (long-term) and 16.5 ± 2 ka (short-term) time-intervals, with half showing no resolvable short-term activity. Active faults record earthquake processes on timescales of thousands to million years and constrain sampling biases, which can lead to under and over estimates of fault parameters. The available data provide no evidence for fault propagation and support a model in which fault lengths were established early in the development of the fault system. Short-term displacement rates (0.09–1.2 mm/year) are generally higher than long-term rates (0.002–0.7 mm/year), with a factor of 4 disparity in the average recurrence intervals for the two time periods (~ 2.5 Kyr vs. ~ 11 Kyr). We attribute these differences to “clustering” of surface-rupturing (e.g., $>M_w6$) earthquakes on individual faults over millennial timescales, and to preferential sampling of the most seismically active faults during the short-term. Displacement rates are comparable when averaged for each time interval on the longest faults (>10 km), indicating that for these faults earthquake “clustering” spans time-intervals of $<\sim 16.5$ Kyr. Paleoearthquakes $> M_w6$ on Crete are at least three times more frequent than historical earthquakes since ~ 1920 , possibly because multi-fault surface-rupturing earthquakes are double counted in the paleo-record.

1. Introduction

Active fault traces generally form due to displacement of the ground surface or seabed during surface-rupturing earthquakes (Gilbert, 1884; McCalpin, 2009; Stein et al., 1988; Wallace, 1987) (Figure 1). Repeated surface-rupturing earthquakes can produce topography, the height of which depends on the total fault displacement and the relative rates of fault displacement and surface processes (i.e., deposition or erosion) (Figure 1, block diagram). Where sedimentation rates exceed fault displacement rates, the faults are buried and their growth histories can be recovered from subsurface information, including seismic reflection lines and trenches (Childs et al., 2003; McCalpin, 2009; Mouslopoulou et al., 2012; Nicol et al., 2005; Sieh et al., 1978). In cases where the rates of surface process are low relative to fault displacement rates, topography can provide a useful proxy for total fault displacement on geological timescales (e.g., Doutsos & Poulimenos, 1992; Roberts et al., 2002; Veliz et al., 2018) (Figure 1, block diagram). For normal faults, such topography occurs in many areas of mainly terrestrial crustal extension including, the Basin and Range (Friedrich et al., 2004; Pierce & Morgan, 1992), the East Africa Rift (Manighetti et al., 2015; Morley, 1999), the Apennines (Roberts et al., 2002), the Gulf of Corinth (Gawthorpe et al., 2018; Poulimenos, 2000), and the Taupo Rift in New Zealand (Nicol et al., 2006, 2010). Many of these systems also contain active fault traces that record displacements arising from small numbers of earthquakes (e.g., <10) which displaced the ground surface (Benedetti et al., 2003; Friedrich et al., 2004; Iezzi et al., 2019; Nicol et al., 2010; Roberts et al., 2002). In such cases, comparison of Late Quaternary displacements from fault scarps that define active traces and Plio-Pleistocene fault displacements along individual faults, permits the characterization of earthquake processes on timescales ranging from hundreds to millions of years (Friedrich et al., 2004; Mouslopoulou

Figure 1. Normal fault growth over different timescales. (a) Schematic block diagram showing the range and basin topography and active fault scarp, together with measurements of Quaternary vertical displacement measured from bedrock and range height. (b) Schematic graph showing displacement accumulation on geological (Quaternary) timescales (thick black line) with the open circle showing the cumulative displacement indicated in the block diagram. Thick dashed line shows average displacement accumulation for the duration of faulting at a rate of 0.5 mm/year. Displacement curve in the box is shown in “c.” (c) Schematic graph showing the accumulation of fault displacement (thick black line) in five earthquakes (labeled EQ1–5). SED in individual earthquakes is indicated by the height of the vertical sections of the curve, while recurrence intervals are defined by the lengths of the horizontal sections of the curve. Thick dashed line shows average displacement accumulation for the duration of faulting at a rate of 0.5 mm/year, while the thick gray line shows the range of displacement rates averaged for two earthquake cycles. SED, single event maximum displacement.

et al., 2009, 2012; Nicol et al., 1997, 2005, 2009, 2010; Roberts et al., 2002; Stein et al., 1988; Veliz et al., 2018; Wallace, 1987) (Figures 1b and 1c).

In this paper, we use a combination of millennial and million-year displacements to analyze displacement accumulation and surface-rupturing earthquakes for active normal faults on the eastern Mediterranean island of Crete. Utilizing these two datasets provides a means of assessing and addressing the sampling biases commonly associated with paleoearthquake data, of defining the variability of earthquake processes, and of examining the role of earthquakes in fault development on timescales up to millions of years. The normal faults studied are developing in the overriding Eurasian plate due to oblique subduction and rollback of the North Africa plate along the Hellenic margin (Caputo et al., 2006; Jolivet et al., 2013; McClusky et al., 2000; Reilinger et al., 2006) (Figure 2c). Surface-rupturing earthquakes produced widespread limestone fault scarps following the Last Glaciation Maximum (Figure 3), while Quaternary displacements of normal faults generated basin and range topography (Figures 2 and 4–6) (Caputo et al., 2006, 2010; Mason et al., 2016; Mouslopoulou et al., 2014). Fault and earthquake analysis has been conducted using maximum displacements, trace lengths, and displacement rates averaged since ~ 2 Ma and from 16.5 ± 2 ka to the present using, respectively, a topographic proxy for displacement and throws from active fault scarps (Fassoulas, 2001; Fassoulas & Nikolakakis, 2005; Mouslopoulou et al., 2014; Veliz et al., 2018) (Figures 1 and 4–6). Fault data have been augmented by historical seismicity from the written (last 2,000 years; Papadopoulos, 2011) and instrumental (1964–2018; National Observatory of Athens) records, and collectively afford information on earthquakes spanning timescales of days to millions of years. The use of datasets spanning different time intervals offers the opportunity to improve understanding of earthquake processes, fault growth, and seismic hazards that would not be possible using the individual datasets alone. Our results may have application to other areas of active normal faulting, both within Greece and elsewhere.

Figure 2. Active faulting on Crete. Fault map of eastern (a) and western (b) Crete. Lines on the digital elevation model (DEM) indicate active normal faults with resolvable activity during the last ~16.5 years (postglacial scarp faults are also highlighted) and late-Quaternary activity alone (with no resolvable postglacial displacement). Numbers next to faults correspond to fault ID's presented in the Table S1. Blue filled circles indicate localities where faults intersect the coastline. The Klima Fault (ID = 24 in Table S1) is extended offshore for ~21 km based on bathymetric data from EMODNET (<http://www.emodnet-bathymetry.eu/>; last accessed December 2018). Localities A-E are discussed in Section 3.2. Yellow circle on the Spili Fault (Fault ID = 25 in Table S1) shows the locality where cosmogenic dating constrained the age of the postglacial period on Crete (that commenced at ~16.5 ka; Mouslopoulou et al., 2014). The localities of Figures 4 and 6 and the study area of Veliz et al. (2018) are indicated. (c) Crete (indicated by the rectangle) is located on the forearc of the Hellenic subduction margin, along which the African and the Eurasian plates converge. Labeled arrows show geotectonically derived site velocities (mm/year) relative to a fixed African plate (Reilinger et al., 2010). WM, White Mountains.

Figure 3. Postglacial carbonate fault scarps on Crete. Photographs (a–e) illustrate postglacial fault scarps on Crete. Numbers by fault names correspond to the fault ID presented in Table S1. The maximum postglacial and Quaternary displacements, together with their uncertainties, are annotated. Circle in (d) highlights a section of the Fournofaraggo Fault (ID = 35 in Table S1) scarp that is being locally buried by fan debris material. Red and green arrows in (a–d) and (e) indicate postglacial and late-Quaternary fault scarps, respectively. PG, postglacial.

2. Tectonic Setting and Active Faults

Active normal faults on Crete are interpreted to have formed in response to rollback of the subducting African plate along the Hellenic subduction margin (Jolivet et al., 2013) (Figure 2c). Crete forms part of the

Figure 4. Active faults on Crete with and without postglacial scarps. (a) DEM of the WMFS in Elounta area with and without the interpreted normal faults. (b) Active normal faulting within the Messara Basin and topographic profiles across faults with Quaternary only (A and A') and Quaternary plus postglacial (B and B') activity. Numbers next to faults correspond to fault ID's presented in the Table S1. The sections of the active faults that present postglacial activity (e.g., well defined scarp) and only Quaternary activity are indicated by red and green lines, respectively. For location of the WMFS and the Messara Basin on Crete see Figure 2b. WMFS, Western Mirabello Fault System.

subaerial forearc of the Eastern Mediterranean Hellenic subduction margin, which accommodates 35–40 mm/year of oblique convergence between the African and Eurasian plates (Figure 2, inset) (Floyd et al., 2010; McClusky et al., 2000; Reilinger et al., 2006). Although the subduction process along the Hellenic margin has been characterized as largely aseismic (Floyd et al., 2010; Reilinger et al., 2006; Vernant et al., 2014), recent global positioning system (GPS) studies show that locally locked patches beneath southwest

Figure 5. Geometric characteristics of normal faulting on Crete. Plots showing active fault orientation, displacements, and lengths for postglacial and Quaternary faults. (a) Graph of fault dip versus fault strike for fault planes exposed along active fault scarps with postglacial displacement. (b) Frequency histogram of fault dip for data in (a). (c) Histogram of fault strike for data in (a). (d) Plot of Quaternary fault displacement measured from topography against postglacial fault displacement measured from active fault scarps. (e) Plot of Quaternary fault length determined from topography against postglacial fault length measured from active fault scarps. Postglacial displacements <3 m and trace lengths <2 km are inferred to be incomplete (see vertical dashed lines in [d] and [e], respectively).

Peloponnese and southern Crete may accommodate up to 85% of the plate-motion (either on the main subduction thrust or on splay-thrust faults) (Howell et al., 2017; Saltogianni et al., 2020). These locked patches are also reflected in the instrumental seismicity catalog where moderate-to-large thrust and strike-slip events are commonly produced in the deeper (>15 km) sections of the crust beneath Crete, and normal-fault focal mechanisms in the overlying upper crust (<15 km) (Kiritzi & Louvari, 2003; Konstantinou et al., 2017). Further, GPS data reveal that the margin-normal component of the relative Eurasian–Africa plate motion decreases from west to east along Crete, with extensional kinematics dominating in eastern Crete (Floyd et al., 2010; Reilinger et al., 2006; Saltogianni et al., 2020). The landscape (e.g., topography)

Figure 6. Fault intersections between synchronously active normal faults. DEM illustrates active faults of various orientations/sizes intersecting one another at high angles in the region of Kastelli, eastern Crete (see Figure 2b for locality). All faults across this intersection demonstrate postglacial activity indicating that both sets of faults ($\sim$ N-S and $\sim$ E-W) were simultaneously active. Displacement profiles (P1–P3) across three of the intersecting faults indicate the relationship between topography and cumulative fault displacement. Numbers by fault names correspond to the fault ID's presented in Table S1.

along Crete is consistent with the contemporary kinematics of deformation, suggesting that active normal faulting may have been operating over million-year timescales (Fassoulas, 2001; Fassoulas & Nikolakakis, 2005; Veliz et al., 2018; Zachariasse et al., 2008). The landscape in western Crete is mountainous (e.g., White Mountains; Figure 2b) and compatible with mainly contraction in the subduction zone with limited normal faulting in the upper plate (Mouslopoulou, Nicol, et al., 2015; Shaw & Jackson, 2010). By contrast, eastern Crete is dominated by basin and range topography which is interpreted to have formed mainly in response to active normal faulting in the upper crust (Caputo et al., 2010; Fassoulas, 2001; Mason et al., 2016; Veliz et al., 2018) (Figures 2–5). As a consequence, the density, size, and rates of active normal faulting on Crete increase eastwards (Figure 2).

Active normal faults in the Crete region have been mapped onshore in the field (Caputo et al., 2006, 2010; Fassoulas, 1999, 2001; Gallen et al., 2014; Ganas et al., 2018; Mason et al., 2016; Mountrakis et al., 2012; Mouslopoulou et al., 2014; Veliz et al., 2018; this study), and in the surrounding offshore using seismic-reflection and multibeam bathymetry data (Andronikidis et al., 2018; Kokinou et al., 2012; Sakellariou & Tsampouraki-Kraounaki, 2019). Active normal faulting in the upper crust of the Crete region is also supported by microseismicity recorded by ocean bottom seismographs (Becker et al., 2010). Some of these active faults probably reactivate faults formed in response to N-S and E-W extension during Middle and Late Miocene, respectively (Angelier et al., 1982; Caputo et al., 2010; Fassoulas, 1999, 2001; Mouslopoulou et al., 2014). The present phase of extension commenced in the Quaternary ($\sim 2 \pm 0.5$ Ma; Fassoulas, 2001; Zachariasse et al., 2008), producing mostly E-W striking normal faults in southern Crete and more northerly striking normal faults in northern and western Crete (Figure 2).

Active normal faults are marked by prominent scarps, which are up to ~ 20 m high and ~ 40 km long and are best preserved throughout Crete where they traverse outcrops of Mesozoic limestone (Caputo et al., 2006, 2010; Mountrakis et al., 2012; Mouslopoulou et al., 2014; Papastamatiou, 1959) (Figures 1 and 3). Active fault scarps accommodate dip-slip and are typically discontinuous (Caputo et al., 2010; Mason et al., 2016; Mouslopoulou et al., 2014; Veliz et al., 2018). They run along the mid to lower slopes of ridge-

es or mountain range fronts, often separating topographic highs from nearby basins. Similar limestone active fault scarps are observed in Italy, mainland Greece, and western Turkey, where they ruptured during historical earthquakes (Benedetti et al., 2003, 2013; Mechernich et al., 2018; Mozafari et al., 2019). In Crete, and the wider Eastern Mediterranean region, postglacial fault scarps and multiple paleoseismic studies are interpreted to indicate that numerous large-magnitude ($>M_w6$) earthquakes ruptured the ground surface (Benedetti et al., 2003, 2013; Caputo et al., 2006, 2010; Hughes et al., 2006; Mason et al., 2016; Mitchell et al., 2001; Mouslopoulou et al., 2014; Veliz et al., 2018). The age of active fault scarps in Greece and western Turkey is primarily constrained by cosmogenic dating which suggests that climatic conditions were favorable for scarp formation from 16.5 ± 2 ka to the present day (Benedetti et al., 2003, 2013; Mechernich et al., 2018; Mouslopoulou et al., 2014; Mozafari et al., 2019). Historical earthquakes in the Mediterranean region support the interpretation that the majority of slip recorded by limestone fault scarps accrues during earthquakes (Benedetti et al., 2003, 2013; Mechernich et al., 2018; Mozafari et al., 2019). The earthquake-slip model for scarp formation in Crete is also consistent with observations from cultural strain markers (e.g., roads and fences) constructed last century that show no evidence of creep on active faults at the ground surface (this study). Despite the abundant geological evidence for past ground-rupturing earthquakes, no large ($M > 5.5$) earthquake has occurred onshore Crete during the last 55 years (<http://bbnet.gein.noa.gr/HL/databases/database>). Further, none of the 11 earthquakes of $>M6$ reported by Papadopoulos (2011) to have occurred onshore Crete during the last $\sim 2,000$ years have been unequivocally correlated with individual active faults (Jusseret & Sintubin, 2012; Jusseret et al., 2013; Mouslopoulou et al., 2014).

3. Data and Sampling

Active normal faults have been studied here using a combination of displacements along active fault scarps and topographic changes across these faults (Figures 1–4, 6, and 7). The locations, map geometries, lengths, displacements, and displacement rates have been determined for 84 individual normal faults with active fault scarps and/or their topographic expression measured using a combination of field observations, high-resolution DEM (5 m pixel size and 2 m vertical resolution—data derived from the Greek Cadastre) and Google Earth images (Figures 1 and 3–7). About half ($N = 44$; Figure 2) of these faults are characterized by measurements from both active scarps and their topographic expression, which includes basin and range topography associated with the larger faults in eastern Crete (e.g., finite displacements of c. 1 km) (Figures

Figure 7. Quaternary fault displacements on Crete. Geological cross-sections across the Ha-Gorge segment of the Ierapetra Fault (ID = 71) (a) and the Kera Fault (ID = 11) (b) in eastern and western Crete, respectively, indicating the relationship between vertical displacement of bedrock and associated topography (modified from Mountrakis et al., 2012 and Mason et al., 2016). Comparison reinforces the notion that topography across mountain ranges bounded by faults may be used as a first-order proxy for long-term fault displacement.

4 and 5; Table S1). The spatial and geometric relationships between normal fault scarps and topography are illustrated in Figures 1, 4, 6 and 7 (the trends of fault scarps are marked by lines on the hillshade models in Figures 4 and 6). The remaining faults studied ($N = 40$; Figure 2) have clear topographic expression, but no observable active fault trace. The geomorphic expression of range fronts bounded by active fault scarps and of those which are not associated with active fault scarps are comparable, with both generally having steep slopes, triangular faceted ridges, and perched valleys in the uplifted footwall blocks (e.g., Figures 3d and 3e). These geomorphic features are consistent with the notion that Quaternary normal-fault displacements produced both the scarps and the topography. In cases where the faults have no clear postglacial expression they may not have ruptured the ground surface following the Last Glacial Maximum, or produced surface displacement during the postglacial time interval that is not resolveable with the available data, either because they were too small or because they were subsequently modified by surface processes.

3.1. Fault Displacements

Displacements were measured for active fault scarps (referred to here as postglacial displacements) and inferred from range-front topography (referred to here as Quaternary displacements). We refer to these active fault scarps as postglacial to establish their approximate age in a global context and, in doing so, are not inferring that glacial processes were widespread on Crete in the last hundred thousand years. Postglacial displacements were measured in the field using laser range finder ($\sim \pm 0.3$ m) and tape measure ($\sim \pm 0.2$ m), and from topographic profiles across scarps in the DEM ($\sim \pm 1$ m). Although these data permit scarp heights of as little as ~ 1 m to be recorded in the field, based on the decrease in the number of faults with scarps < 3 m high and < 2 km long (Figures 5d and 5e) we believe that our dataset is probably incomplete below these values. The incompleteness is partly due to erosion and deposition along fault scarps, which generally make the active faults more difficult to observe, particularly where the scarp heights are small (e.g., < 5 m). Local erosion and deposition along postglacial fault scarps can also modify their heights (Mason et al., 2016; Veliz et al., 2018) (Figure 3e). To reduce the impact of this potential sampling error, scarp heights were sampled from locations where they do not appear to have been modified by natural or anthropogenic surface processes. In addition, to decrease the impact of unidentified modifications to the scarps, heights were measured at multiple locations (e.g., 3–5 measurements along trace lengths of 200–500 m) along strike, with the values presented in Figure 5d being averages (i.e., the average of the maximum throw). At localities where the main slip surface splays into secondary strands, the vertical displacements were aggregated to produce a total value (e.g., Veliz et al., 2018). Fault-scarp heights are estimated to record the maximum vertical displacement that accumulated due to surface-breaking earthquakes. We have adopted an age of 16.5 ± 2 ka for the onset of active fault scarp formation, consistent with cosmogenic dating (^{36}Cl) of limestone fault scarps on the Spili Fault in Crete (Mouslopoulou et al., 2014) and elsewhere in the Mediterranean region (e.g., Benedetti et al., 2003, 2013; Mechernich et al., 2018; Mozafari et al., 2019). This age was used in combination with the displacement accrued on each fault to estimate the maximum vertical displacement rate since the onset of scarp formation (i.e., displacements are averaged over 16.5 ± 2 ka).

Topographic altitude changes across range-fronts defined by normal faults have been measured from strike-perpendicular profiles and are inferred to provide a measure of million-year displacements and displacement rates for the Quaternary (Figures 3–8). As with the active scarp measurements, the maximum altitude change across each fault was averaged from multiple profiles (e.g., 2–4 profiles) and inferred to provide a proxy for the maximum displacement (Table S1). Measurement of topography could produce under estimates of maximum displacement due to footwall erosion and hangingwall deposition (Veliz et al., 2018). Quaternary displacements could also be overestimated if topography was partly formed during Miocene and Pliocene thrusting, prior to the onset of normal faulting in the Early Pleistocene (see Tortorici et al., 2010). Plio-Pleistocene marine stratigraphy was deposited across Crete which remained submerged prior to ~ 2 Ma, and together with analysis of drainage patterns, indicates that there was not significant topography on Crete when Pleistocene normal faulting commenced (Meulenkamp et al., 1994; Roberts et al., 2013; Zachariasse et al., 2008). To examine further the impact of preexisting topography or syn-faulting erosion and deposition on our estimates of Quaternary displacements we use two cross-sections from the literature to compare displacement of stratigraphy with the change in the height of topography across two active N-S trending faults (Mountrakis et al., 2012; Mason et al., 2016) (Figure 7). These cross sections show that for N-S faults topographic height provides a reasonable proxy for fault vertical displacement as the displacement

of stratigraphy compares favorably with the height of topography (Figure 7). Displacement-length (D-L) data show that the Quaternary displacements for E-W faults plot along the D-L trend line defined by the N-S faults (Figure S1), supporting the inference that topographic height also provides a usable estimate of displacement for E-W faults. For the examples presented in Figure 7, the displacement of stratigraphy is <20% greater than the height of topography which supports the use of topography as a first-order measure of the maximum displacement. Nevertheless, for the purposes of this study we are conservative and allow uncertainties of +40% and −20% for maximum displacements derived from topography, which are inferred to account for measurement uncertainties and the influence of surface processes (Table S1). These maximum displacements are used in conjunction with an estimated age of $\sim 2 \pm 0.5$ Ma for the onset of extension (Fassoulas, 2001) to calculate average displacements rates for the Quaternary (for further discussion see Veliz et al., 2018) (Table S1).

3.2. Fault Lengths

Fault length is a key parameter for estimating the dimensions of faults and earthquake ruptures, seismic moments, and earthquake magnitudes (e.g., Biasi & Wesnousky, 2017; Schlische et al., 1996; Walsh and Watterson, 1988; Wells & Coppersmith, 1994; Wesnousky, 2008). Measurement of fault lengths and of active

Figure 8. Along-strike displacement distribution over different timescales. Displacement profiles along the Lastros (a and b) and Sfaka (c and d) faults over two distinct time-intervals: 0–2 Ma and 0–16.5 Kyr (modified from Veliz et al., 2018).

fault scarps that ruptured prehistorically can be subject to significant uncertainty because fault scarps are prone to erosion and burial, earthquakes may not break the ground surface along their entire length at depth, and displacements at fault tips are typically too small to be detected because the vertical resolution of traditional field mapping or aerial photo analysis is generally 0.5–1 m. For these reasons, the lengths of active faults and paleoearthquake ruptures are considered to be minimums, with lengths under estimated by, in some cases, more than 50% (Biasi & Wesnousky, 2017; McCalpin, 2009; Mouslopoulou et al., 2012; Nicol, Van Dissen, et al., 2016; Wesnousky, 2008). We believe that such under estimates also apply to some measurements of active-fault lengths on Crete. In an attempt to take account of this under estimation of active fault lengths, we have measured both the length of fault scarps (referred to here as postglacial scarp length) and the length of topography interpreted to have been produced by each normal fault since ~2 Ma (referred to here as Quaternary topographic length). The plot in Figure 5e compares the two measurements and shows that Quaternary topographic lengths are always equal to ($N = 3$) or greater than ($N = 41$) postglacial scarp lengths, with these differences being up to a factor of 10 (Figure 5e); on average, topographic lengths are 2.5 times greater than scarp lengths. For the available Crete data, the shorter postglacial lengths are considered to primarily arise due to sampling artefacts. Therefore, here we use topographic lengths for estimating paleoearthquake parameters including, single event maximum displacement (SED), earthquake recurrence interval (RI) and moment magnitude (M_w) (Table S1). In all cases, we assume that paleoearthquakes ruptured the entire topographic length of active faults and the resulting estimates of magnitude and slip are therefore maximums. Although more robust than the scarp lengths, these topographic lengths are also subject to uncertainties of up to ± 500 m due to errors in locating fault tips. In addition, 23 of the mostly longer faults (11 in western and 12 in eastern Crete) intersect the coastline and their measured lengths are minimums (blue circles in Figure 2 & blue outlined symbols in Figure 9f). In many of these cases the po-

Figure 9. D-L scaling relationships over different timescales. Plots illustrating D-L relationships for different time-intervals: (a) Postglacial displacement versus postglacial fault scarp length, (b) Postglacial displacement versus topographic fault length, (c) Quaternary displacement versus Quaternary topographic fault length, (d) Postglacial (red) and Quaternary displacement versus Quaternary topographic fault length, indicating the spatial distribution (east vs. west Crete) and the timing of activity (postglacial scarp vs. no postglacial scarp) on each fault, and (e) and (f) as (e) but also highlighting (with blue outline) the faults that intersect the coastline. The best fit line and R^2 values are calculated by excluding (blue) and including (black) the faults that intersect the coastline. The similarity in the R^2 values for the two datasets imply that the impact of coastal censoring in our analysis is minimum. D-L, displacement-length.

sition and orientation of the coastline is influenced by footwall uplift and/or hangingwall subsidence (see A, B, C, D, and E in Figures 2a and 2b). In most cases, the seafloor bathymetry surrounding Crete is not sufficiently well known to map these faults offshore and to estimate their total lengths (Robertson et al., 2019; Sakellariou & Tsampouraki-Kraounaki, 2019). Therefore, earthquake parameters (magnitude, SED, and RIs) calculated for these censored faults are regarded as minimums. Nevertheless, the similarity in the R^2 values of the D-L relationships for datasets that include and exclude the faults that intersect the coastline (Figure 9f) indicate that coastal censoring does not impact our first-order conclusions on paleoearthquakes and long-term accumulation of fault slip during earthquakes.

3.3. Earthquake Parameters

Cosmogenic dating (^{36}Cl) of limestone fault scarps in mainland Greece and Italy indicate that they typically form due to slip in <10 earthquakes with co-seismic throws of up to ~ 2 m (e.g., Benedetti et al., 2003, 2013; Mechernich et al., 2018) (e.g., Figure 1). Similar data are available for the Spili Fault in Crete where Mouslopoulou et al. (2014) identified five events since ~ 16.5 ka, with SED of 1–2.5 m (average 1.8 m) and RIs of 800–9,000 years (average 3,300 years). Direct information on the timing and size of paleoearthquakes is rare for active faults on Crete and cosmogenic dating of all active-fault scarps identified here is impractical. Hence, for the purposes of this study we calculate average maximum SED and RIs for all faults in the database using the maximum postglacial scarp height, the topographic fault length and the SED-length relationship derived for historical earthquakes on normal faults by Wesnousky (2008) (i.e., $\text{SED} [\text{m}] = 0.09 \times \text{Length} [\text{km}]$, see Table S1). For example, the Spili Fault with a postglacial scarp height of 9 ± 0.2 m, a scarp age of 16.5 ± 0.5 ka and a topographic fault length of $\sim 20 \pm 0.5$ km, would require five events with an average maximum SED of 1.8 ± 0.05 m and an average RI of 3.3 ± 0.4 Kyr. These values are comparable to the average earthquake parameters derived using ^{36}Cl analysis by Mouslopoulou et al. (2014), which supports the approach employed to estimate these averages, although due to the sampling issues (discussed below) we regard all earthquake parameters presented here to be first-order only.

A number of sampling deficiencies likely apply to the data used in this study to calculate earthquake parameters. Incomplete sampling of postglacial $>M_w 6$ earthquakes is probable on Crete (as it is in all areas of active faulting), because some events may not rupture the ground surface or because surface erosion or deposition processes are sufficiently high to remove or conceal evidence of surface-rupturing earthquakes (e.g., Hecker et al., 2013; McCalpin, 2009; Nicol, Van Dissen, et al., 2016). This potential incompleteness could have a number of consequences for the population of surface-rupturing earthquakes derived from the postglacial fault scarps. First, because some events on each fault may be sub-resolution, the geological sample should be regarded as defining the maximum average RI and SED (i.e., resolving more events would reduce the RI and the unsampled earthquakes are likely to have relatively small SED). A second consequence of this incompleteness is that the number of active faults and potential earthquake sources may be underestimated for the region of Crete, leading to underestimates in the total number of surface-rupturing events during the postglacial period.

4. Active Fault Geometries and Tectonics

The orientations of active normal faults on Crete change from north to south, while the densities of these faults vary from east to west along the island (Figure 2). Field mapping indicates that the scarps represent exposed fault planes that have dips of $63 \pm 10^\circ$ (1σ), with mainly N-NE and ESE-ENE strikes (Figures 2, 4, and 5a–5c). Active normal faults may also intersect (or step) along strike, with individual structures locally varying in strike by 10 – 20° (see, for example, the southern boundary of Messara Basin in Figure 4b). East-west striking faults ($N = 22$) are primarily confined to southern Crete, with northerly striking faults ($N = 62$) dominating northern and western parts of the island (Figures 2 and 5a and Figure S1). The larger east-west faults extend offshore and likely disrupt the seabed (Figure 2), although offshore faults are not incorporated into our sample. Where orthogonal N-NE and ESE-ENE fault sets intersect they often abut or terminate against each other (Figure 6). Both sets of faults accommodate dip-slip normal displacement (Caputo et al., 2010; Mason et al., 2016; Veliz et al., 2018), suggesting that Crete accommodated extension simultaneously

in two directions during the last 2 Myr and that this extension in ~east-west and ~north-south directions is ongoing.

Onshore, the east-west faults are characterized by approximately equal numbers of Quaternary only (green lines, Figure 2) and Quaternary plus postglacial scarps (red lines, Figure 2). By contrast, more northerly striking faults predominately have Quaternary plus postglacial scarps (41 vs. 23), from which we conclude that onshore northerly striking faults have been more active and accommodated a greater number of surface-rupturing earthquakes during the postglacial interval. This interpretation is consistent with GPS data which indicate that upper plate extension in Crete is predominately east-west, with relatively minor north-south extension along the south coast (e.g., Floyd et al., 2010; Saltogianni et al., 2020).

The numbers of active faults and their postglacial fault displacements change from west to east along Crete. Faults with postglacial scarps are approximately three times as abundant in eastern Crete ($n = 32$) than in western parts of the island ($n = 12$) (Figures 2, and 9e). In addition, faults active in the postglacial period appear to have larger displacements for a given fault length in the east compared to the west (Figure 9a). These data suggest that active faults are more common, have higher displacement rates (for a given fault length) and, on a regional scale, generated more earthquakes (see Section 7) in eastern Crete than in western parts of the island (Figures 9a, 9b, and 9e). Along-strike variations in the kinematics of Crete are reflected in the landscape, with the White Mountains rising to an altitude of >2.5 km in western Crete and eastern Crete being characterized by distinctive basin and range topography controlled by active normal fault displacements. A component of this spatial disparity could arise because the White Mountains constitute ~25% of western Crete (Figures 2b and 2c), and few active faults were recorded in the mountainous terrain, perhaps because of the high rates of surface processes or the steep topography. However, there is also a general paucity of active faults in western Crete outside the White Mountains (compared to eastern Crete), suggesting that geodynamic factors may contribute to the change in density of normal faulting from west to east across the island. Support for a geodynamic origin of the spatial variability of active faulting is provided by the historical and instrumental seismicity on Crete (Figure 10). Shallow (<20 km depth) crustal earthquakes of $\geq M4$ recorded instrumentally (1964–2017) and events of $\geq M6$ onshore Crete in the last 2,000 years, are both more common in eastern Crete than western Crete (Figure 10). Similarly, basin and range topography

Figure 10. Active faulting and historic/instrumental seismicity on Crete. Map showing active fault traces for Crete along with the locations of shallow (<20 km) historical (0–2,000 years B.P.) and shallow (<20 km) instrumental (1964–2017) seismicity data. Yellow (gray in grayscale version of the figure) epicenters represent the only two $M > 6$ earthquakes that appear to have occurred onshore Crete between 2,000 and 500 years B.P. Historical and instrumental seismicity was accessed via the National Observatory of Athens websites (www.gein.noa.gr/en/seismicity/earthquake-catalogs & bbnet.gein.noa.gr/HL/; last accessed August 2018).

Figure 11. D-L scaling: Crete versus Global datasets. Displacement-length data for Quaternary and postglacial measurements from Crete (black and red filled circles, respectively), global displacement-length data for ancient faults (gray-filled circles; Nicol et al., 2017) and single-event displacement rupture lengths for historical earthquakes (blue-filled circles; Wesnousky, 2008). Least squares lines of best fit and R^2 values are also indicated for each dataset. D-L, displacement-length.

formed in response to normal fault displacements is predominately observed in eastern Crete.

Changes in the numbers and rates of normal faulting from west to east across Crete are consistent with the results of earthquake, geodetic, and tectonic uplift studies that indicate temporally transient and spatially variable deformation in the crust beneath Crete (Floyd et al., 2010; Meier et al., 2004; Meulenkamp et al., 1994; Mouslopoulou, Begg, et al., 2015; Mouslopoulou, Nicol, et al., 2015; Reilinger et al., 2006; Saltogianni et al., 2020; Shaw & Jackson, 2010). The seismicity rates (1964–2014) in the Crete region increase significantly eastwards, with most earthquakes in the east rupturing the upper 20 km of the crust (Bocchini et al., 2018; Meier et al., 2004). Lateral variability in the locus and rates of seismicity is consistent with contemporaneous GPS measurements that indicate margin-normal contraction in western Crete (revealing some strain accumulation on the plate-interface zone, a process that is often accompanied by a paucity in background seismicity; Kanamori, 1981), and margin-parallel extension in eastern Crete (Floyd et al., 2010; Reilinger et al., 2006; Saltogianni et al., 2020). These changes in deformation styles may partly reflect the westward shallowing (by c. $>10^\circ$) of the subduction thrust beneath Crete and the eastward increase in the rate of slab roll-back (Bocchini et al., 2018; Jolivet et al., 2013; Meier et al., 2004; Sodoudi et al., 2006; van Hinsbergen & Schmid, 2012). Faster trench retreat along the eastern segment of the Hellenic margin compared to the western is also supported by GPS data (Reilinger et al., 2006).

5. Fault Displacements and Lengths

We examine faulting due to accumulation of earthquake slip using plots of displacement-length (D-L) and displacement rate-length (DR-L) for postglacial fault scarps and Quaternary datasets in Crete (Figures 9, 11, and 12). Similar log-log plots have been widely presented in the literature for inactive fault systems and universally show positive relationships between fault displacements/displacement rates and length (Bilham & Bodin, 1992; Cowie & Scholz, 1992; Kim & Sanderson, 2005; Mouslopoulou et al., 2009; Nicol et al., 2010, 2017, 2020; Schlische et al., 1996; Walsh and Watterson, 1988). The Quaternary data in Crete show a strong positive relationship with a slope of ~ 1.4 ($R^2 = 0.58$, Figures 9c, 9d and 11) and plot in a comparable part of the log-log graph to the global dataset for inactive faults (Figure 11), which typically have D-L slopes of 1–1.5 (e.g., Bailey et al., 2005; Cowie & Scholz, 1992; Kim & Sanderson, 2005; Nicol et al., 2010, 2017, 2020; Schlische et al., 1996; Walsh and Watterson, 1988; Walsh et al., 2002). The slope of the best fit line for Quaternary data (Figures 9c and 9d) is greater than the ~ 0.4 slope for the postglacial scarps and ~ 0.3 slope for the global compilation of normal fault earthquakes from Wesnousky (2008) (Figure 10), with values for postglacial scarps being more scattered than the Quaternary data (R^2 values of 0.18 vs. 0.58) (Figures 9d and 11).

Changes in D-L relations may be dependent on a range of factors including sampling bias, the mechanical properties of the faulted rock, the strain (and number of earthquakes) accommodated by the fault system, the age of the faulted horizons, the degree of fault interaction, and how individual earthquakes accrue on faults over timescales of thousands to millions of years (Bailey et al., 2005; Mouslopoulou et al., 2009; Nicol et al., 2010, 2020; Rotevatn et al., 2019; Watterson et al., 1996). The greater scatter of postglacial D-L observations (compared to the Quaternary data) is consistent with active fault studies globally for which the increased scatter has been interpreted to partly arise due to short-term (e.g., ≤ 18 Kyr) changes in displacement rates (Mouslopoulou et al., 2009; Nicol et al., 2009). These rate changes are often interpreted in the literature to reflect temporal fluctuations in earthquake RIs and SED, with displacement rates varying by up to three orders of magnitude for the same fault depending on the duration of the sample interval (Mouslopoulou et al., 2009). Short-term displacement rate variations typically occur on timescales of 5–10 times the average RI of the fault (Mouslopoulou et al., 2009). Therefore, estimates of displacement rates

Figure 12. Fault displacement rates on Crete over different timescales. Plots of postglacial displacement rate versus topographic fault length (a) and Quaternary (topographic) displacement rate versus topographic fault length (b) for all faults sampled. Black lines show recurrence intervals of 0.1, 1, 10, and 100 Kyr. Black horizontal line at 0.2 mm/year indicates the resolution threshold of our dataset for postglacial scarps. Lines of best fit are least squares values. For displacement rate values see Table S1. (c) Postglacial displacement rates versus Quaternary displacement rates. Black lines show displacement ratios of 10:1 and 1:1 and 1:10.

for the ~16.5 Kyr postglacial period would only be expected to be similar to Quaternary displacement rates when their average earthquake RIs are ~3 Kyr or less (see Figure 13 and Section 6 for further discussion).

A D-L slope of >1 for the Quaternary data requires that average displacement gradients (and the ratio of D to L) are higher on larger faults than smaller faults. These higher gradients could arise for a number of reasons including: (1) most of the larger faults sampled ($>80\%$) intersect or interact with nearby faults and their lengths (and propagation) are restricted, (2) preferential linkage of smaller faults or fault segments that promotes long fault lengths at small displacements (e.g., Cartwright et al., 1995; McLeod et al., 2000), (3) preferential death or temporary abandonment of the smaller faults (e.g., <10 km), and/or (4) fault development primarily achieved by increasing displacements with little increase in length (e.g., Morley, 1999; Nicol et al., 2017, 2020; Rotevatn et al., 2019; Schlagenhauf et al., 2008; Walsh et al., 2002). The preferential death of smaller faults on geological timescales is an established feature of many ancient fault systems and, for those faults characterized by rapid early propagation (perhaps in some cases facilitated by segment linkage) followed by prolonged displacement accumulation with little or no change in fault length (i.e., the constant length coherent fault growth model: Childs et al., 2017; Morley, 1999; Nicol et al., 2017, 2020; Rotevatn et al., 2019; Walsh et al., 2002), will inevitably lead to a progressive increase in D-L slope as earthquakes accrue greater displacement on fault surfaces.

Direct evidence for the constant length coherent fault growth model is most often provided by seismic reflection lines (Childs et al., 2003; Walsh et al., 2002; Mouslopoulou et al., 2012) and from analog models (Schlagenhauf et al., 2008), where increments of displacement mapped using time-lapse techniques and growth strata indicate stationary fault tips. There are no such data available for the present study, however, if the faults in Crete were propagating their maximum lengths would have been reached in the postglacial time interval. Instead, postglacial lengths on Crete are mostly shorter than their topographic lengths (Figure 5e), and provide no evidence for fault propagation over the last ~14 to 18 ka. The absence of such evidence is a common feature of active faults globally (Mouslopoulou et al., 2012) and probably at least partly reflects our inability to sample low displacements (e.g., on Crete <3 m) approaching rupture tips for paleoseismic events. In addition, we propose that the lengths and geometries of active faults on Crete may not have changed significantly in the Late Quaternary. Similarly, static fault dimensions (i.e., length and width) are implicit in many physics-based earthquake simulations (e.g., Richards-Dinger & Dieterich, 2012; Robinson et al., 2009) and our data support the view that output from these models may have value in understanding the long-term (>10 Kyr) earthquake behavior of fault systems.

6. Temporal Variations in Displacement Rates

Fault displacement rates for the postglacial and Quaternary time intervals (Figures 12a and 12b; Table S1) provide information about paleoearthquake processes on active faults in Crete. Displacement rates vary from 0.09–1.2 mm/year for postglacial and 0.0025–0.7 mm/year for Quaternary time intervals, with indi-

vidual faults accommodating postglacial displacement rates up to >10 times faster than their Quaternary (million-year) rates (Figure 12c), as it is commonly observed in global fault datasets (e.g., Mouslopoulou et al., 2009). The lower bound of the postglacial dataset is defined by the estimated ~3 m threshold of the completeness for the displacement measurements (with displacement rates of ≤ 0.2 mm/year), below which the number of observations decreases and we infer that not all faults have been sampled (see horizontal line on Figure 12a). The incompleteness of faults with < 3 m displacement contributes to the absence of a clear positive relationship between displacement rates and fault length for the postglacial period. By contrast, for the Quaternary sample interval larger faults on Crete tend to have higher displacement rates than small displacement faults (Figure 12b). The dependence between displacement rate and fault size arises because longer faults have both shorter recurrence intervals (as indicated by the > 1 slope of data in Figure 12b and shown in Figure 12a) and higher SED (e.g., Wells & Coppersmith, 1994; Wesnousky, 2008). The general positive relationship between displacement rate and fault length has been observed for extensional fault systems globally and leads to the conclusion that larger faults reach their size partly because they are moving faster than small faults in the system (Mouslopoulou et al., 2009; Nicol et al., 1997). One possible explanation for the higher Quaternary displacement rates on longer faults is that these lengths were established in the early stages of faulting (as would be suggested by the constant length coherent growth model proposed by Walsh et al., 2002), with higher stresses on longer faults resulting in more slip and higher displacement rates; support for a positive relationship between fracture dimension and stress concentration has been long established in the material science literature (e.g., Gordon, 1978).

We do not believe that the differences in displacement rates on individual faults for the two sample periods can be entirely accounted for by errors in our estimates of the durations of postglacial and Quaternary faulting or by uncertainties in the measured displacements (Figure 12; Table S1). Instead, we suggest that the observed displacement rate variability in part reflects geological processes. One potential interpretation of the available data is that displacement rates have recently increased on the normal faults of Crete, perhaps due to a recent (e.g., last 18 Kyr) change in the rate of slab rollback along the Hellenic margin or to climatic conditions leading to unloading of normal faults (e.g., Hetzel & Hampel, 2005). However, sea level and loading of normal faults have been rising in the postglacial period for the eastern Mediterranean Sea (Antonioli et al., 2007; Mouslopoulou, Begg, et al., 2015, 2016), while there are no data to support a post-18 Kyr increase in the rates of plate-boundary processes along the Hellenic margin (van Hinsbergen & Schmid, 2012). Alternatively, and perhaps more likely, it is possible that this apparent acceleration in displacement rates reflects variable earthquake RIs and SEDs on individual faults, with sampled faults tending to have been the most seismically active structures during the postglacial interval. This hypothesis has been previously advanced by Nicol et al. (2009), and is the earthquake equivalent of the “Sadler Effect” (Sadler, 1981), which has been widely reported for sedimentary systems. These variations in displacement rates are thought to partly reflect temporal variations in SED and “clustering” of earthquakes (e.g., Marco et al., 1996), where RIs and SED can vary by up to an order of magnitude (Mouslopoulou et al., 2009; Nicol et al., 2009). For example, on the Spili Fault in Crete the average Quaternary displacement rate is 0.4 mm/year with an average RI of 3.3 Kyr, while displacement rates and RIs range from 0.1 to 1.2 mm/year and 0.8 to 9 Kyr respectively (Mouslopoulou et al., 2014). Here, we refer to variations in earthquake recurrence as “clustering,” which suggests that the RIs are bimodal, however, it is also possible that the RIs are defined by log-normal or Weibull distributions (Nicol, Robinson, et al., 2016; Sieh et al., 1989). For these distributions, the “clusters” would mainly contain events close to the mode with RIs less than the mean that are separated by long recurrence events in the tail of the distribution.

Temporal changes in displacement rates on individual active faults may provide information about earthquake processes. Comparison of displacement rates on individual faults for postglacial and Quaternary time intervals suggests that the rates are most similar for the largest faults in the Crete system (Figure 12c). One possible explanation for the comparable displacement rates on the largest faults on Crete is that the duration of the postglacial time interval (i.e., ~16.5 Kyr) is sufficiently long to capture multiple events and the range of displacement rate variability on these faults (Mouslopoulou et al., 2009; Section 7). By contrast, average RIs for surface-rupturing earthquakes on shorter faults (e.g., <5 km) during the Quaternary are typically tens of kiloyears (Figures 12b and 13a) and, except in rare circumstances, too infrequent to be recorded as postglacial scarps (e.g., they are mostly absent

Figure 13. Average earthquake recurrence of normal faulting on Crete. (a) Plot illustrating the average recurrence intervals on individual normal faults on Crete over two sample periods (Postglacial and Quaternary). The lower and upper horizontal dashed lines represent the geometric mean of the recurrence interval for the postglacial (~2.5 Kyr) and Quaternary (~11 Kyr) datasets, respectively. (b) Plot illustrating the inverse relationship between average recurrence interval and regional strain rate. Note that Crete follows the trend defined by the global dataset (for references associated with this dataset see Mouslopoulou et al., 2009). Ap, Apennines (Italy); BR, Basin and Range (USA); Co, Corinth Rift (Greece); Cr, Crete (Greece); SW, South Wanganui Basin (New Zealand); Ta, Taupo Rift (New Zealand); Tar, Taranaki Rift (New Zealand).

from Figure 12a, plotting below the horizontal line). Therefore, the postglacial dataset only captures high displacement rate and low RI component of the surface-rupturing earthquake population. An important consequence of this sampling bias is that for all postglacial data the average (geometric mean) RI is 2.5 Kyr (see dashed line in Figure 13a) and approximately a factor of 4 lower than the ~11 Kyr average recurrence (see black dashed line in Figure 13a) estimated for the Quaternary. We consider the Quaternary value to be representative of the Crete fault system and note that this average recurrence (~11 Kyr) is similar to those of extensional fault systems globally, which indicate that the average earthquake RI for a fault system is likely inversely related to regional strain rates (Figure 13b) (Mouslopoulou et al., 2009).

7. Earthquakes and Seismic Hazard

The present active-fault analysis does not provide direct information on the timing and size of individual paleoearthquakes on Crete, however, it does afford indirect estimates of the magnitudes, locations and numbers of earthquakes generated on active normal faults that ruptured the ground surface in the postglacial time interval. To do this, we have calculated the number of paleo-events using the topographic fault lengths, the postglacial maximum displacement, and the max slip-length equation for historical earthquakes from Wesnousky (2008) (Table S1). The calculated number of surface-rupturing earthquakes for each active fault since 16.5 ± 2 ka ranges from 1 to 21 with a total ~ 370 (66 events in western Crete and 304 in the east) for the 44 faults with mapped postglacial scarps (Figure 2). In addition ~ 80 earthquakes may have occurred on faults with topographic expression but for which postglacial scarps are not preserved (these earthquakes are estimated by summing the average number of earthquakes for each fault since ~ 16.5 ka assuming sub-resolution throw of 3 m). Our calculations suggest a total of ~ 450 surface-rupturing normal-fault earthquakes since ~ 16.5 ka or an average of one every 37 years.

Comparison of the paleoseismic record with historical events provides a basis for assessing the possible impact of fault incompleteness, fault segmentation and multi-fault ruptures (or triggered slip) on the rate of postglacial surface-rupturing earthquakes. Using the topographic lengths and the empirical relationship between length and M_w from Wesnousky (2008), and assuming that each fault ruptures its entire length, we estimate values of 6–6.9 for the faults studied (Table S1). This range of magnitudes is consistent with the observed historical and instrumental records on Crete for the last 2,000 years (<http://bbnet.gein.noa.gr/HL/databases/database>; Papadopoulos, 2011). The historical and instrumental record for $M \geq 6$ earthquakes for the last 100 years is considered complete and there have been no reported surface-rupturing earthquakes on normal faults in Crete during this time. Therefore, the number of earthquakes inferred from the paleoseismic record (one $M \geq 6$ every 37 years) appears to be at least a factor of 3 higher than that observed from the recent historical record (no $M \geq 6$ earthquakes resulting in surface rupture in the last ≥ 100 years). This mismatch would increase by at least a factor of 2 if we employed postglacial trace lengths or if individual fault segments ruptured in separate earthquakes. In addition, the presence of undiscovered active faults, which are likely to exist in all fault systems (e.g., Nicol, Van Dissen, et al., 2016), will further increase the number of paleoearthquakes and exacerbate their mismatch with the historical record.

The apparent overestimate of the rates of $M \geq 6$ earthquakes in the paleo-record corroborates our use of topographic fault lengths (as opposed to shorter postglacial scarp lengths), but does not support the widespread occurrence of fault segmentation or the partial rupture of faults during individual earthquakes. The mismatch may indicate that the last 100 years spanned a seismically quiet period which is not representative of the postglacial sample interval. Alternatively, we may have overestimated the number of surface-rupturing earthquakes from the paleoseismic record, either because the fault-rupture lengths are too short (leading to a decrease in the SED and recurrence intervals), or because some surface-rupturing earthquakes produced slip on more than one fault leading to double counting of events in the paleoseismic record, or because the historical data do not record triggered earthquakes that broke the ground surface and were considered part of an aftershock sequence. Historical earthquakes that rupture multiple faults have been observed internationally and are most common where these faults are closely spaced (e.g., <5 km) or connected (e.g., Beanland et al., 1989; Kurushin et al., 1997; Litchfield et al., 2018; Mouslopoulou et al., 2019). Such fault connections occur at the junction of the Kastelli, Geraki and Nipiditos faults in eastern Crete (Figure 6), in the southern Messara Basin (Figure 4b), and along the Western (Figure 4a) and Eastern (Veliz et al., 2018) Mirabello fault system in eastern Crete (Figure 2a). It is possible that some historical earthquakes on Crete ruptured multiple faults in a single earthquake or part of a sequence (i.e., over time periods of hours to months), such as occurred in the M_w 6.4–6.7 1981 Gulf of Corinth events in mainland Greece (Jackson et al., 1982). Independent of whether multi-fault ruptures or triggered slip events are common on Crete, it is likely that most ($\sim 80\%$) future normal fault earthquakes will occur in eastern Crete, where they will pose an important seismic hazard.

8. Conclusions

Active normal faults on the eastern Mediterranean island of Crete form prominent limestone scarps of postglacial age (16.5 ± 2 Kyr) together with basin and range topography, which provides a proxy for vertical displacements since the onset of extension in the Quaternary (~ 2 Ma). The faults form two orthogonal sets that

strike E-ESE and N-NNE in southern and northern Crete, respectively. Northerly striking faults are more common and have proportionally more active traces than easterly striking faults. The active faults are subject to sampling biases including, sub-resolution displacements, fault censoring at the coast and preferential sampling of faults with the highest postglacial displacement rates, which can lead to undetected active faults and to under estimates of fault lengths. The available data indicate no fault propagation and, for the Quaternary, higher displacement rates on longer faults, supporting a model in which fault lengths and maximum earthquake magnitudes were established early in the development of the fault system. Postglacial displacement rates (0.09–1.2 mm/year) are generally higher than Quaternary rates (0.002–0.7 mm/year). We believe that differences in displacement rates between sample intervals arise in part due to “clustering” of $>M_w6$ earthquakes on timescales of tens of thousands of years, and preferential sampling of the most seismically active faults in the postglacial era. Displacement rates for the two sample intervals converge for longer faults because the ~ 16.5 Kyr duration of the sample interval exceeds the timescale of displacement-rate variations arising from earthquake “clustering.” Earthquakes on normal faults are most likely to occur in eastern Crete where the greatest numbers of active faults were recorded and surface deformation is primarily controlled by slab rollback processes. Paleearthquakes $> M_w6$ on Crete are about a factor of 3 more frequent than historical events for the last 100 years, which could be partly due to ruptures of multiple faults during individual paleearthquakes or to unrecognized triggered slip events in the historical record.

Data Availability Statement

All fault parameters derived are included in <https://zenodo.org/record/4048878>. The seismological data used in this article may be found at: <http://bbnet.gein.noa.gr/HL/databases/database>.

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