

Locating fault tips to aid fault length identification

An example from the Gulf of Corinth rift

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Overview

Research approach

- We investigate the geometry, rates and kinematics of active faulting in the tip zone of a major crustal-scale normal fault, the South Alkyonides Fault System, Gulf of Corinth, Greece.
- Fault offsets are dated using $^{234}\text{U}/^{230}\text{Th}$ coral growth ages and ^{36}Cl exposure dating on wave-cut platforms.

Findings

- Results reveal that there is no clear singular fault tip with deformation in the tip zone distributed across as many as eight faults within 700 m across strike, each of which deforms deposits and landforms associated with the 125 ka marine terrace.
- Summed throw rates in the fault tip zone, close to where the localised 'on-fault' throw decreases to zero, are anomalously high.
- Coulomb stress transfer modelling results suggests that stress enhancement as a result of fault interaction may be the cause of high throw rates in the tip zone.
- Considering the uncertainty in the location of the western tip induced by distributed faulting, the SAFS fault length is uncertain by up to $\pm 6\%$, which equates to a total maximum magnitude uncertainty of Mw 0.1.

Implications for probabilistic seismic hazard analysis (PSHA)

- Fault slip rates used in probabilistic seismic hazard calculations are typically propagated along strike assuming that they decrease toward the tips. Here we show that where along-strike fault interaction occurs, the tip zones may accommodate high values of 'off-fault' deformation, thus the results of such PSHA calculations may be in error.

Background: Perachora Peninsula, Gulf of Corinth

The Perachora Peninsula is located in the eastern Gulf of Corinth, a rapidly N-S extending rift zone in central Greece. Evidence suggests that since the late Quaternary, the 5-15 mm/yr horizontal extension across the gulf is accommodated on north-dipping crustal-scale normal faults located both onshore and offshore. The Perachora Peninsula hosts the north-dipping, 38 km long South Alkyonides Fault System (SAFS), which ruptured during the Gulf of Corinth 1981 earthquake sequence. The SAFS is comprised of the Pisias, Skinos, East Alkyonides and Psatha faults (Roberts et al., 2009).

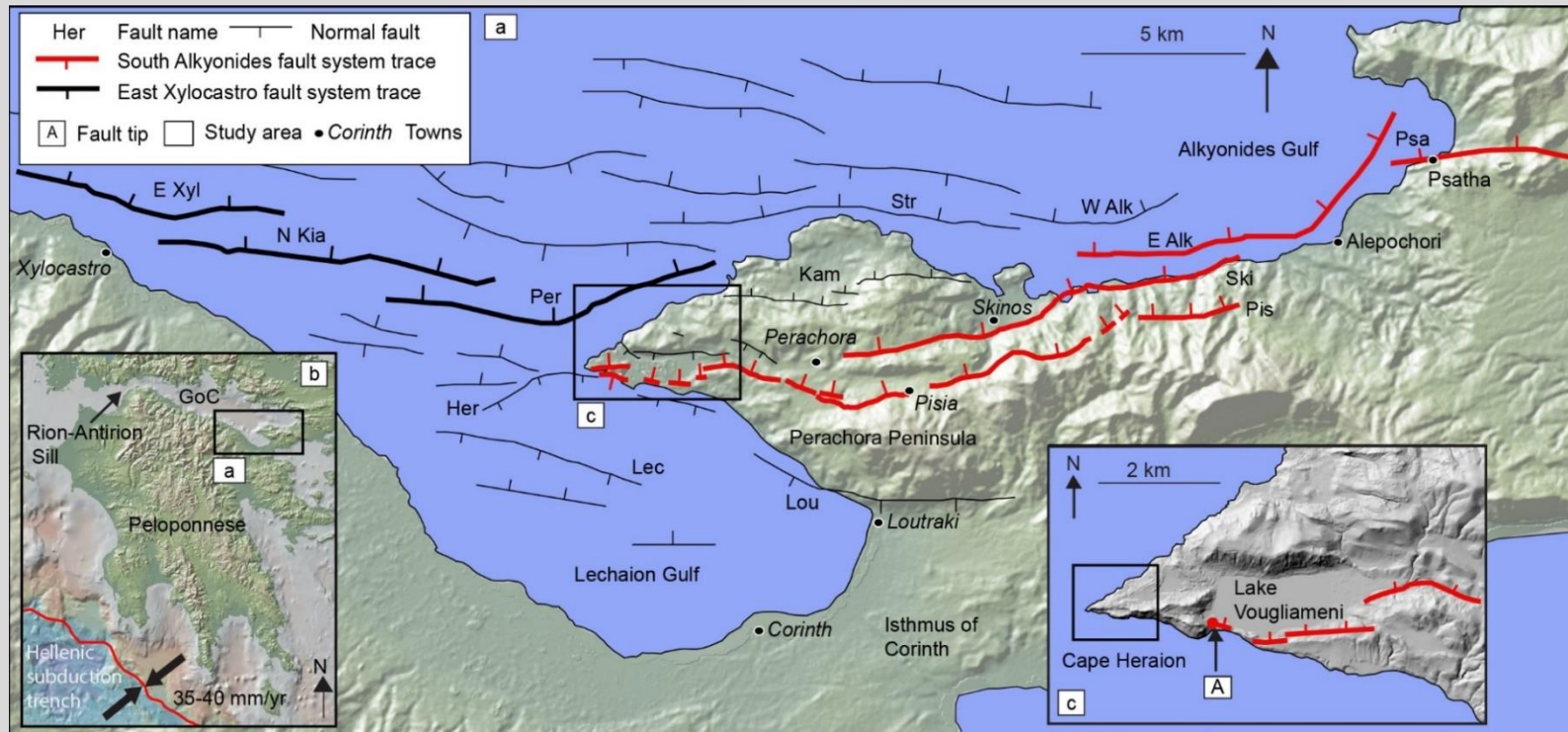


Figure 1: (a) Map of the eastern Gulf of Corinth and the Perachora Peninsula, surface trace of the South Alkyonides Fault system (SAFS) (red) (Morewood and Roberts, 2002), East Xylocastro Fault System (EXFS) trace (Bold) as per Nixon et al., 2016, all other faults as per Nixon et al., 2016. (b) Location of the Gulf of Corinth and Hellenic subduction trench taken from Kreemer and Chamot-Rooke (2004), GPS data from Nocquet (2012). (c) 5 m Digital Elevation Model showing the western surface trace of the SAFS as per Morewood and Roberts (2002) and Cape Heraion. 'A' marks the location of the 'on-fault' tip of the SAFS (Morewood and Roberts, 1999). See Fig. 3 for a detailed map of Cape Heraion.

Approach

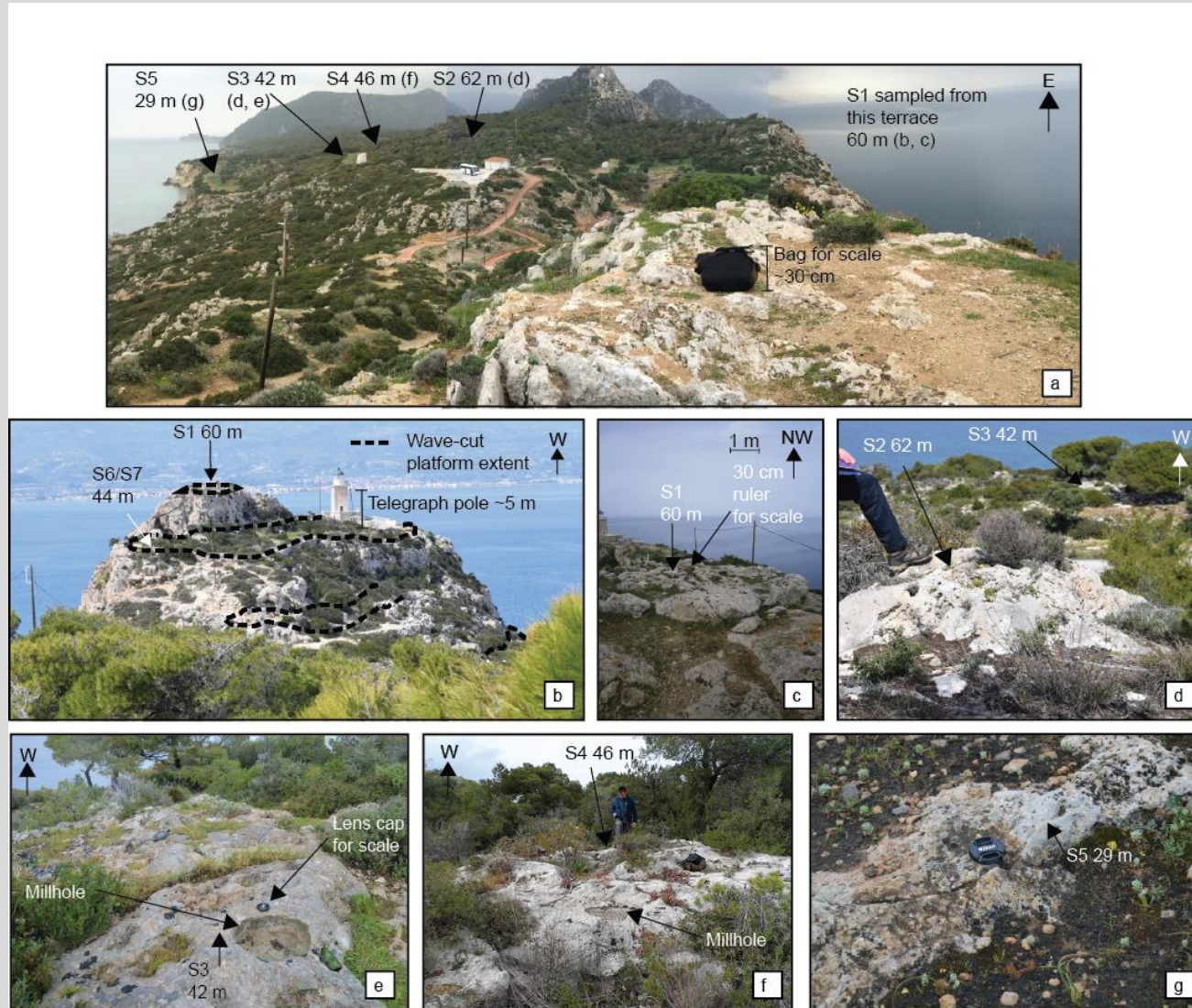
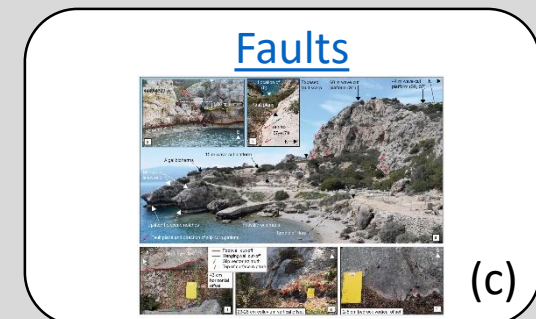
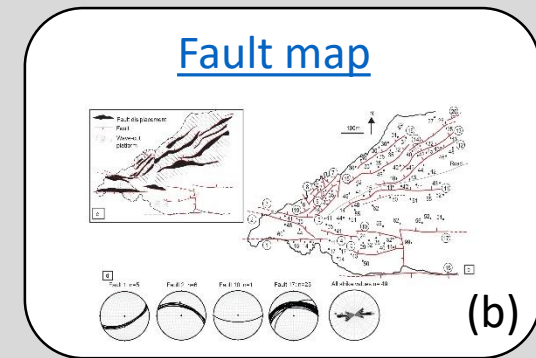
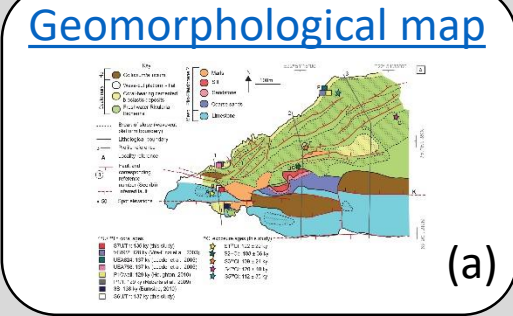


Figure 2: (a) overview of ^{36}Cl sample locations. (b–h) Photographs of ^{36}Cl and $^{234}\text{U}/^{230}\text{Th}$ sample locations. See Fig. 3 for locations of samples

- Detailed geomorphological field mapping determined the offsets of all faults, mapped the lithologies on Cape Heraion and identified wave-cut platform features (such as millholes and lithophagid borings) to ensure that minimal erosion has occurred and that the wave-cut platforms are amenable to exposure dating techniques (Fig. 2) (Robertson et al., 2019)
- Provide absolute ages for wave-cut platforms on Cape Heraion, in the tip zone of the SAFS, to complement existing ages. Two methods are used: $^{234}\text{U}/^{230}\text{Th}$ coral dating and ^{36}Cl exposure dating of wave-cut platforms associated with coral deposits (S1-7, Fig. 2)
- Construction of fault throw profiles to determine deformation rates in the Cape Heraion tip zone to explore deformation rates within the context of the SAFS

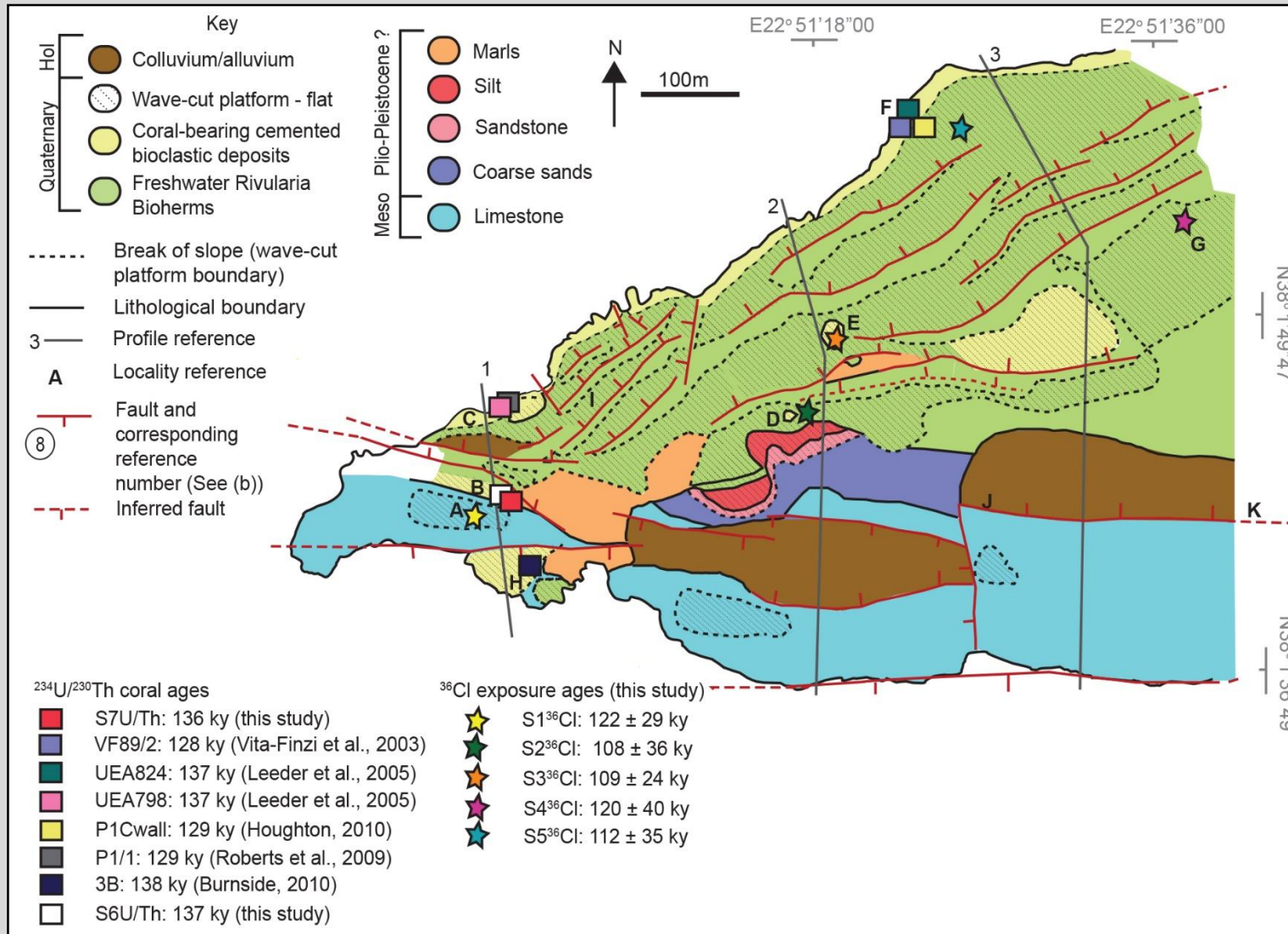
Geological mapping results

- Wave-cut platforms have been cut into the stratigraphy on Cape Heraion (a) and are widespread at various elevations from 6-99 m. These platforms can be mapped along strike into coral-bearing strata.
- The stratigraphy and the wave-cut platforms have been offset by faults that display displacement variations along the faults with slip maxima close to the centre and relay ramps at the fault tips (b)
- Observations and age controls are suggestive that faulting on Cape Heraion has been active since the late Quaternary, over decadal, 10^3 and 10^5 year timescales (c).



Geomorphological map

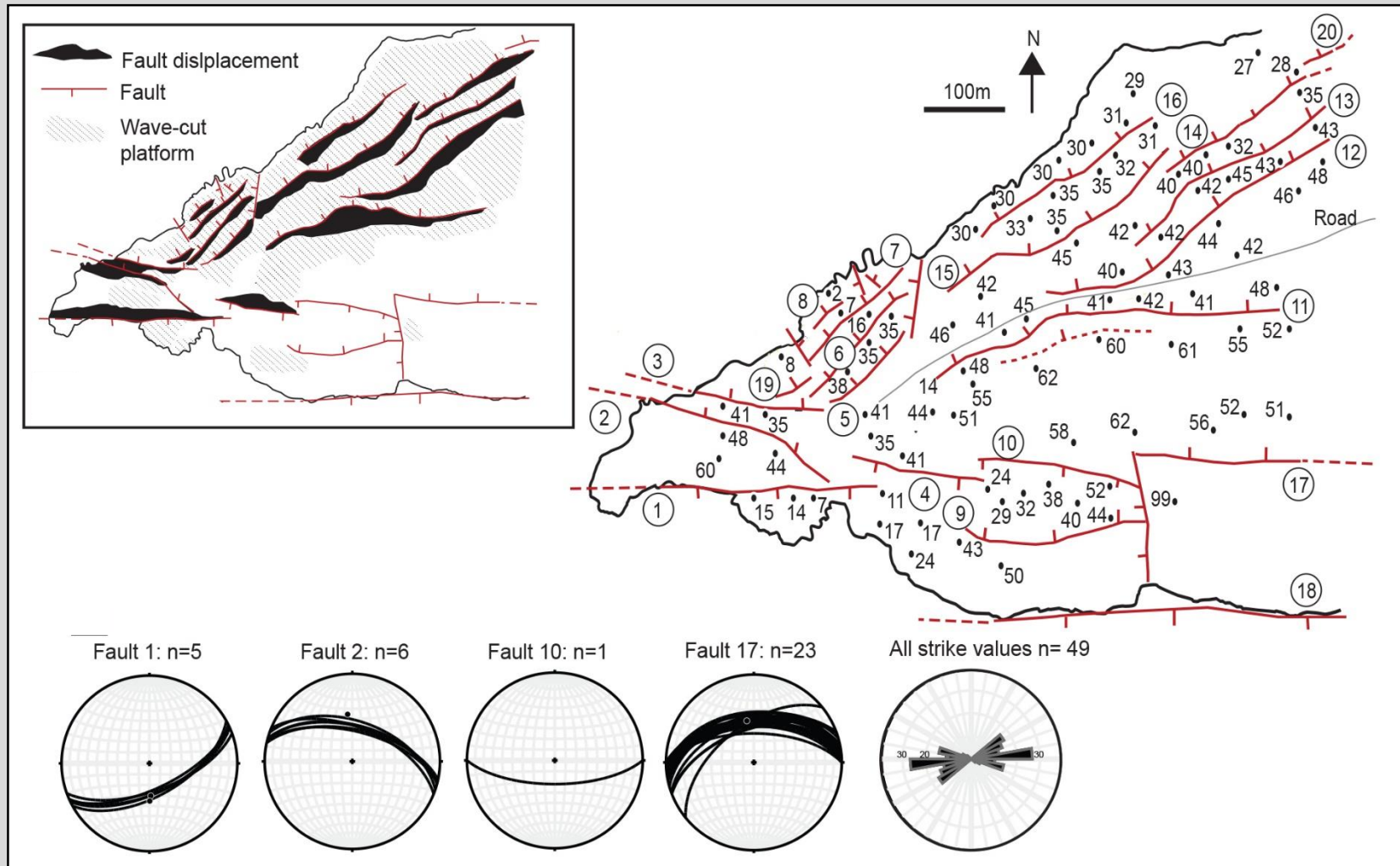
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- Wave-cut platforms are horizontal to sub-horizontal surfaces and exhibit millholes and lithophagid borings, typical of formation in the intertidal zone and low erosion since formation. They form when sea-level is at its highest during interglacial periods.
- As a result of wave erosion impinging on palaeo-Cape Heraion, the wave-cut platforms formed on different stratigraphic units across the area.
- Five samples for ^{36}Cl exposure dating were removed from limestone, bioclastic packstone and algal bioherm wave-cut platforms at different elevations.
- Two coral samples were removed for $^{234}\text{U}/^{230}\text{Th}$ dating to complement existing coral growth ages

Fault map

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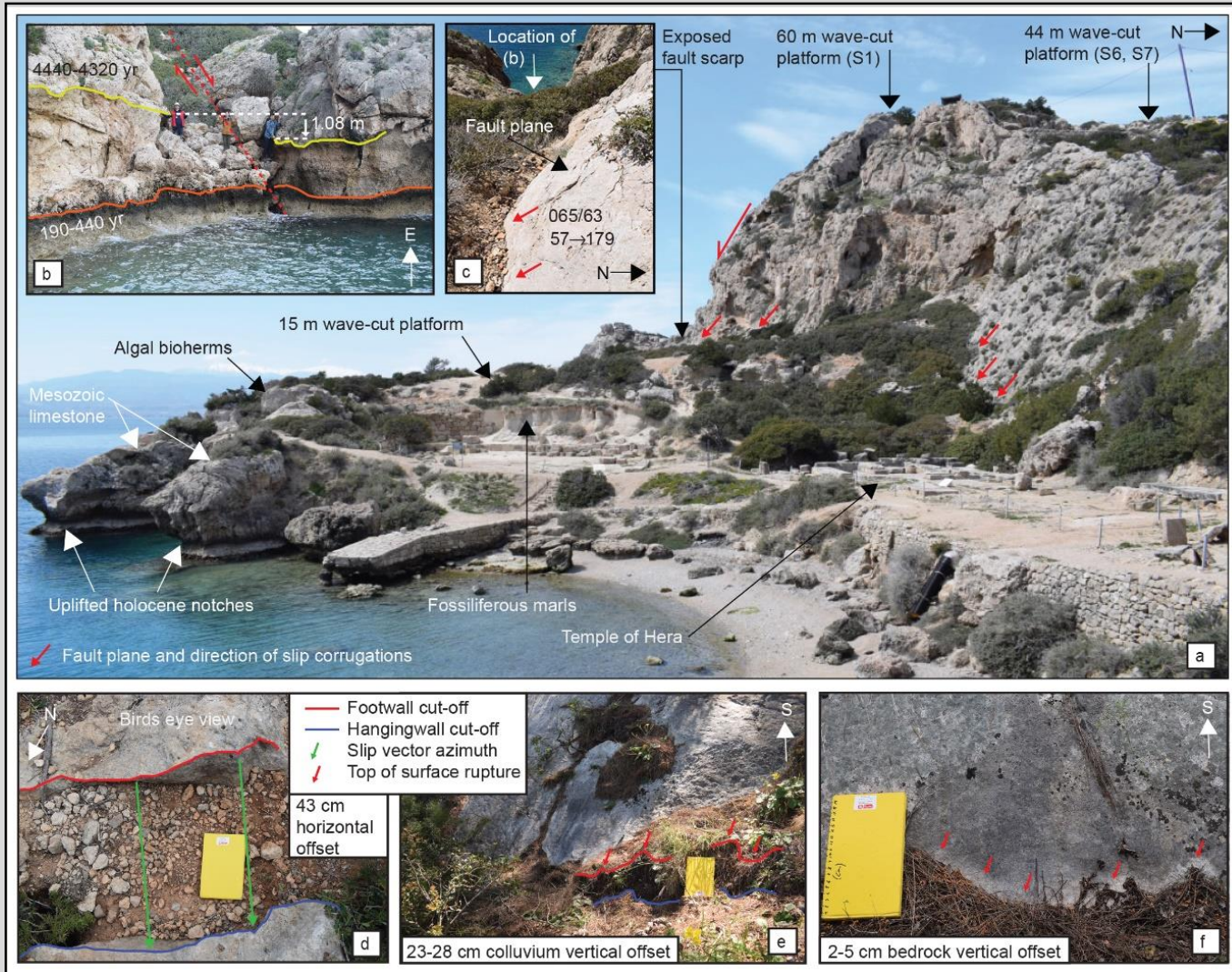


- All of the faults strike parallel-sub parallel to the average 260° of the SAFS between 230° and 300° (with the exception of three faults that strike approximately N–S not considered in this study)
- The faults in the north of the cape are all north dipping and exhibit short fault lengths (100–400 m) and offsets of 2–20 m.
- Faults along the south of the cape are longer, and extend outside of the mapping area to the east and offshore to the west (faults 1, 17 and 18)

Figure 4: (a) Fault map of Cape Heraion and spot height elevations used to plot the fault displacement in (b). (d) Stereonet plots for faults 1, 2, 10 and 17, rose diagram representing all measured strike values.

Faults

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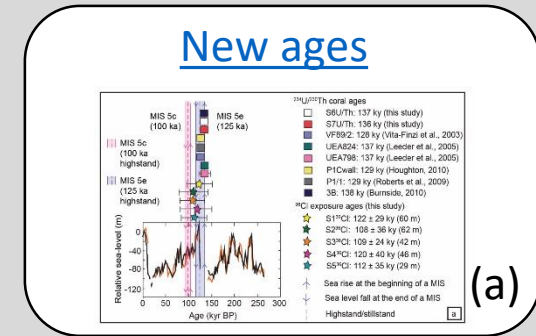


- Recent surface faulting is visible (d, e, f) possibly linked to the 1981 earthquake sequence, observed in the form of a horizontally offset bioherm (c), and surface ruptures in the form of a lichen-free stripe at the base of a carbonate fault plane (f) and offset colluvial deposits in the hangingwall (e).
- Offset notches dated to between 4440 B.C and 440 A.D. provide evidence of Holocene faulting (b)
- Fault 1 (a) offsets a wave-cut platform that formed during the 125 ka highstand (see Fig. 3 for ages)

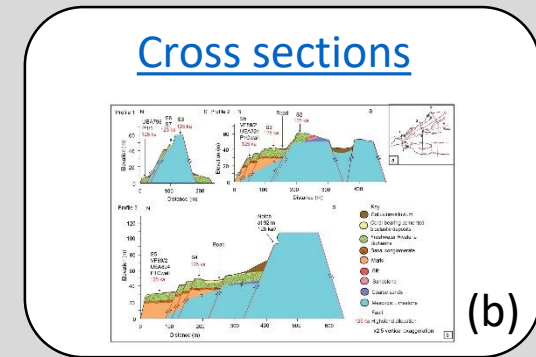
Figure 5: (a) View of Fault 1 (Fig. 3) offsetting a wave-cut platform at 60 m and 15 m. (b) Annotated photograph of offset wave-cut notches on Fault 1 (dated by Pirazzoli et al., 1994). (c) Fault plane and annotated direction of fault slip for Fault 1. (d) North-south horizontal offset of 43 cm on a bioherm on the north side of Cape Heraion at Locality I, Fig. 3. Offset colluvium (e) and bedrock (f) along fault 17 between localities J and K, Fig. 3.

Age results and terrace correlation

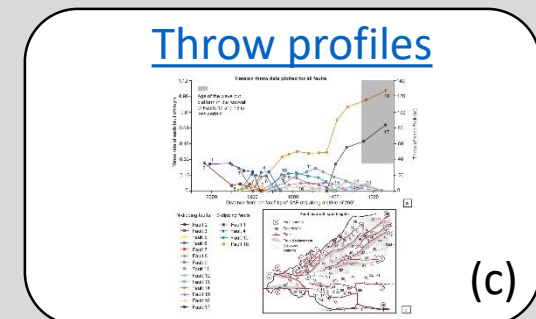
- New $^{234}\text{U}/^{230}\text{Th}$ coral growth ages and ^{36}Cl exposure ages from wave-cut platforms are in agreement with existing $^{234}\text{U}/^{230}\text{Th}$ coral growth ages, suggesting Cape Heraion was formed during Marine Isotope Stage (MIS) 5e, associated with the 125 ka highstand (a).



- Cross sections across Cape Heraion with age controls on wave-cut platforms at different elevations show that a singular platform has been faulted since formation (b).



- Knowledge of the age of the platforms and detailed geological mapping of the displacement along the faults allows us to calculate the throw rates/values on faults within Cape Heraion (c).



^{36}Cl exposure and $^{234}\text{U}/^{230}\text{Th}$ ages

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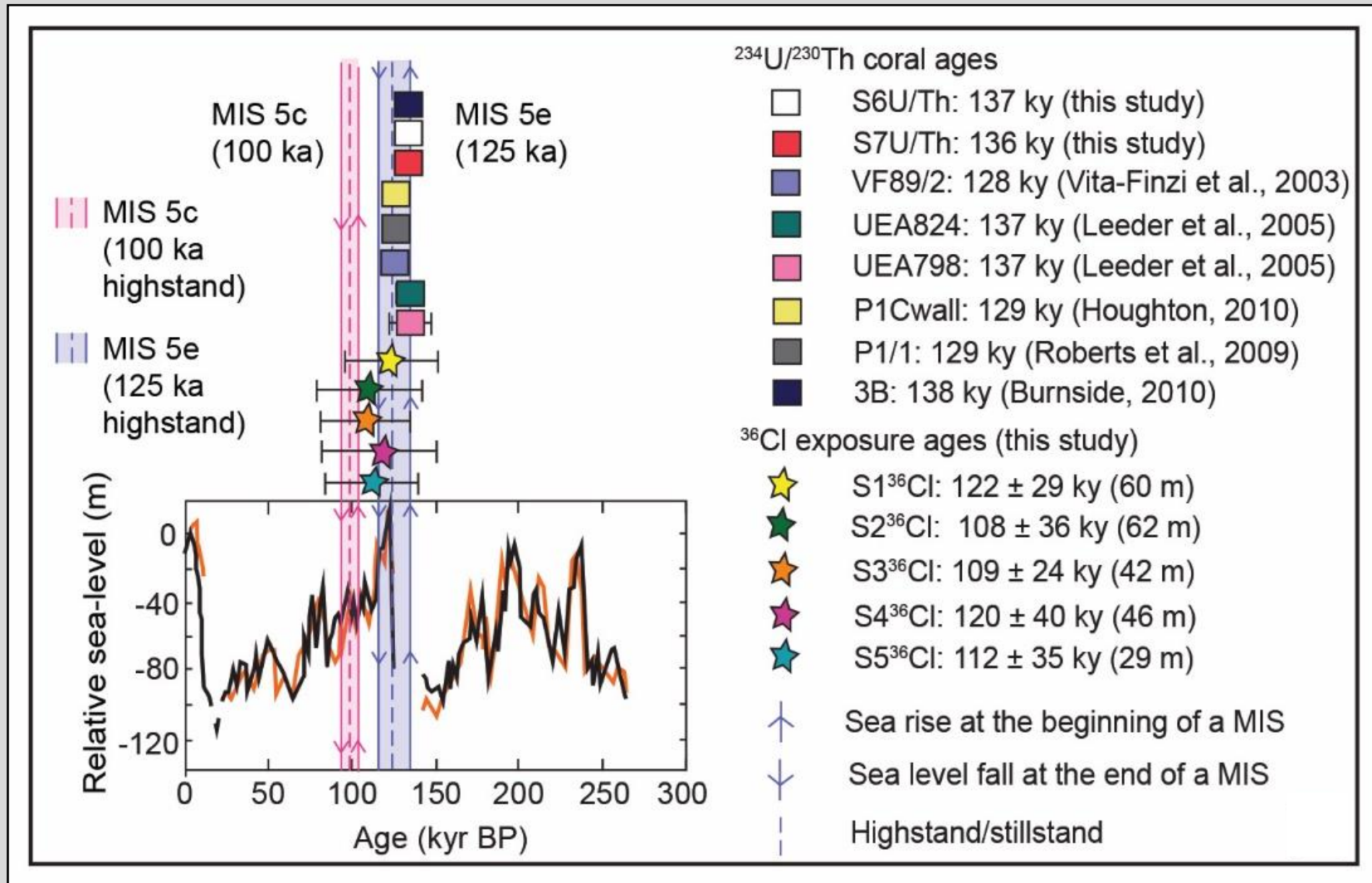


Figure 6 : ^{36}Cl exposure ages and $^{234}\text{U}/^{230}\text{Th}$ coral growth ages plotted against the sea-level curve of Siddall et al. (2003)

- $^{234}\text{U}/^{230}\text{Th}$ coral age dating reveals growth ages of 137 ky and 136 ky, in agreement with existing coral growth ages.
- Results of ^{36}Cl exposure dating show ages between 108-122 ky, all samples date to the 125 ka highstand within error. Note that wave-cut platforms are expected to form close to timing of the highstand ~ 125 ka.
- While some ^{36}Cl samples may suggest formation during the 100 ka highstand within error, this is not consistent with sea-level curve data, fault observations and age controls from corals.

Cross sections

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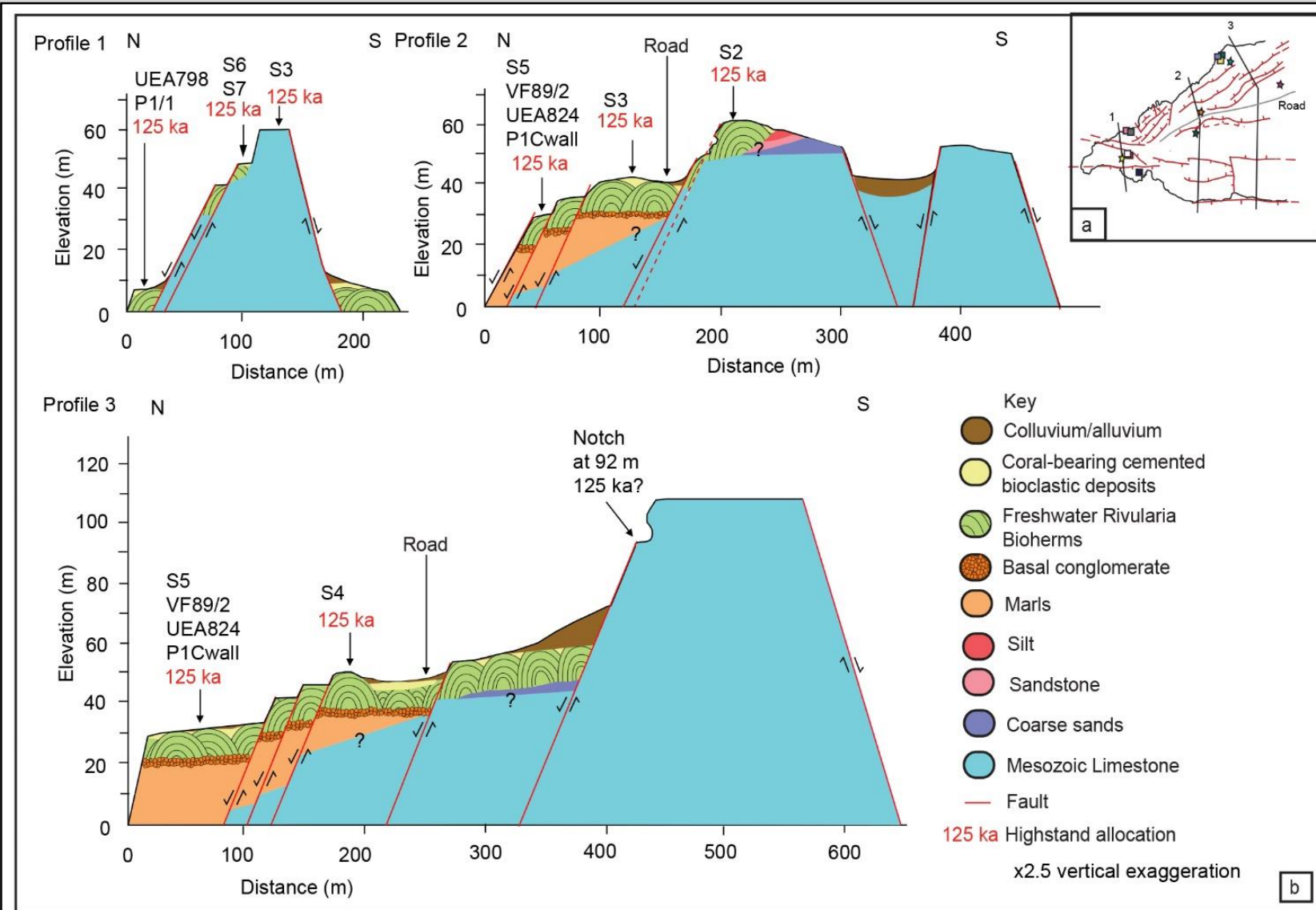
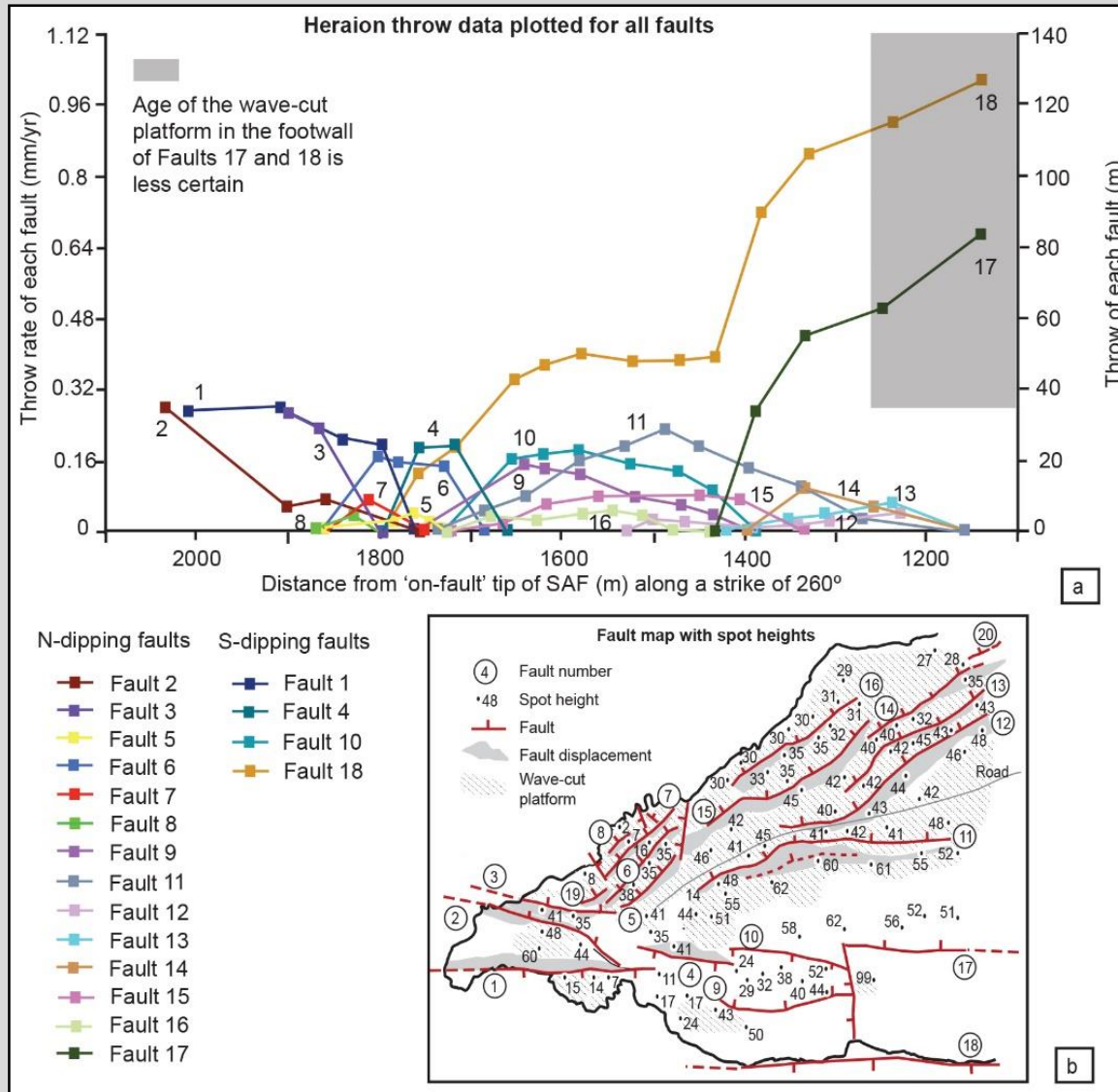


Figure 7: (a) Fault map and the location of profile lines from Fig. 2. (b) Schematic cross sections

- New and existing age controls constrain wave-cut platforms at various elevations across multiple fault transects to formation during the same sea-level highstand
- The ages are consistent with formation of a large wave-cut platform across Cape Heraion during marine Isotope Stage 5e (which occurred between 138-116 ka, 125 ka highstand)
- Wave-cut platforms are at different heights because they have been offset by faults since ~125 ka

Throw profiles

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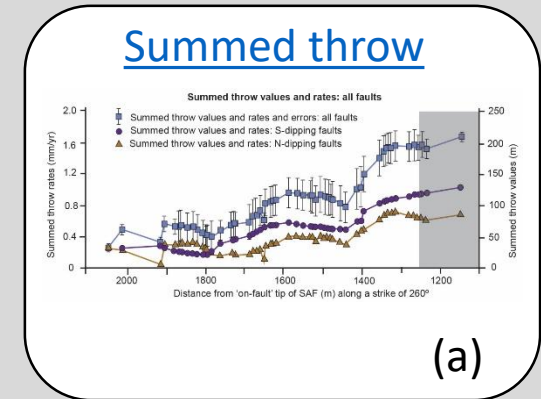


- Throw rates for each fault can be plotted since their offset ~ 125 ka using spot elevations obtained from field campaigns and a 5 m digital elevation model.
- Individual fault throw values/rates show that faults have maximum offset values of 40 m, with the exception of two faults (17 and 18).

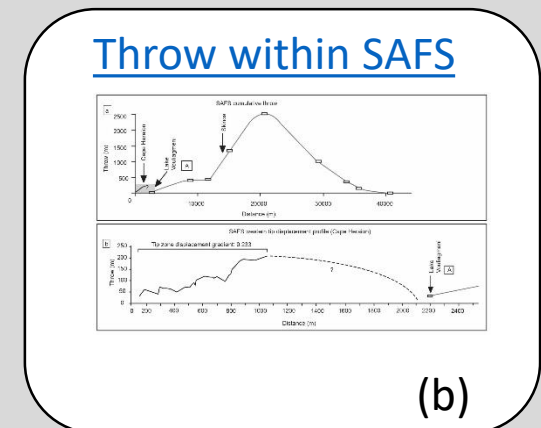
Figure 8: Throw profiles for individual faults (a) constructed using elevation data in (b). Throw is plotted against the distance from the on-fault throw tip in Fig. 1

Cumulative throw and context within the SAFS

- Summing the throw for all of the faults results in a pattern of decreasing displacement from east to west (a), this pattern is consistent with the overall pattern of displacement in from east to west for the south Alkyonides fault system (b).



- Throw values are higher in the tip zone compared to on the fault. This is illustrated by calculating the tip-zone displacement gradient (b).



Summed throw

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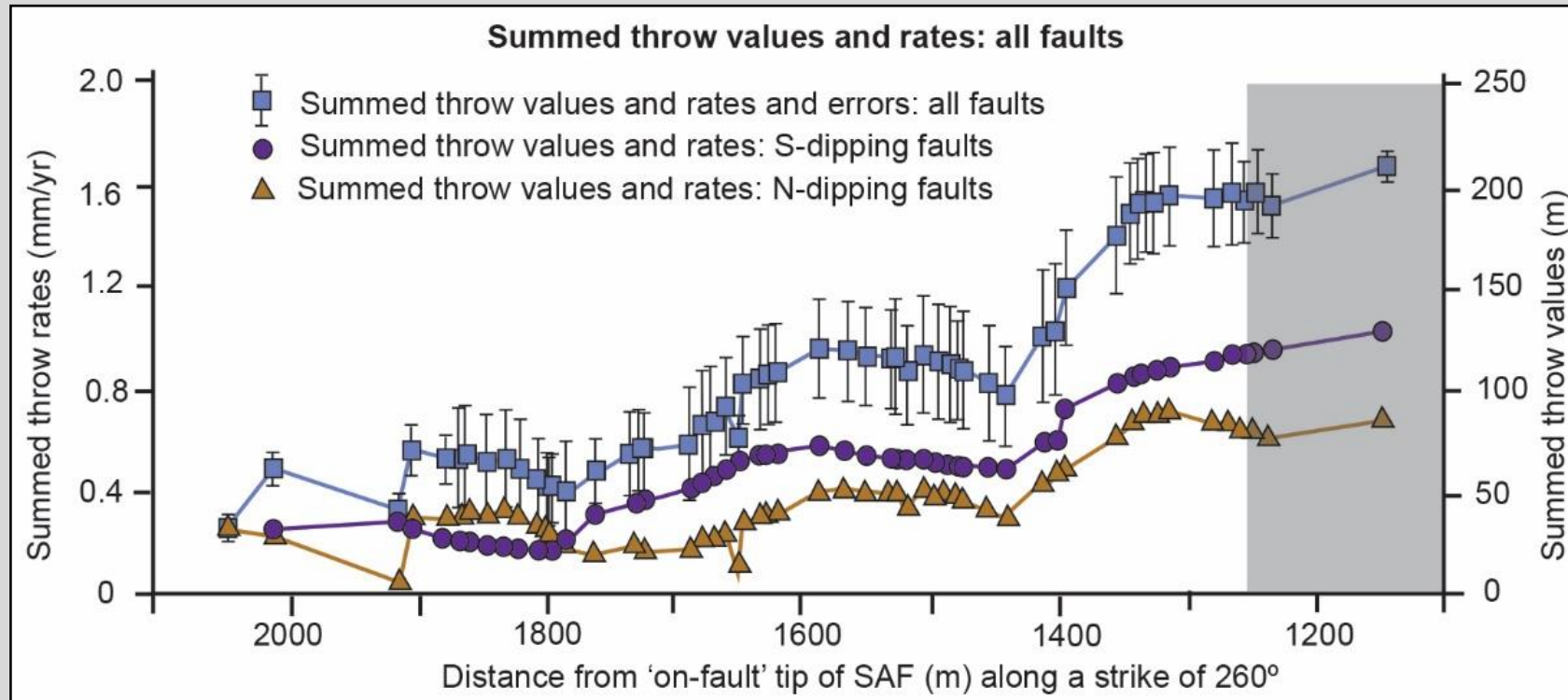


Figure 9: Summed throw values and rates for all faults with uncertainties, summed throw values for north- and south-dipping faults, throw for each fault is plotted against the distance from the on-fault throw tip in Fig. 1

- Summed throw values are as high as ~ 1.6 mm/yr, higher than 'on-fault' throw values
- Four south-dipping faults accommodate more throw compared to 14 north-dipping faults with the exception between 1900 and 1800 m to the west of the 'on fault' throw minima (Fig. 1). This may be a reflection of the broader faulting pattern within the Gulf of Corinth where the polarity of faulting switched from south-dipping faults to north-dipping faults during the late Quaternary. North-dipping faults may be less mature than their south-dipping counterparts.

Tip zone throw within the context of the SAFS

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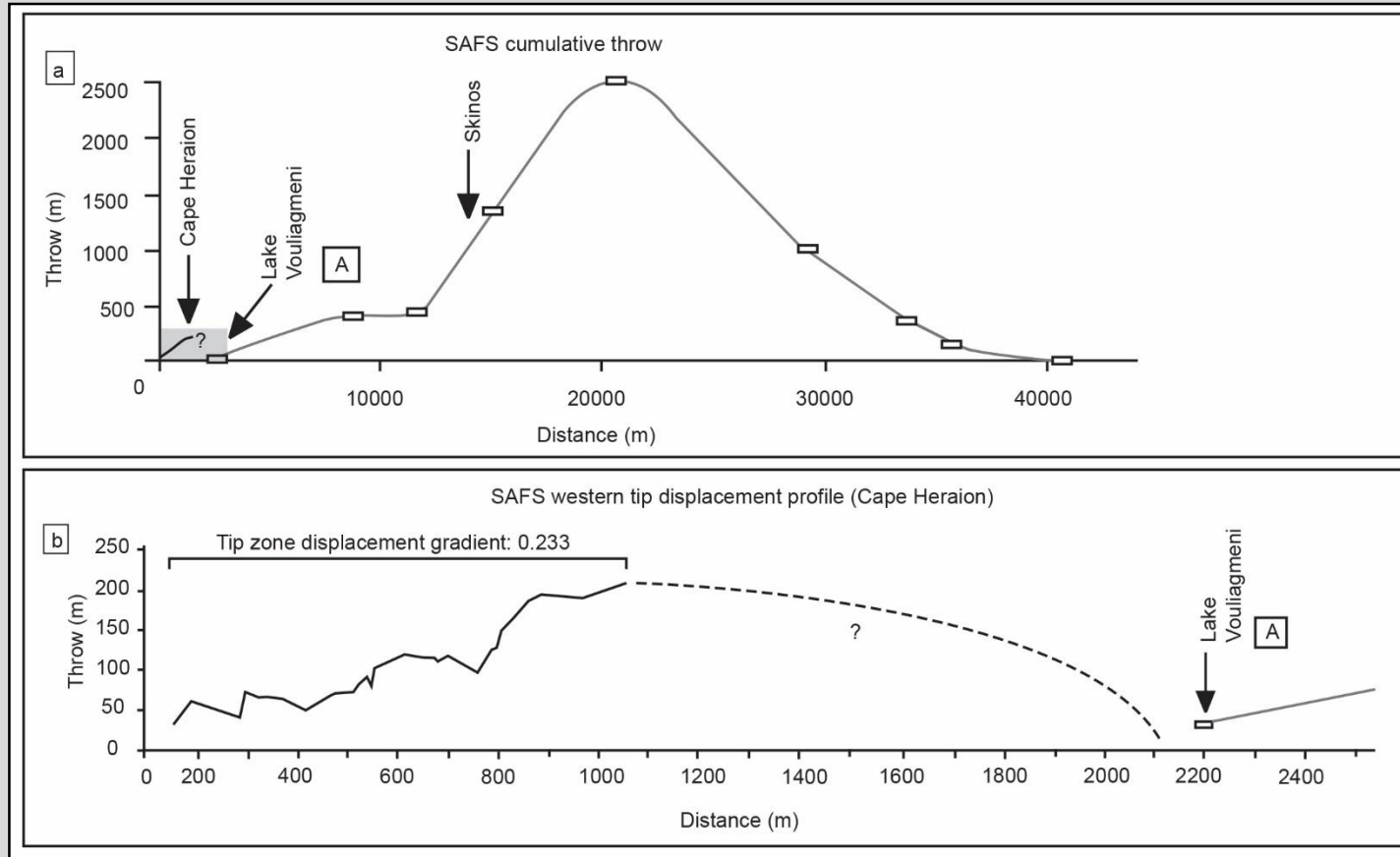
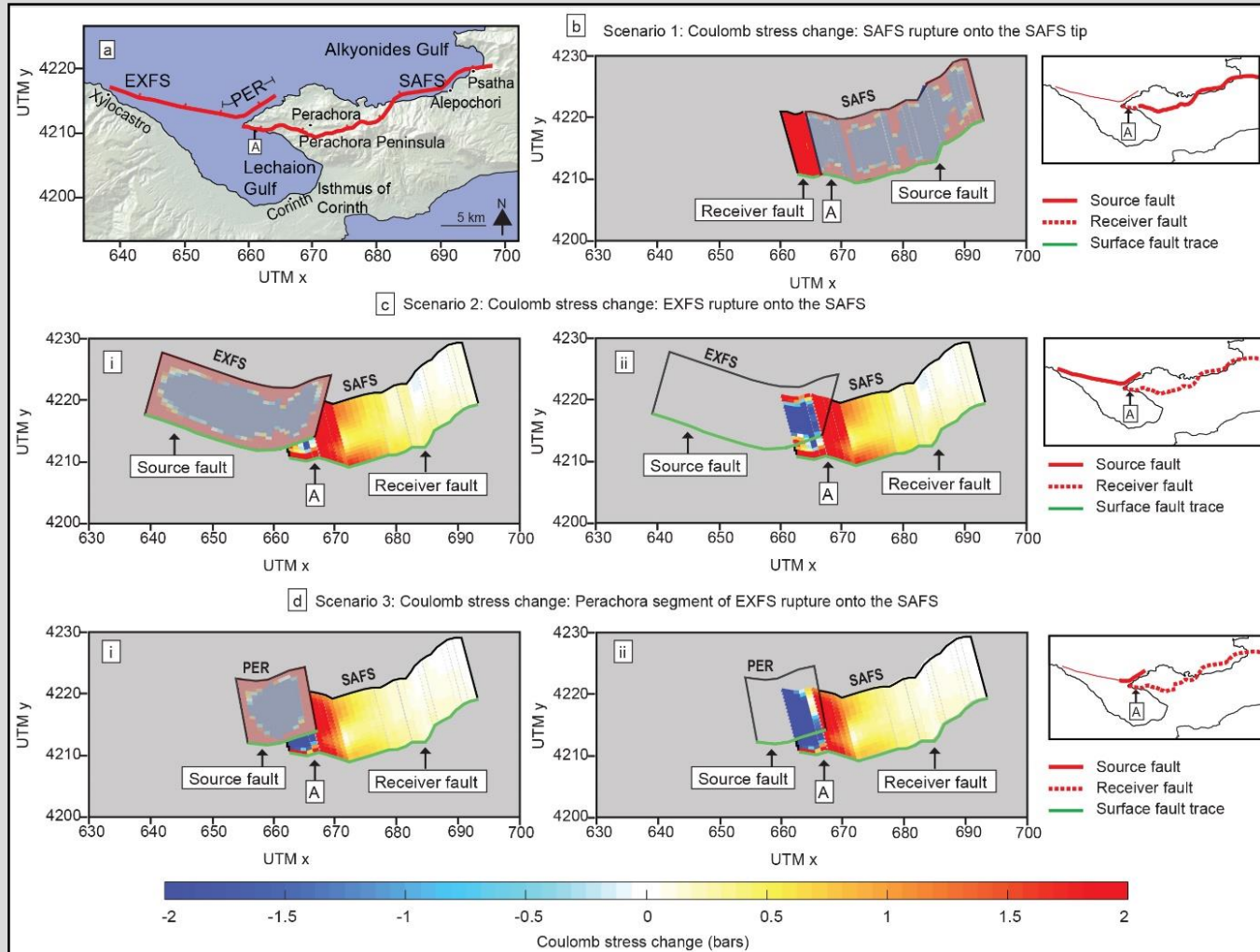


Figure 10: (a) Summed throw of Cape Heraion faults plotted alongside cumulative throw of the SAFS (modified from Morewood and Roberts (1999)). (b) Tip zone throw and displacement gradient from Cape Heraion. See Fig. 1 for the location of A ('on-fault' tip of the SAFS).

- Our findings lead us to question why the tip zone throw values are anomalously high compared to the localised fault (a).
- Studies of tip displacement gradients commonly suggest high gradients occur where the tips of two faults overlap, as a consequence of the interaction between the stress fields of the faults (e.g. Peacock and Sanderson, 1991; Cowie and Shipton, 1998; Gupta and Scholz, 2000).
- A tip zone displacement gradient of 0.233 (b) is at the higher end of the range of those observed in other studies (e.g. Cowie and Shipton, 1998; Cartwright and Mansfield, 1998).
- But why? Could the relatively high summed throw rates on Cape Heraion be due to fault interaction?

Exploring the cause of anomalous throw values



- Here we explore whether the cause of the high tip-zone displacement could be related to interaction between the SAFS and the along-strike set of linked faults that form the East Xylocastro Fault system (EXFS) (see Fig. 1 for location).
- Coulomb stress change modelling of the rupture scenarios shows that an earthquake on all or part of the EXFS (c, d) places a stress shadow on the western tip of the SAFS where Cape Heraion is located.
- Modelling supports the hypothesis that a stress shadow on the tip zone of the SAFS may result in deceleration of the propagation of the tip, which consequently results in displacement accumulating near its interacting tips, causing steeper displacement gradients (Gupta and Scholz, 2000) as the propagating fault cannot overcome the rupture resistance imposed by the adjacent fault (Walsh and Watterson, 1991; Scholz and Lawler, 2004).

Figure 11: (a) Map of eastern Gulf of Corinth showing the fault traces modelled in Coulomb stress change (b–d) for the South Alkyonides Fault System (SAFS) and East Xylocastro Fault System (EXFS) (adapted from Fig. 1). (b) Coulomb stress change from rupturing the source fault (entire SAFS with the exception of the western 5 km) onto the receiver fault (western 5 km section of the SAFS). (c) Coulomb stress change from rupturing the source fault (entire EXFS) onto the receiver fault (SAFS), (i) shows the source fault rupture, (ii) shows the source fault outline only. (d) Coulomb stress change from rupturing the source fault (Perachora segment of the EXFS) onto the receiver fault (SAFS), (i) shows the source fault rupture, (ii) shows the source fault outline only. See Fig. 1 for the location of 'A'.

Implications on seismic hazard

- We show here that the tip zone of a crustal-scale normal fault can accommodate significant displacement 'off the localised fault', possibly linked to interaction with an along-strike neighbouring fault.
- It is known that measurements of slip rate are key inputs into PSHA calculations to gain recurrence intervals and probability of shaking events (Pace et al., 2010, 2016; Valentini et al., 2017). Due to a sparsity of data, it is common to extrapolate slip rate data from measurements collected on a single location along a fault (Faure Walker et al., 2018). This is done by assuming that displacement decreases towards fault tips.
- The present study shows that this approach can be problematic, because the interaction between overlapping and interacting fault tips of neighbouring faults might result in anomalously-high displacement in the tip zone, so that throw and slip rates do not simply decrease along strike. Thus, calculation of recurrence rates and the probabilities of given shaking intensities may be in error in such situations.
- If these patterns of tip-zone deformation are assumed to be typical for other normal crustal-scale faults within fault systems where fault tips overlap along strike (e.g. central and southern Italian Apennines; Basin and Range, USA) then our findings may help shed light on how to incorporate slip/throw values into regional datasets, and whether displacements can jump from one major fault to another.
- Considering the uncertainty in the location of the western tip of the SAFS induced by distributed faulting, the SAFS fault length is uncertain by up to $\pm 6\%$, which equates to a total maximum magnitude uncertainty of Mw 0.1.

Conclusions

- Cape Heraion, in the western tip zone of the South Alkyonides Fault System, deforms via a set of distributed faults that are synthetic and antithetic to the 'main fault' and have been active over decadal, 10^3 yr and 10^5 yr timescales. New age constraints using ^{36}Cl cosmogenic exposure dating and $^{234}\text{U}/^{230}\text{Th}$ age dating of corals reinforce that the marine terraces and associated wave-cut platforms on Cape Heraion are linked to the 125 ka highstand within MIS 5e
- On Cape Heraion, summed throw values and throw rates appear to exceed those reported on the main fault. These deformation rates are reflected in an anomalously high displacement gradient of 0.233. Coulomb stress change modelling suggests that this may be a consequence of the fault interaction between the overlapping tips of the EXFS and the SAFS.
- Our findings have implications for probabilistic seismic hazard calculations as they show that the tip zones of crustal-scale faults may host high deformation rates caused by distributed faulting and as such should be mapped in detail across strike. This is particularly important for fault systems worldwide where crustal-scale faults may overlap and where the slip rates are typically propagated along strike from one or two measurements assuming a fault that linearly decreases to zero at the tips.

Distributed normal faulting in the tip zone of the South Alkyonides Fault System, Gulf of Corinth, constrained using ^{36}Cl exposure dating of late Quaternary wave-cut platforms

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