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Interactive comment on "A Semi-Automated Algorithm to Quantify Scarp Morphology (SPARTA): Application to Normal Faults in Southern Malawi" *by* Michael Hodge et al.

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We thank the reviewers for their constructive reviews and apologize for the delay in returning the manuscript. The lead author, Michael Hodge, has left academia for a job with the Civil Service and the second author, Juliet Biggs, is now acting as corresponding author.

The reviewers raise several interesting points regarding the factors which may affect the along-strike variability of scarp heights. To address these comments, we have added the following paragraph to the end of the introduction:

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Our aim is to develop an algorithm capable of measuring along-strike variations in the height of fault scarps at high resolution across a range of settings. The nature of the subsequent analysis and interpretation will, however, depend on the age and type of fault considered as well as the local lithological and climatic conditions. Individual earthquakes can produce scarps of variable height and a mix of on-fault and off-fault deformation (Wang et al., 2014; Gold et al., 2015; Milliner et al., 2016; Nissen et al., 2016). In some circumstances, ruptures are halted by discontinuities or steps in a fault system, whereas other earthquakes produce complex rupture patterns which include multiple fault segments (e.g. Jackson et al., 1982; Hamling et al., 2017). Between earthquakes, erosion depends on variations in lithological and climatic properties, which can produce dramatic changes in scarp height over short distances in only a few decades. For example, some parts of the scarp formed in the 1981 Alkyonides earthquake, Gulf of Corinth, are well-preserved but others have nearly disappeared (e.g. Mechernich et al., 2018). Some fault scarps are formed by individual earthquakes, others are multi-scarps produced by a few events, while others represent the cumulative effects of numerous earthquake cycles over tens of kyrs. In these cases, variations in scarp height may contain information on fault evolution that can be extracted by identifying structural segmentation (e.g. Watterson, 1986; Giba et al., 2012; Manighetti et al., 2015) and the presence of linking structures (e.g. Soliva and Benedicto, 2004; Nicol et al., 2010). However, these long-term eects will be convolved with variations associated with individual earthquakes. This combination of timescales involved in scarp generation raises the question as to what extent variations in oset and erosion persist across multiple earthquake cycles.

Reviewer specific comments.

Reviewer: This paper is an interesting one, which aims to produce an automated method of analyzing DEMs in order to extract metrics about fault scarps. The aim is a good one, in that it will allow scarp geometries to be analyzed with minimal interpretive input, and rapidly over large areas, which will be useful in terms of documenting and interpreting any along-strike variations that are present (e.g. due to segmentation). I have some comments that I hope will help to improve the clarity of the manuscript.

1. When reading through the discussion, what struck me is that these scarps probably formed in a small number (or possibly one) rupture, as noted by the authors. However, the along-strike patterns of scarp height are interpreted using terminology more usually associated with multiple-earthquake displacement profiles (e.g. p22, line 21, . . .separate faults that have since hard-linked and matured. . .). It seems that in a single, or a few, earthquakes, theres not much chance to create new linkages and mature the system, so it would be helpful to discuss how the variations in scarp height might be interpreted on more of a single-event to few-event timescale. From this perspective, the paper could benefit from more discussion of the literature that deals with along-strike variations in how much earthquake slip is expressed on a single scarp, or distributed over a wide area (and therefore very hard to see, or invisible, in the geomorphology). There have been some nice studies of this (e.g. Milliner et al, GRL, doi 10.1002/2016GL069841, 2016; Wang et al, BSSA, doi 10.1785/0120120364, 2014). It would be good to see a discussion of the degree to which the scarp height variations may represent the geomorphological analogues of the variability of on- versus off-fault deformation seen in these recent earthquakes. (These are both strike-slip events, but the same may well be true for normal-faulting its worth discussing.)

Response: We agree with this point. The issue of off-fault deformation has now be raised in the introduction to acknowledge, up front, the problem of distinguishing whether along-strike variation in scarp morphology relates to cumulative effect of multiple, segmented, earthquakes, or slip variation within a single rupture. We also point out the possibility of scarp height variations reflecting single earthquake complexity in the Discussion Section 7.2 (p. 30, lines 18-19 and p.32 lines 30-35) and Conclusion (p. 36, line 34 onwards).

2. Another point, which in some ways is very closely related to the one above, is the extent to which the scrap height variations may relate to the robustness/weathering of

the scarp. Looking at modern normal faulting earthquakes, when we see them in the field the scarps degrade in a very laterally-variable manner over years and decades. In part this relates to whether they are in bedrock or alluvium, but there is also lots of variety within each lithology, possibly related to the degree of fault damage or consolidation of the rocks. A good example are the scarps from the 1981 Corinth earthquake sequence, some of which are still big and dramatic, and some of which have pretty much disappeared. Its hard to say how this might feed into the results of the authors, as theres nothing very quantitative known about the along-strike variations in scarp degradation from the recent events, but its probably worth some discussion.

Response: We agree with this point. The issue of variable erosion has now be raised in the introduction and the variable preservation of the 1981 Corinth earthquake scarp has been used as an illustrative example.

3. I liked the synthetic testing, but it would be good to make a couple of small alterations. One is that the examples shown in Fig 4 dont have any profiles that look like the real scarps in Fig 2 (I think because the wavelength and possibly amplitude of non-scarp topography in the foot-wall isnt big enough). It would be good to see some synthetics that look more like Fig 2b.

Response: The profiles are intended to represent scarps from around the world as we want to ensure the algorithm is sufficiently generic and avoid over-tuning the methods to the specific cases shown in Figure 2 and subsequently. The algorithm is later re-tuned to the specific characteristics of the Malawian through selection of the most appropriate bin width and threshold using a small number of manually analysed examples which are more similar to those seen in Figure 2.

3. The other thing I thought would be helpful would be to have a graph of the scrap characteristics of the cases where the algorithm failed. The pattern seems to be that the methods and parameters that give the most accurate results are also the ones where there are lots of failures by the algorithm to

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find scarps. It would therefore be good to know whether there is a systematic bias introduced into the results, based on which type of scarps do and dont get recognized by the algorithm. This discussion of whether any bias is introduced would then be useful for later in the paper, when it comes to interpreting the results from Africa.

Response: This is a common feature of automated algorithms - the most accurate methods are often only applicable to a very small number of 'ideal' cases, whereas looser methods may be applicable in a wider number of cases at the cost of accuracy. Investigating the bias this introduces is an interesting idea and in an ideal world, we would investigate it further. However, with the lead author no longer available, a thorough investigation is beyond the scope of achievable revisions. Instead we have added the following sentence to the discussion of algorithm performance 'It is possible that the selection of scarps biases the analysis of scarp height. However, any bias would be towards the larger, sharper scarps and the effect is likely to be minor in comparison to the effects of erosion which tend to reduce estimates of scarp height.'

4. In terms of the slip-length ratios, its worth noting that the 2008 Yutian and 2006 Mozambique normal-faulting earthquakes both had a ratios at seismogenic depths of 1-2 x 10-4. These were mostly blind, but the principle of the biggest continental normal faulting events weve seen having these ratios suggests that its not out of the question that the scarps studied in this paper could be due to single events (if they ruptured to the surface). In general, I think this section (and the one about magnitudes) relies too much on the very sparse record of big modern normal-faulting events, either in Africa or elsewhere. They are rare enough (because of the long repeat times) that our modern record is extremely small, and its an open question how representative it is.

Response: Thanks! We have added the following sentence: The slip-to-length ratios for the normal-faulting 2008 Yutian and 2006 Mozambique earthquakes were 1-2 x 10-4 although both were blind earthquakes which did not rupture the surface (Elliott et al., 2010; Copley et al., 2012). We believe that the present revision of this section suitably reviews cases that set the precedent of plausible coseismic slip to length ratios without too heavily prescribing expectations based on limited observations.

Minor comments:

1. There is a general feeling in the paper (mostly in the introduction) that soft-linkage is likely to halt earthquake ruptures. A famous example at Platea-Kaparelli in 1981 involved two fault segments rupturing in the same earthquake, with the deformation between them occurring by spatially-distributed minor normal-faulting, which in the topography would look like soft linkage. This is only one example, and there are others where soft-linkages have halted ruptures, but it would be good to mention somewhere just to keep things balanced.

Response: Good point. We have inserted a comment in the introduction which says: 'In some circumstances, ruptures are halted by discontinuities or steps in a fault system, whereas other earthquakes produce complex rupture patterns which include multiple fault segments (e.g. Jackson et al., 1982; Hamling et al., 2017)'

2. p3, line 5 I think most people actually do this by fitting lines to slopes that are a safe distance to either side of the scarp, and looking for an offset between them, rather than actually picking the top and bottom of the scarp itself.

Response: Apologies, we explained our methodology poorly in the previous version of the manuscript. While we do pick the location of the crest and base of the scarp to measure scarp width, the height is measured by fitting regression lines as suggested by the reviewer. We have made this clearer by rewording the method description (p. 3, line 5; p. 7, paragraph from line 8 onwards).

3. A small inset showing the location within Africa would be helpful for those not familiar with the area.

Response: Done, included on Fig 1 now.

4. P6 L5 the Pleiades DEM is introduced, but a few notes about its properties/construction would be handy. Also, the resolution is here given as 50 cm, but

elsewhere (e.g. Fig 7) as 5 m.

Response: We have amended references to DEM resolution throughout; it is indeed 5 m. 50 cm is the nominal resolution of the original satellite imagery, but to construct a robust DEM of thorough spatial coverage, we downsample the calculated topographic point cloud.

5. P6 L15 a small sketch on one of the figures explaining the geometry described here would be useful.

Response: We have added a reference to Figure 3 where this geometry is shown

6. P6 L27 (and elsewhere) I see what is being meant by signal-to-noise ratio, but I would describe it as something different (e.g. non-tectonic features in the DEM), to avoid possible confusion with the noise level in the DEM relating to the data and analysis methods used (i.e. the measurement noise).

Response: This is a good point. Throughout the paper, we have replaced 'signal-to-noise ratio' with better description of what we mean, typically 'non-tectonic features' or something to that effect.

7. P7 L14 Is it that it better represents the average, or that its using a different definition of average (i.e. median rather than mean)?

Response: We have adjusted the text here slightly to indicate that the median is preferred as a representation of the average, rather than that we calculated these two values separately.

8. P8, top of page. Most readers probably wont know what G-S and Lowess filters are (including me until I looked it up). It would therefore be good to put some equations and explanation here, to help people see what the filters are actually doing. We understand that many of the Solid Earth readership will not be familiar with these filters, but references are provided to a wide literature.

Response: These are standard filters which are simple to implement in matlab or python. However, they cannot be represented by a single equation, and a full explanation seems inappropriate for this journal when there is a wide literature already available.

9. P11 L 17 there is a mis-match between the labeling of moderate and high between this text and Fig 4.

Response: The terminology has been updated (see previous comments) and this is no longer an issue

10. Fig 4 and 5 it would be nice to put a big bold line on for 0 misfit, to make it clear which parts of the plots represent the ideal result.

Response: After consideration, we have not made this alteration. The line could be misconstrued as the ideal parameters, whereas in fact they're just the result of extrapolations between two values either side of 0

11. Fig 10 it would be good to show the actual values, as well as the moving average.

Response: Done, included in Fig 10 now.

12. Fig 12 I struggled to see what the splitting of S3 into the three lettered sections was based on, so a clearer explanation would help.

Response: This is clearest in the map view, so we have changed the figure reference to Fig 12d to help the reader identify the key points.

References: 1. Biasi and Wesnousky, 2016. Steps and Gaps in ground ruptures: empirical bounds on rupture propagation. Bull Seis. Soc. Am. 106, p 1110-1124. DOI:10.1785/0120150175 2. Cowie and Scholz, 1992. Growth of faults by accumulation of seismic slip. JGR 97, no B7, p 11085-11095. 3. Cowie et al., 2017. Orogen-scale uplift in the central Italian Apennines drives episodic behaviour of earthquake faults. Sci Rep 7:44858, DOI: 10.1038/srep44858 4. Gold et al., 2015. On and off fault deformation associated with the September 2013 Mw 7.7 Balochistan earthquake: implications for geologic slip rate measurements. Tectonophysics 660, p 65-78, doi: 10.1016/j.tecto.2015.08.019 5. Nissen et al., 2014. Coseismic fault zone deformation revealed with differential lidar: Examples from Japanese MwLij7 intraplate earthquakes. EPSL 405, p244-256, DOI: 10.1016/j.epsl.2014.08.031

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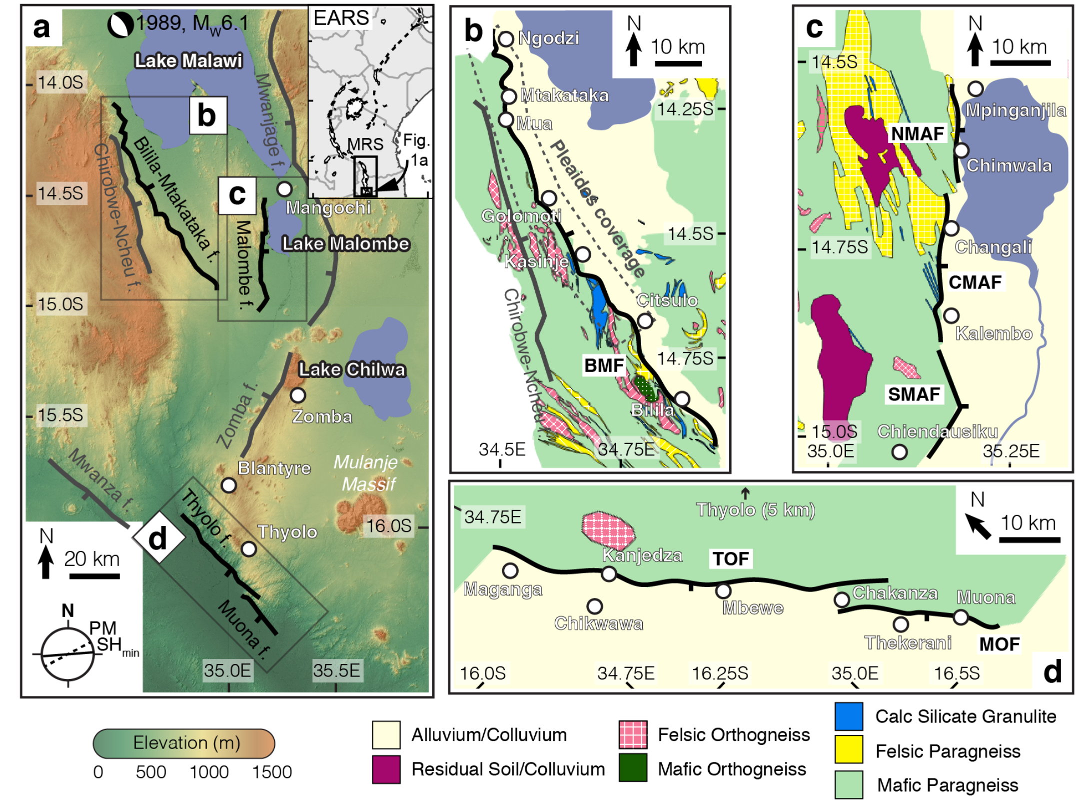

Fig. 1. Fig 1 with new EARS inset

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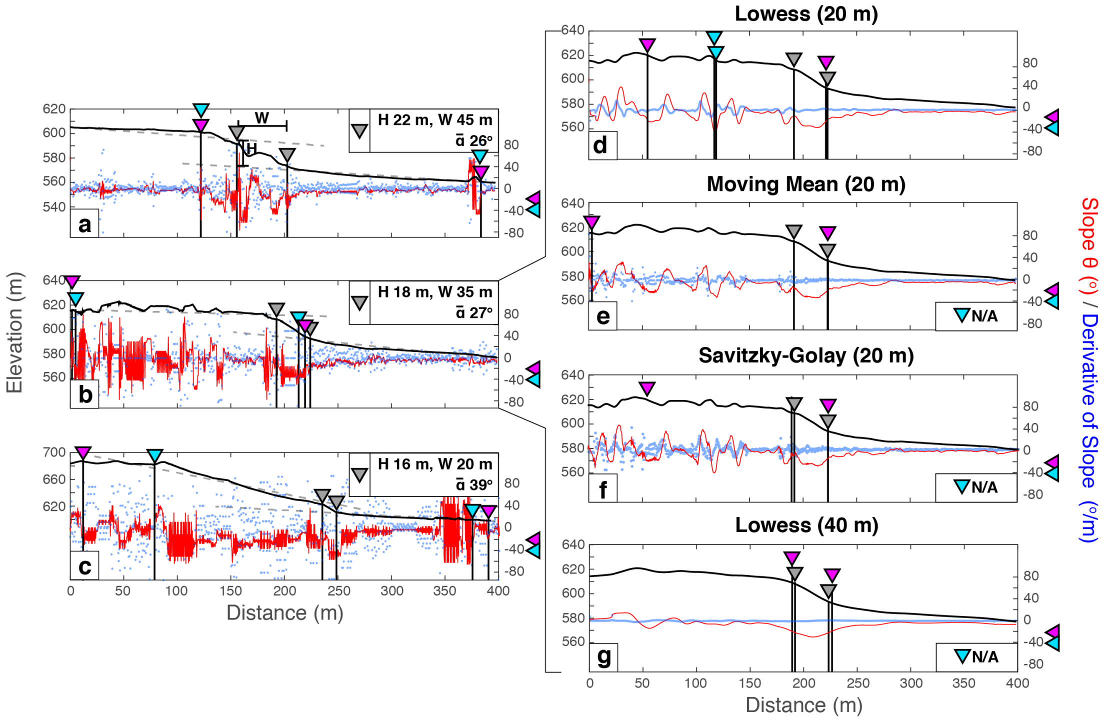

Fig. 2. Fig 2 with correct labels and S-G smoothing example

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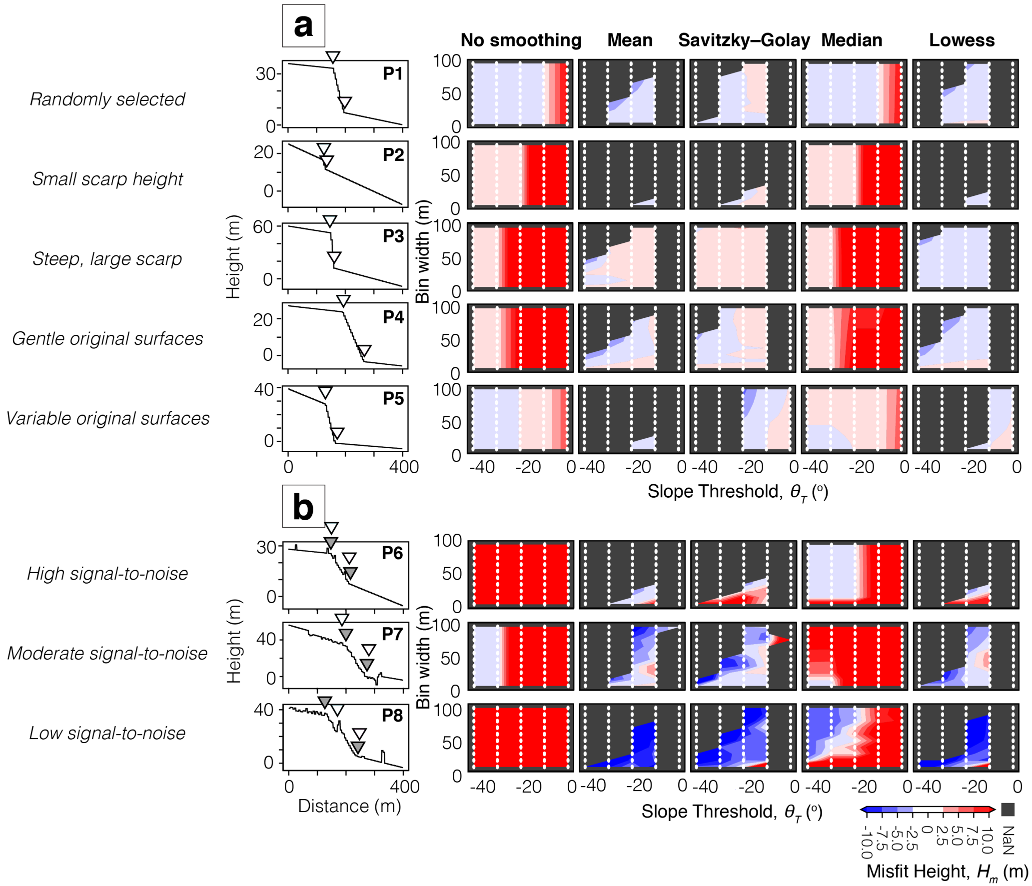

Fig. 3. Fig 4 with scarp markers

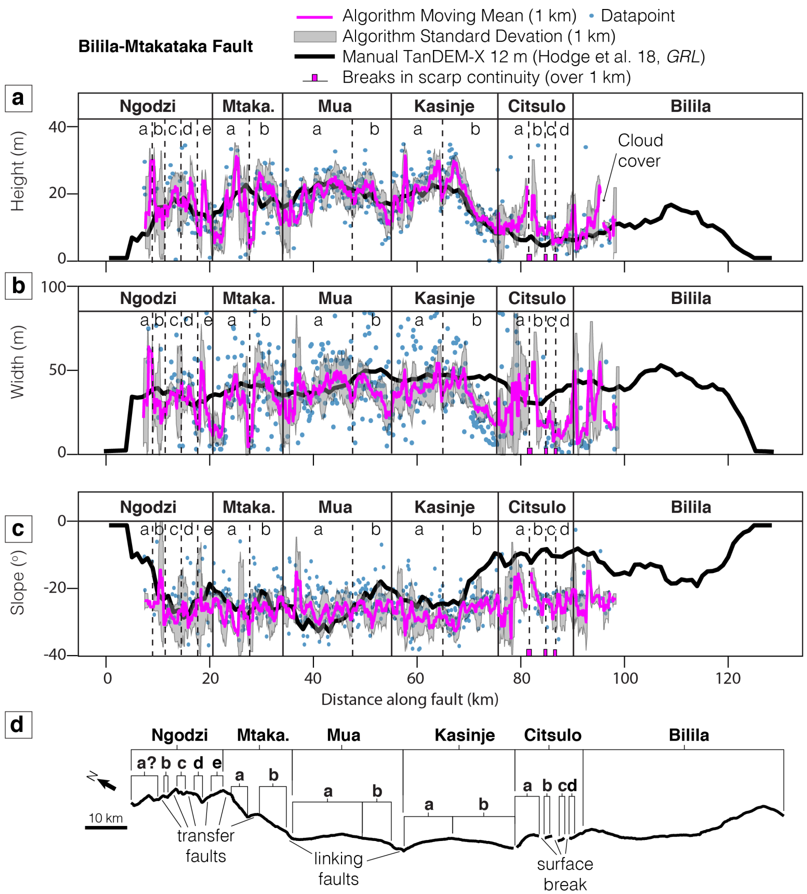

Fig. 4. Fig 10 with raw points

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