"Rift zone-parallel extension during segmented fault growth: application to the evolution of the NE Atlantic"

by Alodie Bubeck and co-authors.

Response to Reviewer: Atle Rotevatn, University of Bergen, Norway
(presently at U. Otago, NZ)

The main issues break down into five main categories. For elaboration on these issues, please scroll further down to the bulk of my comments, or refer to the annotated PDF.

1. There is confusion related to the authors' use of the term 'coherency' (and several other terms), and how they relate to processes fault growth. This creates confusion throughout.
   - Since the datasets do not provide information regarding the timing of slip accumulation/lengthening we cannot reliably assign either dataset to one of the growth models – constant-length or isolated. We have therefore simplified the terminology to avoid a discussion of those fault growth models. It is not the aim of this work to contribute to this debate.

2. Methods are not adequately described. Very importantly, it is not clear how heave or throw were recorded.
   - We have added a new methodology section and a new figure to explain how the datasets were collected, and the differences between different fracture types.

3. The results sections are mixed with background material and interpretations.
   - We have attempted to fix any issues with background and interpretations appearing as "results". Since the paper is quite discussion-focused, it is difficult to in some cases to separate out all results and interpretations, as some interpretation is required early to build up a consideration of scaling. Hopefully the new section subtitles will help with this separation.

4. Some of the interpretations (e.g. those presented in Figures 2c and 4c) are hard to reconcile with the evidence presented.
   - Additional labels have been added to the figures to make direct comparisons easier. We note a mistake in Figure 2c that has now been edited, and should help with making links to the evidence.

5. As a result of the points 2, 3 and 4 above, I find it difficult to fully grasp the discussion and how it relates to the results/data presented in the paper. I suspect it will be much easier to critically assess the discussion when the other points have been addressed – and I'd be happy to comment further on the discussion once this has been done.

In the following I go into depth about the issues above – and there are also many comments in the annotated manuscript PDF.

 Abstract
- at some point in this paper, it would be useful to clarify what you mean by 'mechanical interaction' since you use that term quite a lot. The term is defined in Peacock et al. (2016,

JSG 92, 12-29), is this what you mean?

- Same meaning, i.e. the mechanical behaviour of one fault is influenced by the presence of another fault (or indeed other structures). References have been added to the introduction to make the definition clear.

In terms of interaction, linkage and the presence or absence of kinematic/geometric coherency, I think many would agree with me when I say that there are loads of ambiguous terms, so perhaps a short terminology section would be in order where you define what you mean by various terms (I will list other terms that need clarification as we go along).

- We were referring to the final displacement distribution for a coherent fault array. As the shape of this final profile is the same for both fault growth models, references to geometric/kinematic coherence have been removed for clarity.

Introduction

- P1 L25: "Studies using natural examples and numerical or scaled-analogue modelling techniques have shown that normal faults grow through stages in which initially offset segments propagate towards each other and link to form composite structures (e.g. Trudgill and Cartwright, 1994 Gupta and Scholz, 2000; Peacock, 2002)" – true, but there are also now several studies that suggest otherwise, namely that fault growth may not be dominated by a tip-propagation behavior, but that faults and fault systems (even if segmented) appear to establish their full length very early on (e.g. Walsh et al. 2002; Giba et al. 2012; Jackson & Rotevatn 2013; Nicol et al. 2016; Childs et al. 2017; Jackson et al. 2017). This is known as the 'coherent fault model', which has later been rebranded as the 'constant-length model' and derivations thereof. The fault growth model that you invoke in the first sentence is that of a sympathetic increase in displacement and length over time during fault growth, which some refer to as 'isolated fault growth' (I personally think this name is misleading), and which has dominated the structural geology literature for decades. It is very important to note that neither of the models precludes linkage, interaction, relays and whatnot, and therefore I think both are equally a sound foundation for the topics discussed in this paper. But, the reason for bringing this up is this: you must make a decision about how to deal with this – at present you seem to ignore the 'coherent' view on fault growth in favor of the 'isolated' fault growth model. But then later in the introduction you state that "displacement (throw) gradients on adjacent coherent normal faults are commonly accommodated by relay structures". The key here is your use of the term 'coherent' (you need to define this term; I am not sure what you mean by it), which leads me to ask whether i) you are now buying into the coherent fault growth model instead, or ii) if you think both models are equally valid, or iii) if you are just using these terms without really having a clear position on what your position is on the matter. I think the intro needs to mention both of the two fault models, or at least provide some rationale as to why you prefer one over the other. Or, if you think it is of less importance and beside the point of the paper, rather focus the intro on the fact that faults are universally segmented, and that the faults/segments interact (regardless of whether they grow according to the 'isolated' or 'coherent' view on fault growth), avoiding this problem altogether. If you do this, I would get rid of the first sentence, and lead in with the sentence in L28-29 (starting with "Segmentation is a feature...". Having said all of this, I cannot help myself but wonder if (you think that) it matters whether faults grow according to one model, or the other, or a combination of the two. Does it make a difference in terms of what your findings mean? Or how applicable your findings are? Or, turning it around, can your findings

shed any light on models for fault growth? Again, you may feel that it is beside the point of this paper. Nevertheless interesting as a general topic for discussion in the forum, paper or elsewhere.

- Our initial intention here was to establish that there are different models for the growth and linkage of fault arrays. Admittedly, the way that we had positioned this within the manuscript makes it appear more important to the results than it is, and perhaps gives an impression that it is possible to determine the growth stages in the context of constant-length versus isolated, from the resultant displacement profiles: this is not our intention. We have attempted to simplify the terminology and describe extension deficits with respect to a bell-shaped final displacement profile, for a mature fault array accommodating regional extension. We feel that the rewording of sections throughout the manuscript makes clear that our intention is not to enter the debate concerning the timing of displacement/length accumulation.

- define 'mechanical interaction'
- Definition added: *where the mechanical behaviour of a fault segment is altered in the presence of another segment by the elastic interaction of their respective stress fields, see e.g., Segall and Pollard, 1980; Willemse et al., 1996*

- This is perhaps pedantic (P1 L36), but heave gradients are not horizontal displacement gradients, since heave is not horizontal displacement per se. Heave is simply the horizontal component of the displacement, so in my opinion it would be more correct to talk only of heave gradients.
- We would define the heave as being the horizontal component of the net-slip. For many of the fractures – since they accommodate no throw – the heave *is* the displacement/net-slip. However, it is simple enough to only refer to heave gradients.

- define 'coherent normal fault' – this becomes especially important since you in the first sentence appear to ignore coherent fault growth as an alternative to the more popular isolated fault model.
- Term removed. See previous comments.

- what do you mean by the term 'growth fault' here? Do you mean it as in syn-sedimentary growth faulting? If yes adding using the term 'syn-sedimentary growth fault' would add clarification, at least for me. Others might passionately disagree. This does not become more clear later in the paper, so there is a need to address this.
- Volcanic growth fault (see Macdonald et al., 1996 for definition). We have added the term *syn-volcanic* as equivalence to *syn-sedimentary*.

- I do not feel that the intro fully lands the aims of the paper – I am still not fully aware of what the main mission of the paper is at the end of the intro. I would recommend this be discretized somewhat.
- The primary aim of the manuscript is to consider whether the necessary 3D strains in the relay zone between faults are evidenced in structural sets at larger scales. To make this clearer, we have reworded the final paragraph of the introduction.

Background
- it breaks the flow up a little to have a new intro chapter here, called 'Background' – consider combining Intro and Background chapters to streamline the introduction of key concepts, identify key problems/knowledge gaps and state discrete aims and objectives. At

present (as pointed out in the last comment to the Intro chapter) the paper does not in my opinion express very clearly what the key mission of the paper is.

- Considering the broad readership of the journal, we feel it is important to set up the main topic of the study – relay zone strains within segmented normal fault arrays – before detailed description of the displacement profiles in the coming sections. It is therefore appropriate to keep a general "background", but note that by removing most reference to the end-member models for growth, the section is more easily applied to the following sections.

- P2 L21: here you are back talking about a 'coherent system' – you need to precisely define what you mean. This also relates back to the first major point about the 'coherent fault model'. What is a (kinematically?) coherent system? To you?

- As above, the term coherence has been removed.

- You are leaning quite heavily on Tentler & Acocella (2010). Is it possible to broaden this by looking at what other studies have said about deformation/strain and the degree of underlap/overlap, separation, etc? Names like Long and Imber come to mind.

- Additional references have been added.

- P2 L36 onwards: "In nature, however, the process should graduate through some or all of these stages, as the bounding structures propagate toward each other and link, subjecting the relay zone to distortions as a function of the changing fault cut-off line lengths associated with slip accumulation (Fig. 1c,d)." Back to the first point again. We would like to think it propagates and links (I have done the same in many of my own papers, but looking back I think this view may be too simplistic) but is it also possible that the linkage and rotation of the relays is a process of subsidence (displacement accrual), relay rotation and breaching (but no or limited tip propagation of the main faults), rather than propagation and linkage?

- Yes, our earlier version was not clear on these points. We have reworded to make it clear – in the context of changes elsewhere – that we are not proposing a specific order of slip/length accumulation.

P2 L43 – again you talk about coherency. It is becoming increasingly important that you address this and clearly define what you mean.

- *Coherency* has been removed.

[Methodology]
- The paper is weak on describing the methodologies used. I was left wondering for a long time if the paper actually was based on outcrop work, subsurface (the mention of growth faults pushed me in that direction, but that's a personal bias), or on imagery/remote sensing – or a combination. Stating in brief early in the paper what methods are used, and adding a methodology section would help more clearly explain the nature of the work. I am still not sure if the authors have visited all of the field sites, or if some of this was entirely based on mapping aerial/satellite imagery. This is of course very important for the resolution of the dataset, and has implication for what the throw/heave/extension plots represent. The only places where fieldwork or field mapping is mentioned is in the abstract and the acknowledgements. And there is no detailed description of what was actually done. There is some very general information under each field site, but not specifically what kind of data was collected, and how it was recorded. And what type of imagery has been used to compliment outcrop work? I assume part of the mapping was done based on the imagery in

the figures, but the text does not specify. All of this could be added with ease and would make the paper much easier to follow.

- We have added a short methodology section to clarify the issues raised, including a figure to illustrate the measurement methods that are critical to the described displacement profiles.
In summary:
- Displacement profiles were plotted using field data.
- Extension/heave: recorded manually in the field using offset polygonal cooling joint surfaces (activated at the free surface by fractures) using compass techniques.
- Throw: where applicable, estimated from field observations (offset footwall/hanging wall surfaces) or from high resolution topographic datasets (Hawai'i only).

- Very importantly: it is not clear how heave measurements were recorded, or how throw measurements were recorded (or estimated? – see comments to Figure 3). This needs to be crystal clear, or the results will not be reproducible.
- This should be clear now from methodology section.

[Terminology]
- Some terminology is not clearly defined (see previous comments – coherency is one important term here). I would ask the authors to consider introducing a short terminology section that removes doubt and confusion related to key terms used in the paper.
- Poorly defined terms, like "coherence" have been removed. Other terms that are noted in this review have been defined at the first occurrence, rather than pooling within a terminology section.

Field study areas

- P3 L 24: What do you mean by 'growth faults', and what do you mean by 'interpreted to be growth faults'? On what basis? Please clarify. What does forceful emplacement of dikes have to do with whether they are growth faults or not? Whose interpretation is this? Yours or that of the cited papers? It is quite confusing that this section is a mixture of background, results and interpretations (see several comments in annotated PDF).
- Much of this has been cut, and/or moved following earlier comments. (For instance, growth faults are defined earlier). With the exception of a brief introductory paragraph for the areas, these sections are now entirely observation from this study. Interpretations are separated into specific sections.

- P3 L 45 (pdf comment): It seems odd to talk about surface breaching normal fault segments, since you are working at the surface. If they were not surface-breaching you would not see them. So unless you have any subsurface data that allows you to also see non-surface-breaching faults, this term is redundant in my opinion. Unless you can come up with a good reason to use this term anyway.
- The term is appropriate and commonly applied in studies of dilatant faults. As a function of the upward propagating nature of volcanic growth faults (see field, numerical and scaled-analogue study references cited) and tensile stress distributions ahead of the fault tip, the subsurface expression of these faults can be predicted from the distribution and size/width of precursory (surface) monoclines, and extension fracture networks.

- It is beyond the scope of this work to develop this further than the existing literature has already done. A recently submitted manuscript (JSG) will address this in more detail.

- Figure 2 confuses me. Part C lacks a proper legend and requires deep concentration to reconcile with part B. Hard to follow. Better legend/annotation would help (e.g. it is not immediately obvious in part C which of the structures correspond with sets a,b, c, d in part B).
- Features in Fig. 2C are now labelled to correspond with Fig. 2B.

More importantly – the proposed evolution concerns me because the yellow structures in C bear no resemblance to the yellow structures in B. In C (the proposed evolution) they are almost perpendicular to the main rift strike, whereas in B (the actual studied system) the yellow structures strike at c. 45 degrees relative to the main rift strike.
- We have fixed the error in the figure. Labels are now added to help compare with the map.

Another point about Figure 2 is the arrows that indicate dip directions: Do all faults dip to the N-NE? Are there no antithetic faults here that dip to the S-SW?
- The majority of faults in the Koa'e dip to the N-NNW. In the study area (Fig.2B) there is one surface-breaching fault that dips SE. An arrow has been added to highlight this.

- what is your evidence for the relative ages of the different sets? For example for set D postdating set B as you seem to suggest in your proposed evolution in Fig 2c
- Set D was identified as fresh cracks in following seismicity in 1965.
- At the time of writing, this data was shared with us by Don Swanson at the Hawaiian Volcano Observatory, but was unpublished (but referred to as such). The data are now in press for a GSA Sp. Pub and the reference has been added.
-
- Figure 3 is also confusing to me. Part B: The legend vertical axis records 'heave', but the legend talks about 'total displacement' and 'extension'. This is somewhat confusing. You can address this by naming the axis 'heave/extension' and changing 'total displacement' to 'total heave'.
- Axis and key changed to "extension (in metres)"

It is also quite difficult to see the difference between the different line weights/dashing/colors – you might want to make it clearer.
- Lines edited (also Fig. 5)

Part C: the caption states this is 'estimated vertical displacement' – what do you mean? How was it estimated? Was it not measured? Also you state that "no evidence for throw was identified along NW-SE striking fractures of set B".
- Throw measurements are estimates made from field observations and topographic datasets. Methodology section now explains this.
- Set B (NW-SE striking) are extensional fractures only. There is minor monoclinal flexure of the surface along this trend but no surface-breaking fault segments.
- The figure caption has been edited to make clear that we are showing monocline height values only here.

What do you mean by no evidence for throw? What constitutes evidence of throw? Seems like a peculiar way to get at this. If there is no throw they should be opening

mode fractures or vertical strike-slip faults – you should be able to describe this in clearer terms.
- See comment above.

- I have similar reservations with Figures 4 and 5 so please apply the above suggestions/comments to these figures as well. Again I find it hard to reconcile the orientations of the faults in the evolutionary models with the real data.
- Labels have been added.

- P4 L1 (pdf comment): Herein lies an inherent inference, or interpretation, that the extension fractures are the surface representation of faults in the subsurface - am I right, or am I misunderstanding (if so please clarify, more people will likely misunderstand)? You need to thread carefully so that you do not mix description and interpretation. Save the interpretation for later.
- We have clarified this and added supporting references to the methodology section to explain how measurements were gathered.

- P4 L6-14: since you are not specifying how heave, throw, extension direction (? Yes, you mention this as a measured parameter) etc were measured, it is difficult to understand what these numbers mean and their significance.
- See methodology section.

- P4 L15 onwards: "With no evidence for the relative timings of the bounding and linking fracture sets, simultaneous orthogonal extension directions have produced an area of inherently 3D strain within the relay zone. A kinematically and geometrically coherent fault array (e.g. Walsh et al., 2003) should exhibit an approximately centralized displacement maxima; this is not the case for horizontal (heave) displacement where we find a prominent extensional strain deficit in the centre of the array (Fig. 3b,c). " I have a hard time understanding where you are going with this. Are you saying that you expect all fault arrays to follow an idealized bell-shaped displacement distribution?
- Relative to the final displacement profile for fully linked fault array, which are modelled on a bell-shaped displacement distribution, for both the isolated and constant-length fault growth models. These terms have been edited to simplify the terminology.

Is folding etc accounted for in your plots? And here you are talking about a kinematically and geometrically coherent fault array
- Folding in the vertical plane – as measured via the surface topography - is accounted for in Hawai`i study area as shown in the *vertical* displacement plot. There is little/no folding in the Krafla study area and is therefore not shown. It should be noted however, that the purpose of the manuscript is to focus on strains within the horizontal plane.

– back to the first comment again. Please clarify what you mean and how this is significant. Why does the array have to be kimenatically and/or geometrically coherent? What if the array is not kinematically or geometrically coherent? Is that an option, and what is the consequence of that? Not that it belongs here, it belongs in the discussion.
- See earlier comments.

- the Krafla chapter struggles generally with the same issues as those pointed out above for

the Hawaii dataset (mixing of description with background material, interpretations and discussion plus the other issues listed above). Please revisit this section too, using the Hawaii comments as a guideline.

- We have carried your comments forward for this section, and made edits accordingly.

- Section 3.3 – what do you mean by first-order and second-order faults – do you mean in terms of chronology (you said earlier there were no evidence for age-relations between the Hawaii sets)? Orientation? What sort of hierarchy is being introduced here, what is it based on?

- 1st-order: primary, relay-bounding rift faults; 2nd-order: local deformation, ancillary to 1st-order faults. Terms have been edited to make this clearer.

This statement: "Fracture sets that strike at a low angle to the main rift zone (<45°) show extensional-shear opening (e.g. Krafla: Figure 4)," – relates back to section 3.2 – what do you mean by extensional-shear opening? Are we talking about an opening-mode dominated fracture with a minor component of shear displacement? Or an oblique-slip dominated shear fracture (or oblique-slip fault if you like) with a component of opening?

- Mixed-mode or hybrid opening, i.e. an open-mode fracture with a component of shear displacement (lateral in this case) This term is defined in the new methodology section.

Better description and documentation of the studied structural features would help a lot. For example, it would help tremendously if you provided a picture of what you call extensional-shear opening fractures – and if you would explain how you measure the displacement across such a structure.

- A new figure has been added to methodology section to illustrate the different fracture modes and measurement technique.

Discussion:

- since the methodology and results sections have some unclarities related to i) how key was recorded, ii) the mismatch between data and proposed evolutionary models, and iii) the mixing of data and interpretations/discussion, I had a hard time grasping the discussion properly. The discussion raises a series of interesting ideas – but the way the data in the paper is presented (i.e. lacking proper explanation of how key data was recorded, and the mixing of results and interpretations) it is not helping me to see how the discussion is (or isn't) backed by what the authors present to us. I think therefore, that the best course of action would be if the authors addressed the issues with the manuscript leading up to the start of the discussion – and that the discussion/conclusions can only be fairly evaluated once that has happened. I have indicated to the editor that I would be very, very interested to look at the discussion once more when the mentioned issues have been addressed. Nevertheless I still have some general remarks to the discussions/conclusions at this point:

- how is what you are proposing different from what has already been proposed by previous authors in terms of local perturbation of regional stresses (e.g. Kattenhorn et al. 2000) – what makes the findings of this paper unique compared to previous studies? In other words, can you try to better delineate the relationship between your work, as presented here, and that of previous authors?

- New section titles have been added to the results, and the discussion has been separated from all results. There is no easy way to present the published and new results to show the links between different regions. We have opted here to put both

new and published data that can be considered as observations, within the results, and separated out sections to provide a bit of background info (this needs to be done at this stage to explain *why* we are presenting these larger-scale regions) and the summary and interpretations.

- The occurrence and distribution of high angle structures like these have been described ahead of discontinuous normal faults. However, this work is new for two main reasons: 1) the application is across scales within new areas; 2) The genesis and evolution of strain and resulting structures detailed here differs from previous studies noted above. Kattenhorn et al., 2000 present local rotation of principal stresses (<30deg), and oblique joint formation is the result of bending induced stresses during regional tectonic events (Laramide orogeny in their example). Our study highlights that "local" rotations may be driven by the need to accommodate opposing displacement gradients during interaction, but continued extension: the scale of the structures is dictated by the scaling of the first order faults. Other studies have noted second order structures during rotational strains, but there is an apparent lack of discussion as to the consequences. For instance, bookshelf rotation has been considered previously to accommodate displacement gradients (e.g., Green et al., 2014), but the authors have not discussed the consequent rift-parallel shortening that would be required, and the inherent volume change. Analogue models also show rift parallel volume change, but little discuss is focused in this context, especially across scales.

- is there a risk that, perhaps merely as a function of your choice of words, you are exaggerating the significance of rift-parallel extension? Localized extension on structures forming at high angles to general rift strike is hardly attributable to regional rift-parallel extension – I am not saying you are suggesting it, but in my opinion your choice of words/terms to describe this makes it sound like a regional, rift-wide effect rather than something that occurs localized to relays or steps in the rift axis. I am not sure I fully understand exactly what you are suggesting here. It would be very interesting to revisit this when the rest of the paper is more clear.

- Taking the Faroe Islands as example, we disagree that the strains and structures are not important in the grand scheme of things. The dikes accommodate ~1% rift-parallel extension in the region. Offshore in the Faroe-Shetland basin the Judd fault – a NW-SE striking fault that is normal to the rift – accommodates >500 m of normal displacement; units correlated across fjords in East Greenland suggest kilometer-scale displacements. The margin-oblique structures in the Faroes (ENE and ESE striking) in some cases appear to accommodate kilometer-scale strike-slip displacements, requiring a significant (at least locally) shortening sub-parallel to the rift system.

Conclusions:

- the conclusions embody some of the confusion I experienced when reading the discussion (I would completely rephrase the conclusions), and also underscores some of the problems related to terminology. I am not repeatedly addressing terminology to be pedantic – but unclear use of terms introduces confusion as to what the authors really mean to say and therefore it must be addressed to improve the clarity of the paper.

- Conclusions have been rewritten to carry forward comments throughout this review.

"Discontinuous normal faults in the Koa'e and Krafla fault systems accommodate regional horizontal extensional strains via a combination of fault throw and heave on first-order rift

faults, and by obliquely oriented second-order deformation, driven by heave displacement gradients and vertical axis block rotation within the intervening relay zones."

- This has been reworded and cut down for clarity.

• Accommodating "accommodate regional horizontal extensional strains via a combination of fault throw and heave" is in my opinion a quite peculiar choice of words. Strain is accommodated by means of faulting, the displacement of which can be broken into throw and heave, but throw and heave are not separate 'mechanisms' that accommodate strain.

- Terminology has been corrected.

• "Obliquely oriented second-order deformation" I also find to be fairly vague, and "heave displacement" (an imprecise term) is not a driver of anything – it is just the horizontal component of the total displacement.

- Conclusion removed.

"Second-order deformation within the two studied relay zones accommodate components of the regional extension, but locally accommodate components of extension in a direction parallel to- and oblique to the rift zone."

• Again, as pointed out earlier (in the PDF comments), I do not understand what you mean by introducing a hierarchy of first order and second order deformation/structures – particularly when you have no chronology in at least one of the study areas. Unless you clearly define what first- and second-order means, such terms have limited meaning.

- Definitions earlier in the text should help here, however we note that reference to hierarchical "order" of observations is common within regional structural studies.

• "but locally accommodate components of extension in a direction parallel to…." and so on… to me, talking about extension directions like this implies something more regional – in my opinion it would be more helpful to discuss this in terms of local stress reorientation and opening directions of specific structures/trends, rather than talking about extension directions which has a mega-scale flavour to it. And that is not the intention, is it? If it is, I will be even more confused.

- Since it is the structures that have been mapped, we prefer to refer to strains rather than stresses here. "Local" is an imprecise term as it is scale-dependent as to its meaning here: the strains are local to the scale of separation of the main bounding faults.

"Locally heterogeneous fault populations within relay zones are attributed to locally non coaxial stress states associated with mechanical interaction and resulting fault displacement gradients rather than polyphase tectonic episodes."

• What is a heterogeneous fault population? A fault population with more than one set of different orientations? Mechanical interaction and resulting fault displacement gradients also feels very vague and general, and would better be replaced with something more specific about the effectcs of such interaction, and the specific of what happens to the displacement gradient (those gradients could be quantified).

- Conclusion has been edited to clarify.

Response to Reviewer: L. Perez-Diaz, Royal Holloway University, London, UK.

I'd like to thank the editor for the invitation to review this manuscript. This is the first time I participate in an open-discussion review, and I very much look forward to the improvements arising from it at different stages.

This manuscript discusses formation, development, interaction and strain implications of extensional fault systems within relay zones. Findings obtained from the analysis of newly-acquired data are put in context by the authors by establishing links to global examples. I believe the topic is within the scope of Solid Earth and the manuscript would be of interest to both structural geologists and researchers in tectonics. However, I see two areas for improvement before publication.

First, large sections of the manuscript would benefit from being re-written in a more concise way. The overuse of "technical" terms makes it hard to follow at times, due to the abundance of very long and wordy sentences. There are also several instances in which you use terminology that, to me at least, is not clearly defined (or has been defined in different ways by the geoscience community). This makes the text confusing.

Second, but not less important, I would suggest to re-think your organization of the manuscript. At the moment, certain types of content seem to be spread across sections, and this makes the manuscript hard to follow. You should also draw clear links between your aims, your method, your discussion and your conclusions. Make it easy for the reader to see how one section flows into the next!

In the following I give examples of these two points as well as some other minor corrections, by manuscript section.

1. Introduction
Page 1 L24-25: About growth mechanisms for normal faults: not always through stages. In analogue experiments we often see cases of vertical and lateral growth and linkage but we also see faults develop their full length early on and maintain it. See for example the very recent Jackson et al. (2017) doi: 10.1144/SP439.22
  - We have reworded to make it clear – in the context of changes elsewhere – that we are not proposing a specific order of slip/length accumulation. However, this is certainly an interesting point of discussion for elsewhere!

Page 1 L34: I wasn't entirely sure about what you meant when you say "coherent" normal faults.
  - We have removed this term in an attempt to simplify the terminology. We describe extension deficits with respect to a bell-shaped final displacement profile, for a mature fault array accommodating regional extension.

In the introduction you give me a little bit of background, you tell me what you will address in this paper but you don't tell me why. I think there needs to be a clear connection here between what you do, how you do it and why you do it.

- We have reworded the final paragraph of the introduction to make our aims clearer.

On the "how"… why don't you give any details about your data collection? From the abstract I get that you went to the field, tell me about it! What did you measure, how did you measure it? This is important later on, because in your results section you give a lot of measurements but I'm not sure how you got them.
- Please see related comments to similar points in review 1.

2. Background
The structure of this section is very similar to that of the introduction. You start by giving the reader background and then you move on to focusing on what you will be presenting in this paper. Why go back and forwards twice? I would suggest merging these two sections into one or, at least, if you would like to keep both, differentiate them clearly by their content.
- We have removed reference to the end-member growth models, making the section more easily applied to the following sections.
- Considering the broad readership of the journal, however, we feel it is important to set up the main topic of the study – relay zone strains within segmented normal fault arrays – before detailed description of the displacement profiles in the coming sections. It is therefore appropriate to keep a general "background", but note that by removing reference to the end-member models for growth, the section is much more easily applied to the following sections.

Page 2 L4: "We aim to demonstrate…" This is what I need in the introduction! aims!, why throw this into the background section?
Consider writing an introduction with three distinct key elements: - Background/ previous work - Summary of your findings and how you've obtained them (or, you could have a separate methods section) - Aims/rationale: why is this important, what is this study's motivation.
- We have edited our introduction and cut down the background to address these issues.

3. Field study areas
Page 3 L28: "Approximately 2000 measurements…" You should have told the reader where does your new data come from before this point. Here you do give some detail, such as the use of GPS but skip some other details such as when did your field campaigns take place and what you did in the field. I'd suggest to focus this section on results, and talk about the methodology earlier.
- With the exception of a brief introductory paragraph for the areas, these sections are now entirely observation from this study.
- Methods are separated into an earlier (new) section.

Page 3 L42 "…we infer that..." suggests interpretation. If this is a results section there should be no place for interpretations in it.
- As above, interpretations have been cut or moved.

Page 4 L16 "A kinematically and geometrically coherent fault array…" Wouldn't this be more suited to a discussion? You seem to be making the point that what you see in the field should fit to the Walsh model?

- This has been edited to describe the recorded extensional strains relative to the final displacement profile for a fully linked fault array, accommodating regional extension.

Page 4 L38 "… may represent the first and final stage of deformation: : :" This again seems to be misplaced, it is an interpretation of results.
- This has been reworded to make it clear this is an observation based on the cross-cutting relationships present.

Sections 3.1 and 3.2 You give lot's of numerical values, measurements. I found it hard to follow, perhaps a table would help the reader get the full picture better? Also, your interpretations should be limited to section 3.3, and clear links should be established between those interpretations and the observations that lead you to them.
- We do not feel that tables would benefit the paper as the figures illustrate the relationships highlighted here.
- Interpretations have been removed. Results sections refer to observations only.

Section 3.3
Page 5 L10 "Relay zones, located at the lateral terminations of first-order segments, are characterized by second-order faults and fractures that strike oblique and normal to the bounding rift faults and show a heave displacement deficit in the regional extensional strain" is an extremely long sentence. It illustrates my earlier point that the use of too many technicisms makes the manuscript hard to read. Are what you call "bounding rift faults" the same as "first-order segments"? I'm not sure I follow your point here.
- Yes. These terms have now been defined earlier in the text.

4. Discussion
Personally, I would separate a classic discussion from the evaluation of findings within global settings. Maybe consider having a section where you discuss how your findings can shed light on North Atlantic tectonics? If you do that, you can then keep the discussion lighter and clearer, and use both your findings and the conclusions drawn from applying hypothesis to global examples as topics for discussion.
What motivates me to suggest a change in text structure is that Sections 4.2.1 and 4.2.2 don't read like discussions to me at all, they read like a literature review.
- We have separated data sections into km-scale (Hawai`i and Iceland) and 10s of km-scale (East Greenland and the Faroes).
- The discussion now covers only the rationale for upscaling and comparing the two scales of field study and presents our conceptual model for break-up in the NE Atlantic.

5. Conclusions
I don't doubt the list you provide are conclusions from your work but the link between the two is not clear to me from the manuscript. A shorter and more concise discussion would greatly help the reader see where your conclusions are coming from.
- Conclusions have been rewritten in line with earlier review comments.

Figures:

For some reason the figures in the .pdf are really small! Had to zoom to 300% to read some of the text. Worth considering how the figures would look once embedded in the text and the journal's format – adjust text sizes accordingly.

- Yes… This was a formatting issue with the SE template. This won't be an issue in the final version.

My general comment about the figures is that they could use some cosmetic touch ups. The information is there in most cases but by making small changes it would come across much more easily. Having multiple panels in a figure is fine, but having each panel oriented in a different direction (same for text) is confusing and not very helpful for the reader. Also, it should be clear what part of the figures are keys (by simply putting symbols into a box and label the box for example).
- We have added axes to figures for easier cross examination. This complements other orientation symbols.

Figure 2: Why are the angles of the yellow set with respect to the red set different on the photo and the evolution diagrams?
I would keep the three boxes in section (c) the same size, it would look more tidy.
I struggled to figure out why the symbols over c.i. are there! Maybe that is just me but no harm in making it clear it is a key. (Same for figures 4 and 8)
- We have fixed this error.

Figure 3: I don't quite understand why you have used x-y plots in part a instead of a scale bar? Maybe it is just me but it really confused me.
- The polylines in the plot (A) correspond to the individual D-L profiles in part B. An X-Y plot is used for consistency but we have added a scale bar for clarity.

Figure 4: I'd suggest avoiding having multiple-panel figures where some panels are rotated. This same comment applies to other figures. Perhaps your choice is motivated by trying to keep north up? Part c has text going in all possible directions!
Again, the fault sets in the evolution diagrams seem to be at different angles than in the photos?
- We have added axes to figure.

You have the content for an interesting paper which, if presented in a clear and concise manner will be helpful to many geoscientists. I hope my comments are helpful to you for the revision of the manuscript and please ask for clarification if you need it.

Best of luck, Lucia

Rift zone-parallel extension during segmented fault growth: application to the evolution of the NE Atlantic

Alodie Bubeck[1], Richard. J. Walker[1], Jonathan Imber[2], Robert E. Holdsworth[2], Christopher J. MacLeod[3], David A. Holwell[1]

[1] Department of Geology, University of Leicester, Leicester, LE1 7RH, UK.
[2] Department of Earth Sciences, Durham University, Durham, DH1 3LE, UK.
[3] Department of Earth and Ocean Sciences, Cardiff University, Cardiff, CF10 3AT, UK.

Correspondence to: Alodie Bubeck (ab753@le.ac.uk)

Abstract. The mechanical interaction of propagating normal faults is known to influence the linkage geometry of first-order faults, and the development of second-order faults and fractures, which transfer displacement within relay zones. Here we use natural examples of growth faults from two active volcanic rift zones (Koaʻe, Island of Hawaiʻi and Krafla, northern Iceland) to illustrate the importance of horizontal-plane extension (heave) gradients, and associated vertical axis rotations, in evolving continental rift systems. Second order extension and extensional-shear faults within the relay zones variably resolve components of regional extension, and components of extension and/or shortening parallel to the rift zone, to accommodate the inherently three-dimensional (3D) strains associated with relay zone development and rotation. Such a configuration involves volume increase, which is accommodated at the surface by open fractures, in the subsurface this may be accommodated by veins or dikes oriented oblique- and normal to the rift axis. To consider the scalability of the effects of relay zone rotations, we compare the geometry and kinematics of fault and fracture sets in the Koaʻe and Krafla rift zones with data from exhumed contemporaneous fault and dike systems developed within a >5x10⁴ km² relay system that developed during formation of the NE Atlantic Margins. Based on the findings presented here we propose a new conceptual model for the evolution of segmented continental rift basins on the NE Atlantic margins.

1 Introduction

The primary, regional scale segmentation of extensional terranes is controlled by the development of networks of normal fault systems and the partitioning of strain across them. Normal faults comprise multiple discontinuous, non-collinear segments, with overlaps and segment linkage forming characteristic stepping geometries at a broad range of scales (e.g. Cartwright et al., 1996; Peacock et al., 2000; Acocella et al., 2005; Long and Imber, 2011; Henstra et al., 2015). Fault growth models have been derived using natural examples and numerical, or scaled-analogue modelling techniques, where normal faults grow through stages in which discontinuous segments interact and link across *relay zones* to form composite structures with fault displacement deficits initially accommodated by soft-linkage rotation and/or material folding (e.g. Trudgill and Cartwright, 1994 Gupta and Scholz, 2000; Peacock, 2002; Long and Imber, 2010).

Mechanical interaction (i.e., where the mechanical behaviour of a fault segment is altered in the presence of another segment by the elastic interaction of their respective stress fields, see e.g., Segall and Pollard, 1980; Willemse et al., 1996) between discontinuous fault segments can have an important influence on fault system evolution, including the geometry of first-order (i.e. largest scale of observation) faults, and the development and distribution of second-order (i.e. ancillary) faults and fractures within developing inter-fault (relay) zones. Segmentation is a feature common to all scales of faults and fault development (e.g. Walsh et al., 2003; Long and Imber 2011) and the conservation of regional strain across networks of discontinuous segments has been well-established (e.g. Peacock and Sanderson, 1991; Peacock, 2002; Fossen and Rotevatn, 2016). Normal fault displacement is typically considered with emphasis on the vertical motion (fault throw), which can be measured using offset bedding, either in the field, laboratory, or using high-resolution seismic imaging. In horizontally-layered materials, displacement (throw) gradients on adjacent coherent normal faults are commonly accommodated by relay structures (e.g., Peacock and Sanderson, 1991; Childs et al., 1995; Long and Imber, 2010), requiring horizontal axis bending of the host layering (Fig. 1). The bounding faults of a relay zone also exhibit opposing horizontal displacement (heave)

gradients, which requires a component of vertical axis rotation to maintain the connection between the hanging wall and footwall (e.g. Ferrill and Morris, 2001). Few studies have addressed this rotational strain (see e.g., Koehn et al., 2008), and the resulting horizontal extension profile between faults or the potential for non-plane stresses and strains within the relay zone. Unlike horizontal axis rotation, it cannot be accommodated by layer-parallel or flexural slip between layers (unless layering is vertical) and thus requires the material to bend or stretch within the layer plane.

We present field examples of growth faults from two active volcanic rift zone segments - the Koaʻe (Island of Hawaiʻi) and Krafla (northern Iceland) fault systems - to demonstrate the inherently three-dimensional (3D) strains associated with extensional strain gradients in evolving relay zones. The Koaʻe fault system represents an early stage rift that connects the East and Southwest rift zones of Kīlauea Volcano to produce a continuous zone of extension that facilitates southward flank motion. The Krafla fissure swarm represents a well-established and highly extended portion of the Neo-Volcanic Zone of Iceland, a subaerially exposed segment of the NE Atlantic spreading ridge. Faults in both study areas are interpreted to be upward-propagating (e.g. Tentler, 2005; Martel and Langley, 2006) syn-volcanic growth faults (e.g. Macdonald et al., 1996; Dauteuil et al., 2001; Holland et al., 2006). The two case studies represent, respectively, early and advanced stages in normal fault linkage during rifting.

In both case studies the expression of surface strains records minor (≤20%) extension, in which respect they can be considered analogous to the surface expression of evolving extensional systems. The aim of this paper is to demonstrate the importance of displacement variation as a function of fault heave, rather than throw, and highlight the potential for the development of non-plane strains and volume change at the scale of the intervening relay zones. We consider the potential for such 3D strains to form a viable alternative model to explain complex fault sets in laterally-propagating rift systems: here we contrast structures in the Koaʻe and Krafla regions to upper crustal (e.g. ~1-6 km depth) structures of at least one order of magnitude greater scale, developed along the NE Atlantic margins. For comparison, existing and new kinematic and geometric data are presented for Kangerlussuaq (East Greenland) and the Faroe Islands (European) portions of the NE Atlantic margins. Based on these examples, we suggest a new conceptual model for the evolution of segmented continental rift basins, with specific reference to the NE Atlantic margin.

2 Background: Displacement transfer and relay zones in segmented normal fault systems

Two-dimensional analyses of the stresses surrounding en echelon faults and dikes have demonstrated that mechanical interaction of opposing elastic stress fields produce areas of highly perturbed stress, which exert a control on the growth, slip distribution and geometry of faults (e.g. Segall and Pollard, 1980; Sempere and Macdonald, 1986; Cowie and Scholz, 1992; Crider and Pollard, 1998). To maintain the extensional strain across the fault system as a whole (i.e. representing a fully linked, mature system), the volume ahead of the fault tips is required to accommodate the opposing along-strike displacement gradients on the first-order bounding fault structures. This may be accommodated in this inter-fault region, or relay zone, through components of elastic and inelastic strain (e.g. Peacock and Sanderson, 1991, 1994; Childs et al., 1995; Long and Imber, 2010), and depending on the degree of overlap and separation of individual segments, may lead to different styles of deformation (e.g. Tentler and Acocella, 2010; Long and Imber, 2011; Childs et al., 2017) (Fig. 1A, B).

Using scaled-analogue models, Tentler and Acocella (2010) showed that a large underlap (relative to fracture length) between fracture segments produces elongate relay zones with new linking fractures opening ahead of the tips, striking sub-parallel to the bounding fractures (Fig. 1Di). Decreasing the underlap of the bounding fractures (Fig. 1D, ii-iv) results in the growth of open fractures in the relay zones that strike at increasingly higher angles to the main structures. The propagation of these high angle fractures generate a local component of extension, and volume increase, in a direction parallel or at low angles to the strike of the bounding fractures. At the same time, the component of extension orthogonal to the bounding structures decreases. At larger overlap geometries (Fig. 1D, v), linking fractures strike at a lower angle, resulting in a reduction of the local component of bounding fracture-parallel extension and an increase in the fracture-normal component. The model configurations of Tentler and Acocella (2010) represent single stages of propagation and linkage, rather than the full progression. In nature, however, the process should graduate through some or all of these stages, as the bounding structures propagate toward each other and link, subjecting the relay zone to distortions as a function of the changing fault cut-off line lengths associated with slip accumulation (Fig. 1C, D).

It is typical to consider the distortions associated with normal fault displacement in terms of the vertical motion: the throw (e.g. Fig. 1D). This is perhaps due to the association of normal faults with gently dipping or horizontal bedding, which

2

provides useful and abundant offset markers for measurement. There are fewer studies that have made detailed analysis of horizontal motions – the fault heave – due to the challenges in defining it accurately. Local deficits in fault throw are identified using comparisons with a theoretical final displacement profile for a fully linked set of faults accommodating regional extension, which show a centrally located displacement maxima. Such deficits can be accommodated by the development of new synthetic faults in the relay zone, and/or by folding about a horizontal axis, producing the relay ramp. Any deficits in fault heave, on the other hand, require vertical axis rotation (Fig. 1C, E), which can be accommodated by the formation of new faults (i.e. hard-linkage: e.g. Gawthorpe and Hurst, 1993; Hus et al., 2006), or bending within the plane of bedding (i.e. soft-linkage: e.g. Childs et al., 1995; Faulds and Varga, 1998). The evolution of such structural elements will have a profound influence on the evolving tectono-stratigraphic architecture of rift basins (e.g. Lambiase and Bosworth, 1995; Sharp et al., 2000; Hus et al., 2006) as well as contributing to the sealing potential or fluid flow properties of fault zones (e.g. Morley et al., 1990; Manzocchi et al., 2010; Seebeck et al., 2014).

3 Methodology

Surface-breaching normal faults in the Koaʻe and Krafla fault systems cut sub-horizontal bedded lavas, which exhibit vertical columnar joint sets at a range of scales. Previous work has established that faults in layered basaltic sequences, at low confining pressures, develop as networks of extension fractures, which open along favorably oriented, pre-existing cooling joints in the lava pile, driven by tensile stresses ahead of blind normal faults (e.g. Grant and Kattenhorn, 2004; Martel and Langley, 2006). Eventual linkage of fault and fracture networks at depth results in the development of surface-breaching, sub-vertical normal faults that exhibit components of horizontal and vertical displacement. The polygonal geometry of reactivated cooling joints allows displaced walls to be matched across the aperture of open fractures at multiple points along individual traces for: (1) extension fractures (i.e. mode-I fractures with no throw); (2) extensional-shear fractures (i.e. mixed-mode fractures with open and lateral shear components of offset, but no throw); and (3) normal faults (i.e. throw across subvertical, surface-breaching fault segments). Measurements of extension direction, extension magnitude (i.e. opening, or aperture), mode (i.e. mode-I or mixed-mode: Fig. 2) and individual trace azimuth were gathered using traditional compass techniques (Fig. 2). Cut-off line positions for surface-breaching fault segments and hanging wall monoclines were mapped remotely using satellite imagery (GoogleEarth[TM] and World-View2) and topographic datasets (aerial LiDAR; Hawaiʻi only). The resulting combined dataset contains approximately 2500 measurements and covers up to three orders of length magnitude. Where applicable, fault throw was estimated, either in the field, or remotely using high-resolution topographic datasets. It should be noted that a majority of the structures encountered in the study areas are extension fractures that do not involve a shear component, typical of deformation patterns seen in many near surface rift zones (e.g. Grant and Kattenhorn, 2004; Casey et al., 2006).

Fault and intrusion geometry and kinematic data was collected over several field seasons for Kangerlussuaq and the Faroe Islands, from over 400 localities (Walker, 2010; Walker et al., 2011). Structures were mapped using a combination of field observation and remote sensing analysis. Fault slip data from localities was grouped based on observed cross-cutting relationships where possible, or grouped by fault strike where direct cross-cutting relationships were not clear. Kinematic inversions were performed using the methods described in Walker et al. (2011).

4 Field study areas

4.1 Kilometre-scale segmented fault systems

4.1.1 The Koaʻe fault system, Hawaiʻi

The Koaʻe fault system is ~12 km long and ~3 km wide and is located on the south flank of Kīlauea Volcano, the youngest intraplate volcanic system on the Island of Hawaiʻi. The Koaʻe system connects two prominent rift zones: the Southwest and East Rift Zones, (SWRZ and ERZ: Fig. 3A) to form a near-continuous rift system that accommodates regional NNW-SSE extension (Dzurisin et al., 1984; Wright and Klein, 2006; Poland et al., 2012).

Based on orientation, extension direction, and spatial distribution, we identify two dominant fault and fracture sets in the Koaʻe fault system: (1) ENE-WSW (ERZ-parallel) striking first-order fractures and normal faults that accommodate

3

the regional NNW-SSE extension (sets A, C and D; Fig. 3B); and (2) NW-SE (ERZ-oblique) striking fractures that accommodate a more localised NE-SW extension (set B; Fig. 3B). The NW-SE (ERZ-oblique) striking fractures (set B) are not ubiquitous throughout the Koaʻe fault system. Instead they are restricted to zones of underlap between 1st-order rift faults: here, in the underlap between two major ENE-WSW (ERZ-parallel) striking normal faults: sets A and C (Fig. 2 and 3). NW-SE striking fractures are therefore described as second-order structures, ancillary to first-order bounding rift faults (set A and C). All measured fractures in this NW-SE striking set (set B) show purely extensional opening (Figure 3B), resulting in a local extension direction that is ~40° clockwise of the regional (NNW-SSE) extension. We found no evidence for cross-cutting relationships between ENE-WSW and NW-SE striking fracture sets (sets A, C and B, respectively, Fig. 3Ci, ii). Measurements of fresh ground cracks following the last major rifting event that affected the Koaʻe (December 1965) identified fresh ENE-WSW striking extension fractures (here labelled set D: Fig. 3B, Ciii; Swanson et al., in press), at which time fault and fracture sets A, B, and C had already been mapped; we infer here that these existing sets either formed in a cyclic sequence, or formed contemporaneously.

The ENE-WSW striking sets comprise first-order normal faults that dip dominantly to the north and demonstrate maximum throws of ~5-12 m, and footwall fractures with maximum apertures of ~4-5 m (sets A and C; Fig. 4). Individual surface-breaching normal fault segments show trace lengths of up to ~200 m, and exhibit discontinuous fault-parallel monoclinal flexures in fault hanging walls. Fault sets A and C (Fig. 3 and 4) are separated by ~800 m (measured in a NNW-SSE axis, parallel to the fault dip), and underlap by 200 m. The NW-SE striking fracture set are limited to this zone of underlap, and record smaller strains, with no surface-breaching fault segments, and fractures with trace lengths <200 m and apertures <2.5 m (set B: e.g. Fig. 4B). We interpret this zone of underlap to be a relay zone, bound by fault sets A and C.

Figure 4 shows the summed surface extensional strains for each fracture set in the mapped area, as a function of the total plane-normal extension (i.e., extension measured in the dip azimuth), and the resolved contribution to NNW-SSE (regional) extension. Extension on set B fractures is in deficit compared to the surrounding regions with a total measured heave (aperture) peak of ~3.5 m compared to ~6 m for the northern bounding set A and 4.5 m for the southern bounding set C (Fig. 4B). A vertical displacement (throw) deficit is also recognized (Fig. 4C) from aerial LiDAR datasets with up to ~12 m of displacement measured across fault A and up to ~4 m across fault C and the monocline along fracture set B. The relative contributions of the components of rift zone-normal and rift zone-parallel extension also follow this distribution with a centrally located minimum of 3 m (rift zone-normal extension) on linking set B. This minimum is bound to the north by ~5 m of rift-normal extension on set A and ~4 m on set C to the south. Calculated rift zone-parallel extension is minor on southern bounding set C (up to 1.2 m) and peaks are approximately equal on the linking set B and northern bounding set A (up to 2.5 m). Although set B accommodates a component of rift zone-normal extension, this set contributes relatively little to the regional extensional strain as a whole (Fig. 4B,C).

4.1.2 The Krafla fissure swarm, Iceland

Iceland sits at the junction between the northern termination of the Reykjanes Ridge, and the southern termination of the Kolbeinsey Ridge, with present-day rifting on the island accommodated by the Neo-Volcanic Zone. We focus here on the well-exposed Gjastykki valley, 10 km North of Krafla, within the Krafla fissure swarm (Fig. 5). Regional NW-SE extension in the Krafla fissure swarm is accommodated dominantly on surface-breaching normal faults with maximum throws of 10-30 m; monoclinal surface flexures occur as discontinuous structures in some fault hanging walls, but are rare compared to the Koaʻe fault system. The focus of this study area is a relay zone surrounding the tips of en echelon rift zone-parallel normal faults that strike NNE-SSW (Fig. 5B, C).

Faults and footwall fractures in the Krafla system can be separated into three structural sets based on their orientation, extension direction and extension mode (Fig. 5C, D): (1) NNE-SSW striking (parallel to the rift axis: set A, B, C) first-order fractures and normal faults, that accommodate rift zone-normal (WNW-ESE) extension; (2) NW-SE striking (rift-oblique: set A', B') normal faults and mixed-mode (extensional-shear) fractures that accommodate rift zone-oblique (ENE-WSW) extension; and (3) WNW-ESE striking (rift-normal: set D) fractures that accommodate rift zone-parallel (NNE-SSW) extension. The distribution of NW-SE (set A',B') and WNW-ESE (set D) striking fractures is limited to a zone of underlap ahead of two first-order rift-parallel normal faults (set A and B). Both the NW-SE and WNW-ESE sets are cut by a NNE-SSW striking normal fault showing up to 2 m of throw and set of fractures with up to 3 m of aperture (set B-C). These later structures connect NW-SE striking sets B' and A' and accommodate rift zone-normal extension. Hence, rift-

4

parallel striking faults and fractures, which cut, and are cut by, obliquely oriented sets, are the first and final stage of observed deformation in the rift zone, respectively (Fig. 5E). No consistent cross-cutting relationships are observed between rift-oblique and rift-normal striking structures (Fig. 5E), suggesting that they formed contemporaneously.

5   Figure 6 shows the summed extensional strains for each fracture set in the mapped area, as a function of the plane-normal extension, and the resolved contribution to WNW-ESE (regional) extension. Rift-oblique striking fault and fracture sets (set A', B': Fig. 5C, 6A) are well-developed and branch away from the tips of rift-parallel striking faults, with tensile openings of up to ~8 m (Fig. 6B) and estimated maximum throws of ~ 20 m. Rift-normal striking fractures (set D: Fig. 5C, 6A) represent the smallest strains in the relay zone with maximum fracture apertures of up to 2 m (Fig. 6B) and no vertical

10 displacement (throw). Based on the total measured extension profile (grey dotted line in Fig. 6B), which represents a fully linked fault array that accommodates regional extensional strain, the underlap zone does not appear to be in deficit compared to the surrounding regions. There is an approximately centralized total aperture peak of ~14 m, compared to 8 m for southern bounding set B and 13.5 m for northern bounding sets A and C (Fig. 6B). When the directional components of this total measured extension are plot, however, we are able to define a pronounced heave deficit in the relay zone (blue and red dashed lines on Fig. 6B). Resolved rift zone-normal extension is greatest on northern bounding sets B and C (~12 m),

15 followed by southern bounding set B (~10 m), with a low of ~9 m total aperture for linking fault and fracture sets (A', B', D, B-C: Figure 6B) in the overlap zone. Rift zone-parallel extension within the relay zone is significant for the area at ~ 8 m, compared to a maximum of 1 m for southern bounding set B and a maximum of 5.5 m for northern bounding sets A and C.

4.1.3 Summary and interpretations for the Koaʻe and Krafla fault systems

20 Regional extension in the Koaʻe and Krafla fault systems is accommodated by segmented rift zone-parallel faults that are discontinuous and underlapping at the present-day topographic surface. Relay zones, located between the lateral terminations of first-order bounding rift faults, transfer displacement across second-order, ancillary faults and fractures that strike oblique- and normal to the bounding fault segments. Displacement (extension)-length profiles show an extension deficit in the regional extensional strain, relative to a theoretical displacement profile for fully linked fault array (Figure. 4B and 6B).

25 Fracture sets that strike at a low angle to the main rift zone (<45°) show extensional-shear opening (e.g. Krafla: Fig. 5), and must therefore accommodate a combined rift zone-normal extension direction (i.e. contributing to the regional extension), and a component of rift zone-parallel shortening. Fracture sets that strike at high angles (i.e. >45°) to the main rift-parallel faults are dominantly extensional, and therefore provide a smaller contribution to the regional extension, but nevertheless represent a significant component of rift zone-parallel extensional strain. Simultaneous orthogonal extension directions

30 produce an area of inherently 3D strain within the relay zones.

           Observed rift-oblique extensional-shear fault and fracture sets are dominantly synthetic to each other, rather than bimodal (i.e., conjugate). As such, we infer that they facilitate a vertical axis rotation between the main rift faults, similar to a bookshelf-like faulting mechanism (Mandl, 1987). A bookshelf rotation about a vertical axis would involve a rift zone-normal material thickening, but must also involve a rift zone-parallel material thinning (cf. bookshelf rotations about a

35 horizontal axis, which accommodate horizontal extension and vertical thinning). Fractures with strikes orthogonal to the main rift faults in the Krafla study area, however, display extensional openings that may counteract this shear-induced shortening, leading to an overall volume increase within the rift zone. At the surface, this volume increase is accommodated by open cracks, but may be accommodated in the subsurface by normal faults and dike emplacement oblique to, and normal to the rift axis.

40 ### 4.2 Tens-of-kilometer-scale segmented basin systems: the NE Atlantic passive margins

The pre-break-up configuration of the NE Atlantic involved the development of offset spreading segments (the Reykjanes and Aegir systems; Fig. 7B-D) that accommodated a regional NW-SE extension, culminating in break-up and formation of the contiguous NE Atlantic (Gernigon et al., 2012). The Faroe Islands and Kangerlussuaq were located either side of the SW termination of the Aegir spreading ridge segment, and NE termination of the Reykjanes ridge segment, respectively (Fig.

45 7A), and both ridges record the initiation of oceanic spreading in the Early Ypresian (~55-53 Ma: Gernigon et al., 2012) (Fig. 7C). Prior to NE Atlantic spreading, the Faroes and Kangerlussuaq were located about 80 km apart (Ellis and Stoker,

5

2014). The two regions can therefore be considered remnants of a very large ($\sim 5\times 10^4$ km^2) breached relay system between the eventual ridge segments.

Both areas are dominated by Cenozoic North Atlantic Igneous Province lavas and intrusions, and both exhibit sequential deformation phases that are constrained as having formed prior to, and contemporaneous with, Atlantic opening (Walker et al., 2011; Roberts and Walker, 2016; Guarnieri, 2015. Here we present a combination of new geometric and kinematic data for the Kangerlussuaq region of East Greenland, and published data for Kangerlussuaq and the Faroe Islands, based on field- and remote-mapping of upper crustal (1-6 km depth maximum) faults and intrusions. We do not seek to directly compare the scale or regional dynamics of continental margins with volcanic island faulting or mid-ocean ridges, but rather the kinematic evolution of segmented fault systems. Our comparison is between the surface expression of fault sets (Koaʻe and Krafla), and near-surface brittle deformations on the Atlantic margins. We do not seek here to address full crustal thickness stretching models.

4.2.1. Kangerlussuaq, East Greenland Atlantic margin

Igneous activity in the Kangerlussuaq region of East Greenland (Fig. 8A), associated with continental break-up is thought to have occurred in three phases: 62-59 Ma, 57-54 Ma and 50-47 Ma (Tegner et al., 1998), with emplacement of the 7 km wide, layered gabbroic Skaergaard intrusion at ~56 Ma (Wotzlaw et al., 2012). Deformation is characterized by geometrically and temporally-linked suites of cross-cutting faults and dikes, hosted within the Archaean basement and Cretaceous-Cenozoic stratigraphy (Fig. 8B, C). Importantly, faults and dikes cut the Skaergaard intrusion, and compositionally similar macrodikes (e.g., the Miki Fjord macrodike: Fig. 8A, C) that are thought to be contemporaneous with emplacement of the Skaergaard intrusion (Holm et al., 2006; Holwell et al., 2012), giving a well-constrained maximum age for the deformation.

The ~500 m thick Miki Fjord macrodike strikes parallel to the margin and Reykjanes ridge segment (i.e., NE-SW; Fig. 8A, C), and accommodates margin-normal (NW-SE) extension. The macrodike is cut and offset by ESE-WNW oblique-extensional faults, which show lateral displacements of at least ~100 m (e.g. Fig. 8C), and form a conjugate set with ENE-WSW-striking faults, that accommodates margin-oblique (N-S) extension (Fig. 8Di). These faults also cut the Skaergaard intrusion (Fig. 8B) and strike parallel to conjugate dikes, with which they show a mutual cross-cutting relationship. Skaergaard additionally hosts margin-normal (N-S to NW-SE) faults and dikes, accommodating margin-parallel (NE-SW) extension (Fig. 8B, Dii), which are cut by the margin-oblique structures (Fig. 8B). Locally, margin-parallel dikes are observed in the Skaergaard intrusion, which cut both of those sets (see also Irvine et al., 1998).

4.2.2 The Faroe Islands, European Atlantic margin

Deformation in the Faroe Islands (Fig. 9A) is characterized by sets of cross-cutting faults and intrusive igneous sheets that reflect reorientation of the local extension vector during and following emplacement of the Faroe Islands Basalt Group (57-54 Ma: Passey and Jolley, 2009; Fig. 9B). Based on fault and fracture geometry and kinematics (including paleostress analysis), together with cross-cutting relationships, Walker et al. (2011) identified three main structural sets (Fig. 9C, D, E). These are (oldest to youngest): (1) N-S and NW-SE striking normal faults and dikes (*margin-normal strike*; Fig. 9C, Ei) that accommodate E-W to NE-SW extension; (2) ENE-WSW to ESE-WNW conjugate dikes and strike-slip faults (*margin-oblique strike*; Figure 9C, D, Eii) that accommodate N-S extension; and (3) NE-SW and NNE-SSW-striking strike-oblique-slip faults (*margin-parallel strike*; Fig. 9D, Eiii) that accommodate NW-SE extension. Walker et al. (2011) interpreted the fault and intrusion sets as representing a progressive anti-clockwise rotation in the extension direction before, during and following continental break up. Set 1 (NW and N striking) faults are associated with thickness variations in the Faroe Islands Basalt Group (Passey and Jolley, 2009) suggesting that they are Paleocene in age. Using U-Pb geochronology for calcite-bearing fault rocks, Roberts and Walker (2016) showed that although dating of set 2 (ENE and ESE striking) faults suggest they are Mid-Eocene in age, there was potential for overlap with the ages of set 3 faults (Eocene and Miocene). Roberts and Walker (2016) were unable to constrain ages for set 1 faults, primarily due to high concentrations of common Pb, and very low U concentration within the tested calcite. Margin-parallel (NE-SW striking) faults accommodate extension parallel to the regional extension (i.e. NW-SE). The apparently oldest structures strike NW-SE and are parallel to postulated margin-normal

6

strike-slip (transfer) fault zones reported along the margin (e.g., Ellis et al., 2009). In the Faroe Islands, this set accommodates minor (~1%) extension parallel to the margins, and not strike-slip displacement. The prevalent strain recorded on the Faroe Islands, in terms of distribution and scale of displacements, is associated with the phase of N-S extension, in which ENE-WSW and ESE-WNW conjugate dikes and strike-slip faults accommodate large lateral displacements (potentially up to hundreds of metres).

4.2.3 Summary and interpretations for Kangerlussuaq and the Faroe Islands

Faults and intrusions in Kangerlussuaq and the Faroe Islands record a consistent vertical axis rotation in extensional strains through time, during a period of regional-scale NW-SE extension (Walker et al., 2011). Structures that strike at a high-angle to the NE-SW trending rift segments (i.e. NW-SE striking structures) accommodate NE-SW (rift-parallel) extension (Fig. 8D, 9E), rather than the dominantly strike-slip displacements that have been inferred from seismic and potential field datasets (e.g. Rumph et al., 1993; Ellis et al., 2009). Structures that strike at angles oblique to the rift segments (i.e. ENE- and ESE-striking faults and intrusions) accommodate a component of rift-sub-parallel shortening, and extension oblique to the regional extension vector (Fig. 8D, 9E). Very few structures within the mapped areas accommodate rift-normal extension (NW-SE): the Miki Fjord macrodike accommodates up to ~500 m horizontal extension, and approximately in a NW-SE direction (Fig. 8C). These structures appear to be cut by, and cut, other structural sets, suggesting they represent the first and final observed structures within the study areas.

5. Discussion

5.1 Rift zone-parallel extension associated with normal fault and rift systems

The potential for displacement transfer and locally anomalous (with respect to far-field stresses), three-dimensional strains during fault linkage has been recognized in field studies (e.g. Ferrill et al., 1999; Ferrill and Morris, 2001; Koehn et al., 2008, 2010; Morris et al., 2014), scaled analogue models (e.g. Tentler and Acocella, 2010; see Fig. 1), and numerical simulations (e.g. Segall and Pollard, 1980; Crider and Pollard, 1998; Kattenhorn et al., 2000; Maerten et al., 2002). For instance, Kattenhorn et al. (2000) demonstrated that, depending on the remote stress state, it is possible for a range of ancillary fault or fracture orientations to develop, recording variable amounts of extension parallel to the first-order faults. It is likely that such ancillary deformations record a component of bending strain (e.g. deformation bands in the Delicate Arch relay ramp, Arches National Park, Utah: see Rotevatn et al., 2007).

Bending strains are commonly analyzed in the vertical plane where bedding is horizontal, but bending in the horizontal plane is challenging to identify due to a paucity of reference points. Normal faults in this study demonstrate vertical plane bending, about a horizontal axis, but associated with this extension is an observable component of bending in the horizontal plane, about a vertical axis. The development of strains associated with this bending do not develop instantaneously, rather each set may grow incrementally with slip accumulation on the bounding first-order faults as the relay zone distorts, nor are they restricted to one scale of observation. Such incremental, non-plane strains within evolving relay zones may be responsible for local instances of basin inversion, and reverse and strike-slip faulting in otherwise extensional regimes, and complex compartmentalization characteristics (e.g. Lin and Okubo, 2016; Sachau et al., 2016). Importantly, for basin faults with displacements at the km-scale, significant amounts of horizontal bending and rotation is possible, driving associated strains that may go undetected.

The effect of horizontal heave displacement gradients requires vertical axis rotations (Ferrill and Morris, 2001), and may operate independently of scale (e.g. Morris et al., 2014), in the same manner as other fault characteristics. For instance, worldwide catalogues of relay zone geometry have demonstrated a power-law scaling relationship that covers approximately 8 orders of magnitude (e.g. Peacock, 2003; Long and Imber, 2011). Evidence for heave gradients and locally non-coaxial strains are described at the at the tens of km separation scale in the East African Rift (e.g. Koehn et al., 2008, 2010; Sauchau et al., 2016) and the hundreds of km-scale in the Baikal rift zone (Hus et al., 2006) and the Hold With Hope relay zone in NE Greenland (Peacock et al., 2000). These examples show many characteristics similar to those observed in the Koa'e and

7

Krafla study sites, including (1) segmented bounding faults; (2) progressive development of obliquely oriented ancillary fault structures internal to the relay zone that accommodate non-coaxial strains; and (3) rift zone-parallel connecting faults.

Evidence for vertical axis rotations at the rift zone scale (i.e. tens to hundreds of km) have previously been attributed to bookshelf-type faulting models (e.g. Green et al., 2014; Fig. 10A). In such models, a vertical axis rotation can contribute to rift zone-normal extension. In horizontal axis rotations, via bookshelf faulting, a shear couple in the vertical plane represents a horizontal extension, and a vertical shortening (i.e. crustal thinning). In vertical axis rotation, shortening would require a horizontal material thinning along the rift zone: In plane strain, this would not require vertical crustal thinning. Vertical axis rotations by this mechanism, with a shear couple in the horizontal plane requires horizontal shortening (Fig. 10). For a rigid block model, the rotation has the effect of causing a material thickening orthogonal to the rift zone (e.g. Fig. 1E). Figure 1E shows that this rotation also results in material extension parallel to the rift axis, allowing addition of new material as a volume increase; during non-rigid body rotations (e.g., Fig. 10), second-order faults may act to facilitate the coupled components of rift zone-normal extension and rift zone-parallel shortening (e.g., Fig. 10B). For faults in the Krafla study area we infer that rift zone-parallel shortening is counteracted, contemporaneously, by the extensional component of obliquely oriented extensional shear faults, and rift-normal striking extension fractures at the free surface (e.g., Fig. 10Biii). At depth, this volume increase could occur as veins and/or dikes.

5.2. A vertical axis rotation model for rift basin segmentation in the NE Atlantic

Structures in the Faroe Islands and East Greenland share a common geometric, kinematic, and temporal evolution (Fig. 8 and 9), formed before, and during, continental break-up. Structures accommodate extensional strains at a range of angles relative to the regional extension vector (NW-SE) associated with a vertical axis rotation in the maximum horizontal stress (Figs 8 and 9). Here we apply a geometry and kinematic comparison between the observed structures on the Atlantic margins, and smaller scale structures that evolved in regions of extension deficit and rotation in the Koa'e and Krafla fault systems to consider, by analogy, whether vertical axis rotation during extension presents a viable model for strain evolution at the tens-of-kilometre scale. We focus on the Krafla system, as the extensional strain accommodated there has produced surface breaching structures that are closely comparable to the Atlantic margin.

To make the comparison of relative fault orientations and kinematics between the Krafla analogue and the NE Atlantic margins, we have rotated the Krafla rift datasets into the orientation and overlap configuration of the Atlantic European margin basin systems: i.e. a NE-SW trending, right-stepping rift. Thus, a right-stepping mirror image of the left-stepping Krafla rift is used (Fig. 12A) and compared with the Reykjanes-Aegir system, with the rift-parallel striking faults rotated into parallelism with those of the NE Atlantic margin (Fig. 12B, C). Data rotation is undertaken in two ways here for comparison: (1) by rotating the measured planar data for the Krafla system into an orientation that matches the strike of basin- and sub-basin faults along the Faroe-Shetland Basin; and (2) by rotating the measured planar data for the Krafla system so that the average strike of the rift-parallel structures match the measured strike of rift-parallel structures in the Faroe Islands and East Greenland. The two styles of rotation result in a difference in second order fault orientation of 30°, which is significant for data comparison. However, both types of rotation lead to the second-order data becoming parallel with either ENE or ESE-striking structures mapped in the Faroe Islands and Kangerlussuaq (Fig. 12A-D). All of the study areas show kinematically near-identical fault sets, with a 20-28° spread in extension directions across datasets. Removing one or the other of the reoriented Krafla sets reduces the spread to 12-20°. Importantly, each dataset comprises: rift-parallel striking faults that open normal to the rift axis (red in Fig. 12E); rift-oblique striking structures that accommodate extension oblique to the rift zone (blue in Fig. 12E); rift-normal striking structures that accommodate extension parallel to the rift zone (yellow in Fig. 12E). Rift zone-parallel extension in the Krafla study area is accommodated by extension mode fractures at the surface that strike orthogonal to the bounding rift faults. Equivalent subsurface structural sets exposed in the Faroe Islands and in East Greenland are normal faults and dikes. Notably, evidence for this style of inter-rift system architecture has also been noted in the East Africa Rift where, in younger portions of the rift, obliquely oriented dikes accommodate rift zone-parallel extension in the intervening relay zone between rift segments (tens of km scale: e.g. Muirhead et al., 2015).

Rift-parallel striking fault sets along both margins represent the first and final structural set. Timing relationships of fault sets on the Faroe Islands and in East Greenland imply a progressive vertical axis stress rotation at the regional scale, which is consistent with models that predict break-up involved a series of initially underlapping rift systems during rift propagation (Ellis and Stoker, 2014; Fig. 7B-D). Although the history of fault sets in the Krafla relay zone is less clear, the interpreted pattern fits well with the strains observed at a larger scale along the NE Atlantic margins (Fig. 12). We therefore

8

propose that a vertical axis rotation model (associated with heave gradients) can account for margin-normal striking normal faults, dikes, and lineaments in segmented rift systems, and presents a viable alternative to a polyphase extension and reorganization, or strike-slip – *transfer* – models, that have been applied previously (e.g., Ellis et al., 2009). Our new model, however, cannot and should not be applied along the entire length of the European margin in a simple way. Along this margin segmentation styles vary considerably, from large-scale, localized transform faults, e.g. the Jan Mayan Fracture Zone, or the Senja Fracture Zone in the Norwegian-Greenland sea (e.g. Skogseid and Eldholm, 1987; Gernigon et al., 2009), to distributed, discontinuous continental style accommodation zones along the Møre-Faroes-Rockall portion of the margin.

Variations in the along-strike segmentation and scaling of fault populations have been well-documented in both continental rift (e.g. Hayward and Ebinger, 1996; Scholz and Contreras, 1998; Faulds and Varga, 1998) and oceanic fault populations (e.g. Carbotte and Macdonald, 1994; Macdonald, 1998). Variations have previously been attributed to changes in crustal thickness, strain rate (i.e. heat diffusion/magma supply), segment configuration, and the presence of pre-existing "weak" structures (e.g. Cowie, 1998; Corti et al., 2003; Tentler and Acocella, 2010; Gerya, 2012, 2013). Scaled-analogue models of normal fault populations have demonstrated that increases in effective elastic layer thickness results in a dominance of small and widely distributed faults (Ackermann et al., 1997, 2001). With increasing total extension, these authors noted that faults increased in number and length, producing a close and regularly spaced network. More recent scaled-analogue modeling of ridge-transform fault configurations also suggest that fault style and scaling is a function of strain rate and crustal thickness, with relatively thick lithosphere producing oblique zones of rifting and relatively thin lithosphere resulting in the development of transform faults that link the offset accreting segments (Gerya, 2012, 2013). With estimated crustal thicknesses in the NE Atlantic varying from ~3-10 km in the Norwegian-Greenland Sea to ~10-35 km in the Rockall Basin and the Greenland-Iceland-Faroes Ridge (Smallwood and White, 2002; Gernigon et al., 2009), variations in axis-parallel segmentation patterns are to be expected (e.g. Hayward and Ebinger, 1996). Localized and large-scale fracture zones along the NE Atlantic margins only occur where crustal thicknesses fall below 10 km, elsewhere we find thick crust and distributed fault systems that are dominated by accommodation zone-style stress transfer, rather than regional-scale strike-slip faults. The protracted extensional history of the region and superposition of NE Atlantic rifting on Paleozoic rift systems, themselves influenced by Caledonian and/or older fabrics, mean that pre-existing structural weaknesses are likely to be widespread along the margin (e.g. Doré et al., 1999), and the style of segmentation appears to vary considerably. Although the controls on segmentation style in the NE Atlantic are beyond the scope of this study to investigate, it is nevertheless important to consider the potential role of factors such as pre-existing structures, strain rate or crustal thickness when applying any single model to the entire margin.

5 Conclusions

- Discontinuous normal faults in the Koa'e and Krafla fault systems accommodate regional horizontal extensional strains via a combination of fault throw and heave on first-order rift faults. Obliquely oriented second-order deformation are driven by extension gradients and vertical axis block rotation within the intervening relay zones.

- Second-order faults and fractures serve to accommodate components of the regional extension and variably, a component of shortening and extension in a direction parallel to- and oblique to the rift zone.

- Fault population heterogeneity within relay zones is attributed to locally non-coaxial stress states associated with mechanical interaction and resulting fault displacement gradients, rather than regional-scale polyphase tectonic episodes or changes in the remote stress field.

- Relay zones are considered to occur across most scales of segmented extensional systems, thus, we infer that vertical axis block rotations and the associated local deformation, which accommodate deficits in fault heave, occurs within the same range of scales. The distribution of second-order structures is controlled by the scale of segmentation.

- A displacement deficit-rotation model is applied to the NE Atlantic margins, in which second-order fault sets locally accommodate margin-parallel extension and shortening, during vertical axis rotation. We show that this is a

9

viable alternative model to explain the upper crustal geometry, kinematics, and timing of structures, versus existing strike-slip (transfer) segmentation models for the case study presented, but urge caution in applying the model along the length of a given system.

Deleted: transfer fault zone

References

Ackermann, R. V., & Schlische, R. W. (1997). Anticlustering of small normal faults around larger faults. Geology, 25 (12).

Ackermann, R. V., Schlische, R. W., & Withjack, M. O. (2001). The geometric and statistical evolution of normal fault systems: an experimental study of the effects of mechanical layer thickness on scaling laws. Journal of Structural Geology, 25 23, 1803-1819.

Acocella, V., Morvillo, P., & Funiciello, R. (2005). What controls relay ramps and transfer faults within rift zones? Insights from analogue models. Journal of Structural Geology, 27(3), 397-408. doi:10.1016/j.jsg.2004.11.006.

Carbotte, S. M., & Macdonald, K. C. (1994). Comparison of seafloor tectonic fabric at intermediate, fast, and super fast spreading ridges: Influence of spreading rate, plate motions, and ridge segmentation on fault patterns. Journal of Geophysical 30 Research: Solid Earth, 99(B7), 13609-13631. doi:10.1029/93jb02971.

Cartwright, J., Mansfield, C. S., & Trudgill, B. (1996). The growth of normal faults by segment linkage. In P. G. Buchanan & D. A. Nieuland (Eds.), Modern Developments in Structural Interpretation, Validation and Modelling. (Vol. Geological Society Special Publication No. 99). London, UK: The Geological Society.

Casey, M., Ebinger, C., Keir, D., Gloaguen, R., & Mohamed, F. (Eds.). (2006). Strain accommodation in transitional rifts: 35 extension by magma intrusion and faulting in Ethiopian rift magmatic segments. Geological Society, London, Special Publications, Vol. 259. The Geological Society of London.

Childs, C., Watterson, J., & Walsh, J. J. (1995). Fault overlap within developing normal fault systems. Journal of the Geological Society, London, 152, 535-549.

Deleted: Bott, M. H. P. (1975). Structure and evolution of the north Scottish shelf, the Faeroe block and the intervening region. Petroleum and the continental shelf of North-west Europe, 1, 105-115. [... [6]]

10

Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., & Sokoutis, D. (2003). Analogue modelling of continental extension: a review focused on the relations between the patterns of deformation and the presence of magma. Earth-Science Reviews, 63(3-4), 169-247. doi:10.1016/s0012-8252(03)00035-7.

Cowie, P. (1998). Normal fault growth in three-dimensions in continental and oceanic crust. In W. R. Buck, P. T. Delaney, J. A. Karson, & Y. Lagabrielle (Eds.), Faulting and magmatism at mid-ocean ridges. Washington, D.C. American Geophysical Union. doi:10.1029/GM106p0027.

Cowie, P. A., & Scholz, C. H. (1992). Physical explanation for the displacement-length relationship of faults using a post-yield fracture mechanics model. Journal of Structural Geology, 14(10), 1133-1148. doi:10.1016/0191-8141(92)90065-5.

Crider, J. G., & Pollard, D. D. (1998). Fault linkage: Three-dimensional mechanical interaction between echelon normal faults. Journal of Geophysical Research, 103(B10), 24373. doi:10.1029/98jb01353.

Dauteuil, O., Angelier, J., Bergerat, F., Verrier, S. & Villemin, T. 2001. Deformation partitioning inside a fissure swarm of the northern icelandic rift. Journal of Structural Geology, 23, 1359-1372.

Doré, A. G., Lundin, E. R., Birkeland, O., Eliassen, P. E., & Jensen, L. N. (1997). The NE Atlantic margin; implications of late Mesozoic and Cenozoic events for hydrocarbon prospectivity. Petroleum Geoscience, 3(2), 117-131. doi:10.1144/petgeo.3.2.117.

Doré, A. G., Lundin, E. R., Jensen, L. N., Birkeland, Ø., Eliassen, P. E., & Fichler, C. (1999). Principal tectonic events in the evolution of the northwest European Atlantic margin. 41-61. doi:10.1144/0050041.

Doré, A. G., Lundin, E. R., Kusznir, N. J., & Pascal, C. (2008). Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. Geological Society, London, Special Publications, 306(1), 1-26. doi:10.1144/sp306.1.

Dzurisin, D., Koyanagi, R. Y., & English, T. T. (1984). Magma supply and storage at Kiluea Volcano, Hawaii, 1956-1983. Journal of Volcanology and Geothermal Research, 21, 177-206.

Ellis, D., & Stoker, M. S. (Eds.). (2014). The Faroe-Shetland Basin: a regional perspective from the Paleocene to the present day and its relationship to the opening of the North Atlantic Ocean. In S.J.C. Cannon and D. Ellis (Eds), Hydrocarbon exploration to exploitation West of Shetlands. Geological Society, London, Special Publications (Vol. 397). The Geological Society of London.

Ellis, D., Passey, S. R., Jolley, D. W., & Bell, B. R. (2009). Transfer zones: the application of new geological information from the Faroe Islands applied to the offshore exploration of intra and sub-basalt strata. Paper presented at the Faroe Islands exploration conference: proceedings of the 2nd conference, Torshavn, Faroe Islands.

Faulds, J. E., & Varga, R. J. (1998). The role of accommodation zones and transfer zones in the regional segmentation of extended terranes. In J. E. Faulds & J. H. Stewart (Eds.), Accommodation zones and transfer zones: the regional segmentation of the Basin and Range Province: Boulder, Colorado (Vol. 323): Geological Society of America Special Paper.

Ferrill, D. A., & Morris, A. P. (2001). Displacement gradient and deformation in normal fault systems. Journal of Structural Geology, 23, 619-638.

Ferrill, D. A., Stamatakos, J. A., & Sims, D. (1999). Normal fault corrugation: implications for growth and seismictiy of active normal faults. Journal of Structural Geology, 21, 1027-1038.

Fossen, H., & Rotevatn, A. (2016). Fault linkage and relay structures in extensional settings—A review. Earth-Science Reviews, 154, 14-28. doi:10.1016/j.earscirev.2015.11.014.

Gaina, C., Gernigon, L., & Ball, P. (2009). Palaeocene-Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. Journal of the Geological Society, 166(4), 601-616. doi:10.1144/0016-76492008-112.

Gawthorpe, R. L., & Hurst, J. M. (1993). Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. Journal of the Geological Society, 150(6), 1137-1152. doi:10.1144/gsjgs.150.6.1137.

11

Deleted: Duffield, W. A. (1975). Structure and Origin of the Koae Fault System, Kilauea Volcano, Hawaii. Geological Survey Professional Paper (856).

Gernigon, L., Olesen, O., Ebbing, J., Wienecke, S., Gaina, C., Mogaard, J.O., Sand, M. and Myklebust, R., 2009. Geophysical insights and early spreading history in the vicinity of the Jan Mayen Fracture Zone, Norwegian–Greenland Sea. Tectonophysics, 468(1), pp.185-205.

Gernigon, L., Gaina, C., Olesen, O., Ball, P. J., Péron-Pinvidic, G., & Yamasaki, T. (2012). The Norway Basin revisited: From continental breakup to spreading ridge extinction. Marine and Petroleum Geology, 35(1), 1-19. doi:10.1016/j.marpetgeo.2012.02.015.

Gerya, T. (2012). Origin and models of oceanic transform faults. Tectonophysics, 522-523, 34-54. doi:10.1016/j.tecto.2011.07.006.

Gerya, T. V. (2013). Initiation of transform faults at rifted continental margins: 3D petrological-thermomechanical modeling and comparison to the Woodlark Basin. Petrology, 21(6), 550-560. doi:10.1134/s0869591113060039.

Grant, J. V., & Kattenhorn, S. A. (2004). Evolution of vertical faults at an extensional plate boundary, southwest Iceland. Journal of Structural Geology, 26(3), 537-557. doi:10.1016/j.jsg.2003.07.003.

Green, R. G., White, R. S., & Greenfield, T. (2014). Motion in the north Iceland volcanic rift zone accommodated by bookshelf faulting. Nature Geoscience, 7, 29-33. doi:10.1038/ngeo201210.1038/NGEO2012.

Guarnieri, P. 2015. Pre-break-up palaeostress state along the East Greenland margin. Journal of the Geological Society, 172, 727-739.

Gupta, A., & Scholz, C. H. (2000). A model of normal fault interaction based on observations and theory. Journal of Structural Geology, 22, 865-879.

Hayward, N. J., & Ebinger, C. J. (1996). Variations in the along-axis segmentation of the Afar Rift system. Tectonics, 15(2), 244. doi:10.1029/95tc02292.

Henstra, G.A., Rotevatn, A., Gawthorpe, R.L. and Ravnås, R., 2015. Evolution of a major segmented normal fault during multiphase rifting: The origin of plan-view zigzag geometry. Journal of Structural Geology, 74, pp.45-63.

Holland, M., Urai, J. L. & Martel, S. J. 2006. The internal structure of fault zones in basaltic sequences. Earth and Planetary Science Letters, 248, 301-315.

Holm, P. M., Heaman, L. M., & Pedersen, L. E. (2006). Baddeleyite and zircon U–Pb ages from the Kærven area, Kangerlussuaq: Implications for the timing of Paleogene continental breakup in the North Atlantic. Lithos, 92(1-2), 238-250. doi:10.1016/j.lithos.2006.03.035.

Holwell, D. A., Abraham-James, T., Keays, R. R., & Boyce, A. J. (2012). The nature and genesis of marginal Cu–PGE–Au sulphide mineralisation in Paleogene Macrodykes of the Kangerlussuaq region, East Greenland. Mineralium Deposita, 47(1-2), 3-21. doi:10.1007/s00126-010-0325-4.

Hus, R., De Batist, M., Klerkx, J., & Matton, C. (2006). Fault linkage in continental rifts: structure and evolution of a large relay ramp in Zavarotny; Lake Baikal (Russia). Journal of Structural Geology, 28(7), 1338-1351. doi:10.1016/j.jsg.2006.03.031

Irvine, T. N., Andersen, J. C. Ø., & Brooks, C. K. (1998). Geological Society of America Bulletin, 110(11), 1398. doi:10.1130/0016-7606(1998)110<1398:ibabwb>2.3.co;2.

Jackson, C. A. L., Bell, R. E., Rotevatn, A., & Tvedt, A. B. 2017. Techniques to determine the kinematics of synsedimentary normal faults and implications for fault growth models. In: Childs, C., Holdsworth, R.E., Jackson, C.A.-L., Manzocchi, T., Walsh, J.J. & Yielding, G. (eds) The Geometry and Growth of Normal Faults. Geological Society, London, Special Publications, 439.

Kattenhorn, S.A., Aydin, A. and Pollard, D.D., 2000. Joints at high angles to normal fault strike: an explanation using 3-D numerical models of fault-perturbed stress fields. Journal of structural Geology, 22(1), pp.1-23.

12

Deleted: Holcombe, R. T. (1987). Eruptive history and long-term behaviour of Kilauea Volcano. In R. W. Decker, T. L. Wright, & P. H. Stauffer (Eds.), Volcanism in Hawaii (Vol. 1): US Geological Survey Professional Paper.

Koehn, D., Aanyu, K., Haines, S., & Sachau, T. (2008). Rift nucleation, rift propagation and the creation of basement micro-plates within active rifts. Tectonophysics, 458(1-4), 105-116. doi:10.1016/j.tecto.2007.10.003.

Koehn, D., Lindenfeld, M., Rümpker, G., Aanyu, K., Haines, S., Passchier, C. W., & Sachau, T. (2010). Active transsection faults in rift transfer zones: evidence for complex stress fields and implications for crustal fragmentation processes in the western branch of the East African Rift. International Journal of Earth Sciences, 99(7), 1633-1642. doi:10.1007/s00531-010-0525-2.

Lambiase, J. J., & Bosworth, W. (1995). Structural controls on sedimentation in continental rifts. In J. J. Lambiase (Ed.), Hydrocarbon habitat in rift basins (Vol. Geological Society Special Publications No. 80). London, UK: The Geological Society.

Lin, G., & Okubo, P. G. (2016). A large refined catalog of earthquake relocations and focal mechanisms for the Island of Hawai'i and its seismotectonic implications. Journal of Geophysical Research: Solid Earth. doi:10.1002/2016jb013042.

Long, J. J., & Imber, J. (2010). Geometrically coherent continuous deformation in the volume surrounding a seismically imaged normal fault-array. Journal of Structural Geology, 32(2), 222-234. doi:10.1016/j.jsg.2009.11.009.

Long, J. J., & Imber, J. (2011). Geological controls on fault relay zone scaling. Journal of Structural Geology, 33(12), 1790-1800. doi:10.1016/j.jsg.2011.09.011.

Macdonald, K.C., Fox, P.J., Alexander, R.T., Pockalny, R. and Gente, P., 1996. Volcanic growth faults and the origin of Pacific abyssal hills. Nature, 380 (6570), pp.125-129.

Macdonald, K. C. (1998). Linkages between faulting, volcanism, hydrothermal activity and segmentation on fast spreading centers. In W. R. Buck, P. T. Delaney, J. A. Karson, & Y. Lagabrielle (Eds.), Faulting and magmatism at mid-ocean ridges. Washington, D.C.: American Geophysical Union. doi:10.1029/GM106p0027.

Maerten, L., Gillespie, P., & Pollard, D. D. (2002). Effects of local stress perturbation on secondary fault development. Journal of Structural Geology, 24, 145-153.

Mandl, G. (1987). Tectonic deformation by rotating parallel faults: the "bookshelf" mechanism. Tectonophysics, 141, 277-316.

Manzocchi, T., Childs, C., & Walsh, J. J. (2010). Faults and fault properties in hydrocarbon flow models. Geofluids. doi:10.1111/j.1468-8123.2010.00283.x.

Martel, S. J., & Langley, J. S. (2006). Propagation of normal faults to the surface in basalt, Koae fault system, Hawaii. Journal of Structural Geology, 28(12), 2123-2143. doi:10.1016/j.jsg.2005.12.004.

Morley, C. K., Nelson, R. A., Patton, T. I., & Munn, S. G. (1990). Transfer zones in the East Africa Rift System and their relevance to hydrocarbon exploration in rifts. The American Association of Petroleum Geologists Bulletin, 74(8), 1234-1253.

Morris, A. P., McGinnis, R. N., & Ferrill, D. A. (2014). Fault displacement gradients on normal faults and associated deformation. AAPG Bulletin, 98(6), 1161-1184. doi:10.1306/10311312204.

Muirhead, J. D., Kattenhorn, S. A., & Le Corvec, N. (2015). Varying styles of magmatic strain accommodation across the East African Rift. Geochemistry, Geophysics, Geosystems, 16(8), 2775-2795. doi:10.1002/2015gc005918.

Nicol, A., Childs, C., Walsh, J.J., Manzocchi, T. & Schopfer, M.P.J. 2016. Interactions and growth of faults in an outcrop-scale system. In: Childs, C., Holdsworth, R.E., Jackson, C.A.-L., Manzocchi, T., Walsh, J.J. & Yielding, G. (eds) The Geometry and Growth of Normal Faults. Geological Society, London, Special Publications, 439. First published online March 10, 2016, https://doi.org/10.1144/SP439.9

Passey, S. R., & Jolley, D. W. (2009). A revised lithostratigraphic nomenclature for the Palaeogene Faroe Islands Basalt Group, NE Atlantic Ocean. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 99(3-4), 127. doi:10.1017/s1755691009008044.

Peacock, D. C. P. (2002). Propagation, interaction and linkage in normal fault systems. Earth Science Reviews, 58, 121-142.

Peacock, D. C. P. (2003). Scaling of transfer zones in the British Isles. Journal of Structural Geology, 25(10), 1561-1567. doi:10.1016/s0191-8141(03)00008-7.

Peacock, D. C. P., & Sanderson, D. J. (1991). Displacements, segment linkage and relay ramps in normal fault zones. Journal of Structural Geology, 13(6), 721-733.

Peacock, D. C. P., & Sanderson, D. J. (1994). Geometry and Development of Relay Ramps in Normal Fault Systems. AAPG Bulletin, 78. doi:10.1306/bdff9046-1718-11d7-8645000102c1865d.

Peacock, D. C. P., Price, S. P., Whitham, A. G., & Pickles, C. S. (2000). The World's biggest relay ramp: Hold With Hope, NE Greenland. Journal of Structural Geology, 22, 843-850.

Poland, M. P., Miklius, A., Sutton, A. J., & Thornber, C. R. (2012). A mantle-driven surge in magma supply to Kilauea Volcano during 2003-2007. Nature Geoscience, 5. doi:10.1038/ngeo1426.

Roberts, N. M. W., & Walker, R. J. (2016). U-Pb geochronology of calcite-mineralized faults: Absolute timing of rift-related fault events on the northeast Atlantic margin. Geology, G37868.37861. doi:10.1130/g37868.1.

Rotevatn, A., Fossen, H., Hesthammer, J., Aas, T. E. & Howell, J. A. 2007. Are relay ramps conduits for fluid flow? Structural analysis of a relay ramp in Arches National Park, Utah. In: Lonergan, L., Jolley, R.J.H., Rawnsley, K. & Sanderson, D.J. (eds.) Fractured Reservoirs. Geological Society London Special Publication 270, 55-71. The Geological Society, London.

Rumph, B., Reaves, C. M., Orange, V. G. & Robinson, D. L. 1993. Structuring and transfer zones in the Faeroe Basin in a regional tectonic context. Petroleum Geology Conference Series, 4, 999-1009.

Sachau, T., Koehn, D., Stamps, D. S., & Lindenfeld, M. (2016). Fault kinematics and stress fields in the Rwenzori Mountains, Uganda. International Journal of Earth Sciences, 105(6), 1729-1740. doi:10.1007/s00531-015-1162-6.

Scholz, C. H., & Contreras, J. C. (1998). Mechanics of continental rift architecture. Geology, 26(11), 967-970.

Seebeck, H., Nicol, A., Walsh, J. J., Childs, C., Beetham, R. D., & Pettinga, J. (2014). Fluid flow in fault zones from an active rift. Journal of Structural Geology, 62, 52-64. doi:10.1016/j.jsg.2014.01.008.

Segall, P., & Pollard, D. D. (1980). Mechanics of Discontinuous Faults. Journal of Geophysical Research, 85(B8), 4337-4350.

Sempere, J. C., & Macdonald, K. C. (1986). Overlapping spreading centers: implications from crack growth simulation by the displacement discontinuity method. Tectonics, 5(1), 151-163.

Sharp, I. R., Gawthorpe, R. L., Underhill, J. R., & Gupta, S. (2000). Fault-propagation folding in extensional settings: Examples of structural style and synrift sedimentary response from the Suez rift, Sinai, Egypt. Geological Society of America Bulletin, 112(12), 1877-1899. doi:10.1130/0016-7606.

Skogseid, J., & Eldholm, O. (1987). Early Cenozoic crust at the Norwegian continental margin and the conjugate Jan Mayen Ridge. Journal of Geophysical Research: Solid Earth, 92(B11), 11471-11491. doi:10.1029/JB092iB11p11471.

Smallwood, J. R., & White, R. S. (2002). Ridge-plume interaction in the North Atlantic and its influence on continental breakup and seafloor spreading. In D. W. Jolley & B. R. Bell (Eds.), The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes (Vol. 197, pp. 15-37). London, UK: The Geological Society of London.

Swanson, D.A., Fiske, R.S., Thornber, C.R., and Poland, M.P., in press, Dikes in the Koaʻe fault system, and the Koaʻe-east rift zone structural grain at Kīlauea Volcano, Hawaiʻi: Geological Society of America Special Paper.

Tegner, C., Duncan, R. A., Bernstein, S., Brooks, C. K., Bird, D. K., & Storey, M. (1998). 40Ar-39Ar geochronology of Tertiary mafic intrusions along the East Greenland rifted margin: Relation to flood basalts and the Iceland hotspot track. Earth and Planetary Science Letters, 156, 75-88.

14

Tentler, T. 2005. Propagation of brittle failure triggered by magma in Iceland. Tectonophysics, 406, 17-38.

Tentler, T., & Acocella, V. (2010). How does the initial configuration of oceanic ridge segments affect their interaction? Insights from analogue models. Journal of Geophysical Research, 115(B1). doi:10.1029/2008jb006269.

Trudgill, B., & Cartwright, J. (1994). Relay-ramp forms and normal fault linkages. Canyonlands National Park, Utah. Geological Society of America Bulletin, 106, 1143-1157.

Walker, R. J. 2010. The Structural Evolution of the Faroe Islands, NE Atlantic Margin. Doctor of Philosophy, Durham Univerisity.

Walker, R. J., Holdsworth, R. E., Imber, J., & Ellis, D. (2011). Onshore evidence for progressive changes in rifting directions during continental break-up in the NE Atlantic. Journal of the Geological Society, 168(1), 27-48. doi:10.1144/0016-76492010-021.

Walsh, J. J., Bailey, W. R., Childs, C., Nicol, A., & Bonson, C. G. (2003). Formation of segmented normal faults: a 3D perspective. Journal of Structural Geology, 25(1251-1262).

Willemse, E. J. M., Pollard, D. D. & Aydin, A. 1996. Three-dimensional analyses of slip distributions on normal fault arrays with consequences for fault scaling. Journal of Structural Geology, 18, 295-309.

Wotzlaw, J. F., Bindeman, I. N., Schaltegger, U., Brooks, C. K., & Naslund, R. H. (2012). High-resolution insights into episodes of crystallization, hydrothermal alteration and remelting in the Skaergaard intrusive complex. Earth and Planetary Science Letters, 355-356, 199-212. doi:10.1016/j.epsl.2012.08.043.

Wright, T. L., & Klein, F. W. (2006). Deep magma transport at Kilauea volcano, Hawaii. Lithos, 87(1-2), 50-79. doi:10.1016/j.lithos.2005.05.004.

Formatted: Indent: Left: 0 cm, First line: 0 cm

Deleted:
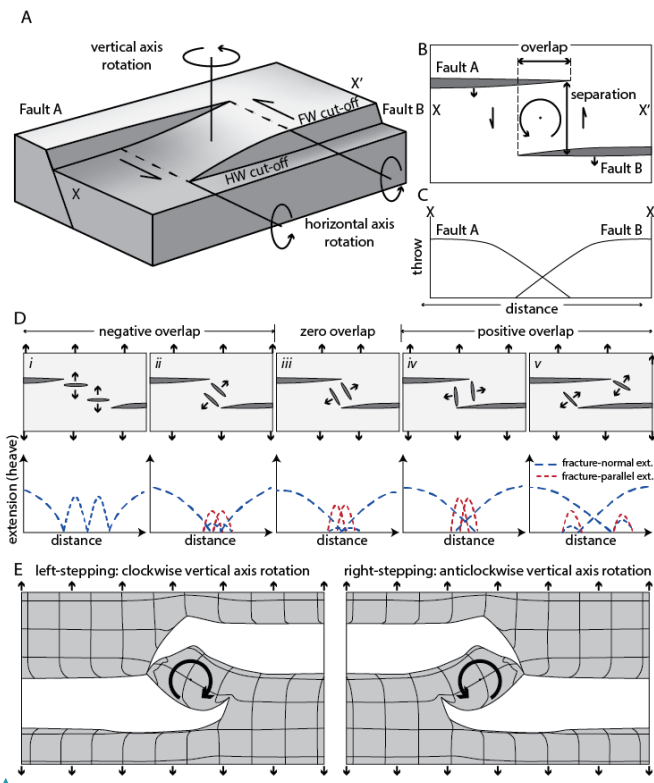
15

Figure 1. (A) Schematic diagram illustrating a relay zone between two normal faults (after Ferrill and Morris, 2001) showing the location of footwall (FW) and hanging wall (HW) cut-off lines; (B) Map view of the block model in (A) showing fault overlap and separation; (C) Distance versus displacement (throw) profile for transect X-X'; (Di-v) Second-order fault geometries as a function of fault overlap (redrawn from Tentler and Acocella, 2010) with local and regional extension directions indicated. Graphs show schematic displacement (extension, or heave)-length plots for the bounding fractures and linking geometries shown; (E) Modelled strain fields and rotation ahead of two left- and right-stepping en echelon open-mode fractures (redrawn from Tentler and Acocella, 2010).

Figure 2. Measurement of fracture geometry and kinematics. (A) Mode-I (extensional) opening across pre-existing cooling joint surfaces allows the traditional measurement of extension direction and magnitude (aperture) and fracture trace azimuth. The fracture in the image shows an aperture of 0.2 m, and an opening direction of 142°, orthogonal to the azimuth of the fracture (052°); (B) Mixed-mode (extensional-shear) opening across a cooling joint. The fracture in the image shows an aperture of 0.25 m, and an opening direction of 036°, oblique to the azimuth of the fracture (~080°), indicating a component of right-lateral shear.

17

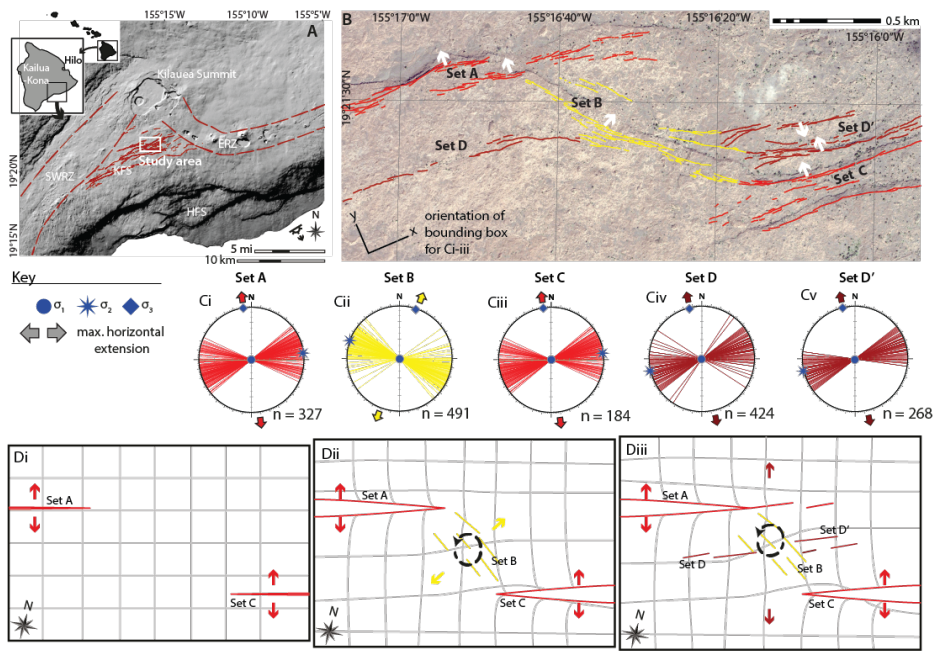**Figure 3.** (A) Simplified structural elements map of Kīlauea Volcano's, showing the study area within the Koa`e fault system (KFS). ERZ: East Rift Zone. SWRZ: Southwest Rift Zone. HFS: Hilina Fault System. Inset shows relative position of A, on the south coast of Island of Hawai`i; (B) WorldView image of the study area showing the distribution and orientation of mapped fractures. White arrows indicate dip directions of monocline limbs and fault scarps; (C) Lower hemisphere stereographic projections showing measured fault/fractures as planes and measured extension directions for each of the three structural sets; (D) Proposed schematic evolution of fault sets: (i) Propagation of the main rift-fault set (set A and C); (ii) interaction between sets A and C produces deficits of heave displacement, requiring vertical axis block rotation in the relay zone, and local reorientation of extension direction (set B); (iii) development of new rift-parallel structures (set D: Swanson et al., in press). Bounding box is aligned with 1st-order rift faults (set A and C).
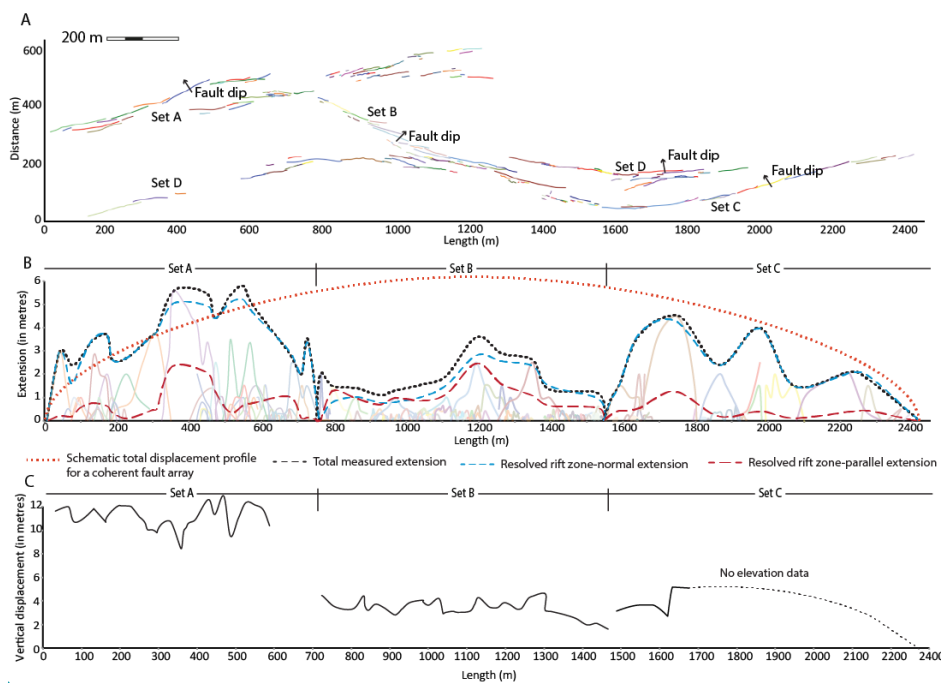
18

Figure 4. (A) Distribution of mapped fractures in the study area; (B) Profile of horizontal displacement (heave) vs length for mapped fractures. Dotted grey line indicates cumulative aperture for each set. Dashed blue lines indicate the calculated component of rift zone-normal extension on each fracture set. Dashed red lines indicate the calculated component of rift zone-parallel extension on each fracture set. Dotted orange line represents a hypothetical total displacement profile for a single fault (e.g. Gupta and Scholz, 2000), or fully linked, mature fault array (e.g. Childs et al., 2017) where the maximum displacement is located centrally along the fault, or array; (C) Profile of estimated vertical displacement (monocline height and throw) vs length for segments of surface-breaking faults. No evidence for throw was identified along NW-SE striking fractures of set B. With no surface-breaching fault segments along NW-SE striking fractures of set B we present monocline height values only. Dotted line indicates extent of elevation data where the profile is estimated from field observations and aerial imagery.
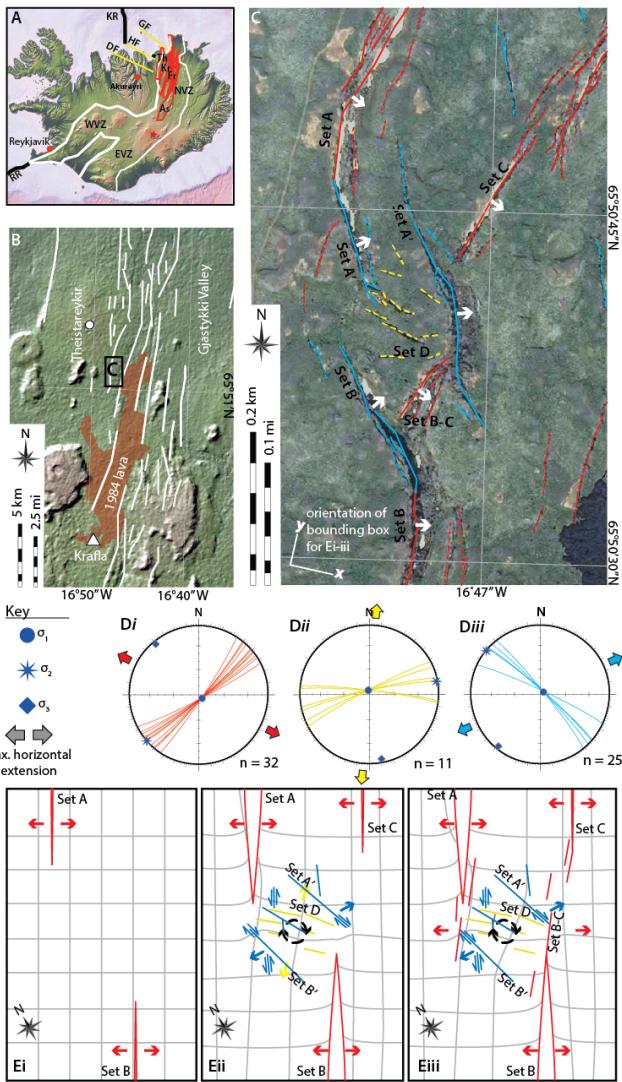
19

Figure 5. (A) Map of Iceland highlighting the major tectonic elements: Reykjanes Ridge (RR); the Kolbeinsey Ridge (KR); South Iceland Seismic Zone (SISZ); West Volcanic Zone (WVZ); East Volcanic Zone (EVZ); Neo-Volcanic Zone (NVZ: the axial rift zone); Askja volcanic centre (As); Fremri-Namur volcanic centre (Fr); Krafla volcanic centre (Kr); Theistareykir volcanic centre (Th); the Tjörnes Fracture Zone (TFZ) comprising the Dalvik lineament (DF), the Husavik-Flatey Fault (HF) and the Grimsey lineament (GF); (B) Location of study area in the Gjastykki Valley within the Krafla fissure swarm. White arrows indicate dip direction for fault scarps in the area; (C) Mapped structures in the study area, color-coded based on orientation and kinematics: (1) rift zone-parallel faults and fractures (red); (2) rift zone-oblique faults and fractures (blue); and (3) rift zone-normal fractures (yellow); (D) Lower hemisphere stereographic projections showing measured extension directions for each of the three structural sets; (E) Proposed schematic evolution of fault sets: (i) Propagation of the main rift-fault sets A and B; (ii) interaction between sets A and B leads to a horizontal displacement deficit and vertical axis block rotation in the relay zone, and induced local reorientation of extension direction accommodated on variably oriented ancillary faults and fractures; (iii) continued propagation of the main rift faults (A, B and C) leads to the development of new rift-parallel structures. Bounding box is aligned with 1st-order rift faults (set A and B).
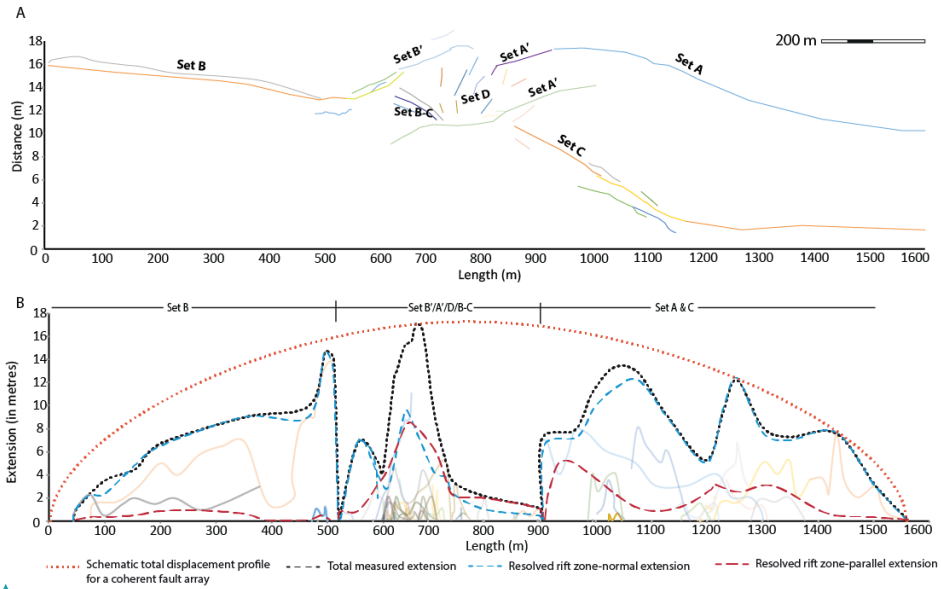
Figure 6. (A) Distribution of mapped faults and fractures in the study area; (B) Profile of horizontal displacement (extension, or heave) vs length for mapped fractures. Dotted black line indicates the total measured extension for structures in each set. Dashed blue lines indicate the calculated component of extension on each fracture set that occurs in a direction orthogonal to the rift zone. Dashed red lines indicate the calculated component of extension on each fracture set that occurs in a direction parallel to the rift zone. Extension across the system as a whole is represented by a hypothetical displacement

profile for a fully linked, mature fault array where the maximum displacement is located centrally along the fault, or array, and tapers to zero at the lateral tips (dotted orange line).

5 **Figure 7.** (A) NE Atlantic tectonic elements map: Hatton Rise (HR), Hatton Basin (HB), Rockall High (RH), South Rockall Basin (SRB), North Rockall Basin (NRB), Faroe-Shetland Basin (FSB), Shetland Islands (SI), Møre Basin (MB), Vøring Basin (VB), Jan Mayan (JM), Jan Mayan Fracture Zone (JMFZ), Tjörnes Fracture Zone (TFZ), Faroes Fracture Zone (FFZ). Map was compiled using: basin ages from Doré et al., (1997); oceanic magnetic anomalies from Gaina et al. (2009); Iceland stratigraphic ages from Doré et al. (2008). Study localities indicated by stars; (B-D) Schematic model for a segmented
10 opening of the NE Atlantic during the Paleogene (after Ellis and Stoker, 2014). Faroe Islands (FI); Kangerlussuaq (KL).

Figure 8. (A) Geological map of the Skaergaard intrusion and surrounding area (redrawn from Holwell et al., 2012). Contours indicate 50 m elevation intervals from sea level; (B) Margin-normal striking faults and dikes cut the Skaergaard intrusion, which are in turn cut by margin-oblique striking faults and dikes; (C) Margin-oblique striking faults cut the margin-parallel Miki Fjord macrodike; (D) Lower hemisphere stereographic projections for relative-age-constrained examples of the three main fault sets observed.

24

Key
- **Mapped fault/dyke** (yellow)
- **sills** (red)
- **Enni Fmn** (green)
- **Sneis Fmn** (olive)
- **Malinstindur Fmn** (dark green)
- **Hvannhagi Fmn** (orange-red)
- **irregular** (pink)
- **Prestfjall Fmn** (dark red)
- **Beinisvørð Fmn** (dark olive)

Bathymetry Depth / m
0 — 190

Calculated extension directions
Set 1 Set 2 Set 3

20 km
15 mi

C
sedimentary marker horizon
margin-oblique faults/dikes N-S-extension
margin-normal faults NE-SW-extension

0.1 mi
0.1 km

D
margin-parallel faults NW-SE-extension
margin-oblique faults/dikes N-S-extension

0.5 km
0.2 mi

E*i*   margin-normal strike
N
n= 20

E*ii*   margin-oblique strike
n= 63

E*iii*   margin-parallel strike
N
n= 39

Key
σ₁   σ₂   σ₃

max. horizontal extension   max. horizontal compression

25

Figure 9. (A) Onshore structural element map of the Faroe Islands; (B) Inferred extension directions indicating an island-wide anticlockwise rotation in extension direction through time; (C) Margin-oblique faults cut margin-normal faults; (D) Margin-parallel faults cut rift-oblique faults and dikes; (E) Lower hemisphere stereographic projections for relative-age-constrained examples of the three main fault sets observed.
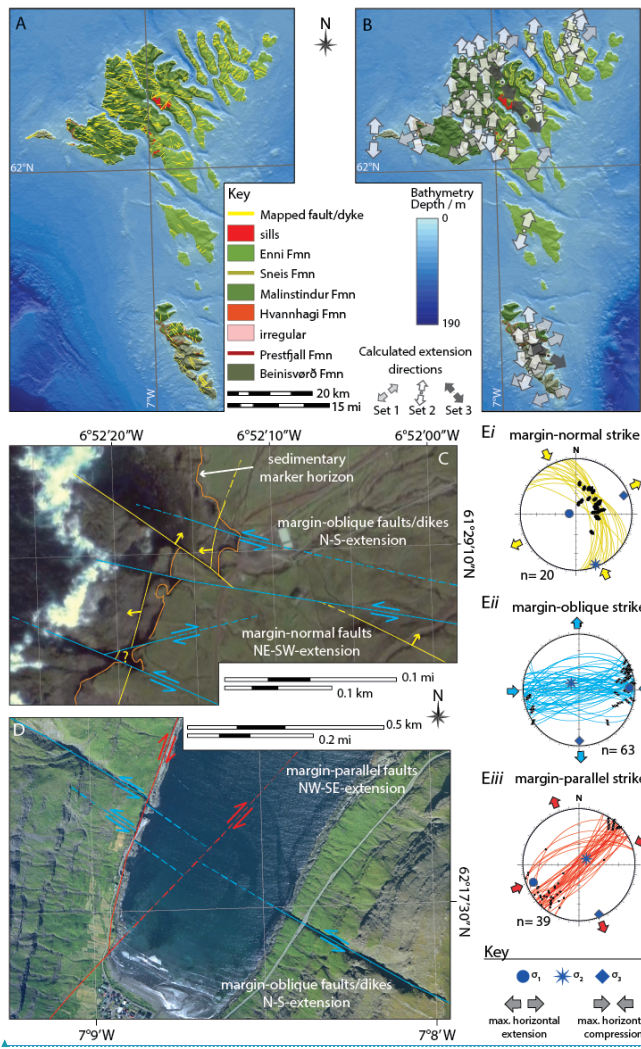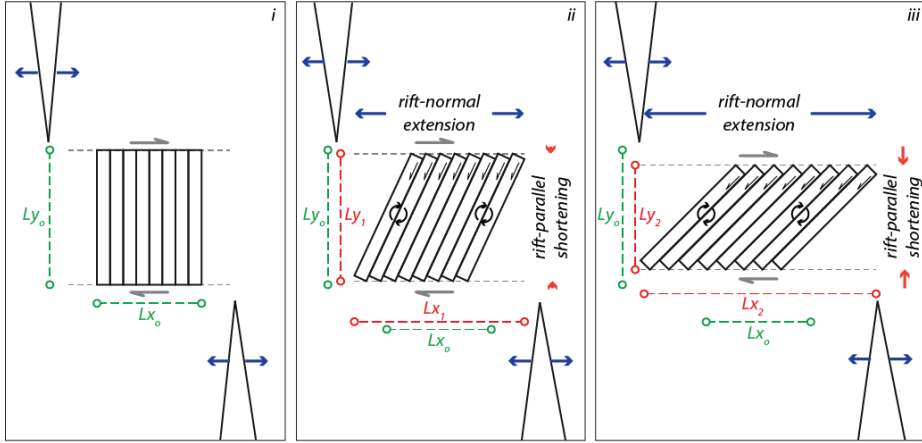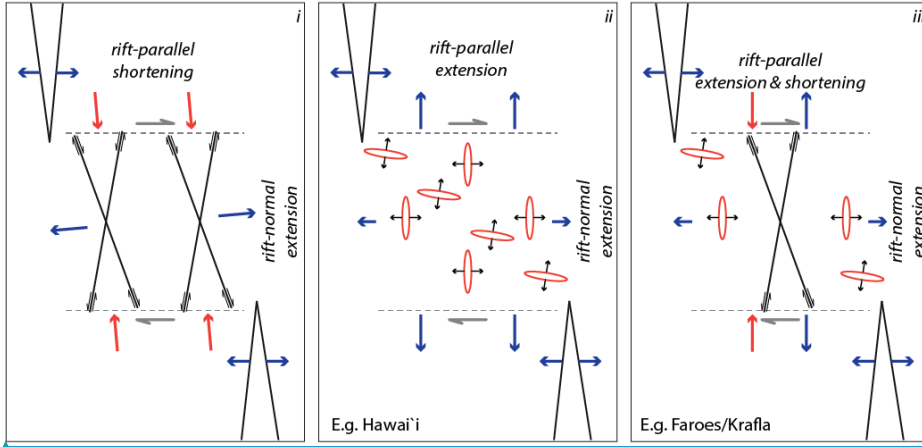
5

A. Plane strain: bookshelf rotation

B. Plane strain / non-plane strain

26

Figure 10. Horizontal plane 2D conceptual models for inter-fault/inter-rift relay rotation. (A) Bookshelf rotation model showing (i-iii) progressive rotation leading to rift normal extension, and rift-parallel shortening; (B) Schematic models for structures observed in the study areas presented here: (i) conjugate extensional shear faults, (ii) extension fractures, and (iii) a combination of extension fractures and conjugate extensional shear faults. If faults develop throw, as in the Krafla example, the system becomes non-plane strain. Models are not to scale.

27
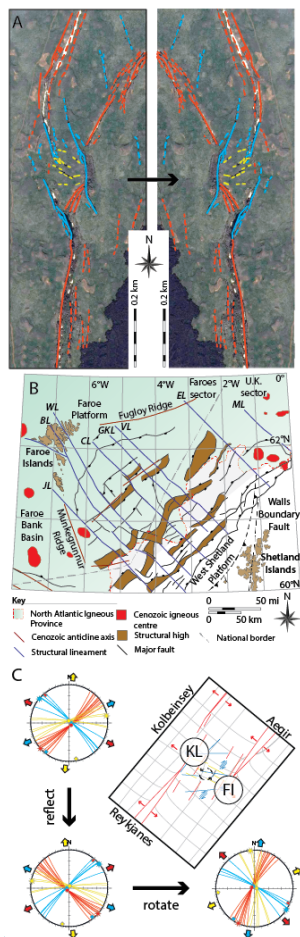
Figure 11. (A) Reflection of left-stepping Krafla faults to a right-stepping NE Atlantic rift configuration; (B) Map of the European margin of the NE Atlantic showing the broad NE-SW basin trend. JL: Judd Lineament; CL: Clare Lineament; GKL: Grimur Kamban Lineament; VL: Victory Lineament; EL: Erlend Lineament; ML: Møre Lineament; BL: Brynhild Lineament; WL: Westray Lineament; (C) Krafla faults are rotated into the orientation of the Atlantic European margin basin system and compared with the Reykjanes-Aegir system.

28
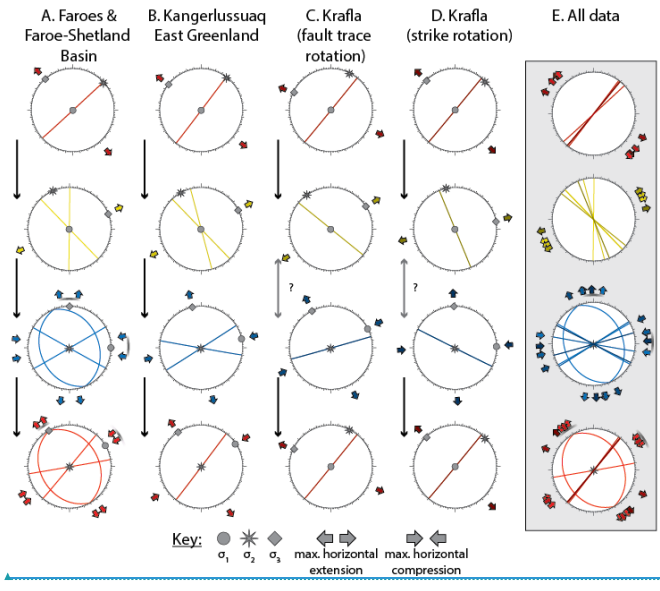
Figure 12. Comparison of averaged structural orientations and kinematics for the Faroe Islands (A) and East Greenland (B); (C) Krafla data is reflected and rotated so that the surface traces match the NE Atlantic basin system; (D) Krafla data is reflected and rotated so that the measured planar data matches the measured data from the NE Atlantic basin system; (E) Combined summary of orientations and kinematics from each study area.

2 Background

The primary, regional scale segmentation of extensional terranes is controlled by the development of networks of normal fault systems and the partitioning of strain across them. Normal faults comprise multiple discontinuous, non-collinear segments, with overlaps and segment linkage forming characteristic stepping geometries at a broad range of scales (e.g. Cartwright et al., 1996; Peacock et al., 2000; Acocella et al., 2005; Long and Imber, 2011).

3 Field study areas

3.1 The Koa'e fault system, Hawai'i

Normal faults in the Koa'e fault system are subvertical and interpreted to be growth faults, associated with the forceful emplacement of dikes in the ERZ, the cumulative effect of which has been ~25-30 m of extension since the last volcanic resurfacing event 400-750 years ago (Duffield et al., 1975; Holcombe, 1987). Here we focus on a 3 km^2 area, ~5 km south of Kilauea's summit in the centre of the Koa'e fault system (Fig. 2a, b). Approximately 2000 measurements, covering three orders of length magnitude, were collected for: (1) extension fractures (hereafter, fracture), which develop in the footwalls of upward propagating normal faults (e.g. Martel and Langley, 2006); and (2) normal faults using differential GPS (dGPS) to record surface-breaching fault cut-off line positions at <10 cm horizontal resolution within the 3 km^2 area. Fractures were measured for strike and extension direction; aperture (the amount of opening measured normal to the plane) was also measured at several positions along each fracture.

his suggests that although set B accommodates a component of rift zone-normal extension, this set contributes relatively little to the regional extensional strain as a whole. With no evidence for the relative timings of the bounding and linking fracture sets, simultaneous orthogonal extension directions have produced an area of inherently 3D strain within the relay zone. A kinematically and geometrically coherent fault array (e.g. Walsh et al., 2003) should exhibit an approximately centralized displacement maxima; this is not the case for horizontal (heave) displacement where we find a prominent extensional strain deficit in the centre of the array (Fig. 3b,c).

4 Discussion

4

Bott, M. H. P. (1975). Structure and evolution of the north Scottish shelf, the Faeroe block and the intervening region. Petroleum and the continental shelf of North-west Europe, 1, 105-115.

Bürgmann, R., & Pollard, D. (1994). Slip distributions on faults: effects of stress gradients, inelastic deformation, heterogeneous host-rock stiffness, and fault interaction. Journal of Structural Geology, 16(12), 1675-1690.

Figure 1. (a) Schematic diagram illustrating a relay zone between two normal faults (after Ferrill and Morris, 2001); (b) Map view of the block model in (a) showing fault overlap and separation; (c) Distance versus displacement (throw) profile for transect X-X'; (di-v) Second-order fault geometries as a function of fault overlap (redrawn from Tentler and Acocella, 2010) with local and regional extension directions indicated. Graphs show schematic displacement (heave)-length plots for the bounding fractures and linking geometries

shown; (e) Modelled strain fields and rotation ahead of two left- and right-stepping en echelon open-mode fractures (redrawn from Tentler and Acocella, 2010).

Figure 2. (a) Simplified structural elements map of Kīlauea Volcano's south flank, showing the study area within the Koaʻe fault system (KFS); ERZ: East Rift Zone; SWRZ: Southwest Rift Zone; HFS: Hilina Fault System. Inset shows position of A, on the south coast of Big Island, Hawaii; (b) WorldView image of the study area showing mapped fractures. White arrows indicate fault dip directions. Lower hemisphere stereographic projections indicate mapped fracture orientations and observed extension directions. Dashed lines are not included in this analysis; (c) Proposed evolution of fault sets: (i) propagation of the main rift-fault set (set A and C); (ii) interaction between sets A and C produces deficits of heave displacement, requiring vertical axis block rotation in the relay zone, and local reorientation of extension direction (set B); (iii) development of new rift-parallel structures (set D).

Figure 3. (a) Distribution of mapped fractures in the study area; (b) Profile of horizontal displacement (heave) vs length for mapped fractures. Dotted grey line indicates cumulative aperture for each set. Dashed blue lines indicate the calculated component of rift zone-normal extension on each fracture set. Dashed red lines indicate the calculated component of rift zone-parallel extension on each fracture set. Dotted orange line represents a hypothetical total displacement profile for a single fault (e.g. Gupta and Scholz, 2000), or a kinematically and geometrically coherent fault array (e.g. Walsh et al., 2003) where the maximum displacement is located centrally along the fault, or array; (c) Profile of estimated vertical displacement (throw) vs length for segments of surface-breaking faults. No evidence for throw was identified along NW-SE striking fractures of set B.

Figure 4. (a) Map of Iceland highlighting the major tectonic elements: Reykjanes Ridge (RR); the Kolbeinsey Ridge (KR); South Iceland Seismic Zone (SISZ); West Volcanic Zone (WVZ); East Volcanic Zone (EVZ); Neo-Volcanic Zone (NVZ: the axial rift zone); Askja volcanic centre (As); Fremri-Namur volcanic centre (Fr); Krafla volcanic centre (Kr); Theistareykir volcanic centre (Th); the Tjörnes Fracture Zone (TFZ) comprising the Dalvik lineament (DF), the Husavik-Flatey Fault (HF) and the Grimsey lineament (GF); (b) Location of study area in the Gjastykki Valley within the Krafla fissure swarm. White arrows indicate dip direction for fault scarps in the area; (c) Mapped structures in the study area, color-coded based on orientation and kinematics: (1) rift zone-parallel faults and fractures (red); (2) rift zone-oblique faults and fractures (blue); and (3) rift zone-normal fractures (yellow); (d) Lower hemisphere stereographic projections showing measured extension directions for each of the three structural sets; (e) Proposed evolution of fault sets: (i) Propagation of the main rift-fault sets A and B; (ii) interaction between sets A and B leads to a horizontal displacement deficit and vertical axis block rotation in the relay zone, and induced local reorientation of extension direction accommodated on variably oriented ancillary faults and fractures; (iii) continued propagation of the main rift faults (A, B and C) leads to the development of new rift-parallel structures.

Figure 5. (a) Distribution of mapped faults and fractures in the study area; (b) Profile of horizontal displacement (heave) vs length for mapped fractures. Dotted grey line indicates the total measured aperture for structures in each set. Dashed blue lines indicate the calculated component of extension on each fracture set that occurs in a direction orthogonal to the rift zone. Dashed red lines indicate the calculated component of extension on each fracture set that occurs in a direction parallel to the rift zone. Extension across the system as a whole is represented by a hypothetical displacement profile for a single fault or kinematically and geometrically coherent fault array (dotted orange line).

Figure 6. Horizontal plane 2D conceptual models for inter-fault/inter-rift relay rotation. (a) Bookshelf rotation model showing (i-iii) progressive rotation leading to rift normal extension, and rift-parallel shortening; (b) Schematic models for structures observed in the study areas presented here: (i) conjugate extensional shear faults, (ii) extension fractures, and (iii) a combination of extension fractures and conjugate extensional shear faults. If faults develop throw, as in the Krafla example, the system becomes non-plane strain. Models are not to scale.

Figure 7. (a) NE Atlantic tectonic elements map: Hatton Rise (HR), Hatton Basin (HB), Rockall High (RH), South Rockall Basin (SRB), North Rockall Basin (NRB), Faroe-Shetland Basin (FSB), Shetland Islands (SI), Møre Basin (MB), Vøring Basin (VB), Jan Mayan (JM), Jan Mayan Fracture Zone (JMFZ), Tjörnes Fracture Zone (TFZ), Faroes Fracture Zone (FFZ). Map was compiled using: basin ages from Doré et al., (1997); oceanic magnetic anomalies from Gaina et al. (2009); Iceland stratigraphic ages from Doré et al. (2008). Study localities indicated by stars; (b-d) Schematic model for a segmented opening of the NE Atlantic during the Paleogene (after Ellis and Stoker, 2014). Faroe Islands (FI); Kangerlussuaq (KL).

Figure 8. (a) Onshore structural element map of the Faroe Islands; (b) Inferred extension directions indicating an island-wide anticlockwise rotation in extension direction through time; (c) Margin-oblique faults cut margin-normal faults; (d) Margin-parallel faults cut rift-oblique faults and dikes; (e) Lower hemisphere stereographic projections for relative-age-constrained examples of the three main fault sets observed.

Figure 9. (a) Geological map of the Skaergaard intrusion and surrounding area (redrawn from Holwell et al., 2012). Contours indicate 50 m elevation intervals from sea level; (b) Margin-normal striking faults and dikes cut the Skaergaard intrusion, which are in turn cut by margin-oblique striking faults and dikes; (c) Margin-oblique striking faults cut the margin-parallel Miki Fjord macrodike; (d) Lower hemisphere stereographic projections for relative-age-constrained examples of the three main fault sets observed.

Figure 10. (a) Reflection of left-stepping Krafla faults to a right-stepping NE Atlantic rift configuration; (b) Map of the European margin of the NE Atlantic showing the broad NE-SW basin trend. JL: Judd Lineament; CL: Clare Lineament; GKL: Grimur Kamban Lineament; VL: Victory Lineament; EL: Erlend Lineament; ML: Møre Lineament; BL: Brynhild Lineament; WL: Westray Lineament; (c) Krafla faults are rotated into the orientation of the Atlantic European margin basin system and compared with the Reykjanes-Aegir system.

Figure 11. Comparison of averaged structural orientations and kinematics for the Faroe Islands (a) and East Greenland (b); (c) Krafla data is reflected and rotated so that the surface traces match the NE Atlantic basin system; (d) Krafla data is reflected and rotated so that the measured planar data matches the measured data from the NE Atlantic basin system; (e) Combined summary of orientations and kinematics from each study area.