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## Volcanic edifice slip events recorded on the fault plane of the San Andrés Landslide, El Hierro, Canary Islands

Jan Blahůt, Ivanka Mitrovic-Woodell, Ivo Baroň, Miloš René, Matt Rowberry, Pierre-Henri Blard, Filip Hartvich, Jan Balek, Stavros Meletlidis

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Abstract: Volcanic flank collapses often result in giant debris avalanches that are capable of travelling tens of kilometres across the ocean floor and generating tsunamis that devastate distant communities. The San Andrés Landslide on El Hierro, Canary Islands, represents one of the few places in the world where it is possible to investigate the landslide mass and fault planes of a volcanic collapse structure. In this study, a new conceptual model for the development of this enormous slump is presented on the basis of structural geological and geomorphological measurements, petrological and microstructural analyses, and cosmogenic radionuclide dating. Structural geological and geomorphological measurements indicate that the fault plane records two distinct events. Petrological and microstructural analyses demonstrate that a thin layer of frictionite covers the surface of the fault in contact with an oxidised tectonic breccia that transitions into the underlying undeformed basanite host rock. This frictionite comprises a heterogeneous cataclastic layer and a translucent silica layer that are interpreted to represent two separate slip events on the basis of their architecture and crosscutting relationships. Cosmogenic  $^3\text{He}$  dating reveals a maximum exposure age of  $183 \pm 17$  ka to  $52 \pm 17$  ka. Arguments are presented in support of the idea that the first slip event took place between 545 ka and 430 ka, prior to significant clockwise rotation of El Hierro, and the second slip event took place between 183 ka and 52 ka, perhaps in association with one of the giant debris avalanches that occurred around that time. This is the first time that more than one slip event has been recognised from the fault plane of the San Andrés Landslide. It is also believed to be the first time a silica layer resulting from frictional melt has been described in a volcanic setting.

Research Data Related to this Submission

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There are no linked research data sets for this submission. The following reason is given:

Data will be made available on request



**ÚSTAV STRUKTURY A MECHANIKY HORNIN**  
*Akademie věd ČR, v.v.i.*

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25/12/2019

Prague, Czechia

Dear Editor,

In name of all the co-authors I would like to submit a reviewed manuscript entitled „Volcanic edifice slip events recorded on the fault plane of the San Andrés Landslide, El Hierro, Canary Islands”. We have made thorough revision and we have incorporated the requested information from the editor and both reviewers.

We hope, that the revised manuscript will now be more clear to read and may attract more potential readers.

I hope our manuscript is now in acceptable form,

Yours sincerely,

Jan Blahut

**Volcanic edifice slip events recorded on the fault plane of the San Andrés Landslide, El Hierro, Canary Islands**

Volcanic flank collapses often result in giant debris avalanches that are capable of travelling tens of kilometres across the ocean floor and generating tsunamis that devastate distant communities. The San Andrés Landslide on El Hierro, Canary Islands, represents one of the few places in the world where it is possible to investigate the landslide mass and fault planes of a volcanic collapse structure. In this study, a new conceptual model for the development of this enormous slump is presented on the basis of structural geological and geomorphological measurements, petrological and microstructural analyses, and cosmogenic radionuclide dating. Structural geological and geomorphological measurements indicate that the fault plane records two distinct events. Petrological and microstructural analyses demonstrate that a thin layer of frictionite covers the surface of the fault in contact with an oxidised tectonic breccia that transitions into the underlying undeformed basanite host rock. This frictionite comprises a heterogeneous cataclastic layer and a translucent silica layer that are interpreted to represent two separate slip events on the basis of their architecture and crosscutting relationships. Cosmogenic  $^3\text{He}$  dating reveals a maximum exposure age of  $183\pm 17$  ka to  $52\pm 17$  ka. Arguments are presented in support of the idea that the first slip event took place between 545 ka and 430 ka, prior to significant clockwise rotation of El Hierro, and the second slip event took place between 183 ka and 52 ka, perhaps in association with one of the giant debris avalanches that occurred around that time. This is the first time that more than one slip event has been recognised from the fault plane of the San Andrés Landslide. It is also believed to be the first time a silica layer resulting from frictional melt has been described in a volcanic setting.

Dear Editor,

The comments of you and the reviewers are in black, while our responses are in red.

**Editor:**

Dear authors,

At long last I have received two evaluations of your work — many potential reviewers have in fact turned down the review invitation.

While the manuscript has clear merits, there are still some significant issues:

— a more thorough and general introduction should be provided on fault slip and as to how peculiar volcanic edifices may be, and why we should care about the seismicity of landslides there. As Rev#1 points out, it is somewhat unclear "why being in a volcanic setting is noteworthy". This echoes one of your conclusions, ie "This is the first time that more than one slip event has been recognised from the fault plane of the San Andrés Landslide", which does not sound so ground breaking to me (if I may play with words).

We have rewritten the introduction to capture the readers' interest. We hope, that now the scope of the study is clearer.

— Some petrographic features at the dm-cm scale are missing to ensure a correct scale transfer of descriptions, say from Fig.2 to say Fig. 5.

We have added new photos of MSA1 and MSA2 samples to Fig.2, followed by detailed description. We believe, that this might be sufficient to transfer from Fig.2 to Figs. 5, 6 and 7.

— why are cosmogenic ages not discussed more thoroughly and reported on the surface? I find this really problematic. Table 1 is simply not enough and data should be scrutinized.

We have carefully rewritten this part as we understand that the explanation presented was not enough. We explained the reasons why the cosmogenic ages yielded such different results.

— any hint as to the respective sizes of the landslides? as to a paleomagnitude?...

We have added this information to chapter 2.1.

— You should pay attention to details. Care should be taken about statements such as: "strong ground shaking" (L493), which is not substantiated.

We have corrected this statement – see answer to reviewer 2 (p. 18, l. 493). We also checked the manuscript and corrected such general statements where needed.

— the write-up could be improved. For example, conclusions should be made much more concise and straight to the point. The first part basically repeats the incentive of the study.

We have rewritten the conclusions to be more concise.

— Take-home message: note that there is no scale to Fig. 9. This also does not seem to me like a very impactful take-home message figure and could probably be improved.

We have added the scale to Fig. 9. As the reviewer 2 likes the figure being very illustrative we would like to keep this figure in the manuscript.

Should you be able to address this criticism with the greatest care, I would welcome receiving a thoroughly revised version of your work.

Good luck with your efforts,  
Best regards  
Philippe

### **Reviewer 1:**

Reviewer #1: I am afraid that I was not the best choice of reviewer for this manuscript as I have no expertise to evaluate most of the material presented. Acknowledging my nearly complete lack of knowledge about how to measure and interpret geologic features at the scales considered in this paper, or the analyses used, the manuscript seems clearly written and analyses very thorough. The authors do not appear to over-interpret the results, acknowledging the uncertainties in the various measurements and interpretations and how they may or may not fit together. Again, I am unable to comment on any of the details. My only recommendation is that the paper would have broader appeal if there was greater motivation and discussion of issues related to fault slip in a broader context; what do their results imply for current models of fault reactivation, stationarity in process, etc., at multiple scales? The authors also emphasize the fact that this is the first time some of their observations have been made in a volcanic setting, and while perhaps it may be obvious to some why being in a volcanic setting is noteworthy, it is not clear to me why this is noteworthy. Is there something about a volcanic setting that makes the faulting processes inferred surprising?

We have rewritten the abstract, introduction and conclusions so the scope of our study should be clearer and have broader appeal.

I have included very minor comments (mostly grammatical suggestions) in the annotated manuscript returned

p.18, l. 486-487: The typing error in Széreméta et al. (1997) was corrected to (1999).

1. Surname of the corresponding author is Blahůt, in caps BLAHŮT (see references, small circle over the u/U). This was corrected. I used to use "Blahut" without circle over u in the past.

2. Some sentences are difficult to understand, I recommend to reformulate them:

p. 7, r. 161: *The first gives a ground plan view ...* – missing subject  
This was corrected.

p. 7, r. 169: *In total eighty eight test sites were sampled ...* – missing subject  
This was corrected.

p.7, r. 171: ..., *as is standard protocol*, ... – missing subject

This was corrected.

p. 12, r. 316-318: *The host rocks ... These are mainly pyroxene, plagioclase, olivine, and amphibole together with the accessory minerals apatite, chromite, magnetite, and Ti-magnetite.* – “These” means minerals or rocks, or adjectives to rocks??

This was corrected – These means rocks.

p. 12, r. 319: ... *with an acid rim, An45–70, and a basic core, An79–83.* – I suppose description from core to rim.

This was corrected.

p. 12, r. 321–322: *A high amount of volcanic glass is present while basanites with subordinate amounts of volcanic glass contain frequent phenocrysts of olivine.* – The sentence that follows the previous description of bazanites makes no sense in this formulation.

This was corrected.

p. 12, r. 328: ... *The tectonic breccias host cracks filled by zeolite veins ...* – either the breccias are cut by zeolite veins, or cracks are filled by zeolite. Veins are “filled cracks”.

This was corrected.

p. 13, r. 338–339: *Instead attention focuses here on the layers that overlie the tectonic breccia.* – Totally incomprehensible formulation for me.

This was corrected.

p. 13, r. 355: ... *cracks parallel ...* - missing *are*?

This was corrected.

p. 16, r. 429: ... *with horizontal Y- shears, parallel to the slip surface ...* – the slip surface is inclined: what does it mean “horizontally” – in the field or in a figure 5?

This was corrected. Y-shears are parallel to the slip surface.

p. 18, r. 479: ... *due to the fact it acts as a lubricant ...* - missing “that”?

This was corrected.

p. 18, r. 497–498: ... *the fault could only have been active only for a geologically short period ...* – double “only”.

This was corrected.

p. 29, r. 787: The caption “*Stereoplot of the structural geological measurements ...*” says nothing about what it is. I recommend to use “*Orientation of the fault surface ...*” supplemented by information that it is an *azimuthal projection in the lower hemisphere*.

This was corrected.

3. It is necessary to unify the designation of the year: *yr* (p. 6, r. 140) vs. *a* (p. 9, r. 238 and others). The unit *mm/yr–1* at the same place is nonsense (double “over”).

This was corrected to “a” to be unified with the rest of the paper.

4. A problem that goes through much of the text is writing a comma. Use commas to set off introductory elements (as it correctly shown):

- p. 2, r. 26: ... *study, a new ...*



- p. 6, r. 160: ... *cloud, it was* ...
- p.9, r. 244: ... *In theory, the magmatic* ...
- p. 11, r. 293: ... *Most commonly, the striations* ...
- p. 13, r. 339: ... *microscopy, it is* ...
- p. 13, r. 345: ... *samples, it is* ...
- p. 17, r. 450: ... *senses, they are* ...
- p. 18, r. 496: ... *In that study, it was* ...
- p. 19, r. 516: ... *surface, it has been* ...

I suppose to use comma in other cases, such as:

- p. 19, r. 517: ... *event, as evidenced by the cataclastic layer, is proposed* ...
- p. 4 r. 101: ... *Series, which* ... ; p. 6, r. 149: ... *slickenlines, which* ..., etc.

Comma is not needed behind series of adjectives, such as:

- p. 5, r. 103 ... *The most recent, ongoing phase* ...
- p. 5, r. 127 ... *acurate, and presumably listric fault system* ...
- p.15, r. 398: ... *minor, most probably slow displacement* ...

The commas were corrected.

5. Do not use the word *measurements* for data obtained (or directional data): p. 4, r. 84; p. 11, r. 283; p. 29, r. 787.

This was corrected.

6. Indicate that the directions are given as azimuths (p. 11).

This was corrected.

7. For better understanding of the text, I recommend inserting referenced word after the pronouns, such as *this* (p. 6, r. 149), *these* (p. 11, r. 295; p. 12, r. 316), *those* (p. 17, r. 449), although it is not essential.

This was corrected.

8. Two brackets next to each other are not suitable: p. 5, r. 112; p. 9, r. 225; p. 12, r. 325. Two brackets inside each other are not suitable: p. 9, r. 241; p. 13, r. 348.

This was corrected.

9. I suppose to use original spelling for *pseudotachylyte* (Shand, 1916: The Pseudotachylyte of Parijs, Orange Free State, and its Relation to 'Trap-Shotten Gneiss' and 'Flinty Crush-Rock'. *Quarterly Journal of the Geological Society*, **72**, 1–4, 198–221.) instead of misspelled *pseudotachylite* (p. 15, r. 413 and others), even if it is incorrectly mentioned in the recommendation of Subcommittee on the Systematics of Metamorphic Rocks (Fettes & Desmons, 2007: *Metamorphic Rocks – A Classification and Glossary of Terms*).

This was corrected. We accept the recommendation from the reviewer to use the original term (after Shand 1916). A lot of researchers use the other spelling version, as it is seen as the correct one. Out of curiosity, a Tweeter poll was conducted by one of the authors to check what researches prefer: 61% voted for “pseudotachylite”, and 39% for “pseudotachylyte” (out of 83 votes).

**Reviewer 2:**

Abstract

This was corrected.

p.3, l. 52-53: Where? Globally, in the Nicaraguan Highlands (presumably in Nicaragua?), Canary Islands?

In the whole world – this was corrected.

p.3, l. 54: put in parentheses

This was corrected.

p.3, l. 69: "... development of foliation." Is this what distinguishes cataclasites from frictionite, or are cataclasites a type of frictionite?

We have rewritten this part to be more clear.

p.3, l. 69-70: "Fast slip along shallow fault.." Are the features described here for faults also considered frictionite? The potential similarities and differences between faults and landslides needs clarification; is the implication that they form similar, but not identical structures?

We have rewritten this part to be more clear.

p. 4, l. 77-78: As noted above, it isn't clear that these aggregates or silica layers are observed on landslides generally? Might be useful to say why one might expect things to be different or similar in a volcanic setting (i.e., why does the setting matter)?

Cataclasites or frictionites are normally not observed on landslides. Only few exceptions exist (e.g. Köfels, Tsego-Ri, Arequipa) in case there is large landslide (or rockslide/rock avalanche in particular) able to generate enough frictional heat to produce re-melting of thin layer of rocks.

p. 5, l. 105: How could it have ended in 2012 and lasted until 2014?

The seismic activity lasted from July 2011 till 2014, during that period an offshore eruption occurred (10/10/2011 – March 2012). This sentence was rewritten.

p. 17, l. 458: This sentence needs a verb!

This was corrected.

p. 17, l. 471: This sentence also needs a verb!

This was corrected.

p. 18, l. 481: Figures 8 and 9 are great - they summarize the interpretation in simple, straightforward ways!

Thank you, we also improved these figures according to the reviewers' and editor's suggestions.

p. 18, l. 493: "... accompanied by ground shaking..." Is the implication here that shaking initiated both the El Golfo debris avalanche and this second slip event, or that the former caused the shaking? If the latter, it's not clear that the shaking would be sufficient (I'd expect low amplitude shaking from a debris avalanche as the coupling efficiency would be low).

We agree with the reviewer, that the shaking induced from the debris avalanche itself wouldn't be probably enough to cause re-activation of San Andrés Landslide. As more information about triggers of these giant debris avalanches is not known we changed the sentence to reflect this.

p. 18, l. 494: should be 'a model'

This was corrected.

p. 18, l. 497: omit "only"

This was corrected.

Figure 3: What do different colors represent?

The different colours of arrows represent distinct sets of striations and elongated bumps. We have added this explanation to the captions.

Figure 4: should be 'black circles' or 'black dots'?

This was corrected.

Figure 8: Add 'Age before present' to indicate what these numbers are?

We have added this to the figure captions as it is graphically nicer.

### Highlights

- Landslide frictionite adorns the fault plane of the San Andrés Landslide on El Hierro
- The frictionite comprises a dark cataclastic layer and a translucent silica layer
- These cataclastic and silica layers formed during two separate fault slip events
- Microstructural observations in good agreement with observations at the outcrop scale
- It is suggested that the fault slip events occurred between 545-430 ka and 183-52 ka
- First time that more than one slip event has ever been recognised on a single fault plane resulting from volcanic flank collapse on an oceanic island
- First time a silica layer resulting from frictional melt has been described from a volcanic setting

1 Volcanic edifice slip events recorded on the fault plane of the San Andrés Landslide, El Hierro, Canary Islands

2

3

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24 | **Abstract:** [Volcanic flank collapses often result in giant debris avalanches that are capable of travelling tens of](#)  
25 | [kilometres across the ocean floor and generating tsunamis that devastate distant communities.](#) The San Andrés  
26 | Landslide on El Hierro, Canary Islands, represents one of the few places in the world where it is possible to  
27 | investigate the landslide mass and fault planes of a volcanic collapse structure. In this study, a new conceptual  
28 | model for the development of this enormous slump is presented on the basis of structural geological and  
29 | geomorphological measurements, petrological and microstructural analyses, and cosmogenic radionuclide  
30 | dating. Structural geological and geomorphological measurements indicate that the fault plane records two  
31 | distinct events. [The first event is associated with features plunging 111° and the second is associated with](#)  
32 | [features plunging 125° and 131°.](#) Petrological and microstructural analyses demonstrate that a thin layer of  
33 | frictionite covers the surface of the fault in contact with an oxidised tectonic breccia [which that](#) transitions into  
34 | the underlying undeformed basanite host rock. This frictionite comprises a heterogeneous cataclastic layer and  
35 | a translucent silica layer [which that](#) are interpreted to represent two separate slip events on the basis of their  
36 | architecture and crosscutting relationships. Cosmogenic  $^3\text{He}$  dating reveals a maximum exposure age of  $183 \pm 17$   
37 | ka to  $52 \pm 17$  ka. [The high degree of variability between the replicate samples reflects the uncertainty associated](#)  
38 | [with estimating the magmatic  \$^3\text{He}\$ .](#) Arguments are presented in support of the idea that the first slip event took  
39 | place between 545 ka and 430 ka, prior to significant clockwise rotation of El Hierro, and the second slip event  
40 | took place between 183 ka and 52 ka, perhaps in association with one of the giant debris avalanches that  
41 | occurred around that time. This is the first time that more than one slip event has been recognised from the  
42 | fault plane of the San Andrés Landslide. It is also believed to be the first time a silica layer resulting from  
43 | frictional melt has been described in a volcanic setting.

44 |  
45 | **Keywords** volcanic collapse; frictionite; cataclastic metamorphism; silica layer formation; cosmogenic  
46 | radionuclide dating; Canary Islands

47 **1. Introduction**

48 Gravitational slope failures ~~generate often produce~~ geological structures at a range of scales that are either  
49 similar or identical to those ~~that result from related to endogenous~~ tectonic processes (Jaboyedoff et al., 2013).  
50 ~~Consequently, F~~ faults ~~generated that originate~~ as a result of large ~~slope failures landslides~~ are often analogous  
51 to ~~their ose produced by~~ tectonic ~~counterparts processes~~ (Gomberg et al., 1995). ~~Some of the largest slope~~  
52 ~~failures on Earth are represented by volcanic flank collapses on oceanic islands – these events are so enormous~~  
53 ~~that they are also comparable to the largest mass movements on Mars (Blahût et al., 2019). The processes that~~  
54 ~~lead to volcanic flank collapses on oceanic islands are not well understood despite their potential to generate~~  
55 ~~catastrophic tsunamis (Paris et al., 2018; Walter et al., 2019). In part this situation reflects the dearth of events~~  
56 ~~as volcanic flank collapses are estimated to have only occurred four times a century in for the past five hundred~~  
57 ~~years (Siebert, 1992). Volcanic flank collapses on oceanic islands are usually represented by debris avalanches~~  
58 ~~(sensu Ui et al., 2000), which displace huge volumes of rock and create amphitheatre shaped calderas (Siebert,~~  
59 ~~1984). Such debris avalanches localise shear deformation along thin sliding surfaces at the base of the~~  
60 ~~displaced mass (De Blasio and Elverhøi, 2008). These events are triggered by a range of factors which can be~~  
61 ~~broadly categorised as seismogenic or magmagenic (McGuire, 1996). Therefore, while huge debris avalanches~~  
62 ~~may occur in other settings, volcanic flank collapses on oceanic islands are especially dangerous due to the~~  
63 ~~interminable nature of the potential triggering events, i.e. volcanic tremors and related seismicity, coupled with~~  
64 ~~the adjacency of an extremely high risk impact environment, i.e. seawater. The run-up heights of consequent~~  
65 ~~tsunami waves may exceed 100 m (Karstens et al., 2019; Walter et al., 2019). Occasionally, volcanic collapses~~  
66 ~~are represented by creeping or slumping but only a small number of studies have focused on these processes.~~  
67 ~~Examples come from Mount Etna in Sicily (Rasa et al., 1996), Pico Ridge in the Azores (Hildebrand et al., 2012),~~  
68 ~~San Andrés in the Canary Islands (Blahût et al., 2017), and Hilina Slump in the Hawaiian Islands (Liu et al. 2018).~~  
69  
70 ~~Volcanic collapses usually occur as debris avalanches (sensu Ui et al., 2000), removing huge volumes of rock~~  
71 ~~and generating amphitheatre shaped calderas (Siebert, 1984). These debris avalanches, as with other types of~~  
72 ~~slope deformation, localise shear deformation along thin sliding surfaces at the base of the sliding mass (De~~  
73 ~~Blasio and Elverhøi, 2008). In some instances, it possible to obtain information pertaining to creeping or~~  
74 ~~slumping but such studies are rare. Examples come from Mount Etna in Sicily (Rasa et al., 1996), Pico Ridge in~~

75 [the Azores \(Hildebrand et al., 2012\), San Andrés in the Canary Islands \(Blahút et al., 2017\), and Hilina Slump in](#)  
76 [the Hawaiian Islands \(Liu et al. 2018\).](#)

77

78 ~~In a volcanic setting it has been found that slow collapse of a Tertiary shield volcano in the Nicaraguan~~  
79 ~~Highlands during the Holocene modified the local palaeostress field and generated normal, reverse, and strike~~  
80 ~~slip faults (Baroň et al., 2011). However, volcanic collapses are somewhat difficult to study because they are~~  
81 ~~comparatively rare events. Such failures have occurred at least four times a century for the past five centuries~~  
82 ~~(Siebert, 1992). These events are triggered by a range of factors which can be broadly categorised as~~  
83 ~~seismogenic or magmatic (McGuire, 1996). Volcanic collapses usually occur as debris avalanches, (sensu Uli~~  
84 ~~et al., (2000), removing huge volumes of rock and generating amphitheatre shaped calderas (Siebert, 1984).~~  
85 ~~These debris avalanches, as with other types of slope deformation, localise shear deformation along thin sliding~~  
86 ~~surfaces at the base of the sliding mass (De Blasio and Elverhøi, 2008). In some instances, it has been possible~~  
87 ~~to obtain information pertaining to creeping or slumping but such studies are rare. Examples come from Mount~~  
88 ~~Etna in Sicily (Rasa et al., 1996), Pico Ridge in the Azores (Hildebrand et al., 2012), San Andres in the Canary~~  
89 ~~Islands (Blahút et al., 2017), and Hilina Slump in the Hawaiian Islands (Liu et al. 2018). It is, however, probable~~  
90 ~~that more data will be collected in the future due to the increasingly widespread use of GPS and InSAR.~~

91

92 During landslide emplacement, flash heating may occur along thin shear layers to produce frictional melt,  
93 referred to as frictionite or landslide pseudotachylite (Masch et al., 1985; Maddock, 1986; Legros et al., 2000;  
94 Lavallée et al., 2012; Mitchell et al., 2015). [Frictionite is a subtype of pseudotachylite, sensu lato, which is](#)  
95 [generated at the base of landslides, as opposed to pseudotachylite, sensu stricto, which is generated in greater](#)  
96 [depths with higher pressure and temperature conditions \(Maddock, 1986\).](#) Frictionite tends to have  
97 thicknesses of between one and three centimetres and develops parallel or subparallel to the dip of the  
98 landslide (Weidinger et al., 2014). Indicators of frictionite include significant grain size reduction, [evidence for](#)  
99 [fluidised flow, and](#) the presence of amorphous material, ~~and evidence for fluidised flow.~~ [Other types of](#)  
100 [cohesive fault rocks, such as microbreccias and cataclases, are common also form](#) during [the emplacement](#)  
101 [of large landslides.](#) ~~typical indicators of cataclastic deformation are~~ [Cataclases typically show](#)  
102 grain size reduction, [compared to the host rock, with](#) ~~and the~~ development of foliation. [To accurately assess](#)  
103 [the hazard relating to volcanic flank collapses it is crucial to be able to estimate the strength and velocity of the](#)



104 [landslide](#). Fast slip along shallow faults ~~is evidenced~~ [can be inferred](#) by the presence of [devitrified material](#)  
105 [observed in pseudotachylytes](#), clast-cortex aggregates (Smith et al., 2011; Han and Hirose, 2012; Rempe et al.,  
106 2014), ~~and~~ silica layers (Kirkpatrick et al., 2013; Faber et al. 2014), [and other type of fault rock architecture](#).  
107 [Pseudotachylytes and frictionites are ultrafine-grained rocks, with the presence of partial melt. The Clast-cortex](#)  
108 [aggregates former are composed](#) [comprise](#) of a central clast enclosed within a layer, or concentric layers, of  
109 material akin to the matrix (e.g. Anders et al., 2010; Rowe et al., 2012). [Silica layers while the latter](#) are  
110 composed of translucent silica ~~gel layer~~ with microstructures that exhibit flow banding, armoured clasts, and  
111 extreme comminution compared to adjacent rocks (Kirkpatrick et al., 2013; Faber et al., 2014). [These fault rock](#)  
112 [structures are not common – they are known to occur in a range of tectonic settings but have not been](#)  
113 [reported in relation to volcanic flank collapses](#). The first report of frictionite at the base of a landslide was  
114 described from the Köfels landslide in the Austrian Alps (Masch et al., 1985) while the first report of frictionite  
115 at the base of a landslide in a volcanic environment was described from the Arequipa volcanic landslide deposit  
116 in Peru (Legros et al., 2000). [Furthermore, volcanoes tend to be basic in composition and silica layers are not](#)  
117 [expected to form in predominantly basic environment](#). ~~Neither clast-cortex aggregates nor silica layers are~~  
118 ~~thought to have ever been reported from a volcanic setting~~.  
119  
120 [Reconstruction of past volcanic failures in their source areas is extremely rare as there is usually no material](#)  
121 [to study and/or the main scarp has since been covered by younger eruptions. For that reason, the majority of](#)  
122 [studies have focused on the sedimentological properties of these failures \(e.g. Hunt et al., 2013\). Until recently](#)  
123 [years, it has been assumed that the volcanic flank collapses occur as one major event that displaces hundreds](#)  
124 [of cubic kilometres of rock. However, new research suggests that at least some of these collapses occurred in](#)  
125 [multiple stages \(Hunt et al., 2013, 2018; León et al., 2017\). Such findings may have serious implications for the](#)  
126 [calculated frequency of such hazards and reopens questions about the possible reactivation of apparently](#)  
127 [inactive structures](#). The San Andrés Landslide on El Hierro in the Canary Islands represents one of the few  
128 places in the world where it is possible to investigate the ~~landslide mass and~~ fault planes [and landslide mass](#) of  
129 a volcanic collapse structure. This study integrates a range of structural geological and geomorphological  
130 measurements, petrological and microstructural analyses, and cosmogenic nuclide dating in order to  
131 reconstruct the developmental history of this huge [gravitational](#) slope failure. [Measurements Data](#) have been  
132 obtained - directly or indirectly - from the surface of the fault plane while samples were collected from both

133 the fault plane itself and an adjacent gully perpendicular to the footwall. Our hypothesis states that this  
134 landslide is not the result of a single event, as proposed by Day et al. (1997), but instead results from a number  
135 of successive events spanning a protracted period. This hypothesis is not straightforward to address as  
136 unambiguous evidence for multiple slip events along a single fault is difficult to elucidate due to problems  
137 associated with overprinting and weathering. Nonetheless, [on the basis of previously published research and](#)  
138 [the results obtained during this study, it has been possible to propose](#) a new ~~developmental~~ [conceptual](#) model  
139 ~~is proposed~~ for the [development of the](#) San Andrés Landslide, ~~which is based on previously published research~~  
140 ~~and the results obtained during this study.~~

141

## 142 2. Geological setting

### 143 2.1 *The island of El Hierro*

144 El Hierro is an active volcanic edifice that constitutes the smallest and youngest of the Canary Islands (Figure 1).  
145 Its oldest subaerially exposed rocks are represented by the Tiñor Unit, with a maximum age of 1.12 Ma (Guillou  
146 et al., 1996), which form the northern and northeastern parts of the island. This unit is thought to have  
147 developed rapidly until around the time of the Tiñor debris avalanche at 0.88 Ma (Carracedo et al., 2001).  
148 Thereafter, the rocks of the El Golfo-Las Playas Unit, with a maximum age of 0.55 Ma (Guillou et al., 1996),  
149 capped much of the Tiñor Unit and infilled the scarp area of the Tiñor debris avalanche (Carracedo et al., 2001).  
150 ~~Its~~The youngest [subaerially exposed](#) rocks are represented by the Rift Series, ~~with which has~~ a maximum age of  
151 0.16 Ma (Guillou et al., 1996). Over the past 33 000 years onshore eruptions [have](#) reoccurred approximately  
152 once every 1 000 years (Becerril et al., 2016a). The ~~most recent~~ [latest](#), ongoing, phase of volcanism began  
153 around 2.5 ka (Carracedo et al., 2001). ~~Latterly a~~ [Recently a](#) period of intense seismic activity [commenced](#)  
154 [spanned from](#) ~~in~~ July 2011 (López et al., 2012) [to 2014 \(Benito-Saz et al., 2017\)](#). ~~During this period~~ ~~–prior to–~~ an  
155 offshore eruption ~~started that began~~ on 10 October 2011 and ~~finished ended~~ in March 2012 (Meletlidis et al.,  
156 2015), ~~–and lasted until 2014 (Benito-Saz et al., 2017)~~. A more detailed description of the geology of island has  
157 recently been presented elsewhere ([Carracedo and Troll, 2016](#)), ~~Blahút et al., 2018a~~.

158

159 The flanks of El Hierro have hosted a number of enormous gravitational slope failures which have contributed  
160 to the development of its characteristic ~~three point~~ [three-point](#) star morphology (Figure 1). Until now, seven  
161 debris avalanches have been identified: Tiñor (< 880 ka), Las Playas I (545-176 ka), Las Playas II (176-145 ka), El

162 | Julan (> 158 ka), El Golfo A (176-133 ka), El Golfo B (87-39 ka), and Punta del Norte ~~with (of unknown age)~~  
163 | (Masson, 1996; Urgeles et al., 1996, 1997; Carracedo et al., 1999, 2001; Masson et al., 2002; Longpré et al.,  
164 | 2011; Becerril et al., 2016b; Carracedo and Troll, 2016; León et al., 2017; Blahút et al., ~~2018b~~2018a). The  
165 | volumes of these debris avalanches vary between 50 km<sup>3</sup> and 234 km<sup>3</sup>, which makes them average from the  
166 | known volcanic slope failures (for additional morphometric characteristics, see Blahút et al., 2019). In addition,  
167 | a large slump, sensu Moscardelli and Wood (2008), or a deep seated gravitational slope deformation, sensu  
168 | Sorriso-Valvo et al. (1999) or Agliardi et al. (2001), is located on the southeast flank of the volcanic edifice. This  
169 | feature, the San Andrés Landslide, is defined by a group of pronounced faults which represent landslide  
170 | detachment planes. While its volume has not been determined however, the deformed toe is visible around 18  
171 | km off coast at a depth of more than 3 km (Becerril et al., 2016b). Similar features have been described from  
172 | other volcanic islands including the Azores (Hildenbrand et al., 2012) and the Hawaiian Islands (Duffield, 1975).  
173 | It has previously been proposed that the San Andrés Landslide is an anchored block associated with the debris  
174 | avalanche Las Playas I (Day et al., 1997).

175

## 176 | 2.2 *San Andrés Landslide*

177 | The San Andrés Landslide has developed in the volcanic rocks of the Tiñor Unit. This unit comprises three  
178 | distinct subunits (Gómez Sainz de Aja et al., 2010): the basal subunit is represented by relatively thin, 20-40 cm,  
179 | steeply dipping lava flows; the intermediate subunit, which forms the majority of the unit, is represented by  
180 | thicker, up to 4 m, shallow dipping lava flows; while the ~~third~~ uppermost subunit is represented by emission  
181 | vents with well-preserved craters and associated lavas. The broad arcuate, and presumably listric, fault system  
182 | which defines the boundaries of the slope deformation to the northeast is terminated to the southwest by an  
183 | escarpment associated with the giant debris avalanche Las Playas II. Previously the San Andrés Landslide has  
184 | been interpreted as either an aborted collapse structure (Day et al., 1997) or a deep seated gravitational slope  
185 | deformation (Klimeš et al., 2016).

186

187 | It has been reasoned that the fault system must have developed at some point between 545 ka and about 261-  
188 | 176 ka (Day et al., 1997). If correct, this implies that the collapsed landslide mass has remained anchored  
189 | during all each of the subsequent giant debris avalanches on El Hierro (Carracedo and Troll, 2016). Support for  
190 | the notion of protracted inactivity is provided by the presence of younger lavas crossing the fault without

191 displacement and the presence of scree covering lava flows as old as 145 ka in the gully of Las Playas  
192 (Carracedo et al., 1997). However, recent research is starting to challenge these arguments. The step-like  
193 structure of the incised gullies in the collapsed mass, together with records of progressive creep along its main  
194 detachment plane, in the order of  $0.5 \text{ mm/yr}$ , suggests that the landslide mass may be moving steadily to  
195 the east and southeast (Klimeš et al., 2016; Blahůt et al., 2017, 2018a, 2018b).

196  
197 The part of San Andrés Fault system investigated in this study is exposed along a narrow road which traverses  
198 the Barranco de Tiñor ( $27^{\circ}47'18.82''\text{N}$ ,  $17^{\circ}55'19.04''\text{W}$ ). This outcrop is situated at c. 490 m asl, has a length of  
199 c. 70 m, and dips between  $65^{\circ}$  and  $75^{\circ}$  to the SE (Figure 2). The fault zone has a total thickness of between one  
200 and two metres. Both the footwall and hanging wall rocks comprise basaltic lavas of the Tiñor Unit with a few  
201 thin intercalated lapilli beds and soil horizons (Carracedo et al., 1997). No indurated breccia is present on the  
202 hanging wall. Its eastern section has only been uncovered relatively recently as a result of road construction  
203 and is distinguished by its whitish surface. This part of the fault surface hosts well-preserved slickenlines, which  
204 range in size from several millimetres to metre scale surface undulations. Detailed petrographic examinations  
205 of the fault rocks have been published previously (Day et al., 1997).

### 207 3. Methods

#### 208 3.1 *Field measurements-data and structural analyses*

209 Structural analyses of the surface of the San Andrés Fault plane incorporated structural geological field  
210 measurements alongside the interrogation of a high resolution digital terrain model (DTM). This DTM was  
211 constructed on the basis of photogrammetric imagery obtained from an unmanned aerial vehicle (UAV) which  
212 was then and processed using the commercial software Agisoft PhotoScan (Agisoft LLC, 2014). The accuracy of  
213 terrain models constructed following this approach is directly comparable to those constructed on the basis of  
214 laser scanning (Balek and Blahůt, 2017). From the photogrammetric point cloud, it was possible to derive two  
215 complimentary slope gradient maps with grid cells of  $2 \times 2 \text{ cm}$ . The first gives a ground plan view of the fault  
216 (Figure 3A) while the second gives a fault perpendicular view (Figure 3B). These maps have been analysed in  
217 detail using the ESRI® ArcGIS applications ArcMap and ArcScene. Slope gradient maps, in contrast to hillshade  
218 maps, are particularly suited for the identification of linear features irrespective of their spatial distribution and

219 orientations. The obtained data were then compared to the structural geological field measurements recorded  
220 on the outcrop.

221

222 Schmidt hammer sampling ~~can be~~ used [in geomorphological research](#) to estimate rates of weathering ~~or and~~  
223 to obtain information relating to relative exposure ages for rock surfaces on the basis of rebound values, R

224 (Aydin and Basu, 2005; Goudie, 2006). ~~In a total of eighty-eight~~ [eighty-eight](#) test sites were sampled [on the fault](#)  
225 [plane](#) using a Proceq SilverSchmidt ST-PC. Each site was sampled twelve times in a direction perpendicular to  
226 [the fault's](#) surface. Of these twelve samples, the uppermost and lowermost values were disregarded,  
227 [according to](#) standard [sampling](#) protocol, and the remaining ten were used to calculate the rebound value.

228 These R values were processed in a GIS. Initially, an orthophotograph of the fault scarp had to be created from  
229 a set of photoshots. The position of each test site was recorded on a printed copy of the orthophotograph prior  
230 to image rectification in the GIS. The relative positions of several test sites were measured in the field and used  
231 as reference points during georeferencing. Each test site is represented by a point placed approximately in its  
232 centre and then the calculated R value was added to each test site. Interpolation of these values indicates  
233 changes in the relative surface hardness across the exposed part of the fault scarp. Several interpolation  
234 algorithms were tested but the character of the data led us to select the natural neighbour technique.

235

### 236 3.2 *Petrographic and microstructural analyses*

237 Petrographic analyses of the sampled rocks were performed at the Institute of Rock Structure [& and](#) Mechanics  
238 CAS and the Institute of Geology CAS in Prague. Optical microscopy was conducted using the polarisation

239 microscope Leica DMR while chemical analysis of the primary and accessory minerals was conducted [using](#)  
240 the electron microprobe CAMECA SX-100. Microstructural investigations have been made through the

241 application of optical microscopy, scanning electron microscopy ([SEM](#)), and energy dispersive spectroscopy  
242 ([EDS](#)). [These](#) investigations were made at the University of Vienna. Thin sections were cut perpendicular to the  
243 shear plane and parallel to the direction of sliding prior to mechanical polishing to thicknesses [of](#) c. 30 µm.

244 ~~Selected samples were carbon coated for SEM.~~ Optical microscopy was conducted using the polarisation  
245 microscope Leica DM4500 P with micrographs obtained under both plane polarised light (PPL) and crossed

246 polarised light (XPL). ~~Selected samples were carbon coated for SEM.~~ [The SEM imaging Scanning electron](#)  
247 [microscopy](#) was conducted using ~~a the SEM microscope~~ FEI Inspect S with an accelerating voltage of 10-15 kV

248 for spot sizes of 5-7. Images were obtained [and presented](#) in the back scattered mode ([BSE](#)). Element energy  
249 dispersive spectroscopy was [also](#) conducted to better understand the chemical effects of fault slip. The EDAX  
250 EDS systems were used as an add-on to the [FEI Inspect S-SEM](#). Using the TEAM™ Software Suite and Smart  
251 Phase Mapping it was possible to collect spectra and generate phase maps showing elemental distribution and  
252 associated spectra. The EDS operating conditions were 15 kV accelerating voltage for spot size of 5, at  
253 resolution of 514 x 514, dwell 200 μs.

254

### 255 3.3 *Cosmogenic radionuclide dating*

256 Cosmogenic radionuclide dating constrains the amount of time a rock has been situated at or near the surface  
257 of the Earth (e.g. Lal, 1991). Normal fault planes represent ideal objects for this dating technique as the  
258 incoming cosmic rays are only able to penetrate the progressively exposed parts of the fault (e.g. Palumbo et  
259 al., 2004). The basaltic lithologies of El Hierro determine that the most suitable cosmogenic nuclide with which  
260 to constrain periods of fault activity is <sup>3</sup>He (e.g. Kurz, 1986; Poujol et al., 2014). The sampling strategy aimed,  
261 first, to obtain samples from the least eroded parts of the fault and, second, to avoid obtaining samples from  
262 the whitish part of the fault plane as this was [known to have been](#) exposed during road construction. Five  
263 samples were collected from two profiles along the footwall (Figure 2). These samples range in thickness from  
264 two to five centimetres and belong to the same basaltic sequence [which that](#) erupted 1.05±0.02 Ma (Carracedo  
265 et al., 2001). Samples were crushed and sieved to isolate fractions of [less than 0.25 mm, 0.25-0.5 mm, and 0.5-](#)  
266 [2.0 mm. 0.2 mm to 2 mm and 0.25 mm to 0.5 mm](#). Several physical separation techniques including magnetic  
267 separation and density separation were used to isolate pure olivine and pyroxene phenocrysts.

268

269 All helium analyses were performed in the noble gas platform of the Centre de Recherches Pétrographiques et  
270 Géochimiques in Nancy. Samples were fused *in vacuo* at 1600°C for 15 minutes using the new custom designed  
271 metal induction furnace of CRPG (Zimmermann et al., 2018). Typical furnace blanks were  $(1.9 \pm 0.6) \times 10^{-19}$  and  
272  $(5 \pm 4) \times 10^{-15}$  mol.g<sup>-1</sup> for <sup>3</sup>He and <sup>4</sup>He, respectively, [which -This](#) represented an average of 1% and 0.1% of the  
273 <sup>3</sup>He and <sup>4</sup>He concentrations measured in the samples, respectively. [n the](#) extracted gas [then](#) underwent  
274 standard gas purification (Blard et al., 2015). Helium was cryofocused at 8K before being released at 70K and  
275 introduced into the Split Flight Tube mass spectrometer, a Nier source static mass spectrometer optimised for  
276 the analysis of cosmogenic nuclides (Protin et al., 2016). The linearity of the mass spectrometer was carefully

277 established by analysing standard splits with similar  $^4\text{He}$  pressure to those of the samples. During the ~~one~~  
 278 ~~month~~ ~~one-month~~ analytical period the observed reproducibility of the system was 2 % at  $1\sigma$ , ~~both~~ for ~~both~~  $^3\text{He}$   
 279 and  $^4\text{He}$ . Furthermore, during this ~~one-month~~ ~~one-month~~ period, two CRONUS-P pyroxene standards were  
 280 analysed. These yielded  $^3\text{He}$  concentrations of  $(4.86 \pm 0.14) \times 10^9 \text{ at.g}^{-1}$  and  $(5.01 \pm 0.14) \times 10^9 \text{ at.g}^{-1}$ . Both values  
 281 stand within the internationally recognised error limits for this material (Blard et al., 2015). To determine the  
 282  $^3\text{He}/^4\text{He}$  ratio of the magmatic component step crushing *in vacuo* was conducted on 0.5 mm to 2 mm olivines  
 283 and pyroxenes obtained from Sample 5III (1<sup>st</sup> step: 100 strokes, 1 min; 2<sup>nd</sup> step: 500 strokes, 5 mins) (Table 1).  
 284 Crushing blanks were  $(3 \pm 2) \times 10^4$  and  $(7 \pm 2) \times 10^9$  for  $^3\text{He}$  and  $^4\text{He}$ , respectively. This represented 1 % and 4 % of  
 285 the  $^3\text{He}$  and  $^4\text{He}$  analysed during the second crushing step.

286  
 287 To determine cosmogenic  $^3\text{He}$  concentrations it was necessary to correct the melted  $^3\text{He}$  concentrations  
 288 ( $^3\text{He}_{\text{melt}}$ ) from the nucleogenic ( $^3\text{He}_{\text{nucleo}}$ ) and the magmatic ( $^3\text{He}_{\text{mag}}$ ) components:

289  
 290 
$$^3\text{He}_{\text{cos}} = ^3\text{He}_{\text{melt}} - ^3\text{He}_{\text{nucleo}} - ^3\text{He}_{\text{mag}}$$

291  
 292 With:

293  
 294 
$$^3\text{He}_{\text{nucleo}} = P_{3\text{nuc}} \times T_{\text{eruption}},$$

295  
 296  $P_{3\text{nuc}}$  is the production rate of nucleogenic  $^3\text{He}$ . In this study, a value of  $6 \times 10^{-3} \text{ at.g}^{-1} \cdot \text{a}^{-1}$  has been used,  
 297 computed using the equations of Andrews (1985) and the chemical composition measured in the phenocrysts  
 298 and bulk rock samples (Supp. Table A). Combined with a value of  $1.05 \pm 0.02 \text{ Ma}$  for  $T_{\text{eruption}}$  (based on the K-Ar  
 299 age of the San Andrés basalt presented in Carracedo et al. (2001)), this yielded a value of  $(6 \pm 3) \times 10^3 \text{ at.g}^{-1}$  for  
 300  $^3\text{He}_{\text{nucleo}}$ .

301  
 302 In theory, the magmatic  $^3\text{He}$  component has to be computed following this equation from Blard and Farley  
 303 (2008):

304  
 305 
$$^3\text{He}_{\text{mag}} = (^4\text{He}_{\text{melt}} - ^4\text{He}_{\text{rad}}) \times (^3\text{He}/^4\text{He})_{\text{crush}}$$

306

307 With

308

309  ${}^4\text{He}_{\text{rad}} = P_{4\text{rad}} \times T_{\text{eruption}},$

310

311  $P_{4\text{rad}}$  being the radiogenic  ${}^4\text{He}$  production rate in the analysed olivines and pyroxenes.  $P_{4\text{rad}}$  is computed using  
312 the equations of Blard and Farley (2008) and the U, Th, and Sm concentrations measured in samples COS4-I and  
313 COS5-II (Supp. Table A). Using the  $1.05 \pm 0.02$  Ma value for  $T_{\text{eruption}}$ , this yields  ${}^4\text{He}_{\text{rad}}$  theoretical concentrations  
314 ranging from  $1.2 \times 10^{12}$  at.g $^{-1}$  to  $4.1 \times 10^{12}$  at.g $^{-1}$ .

315

316 Such  ${}^4\text{He}_{\text{radio}}$  concentrations are similar to the total  ${}^4\text{He}$  concentrations measured by fusing the samples, which  
317 range from  $6.2 \times 10^{12}$  at.g $^{-1}$  to  $1.36 \times 10^{13}$  at.g $^{-1}$ , for an average of  $(3.3 \pm 4.6) \times 10^{12}$  at.g $^{-1}$ .

318

319 Thus the outlined approach for estimating  ${}^4\text{He}_{\text{rad}}$  represents the main source of uncertainty when computing  
320 the magmatic  ${}^3\text{He}$  correction and, in turn, the main source of uncertainty when computing the final cosmogenic  
321  ${}^3\text{He}$  concentrations.

322

323 Instead, we decided to apply the following approach and compute a minimal and a maximal value for the  
324 cosmogenic  ${}^3\text{He}$  concentrations, as follow (Table 1):

325

326  ${}^3\text{He}_{\text{cos min}} = {}^3\text{He}_{\text{cos min}} - {}^3\text{He}_{\text{nucleo}} - {}^3\text{He}_{\text{crush mag}},$

327

328 assuming that  ${}^3\text{He}_{\text{crush mag}}$  is the magmatic  ${}^3\text{He}$  concentration from the prolonged crushing  $(4.3 \pm 2.0) \times 10^6$  at.g $^{-1}$

329

330  ${}^3\text{He}_{\text{cos max}} = {}^3\text{He}_{\text{cos min}} - {}^3\text{He}_{\text{nucleo}}$

331

332  ${}^3\text{He}_{\text{cos min}}$  concentrations range from less than  $2 \times 10^6$  at.g $^{-1}$  to  $(1.19 \pm 0.20) \times 10^7$  at.g $^{-1}$  while  ${}^3\text{He}_{\text{cos max}}$  range from  
333  $(2.22 \pm 2.04) \times 10^6$  at.g $^{-1}$  to  $(2.17 \pm 0.21) \times 10^7$  at.g $^{-1}$ .

334



335 Finally,  $^3\text{He}_{\text{cos}}$  exposure ages were computed using the CREP calculator (crep.crpq.cnrs-nancy.fr), with the world  
336 averaged  $^3\text{He}$  production rate, the standard atmosphere, and the Lal-Stone time dependent model (Martin et  
337 al., 2017). The production rate was computed taking into account the spatial characteristic of the samples,  
338 including self-shielding (Table 1).

339

#### 340 4. Results

##### 341 4.1 *Field ~~measurements-data~~ and structural analyses*

342 The NE section of the San Andrés Fault outcrop is morphologically well preserved while its SW section has been  
343 smoothed as a result of weathering and ~~incurred~~~~received~~ some damage during road construction. In general,  
344 the exposed fault plane is straight with an orientation of approximately 170/70° (dip direction/dip angle). Only  
345 some irregularities can be observed such as two remarkable fault plane undulations protruding from ~~the~~  
346 ~~fault~~~~its~~ surface, with widths of up 4 m, separated by a parallel depression (Figure 3A-B). These irregularities  
347 were also ~~recognised~~~~identified~~ during structural geological measurements. In greater detail, it has been  
348 possible to identify numerous linear features, which have been grouped into three families on the basis of their  
349 character and orientation (Figure 3A-C). First, a family of centimetre to metre scale striations were identified on  
350 the basis of structural measurements and from the slope gradient maps. These striations cover most of the  
351 outcrop but are best preserved on the fault plane undulations. Most commonly, the striations ~~have~~ plunge ~~with~~  
352 ~~directions of~~~~azimuths of~~ 125° and 131°. Second, a family of smooth elongated undulations and strongly  
353 elongated ~~protrusions~~~~bumps~~ were also identified on the basis of structural measurements and from the slope  
354 gradient maps. These ~~features~~ are best seen in the ~~depressions and flats in the~~ northeastern section of the  
355 fault plane. The undulations and ~~bumps~~~~protrusions~~ ~~have a~~ plunge ~~direction of~~~~with an~~ ~~azimuth of~~ 111°. Third, a  
356 family of very smooth, spatially limited, slightly elongated ~~bumps~~~~protrusions~~ were identified from the fault  
357 perpendicular slope gradient map. These are found in the lower SW and upper NE part of the 4 m wide fault  
358 plane undulation as well as at the crest of the other undulation protruding from surface to the NE. The ~~bumps~~  
359 ~~protrusions~~~~have a~~ plunge ~~with~~~~direction of an~~ ~~azimuth of~~ 158°.

360

361 A ~~photomosaic offering a~~ perpendicular view of the fault outcrop ~~in the background photomosaic~~ overlain by a  
362 raster of interpolated R values is presented on Figure 4. Proportional plots ~~have been used to~~ illustrate the  
363 spatial variability in rock hardness across the outcrop. In general, higher R values have been measured on the

364 lower and right side of the fault outcrop than have been measured on its upper and left side. However, notably  
365 low R values have been recorded in a wedge-shaped zone between 23 m and 26 m ( $R < 25$ ), in an area where a  
366 rather soft gouge material is attached to the fault surface. However, as the vegetation cover descends much  
367 lower here than elsewhere, it is suggested that chemical and biological weathering processes are more intense  
368 hereabouts. The highest R values, indicating the least weathering, have been recorded in the lowermost part of  
369 the fault outcrop on its right side ( $R > 50$ ). This finding is not surprising given that the hard whitish surface was  
370 exposed only recently during ~~road~~ construction of the road. ~~In addition, high~~ High R values have also been  
371 recorded on the far left side of the fault outcrop ( $R > 40$ ). This finding is more surprising but it can be explained  
372 by several tens of centimetres of erosion on the fault surface and the presence of harder basalt blocks within  
373 the tectonic breccia. Conspicuously low R values have been recorded in a wedge-shaped zone between 23 m  
374 and 26 m ( $R < 25$ ). Here a rather soft gouge material is attached to the fault surface and the vegetation cover  
375 descends much lower than elsewhere – this suggests that chemical and biological weathering processes are  
376 more intense in this area.

377

#### 378 4.2 Petrographic analyses

379 The host rock basanites are ~~composed of~~ fine grained basic ~~volcanic~~ rocks (samples PET3 and PET4). These  
380 ~~rocks contain~~ are mainly pyroxene, plagioclase, olivine, ~~and~~ amphibole and volcanic glass, together with the  
381 accessory minerals (apatite, chromite, magnetite, and Ti-magnetite). The pyroxene is represented by mainly  
382 comprises the monoclinic mineral diopside. Te while the plagioclases are usually tends to be zoned ~~at~~ with an  
383 basic core ( $An_{79-83}$  acid rim) and acid rim ( $An_{45-70}$ ), and a basic core,  $An_{79-83}$ . Olivine occurs only in basanites with  
384 subordinate amounts of volcanic glass. The olivine is enriched by has a predominant forsterite component; (75-  
385 80 mol. %), ~~while~~ the amphibole is represented by spans from magnesiohornblende to hornblende  
386 tschermakite. ~~A high amount of volcanic glass is present while basanites with subordinate amounts of volcanic~~  
387 glass contain frequent phenocrysts of olivine. The texture of the groundmass is mostly ophitic and gives no  
388 indication of a pre-existing preferred fabric orientation. The tectonic breccias sampled from the fault plane are  
389 composed ~~by of~~ fragments of volcanic rock (up to several centimetres), ~~cemented by~~ a very fine grained  
390 groundmass containing abundant fragments of the original volcanic rock (millimetres to centimetres on  
391 samples) (PET1 and PET2). The higher proportion of fine grained Fe-oxides and Fe-hydroxides imparts a rusty  
392 colour of these tectonic breccias to the rock. However, the volume of Fe-oxides and Fe-hydroxides is highly

393 variable, with significant enrichment in the fine grained groundmass of the original volcanic rock. The tectonic  
394 breccias ~~host cracks of highly variable orientation and sizes, filled, are cross-cut filled~~ by zeolite veins ~~that~~  
395 ~~exhibits~~ in a range of orientations and sizes. Frictionite, or landslide pseudotachylite, was found in samples  
396 obtained directly from the fault plane (Figure 2). ~~This~~ is composed of relict frictional melt and material similar  
397 to tectonic breccia (Figures 5-7).

398

#### 399 4.3 Microstructural analyses

400 The NE part of the fault outcrop is covered by a whitish layer which attains a maximum thickness in the order  
401 of several centimetres. ~~Figure 2 shows examples of the~~ This whitish layer ~~that usually~~ overlies the greyish  
402 cataclasite and microbreccias. ~~and in some cases but it sometimes~~ this whitish layer comes into ~~direct~~ contact  
403 with tectonic breccia. ~~The tectonic breccia is highly oxidised (Figure 2D, F). Brecciation intensity increases from~~  
404 ~~the undeformed basanite to the more deformed breccia, i.e. towards the fault surface. This~~ This ~~The~~ tectonic  
405 breccia ~~marks the transition from undeformed basanite, at greater depths, to more deformed breccia, at the~~  
406 ~~fault surface. The breccia, and is highly oxidised (Figure 2D, F). It has not been analysed further but and it~~ may  
407 be ~~a~~ the product of an earlier slip event. ~~However, in this study, here we focus on the cataclasite and the~~  
408 ~~whitish layer, i.e. Instead attention focuses here on the those~~ layers that overlie the tectonic breccia. ~~On the~~  
409 ~~basis of~~ Using optical microscopy it is possible to differentiate two distinct layers within the frictionite by their  
410 composition and microstructure: a structurally lower cataclasite and a structurally higher silica layer.

411

412 The cataclasite cuts the tectonic breccia while in places it is cut by the silica layer. Contact with the host rock is  
413 characterised by a sharp boundary that is observed in both hand samples and optical micrographs (Figure 6).

414 Although the cataclasite is grey in hand samples, it is dark brown in optical micrographs (Figure 6A, BA, B) while  
415 the sharpness of the contact is accentuated by the truncation of several clasts (Figures 6 & 7). The main  
416 characteristics of this layer are grain size reduction and P- foliation, ~~(according to~~ terminology ~~of~~ Passchier  
417 and Trouw, (2005)). The zones of grain size reduction, in which grain sizes range from c. 10 µm to c. 100 µm,  
418 are defined by P- and Y- shears (Figure 6B, DB, D). A dextral sense of shear is indicated by the P- and Y- shears  
419 along with a winged inclusion visible in the optical micrographs (Figure 6A, BA, B). This finding is consistent with  
420 structural observations made at the outcrop scale. Elemental maps highlight the similarity between the  
421 composition of the host rock and the composition of the cataclasite (Figure 6E, FE, F). Moreover, this similarity

422 is accentuated by the apparent resemblance in composition of a truncated clast, itself in contact with the  
423 cataclasite (Figure 6E,F,E). A second cataclasite has a more lensoid shape which is apparently defined by P-  
424 and Y- shears (Figure 7). It exhibits strong P-foliation which is seen most readily in the elemental maps (Figure  
425 7C,EC,E). Interestingly, In addition, cracks ~~are~~within this layer are parallel to both the Y-shear~~ing~~, and to the  
426 slip surface, and are filled with silica ~~gel~~(Figure 7E).

427  
428 The silica layer cuts both the tectonic breccia and the cataclastic layer. The boundary between the silica layer  
429 and the subjacent rocks is a sharp, single line, which crosscuts foliation in the cataclasite and truncates clasts in  
430 the tectonic breccia. The boundary between the cataclasite layer and the silica layer is sometimes marked by  
431 shiny sublayers that parallel the boundary (Figure 6B,HB,H) and exhibit a high interference colour when seen  
432 under cross polarised light with a gypsum tint plate (Figure 5C). There is no indication of mixing between the  
433 cataclasite and the silica layer across the boundary ~~between~~separating these layers. The silica layer appears to  
434 be translucent, white to pale coloured under plane polarised light (Figures 5-7). It is composed of a  
435 microcrystalline to amorphous silica matrix with a thickness of c. 250 µm to 350 µm. The architecture varies:  
436 the matrix consists of an inclusionless silica material that develops into complex structures with flow bands  
437 (Figures 5-7), cataclastic sublayers (Figure 5H), and clast-cortex aggregates (Figure 6G,G,I). Flow bands, which  
438 vary in thickness from c. 25 µm to c. 110 µm, correspond to P- and Y- shears in the cataclastic layer fabric and  
439 are characterised by a change in the amount of Mg (Figure 5L and Figure 6C,DC,D). Cataclasite sublayers form  
440 lenticular shapes (Figure 5H). These sublayers appear to have a similar composition to the cataclasite layer but  
441 with a finer grain size and present evidence of material mixing with the silica layer. Some clasts embedded in  
442 the silica layer have a cortex, or armour, and these are referred to as clast-cortex aggregates. The clast-cortex  
443 aggregates vary in size, from c. 90 µm to 290 µm, complexity, and composition. Those clasts within the  
444 aggregates consist of fragments of adjacent rock (Figure 7G) or silica matrix (Figure 6I). A complex cortex  
445 texture with what appears to be several coatings has been observed (Figure 6G). Elemental maps show that the  
446 cortex composition varies as well (e.g. Figure 6L and Figure 7D,FD,E). It is believed that a significant amount of  
447 the cortex material was lost during preparation of the thin sections (e.g. Figure 6G-I).

448

449 4.4 *Cosmogenic radionuclide dating*

450 Cosmogenic <sup>3</sup>He exposure ages reveal significant differences between each of the two sampled profiles. Sample  
451 COS1 has yielded a maximum exposure age of 21±20 ka while samples COS2 and COS3 have yielded a  
452 maximum exposure age of 26±18 ka. Replicates of sample COS4 yielded exposure ages ranging from 21±19 to  
453 61±19 ka while replicates of sample COS5 yielded exposure ages ranging from 52±17 to 183±17 ka (Table 1).

454 ~~The older exposure ages obtained from the left hand profile may simply reflect more recent exhumation or~~  
455 ~~more intensive erosion on the right hand part of the fault. These results indicate that movement across the~~  
456 ~~currently exposed portion of the fault plane occurred over a short period of time as suggested by the fact that~~  
457 ~~there is no gradual decrease in exposure ages from upper to lower part of the two profiles.~~

459 ~~The right hand profile (samples COS1-3) revealed exposures ages that are below the detection limit i.e. these~~  
460 ~~were exposed between 0 and 26 ka. These young exposure ages most probably reflect recent exhumation on~~  
461 ~~the right hand part of the fault owing to the fact that the right hand profile is separated from the left hand~~  
462 ~~profile by only 6-7 m. Intense erosion of the right hand profile can be excluded as the R values indicate much~~  
463 ~~greater hardness, i.e. less weathering, here than on the left hand profile.~~

464  
465 ~~The left hand profile (samples COS4 and COS5) revealed exposure ages between 21 and 183 ka. The higher~~  
466 ~~sample COS4 provides a younger age than the lower sample COS5. Under normal circumstances this should not~~  
467 ~~be possible – the highest parts of the fault should be exposed before its lower parts – and it suggests that the~~  
468 ~~higher sample has been subjected to weathering. Consequently sample COS5 offers the most reliable results as~~  
469 ~~it has neither been affected by weathering nor by recent exhumation. The high variability of computed~~  
470 ~~exposure ages between the replicate in this sample is~~ due to the considerable uncertainty associated with the  
471 estimate of the magmatic <sup>3</sup>He component as outlined in Section 3.3. ~~Nonetheless it is believed that the most~~  
472 ~~recent fault reactivation occurred between the calculated exposure ages of sample COS5 (52±17 to 183±17 ka).~~

473

## 474 5. Interpretation and discussion

### 475 5.1 *Landslide displacement direction*

476 Distinct families of linear and elongated features ~~on-at~~ the fault plane evidence past behaviour of the rock mass  
477 (Sagy et al., 2007). ~~Two major slip events are interpreted to have occurred on the studied fault plane On-on~~ the  
478 basis of the relative position and general morphology of ~~such its linear and elongated features, two major slip~~

479 ~~events are interpreted to have occurred on the studied fault plane.~~ The older phase is represented by the  
480 family of smooth elongated undulations and strongly elongated bumps, best preserved in the depressions and  
481 flats in the northeastern section of the fault plane, which have a plunge direction of 111°. During this phase the  
482 rock mass moved towards the ESE. The younger phase is represented by the other two families of linear and  
483 elongated features. The onset of this phase is interpreted to have commenced with minor, most probably slow,  
484 displacement towards the SSE. Support for this ~~slow displacement~~ is gleaned from the smooth, spatially  
485 limited, elongated bumps which have a plunge direction of 158°. The ~~displacement rate of displacement~~ is then  
486 interpreted to have accelerated as the rock mass moved more towards the SE. Support for this is gleaned from  
487 the centimetre to metre scale striations which cover most of the fault outcrop and have plunge directions of  
488 125° and 131°. The general appearance of these ~~linear and elongated~~ features is sufficiently similar to assume  
489 that they developed during a single slip phase. It is supposed that ~~the this~~ shift in the displacement direction,  
490 from the SSE to the SE, can be explained by either a sudden change in the geometry of the slip surface or a  
491 fundamental change in the morphology of the entire volcanic edifice. It is known that El Hierro underwent a  
492 clockwise rotation of 15°, beginning ~~at~~ around 440 ka (Szérméta et al., 1999), and it has been suggested that  
493 this rotation could ~~be associated with relate to~~ activity on the San Andrés Landslide and the debris avalanche  
494 Las Playas I (Carracedo, 2008).

495

## 496 5.2 *Fault related microstructures and dynamic rock reworking*

497 ~~It is contended that t~~The microstructures seen ~~at on~~ the surface of the San Andrés Fault ~~are believed to be a~~  
498 result ~~of fast slip, associated with from~~ frictional heating and ~~partial~~ melting during landslide emplacement,  
499 ~~and, therefore, this rock is a frictionite (or landslide pseudotachylite).~~The first line of evidence ~~for flash~~  
500 ~~heating during flank collapse is observed in comes from~~ both hand samples and polished slabs as ~~energy is seen~~  
501 ~~to have heat~~ diffused in the underlying material. ~~The~~ adjacent host rock and tectonic breccia ~~exhibits~~  
502 ~~increasing level of are only~~ oxidation ~~when in immediate contact with the frictionite towards the fault~~  
503 ~~surface~~. This is similar for pseudotachylites reported from the Köfels landslide (Masch et al., 1985) and from  
504 the Arequipa volcanic landslide deposit ~~in Peru~~ (Legros et al., 2000). The second line of evidence comes from  
505 the crosscutting relationships between either the host rock or the tectonic breccia and the deformation layers.  
506 All of the ~~observed~~ contacts are sharp and accentuated by multiple truncated clasts. This type of crosscutting  
507 relationship indicates fast displacement and is often considered a strong indication of a seismic slip (Passchier

508 and Trouw, 2005; Price et al., 2012; Smeraglia et al., 2017). The third line of evidence comes from the boundary  
509 between the silica layer and the adjacent rocks. ~~This boundary is characterised by, which has~~ shiny bands ~~that,~~  
510 exhibiting a high interference colour under cross polarised light and a positive optical sign under cross polarised  
511 light using a gypsum tint plate. These bands are tentatively interpreted as recrystallised material resulting from  
512 frictional melting but further analyses are needed ~~in order~~ to confirm this supposition.

513  
514 The cataclastic layer exhibits P-foliation, grain size reduction, and the development of winged clasts in a  
515 heterogeneous matrix. The winged clast presented in Figure 5 resembles those of Grasemann & Dabrowski  
516 (2015) and Grasemann et al. (2019). The foliation developed within this layer is typical of brittle deformation,  
517 with ~~horizontal~~ Y-shears, parallel to the slip surface, and ~~inclined~~ P-shears inclined relative to the slip surface  
518 (i.e. Figure 5). This type of foliation cannot be used as an indicator for fast slip as it is recorded in association  
519 with both seismic and creep phenomena (Verberne et al., 2013; Smeraglia et al., 2017). However, unequivocal  
520 evidence for fast slip, ~~instead of rather than~~ progressive creep, is provided by the fact that the contact between  
521 the cataclastic layer and the adjacent rock is sharp and accentuated by multiple truncated clasts. The  
522 cataclastic architecture is similar to those described in other volcanic pseudotachylites (Lavallée et al., 2012,  
523 2014; Kendrick et al., 2012, 2014) as well as to that described ~~for in~~ seismically deformed limestones (Smith et  
524 al., 2011). Therefore, it is necessary to define this cataclastic layer as frictionite *sensu lato*, as it was ~~probably~~  
525 almost certainly emplaced during catastrophic landslide emplacement but there is no decisive proof of flash  
526 heating.

527  
528 In contrast, the silica layer is defined as frictionite *sensu stricto*, ~~due to the fact that as~~ it is comparable to  
529 traditional pseudotachylites (e.g. Passchier and Trouw, 2005; Price et al., 2012; Rowe and Griffith, 2015).  
530 ~~Identification criteria of deformed pseudotachylites are presented elsewhere (e.g., Passchier and Trouw,~~  
531 2005; Price et al., 2012). ~~For example, Nonetheless the following the identification criteria of deformed~~  
532 pseudotachylites (Passchier and Trouw, 2005; Price et al., 2012) we list features Here a list of particularly  
533 pertinent features is presented with reference to the identification criteria for deformed pseudotachylites  
534 (Passchier and Trouw, 2005; Price et al., 2012) in the context of this study;

535

536 | ~~i. *(i) crosscutting*~~ *Crosscutting relationships with sharp layer boundaries.* The silica layer cuts the  
537 | cataclasite foliation and the boundaries are accentuated by clast truncation and presence of shiny  
538 | bands which have been interpreted as recrystallised material from frictional melting. Analogous  
539 | microstructural features have been reported from numerous natural and experimental cases of  
540 | seismic slip (e.g. Fondriest et al., 2013; Smeraglia et al., 2017; Tesei et al., 2017).

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541 |  
542 | ~~ii. *Second, the*~~ *The presence of fragments of host rock.* Fragments of adjacent rock appear as isolated  
543 | islands and vary in size, shape, and complexity. The more complex clasts have an encasing cortex,  
544 | or armour, ~~and are~~ referred to as clast-cortex aggregates. Typically, those ~~fragments~~ described  
545 | here have a volcanic clast in the core, cataclastic material in the rim, and they parallel the  
546 | foliation. In a number of senses, they are similar to “armoured clasts” or “accretionary rounded  
547 | grains” (Anders et al., 2010; Rowe et al., 2012; Kirkpatrick et al., 2013) and clay-clast aggregates  
548 | (Boutareaud et al., 2008; Han et al., 2011). The main differences are the ratio between the clast  
549 | and the rim and their composition. The rims described here appear to be wider than previously  
550 | reported while they are neither composed of clay nor any other mineral assemblage.  
551 | Consequently, the clast-cortex aggregates ~~presented~~ *described here in this study* are most readily  
552 | comparable to the accretionary rounded grains described from the Corona Heights Fault  
553 | (Kirkpatrick et al., 2013).

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554 |  
555 | ~~iii. *Third, the*~~ *The presence of an ultra-fine grained matrix.* The silica layer comprises a homogenous  
556 | silica matrix, ultra-fine grained to amorphous, which is very similar to silica gel (Kirkpatrick et al.,  
557 | 2013; Faber et al., 2014) and amorphous nanopowder (Rowe et al., 2019). More detailed studies  
558 | are needed in order to measure the amount of water and crystalline material that occurs in this  
559 | matrix. The presence of new grains that have grown in the voids or bubbles ~~suggests~~ *indicates*  
560 | that at least some of this matrix must be crystalline.

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561 |  
562 | ~~iv. *Fourth, i*~~ *nherited compositional variations from flow structures.* Flow bands in the silica layer are  
563 | defined by optical and compositional variations. Optical variations are evident as shiny bands and  
564 | they can be traced along the whole length of the layer. ~~More detailed analyses are needed to fully~~

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565 | ~~understand their origin.~~ The flow bands are structurally controlled, as they parallel the P- and Y-  
566 | shears, and they localise clasts and clast-cortex aggregates as well as Mg-enriched material.  
567 | ~~Further analyses are needed to fully understand their origin.~~ Similar to these flow bands are the  
568 | cataclastic sublayers, which are also structurally controlled, but with evidence for the reworking  
569 | of cataclastic material. This feature, together with presence of clast-cortex aggregates ~~is, can be~~  
570 | interpreted as fluidised granular flow ~~which has been~~ reported in many geologic settings  
571 | (Boutareaud et al., 2008; Anders et al., 2010; Ujiie et al., 2011; Kirkpatrick et al., 2013).  
572 | Furthermore, fluidised cataclasites have been suggested as a record of seismic slip rates (Brodsky  
573 | et al., 2009; Rowe et al., 2005).

574 |  
575 | ~~±v.~~ ~~Fifth, differences~~ Differences between the matrix and host rock mineral assemblages. The most  
576 | conspicuous difference between the silica layer and the adjacent rocks is in the mineral  
577 | assemblage. The homogenous silica layer contrasts greatly with the polymineralic cataclasite and  
578 | the host rock. Even though the silica layer can be assumed to be a product of hydrothermal fluid  
579 | deposition, the presence of kinematic indicators such as shears and flow bands consistent with  
580 | observations at the outcrop scale, indicate that the silica layer was formed as a product of  
581 | frictional slip. Silica has been reproduced in fast slip experiments (e.g. Di Toro et al., 2011;  
582 | Kirkpatrick et al., 2013; Rowe et al., 2019) ~~and~~ ~~it is~~ considered to be a product of frictional wear  
583 | ~~that~~ ~~which~~ weakens the fault, ~~due to the fact that it~~ actings as a lubricant (Rowe et al., 2019).  
584 |

### 585 | 5.3 ~~Developmental~~ Conceptual model for the San Andrés Landslide

586 | A ~~conceptual~~ ~~developmental~~ model for the development of the San Andrés Landslide is proposed here on the  
587 | basis of the findings presented in this study and age estimates presented elsewhere in the published literature  
588 | (Figure 8). The first slip event as evidenced by the cataclastic layer is proposed to have occurred between 545  
589 | ka and 430 ka. The lower limit for fault activity is defined by the onset of volcanism associated with the El Golfo  
590 | Series (Guillou et al., 1996) while the upper limit for fault activity is defined by the onset of the clockwise  
591 | rotation of El Hierro (Szérméta et al., ~~1997~~ 1999). The second slip event as evidenced by the silica layer is  
592 | proposed to have occurred between  $183 \pm 17$  and  $52 \pm 17$  ka based on the presented cosmogenic  $^3\text{He}$  exposure  
593 | dates. This age range spans termination of volcanism associated with the El Golfo-Las Playas Unit and the onset

594 of volcanism associated with the Rift Series at 145 ka (Guillou et al., 1996). The lower limit for fault activity  
595 broadly relates to the probable timing of the debris avalanches El Golfo A, between 176 ka and 133 ka, and Las  
596 Playas II, between 176 ka and 145 ka. Moreover, the upper limit for fault activity broadly relates to the  
597 probable timing of the debris avalanche El Golfo B, between 87 ka and 39 ka. ~~One of these giant debris~~  
598 ~~avalanches, accompanied by strong ground shaking. Thus, it is believed that the factor, or factors, which~~  
599 ~~triggered one of these giant debris avalanches~~ may have triggered the second slip event described ~~in this~~  
600 ~~study here but no other data have yet been found to support this hypothesis.~~ In addition, ~~a conceptual~~ model  
601 is presented for the development of the surface of the San Andrés Fault (Figure 9). The developmental model  
602 outlined here is broadly consistent with the findings of Day et al. (1997). In that study, it was suggested that the  
603 minimum age of the San Andrés Fault should be between 250 ka and 150 ka and that the fault could ~~only~~ have  
604 been active only for a geologically short period of less than 400 ka. Their ~~findings assertions~~ are based on a  
605 younger undisturbed lava flow which covers the southern part of the fault.

606  
607

## 608 6. Conclusions

609 ~~In this study~~~~The the~~ fault plane of the San Andrés Landslide on El Hierro in the Canary Islands has been  
610 investigated ~~in this study~~ through a combination of geological and geomorphological measurements,  
611 petrological and mineralogical analyses, and cosmogenic <sup>3</sup>He exposure dating.

612 • ~~The steeply dipping~~ fault surface is composed of a striated frictionite, ~~with a thickness of up to 5 cm,~~  
613 which is in contact with a highly oxidised tectonic breccia, ~~with a thickness of up to 1.5 m.~~ The tectonic  
614 breccia transitions into the underlying undeformed basanite host rock. Microstructural analysis of the  
615 frictionite has revealed two distinct layers: a dark heterogeneous cataclastic layer and a translucent  
616 silica layer with a thickness of up to 1 cm.

617 • ~~The architecture of the samples and the observed~~ crosscutting relationships ~~between the layers and~~  
618 ~~adjacent host rock~~ suggest that the cataclastic layer and the silica layer represent two separate slip  
619 events associated with seismic rupture during landslide emplacement. ~~The older cataclastic layer cuts~~  
620 ~~the tectonic breccia and presents evidence for P-fabrics and grain size reduction. The younger silica~~  
621 ~~layer cuts the tectonic breccia and the cataclastic and preserves clast cortex aggregates, flow bands,~~  
622 ~~and reworked cataclastic material in an ultra-fine grained to amorphous matrix. Moreover, the notion~~

623 ~~of These~~ two distinct slip phases ~~is supported by are in accordance with the~~ kinematic markers ~~etched~~  
624 on the fault surface.

625 • ~~This Coupling this~~ information ~~– coupled~~ with the cosmogenic <sup>3</sup>He exposure ~~ages dating~~ and ~~current~~  
626 knowledge about the ~~geological history of the island – forms basis of a conceptual model for the~~  
627 development ~~of the fault surface, it has been possible to propose a development model for of~~ the San  
628 Andrés Landslide. The first slip event, ~~represented as evidenced~~ by the cataclastic layer, is ~~proposed~~  
629 ~~thought~~ to have occurred between 545 ka and 430 ka while the second slip event, ~~represented as~~  
630 ~~evidenced~~ by the silica layer, is ~~thought proposed~~ to have occurred between  $183 \pm 17$  and  $52 \pm 17$  ka,  
631 ~~based on the presented cosmogenic <sup>3</sup>He exposure dates.~~

632  
633 This is the first time that more than one slip event has ~~ever~~ been recognised ~~on a single fault plane resulting~~  
634 ~~from volcanic flank collapse on an oceanic island. It suggests that the possibility of reactivating supposedly~~  
635 ~~inactive fault structures may be far greater than hitherto assumed. This is a key finding, which may lead to re-~~  
636 ~~evaluation of the threats related to volcanic islands collapses. Furthermore, it is believed that this is the first~~  
637 ~~time a silica layer resulting from frictional melt has been described from a volcanic setting. from the fault plane~~  
638 ~~of the San Andrés Landslide. It is also believed to be the first time a silica layer resulting from frictional melt has~~  
639 ~~been described in a volcanic setting.~~

640  
641

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646 ~~manuscript.~~

647

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652

### 653 References

654 Agisoft LLC, 2014. Agisoft PhotoScan User Manual, Professional Edition, Version 1.1. Agisoft LLC, St. Petersburg,  
655 78 pp.

656 Agliardi, F., Crosta, G., Zanchi, A., 2001. Structural constraints on deep seated slope deformation kinematics.  
657 Engineering Geology 59, 83-102. [https://doi.org/10.1016/S0013-7952\(00\)00066-1](https://doi.org/10.1016/S0013-7952(00)00066-1)

658 Ancochea, E., Barrera, J., Bellido, F., Benito, R., Brändle, J., Cebriá, J., Coello, J., Cubas, C., De la Nuez, J., Gómez,  
659 J., 2004. Canarias y el vulcanismo neógeno peninsular. In: Vera, J. (Ed.), Geología de España. Sociedad  
660 Geológica de España-Instituto Geológico y Minero de España, Madrid, pp 635-682.

661 Anders, M., Fouke, B., Zerkle, A., Tavarnelli, E., Alvarez, W., Harlow, G., 2010. The role of calcining and basal  
662 fluidization in the long runout of carbonate slides: an example from the Heart Mountain Slide Block,  
663 Wyoming and Montana, U.S.A. The Journal of Geology 118, 577-599. <https://doi.org/10.1086/656383>

664 Andrews, J., 1985. The isotopic composition of radiogenic helium and its use to study groundwater movement  
665 in confined aquifers. Chemical Geology 49, 339-351. [https://doi.org/10.1016/0009-2541\(85\)90166-4](https://doi.org/10.1016/0009-2541(85)90166-4)

666 Aydin, A., Basu, A., 2005. The Schmidt hammer in rock material characterization. Engineering Geology 81, 1-14.  
667 <https://doi.org/10.1016/j.enggeo.2005.06.006>

668 Balek, J., Blahůt, J., 2017. A critical evaluation of the use of an inexpensive camera mounted on a recreational  
669 unmanned aerial vehicle as a tool for landslide research. Landslides 14, 1217-1224.  
670 <https://doi.org/10.1007/s10346-016-0782-7>

671 ~~Baroň, I., Kernstocková, M., Novotný, R., Buriánek, D., Hradecký, P., Havlíček, P., Melichar, R., 2011.~~  
672 ~~Palaeostress analysis of a giant Holocene rockslide near Boaco and Santa Lucia (Nicaragua, Central~~  
673 ~~America). In: Jaboyedoff, M. (Ed.), Slope Tectonics. Geological Society of London, Special Publication~~  
674 ~~351, 133-145. <https://doi.org/10.1144/SP351.7>~~

675 Becerril, L., Ubide, T., Sudo, M., Martí, J., Galindo, I., Galé, C., Morales, J., Yepes, J., Lago, M., 2016a.  
676 Geochronological constraints on the evolution of El Hierro (Canary Islands). *Journal of African Earth*  
677 *Sciences* 113, 88-94. <https://doi.org/10.1016/j.jafrearsci.2015.10.012>

678 Becerril, L., Galve, J., Morales, J., Romero, C., Sánchez, N., Martí, J., Galindo, I., 2016b. Volcanostructure of El  
679 Hierro (Canary Islands). *Journal of Maps* 12, Supplement 1, 43-52.  
680 <https://doi.org/10.1080/17445647.2016.1157767>

681 Benito-Saz, M., Parks, M., Sigmundsson, F., Hooper, A., García-Cañada, L., 2017. Repeated magmatic intrusions  
682 at El Hierro Island following the 2011-2012 submarine eruption. *Journal of Volcanology and Geothermal*  
683 *Research* 344, 79-91. <https://doi.org/10.1016/j.jvolgeores.2017.01.020>

684 Blahůt, J., Rowberry, M., Balek, J., Klimeš, J., Baroň, I., Meletlidis, S., Martí, X., 2017. Monitoring giant landslide  
685 detachment planes in the era of big data analytics. In: Mikoš, M., Arbanas, Ž., Yin, Y., Sassa, K. (Eds.),  
686 *Advancing Culture of Living with Landslides, Volume 3*. Springer, Cham, pp. 333-340.  
687 [https://doi.org/10.1007/978-3-319-53487-9\\_38](https://doi.org/10.1007/978-3-319-53487-9_38)

688 ~~Blahůt, J., Baroň, I., Sokol, L., Meletlidis, S., Klimeš, J., Rowberry, M., Melichar, R., García-Cañada, L., Martí, X.,~~  
689 ~~2018a. Large landslide stress states calculated during extreme climatic and tectonic events on El Hierro,~~  
690 ~~Canary Islands. *Landslides* 15, 1801-1814. <https://doi.org/10.1007/s10346-018-0993-1>~~

691 Blahůt, J., Klimeš, J., Rowberry, M., Kusák, M., 2018<sup>ab</sup>. Database of giant landslides on volcanic islands - first  
692 results from the Atlantic Ocean. *Landslides* 15, 823-827. <https://doi.org/10.1007/s10346-018-0967-3>

693 ~~Blahůt, J., Baroň, I., Sokol, L., Meletlidis, S., Klimeš, J., Rowberry, M., Melichar, R., García-Cañada, L., Martí, X.,~~  
694 ~~2018<sup>ab</sup>. Large landslide stress states calculated during extreme climatic and tectonic events on El~~  
695 ~~Hierro, Canary Islands. *Landslides* 15, 1801-1814. <https://doi.org/10.1007/s10346-018-0993-1>~~

696 ~~Blahůt, J., Balek, J., Klimeš, J., Rowberry, M., Kusák, M., Kalina, J., 2019. A comprehensive global database of~~  
697 ~~giant landslides on volcanic islands. *Landslides* 16 (10), 2045-2052. <https://doi.org/10.1007/s10346->~~  
698 ~~019-01275-8~~

699 Blard, P.-H., Balco, G., Burnard, P., Farley, K., Fenton, C., Friedrich, R., Jull, A., Niedermann, S., Pik, R., Schaefer,  
700 J., Scott, E., Shuster, D., Stuart, F., Stute, M., Tibari, B., Winckler, G., Zimmermann, L., 2015. An inter-  
701 laboratory comparison of cosmogenic <sup>3</sup>He and radiogenic <sup>4</sup>He in the CRONUS-P pyroxene standard.  
702 *Quaternary Geochronology* 26, 11-19. <https://doi.org/10.1016/j.quageo.2014.08.004>

703 Blard, P.-H., Farley K., 2008. The influence of radiogenic  $^4\text{He}$  on cosmogenic  $^3\text{He}$  determinations in volcanic  
704 olivine and pyroxene. *Earth and Planetary Science Letters* 276, 20-29.  
705 <https://doi.org/10.1016/j.epsl.2008.09.003>

706 Boutareaud, S., Calugaru, D.-G., Han, R., Fabbri, O., Mizoguchi, K., Tsutsumi, A., Shimamoto, T., 2008. Clay-clast  
707 aggregates: a new textural evidence for seismic fault sliding? *Geophysical Research Letters* 35, L05302.  
708 <https://doi.org/10.1029/2007GL032554>

709 Brodsky, E., Rowe, C., Meneghini, F., Moore, J., 2009. A geological fingerprint of low viscosity fault fluids  
710 mobilized during an earthquake. *Journal of Geophysical Research, Solid Earth* 114, B01303.  
711 <https://doi.org/10.1029/2008JB005633>

712 Carracedo, J.-C., 2008. *Canarian Volcanoes IV: La Palma, La Gomera, El Hierro*. Editorial Rueda S.L., Madrid, 213  
713 pp.

714 Carracedo, J.-C., Day, S., Guillou, H., Pérez Torrado, F., 1997. Geology of the island of El Hierro, Canary Islands:  
715 stratigraphy, volcanology, and structure. *Excursion Guidebook, International Workshop on Volcanism  
716 and Volcanic Hazards in Immature Intraplate Oceanic Islands, La Palma*, 43 pp.

717 Carracedo, J.-C., Day, S., Guillou, H., Pérez Torrado, F., 1999. Giant quaternary landslides in the evolution of La  
718 Palma and El Hierro, Canary Islands. *Journal of Volcanology and Geothermal Research* 94, 169-190.  
719 [https://doi.org/10.1016/S0377-0273\(99\)00102-X](https://doi.org/10.1016/S0377-0273(99)00102-X)

720 Carracedo, J.-C., Rodríguez Badiola, E., Guillou, H., De la Nuez, H., Pérez Torrado, F., 2001. Geology and  
721 volcanology of the western Canaries: La Palma and El Hierro. *Estudios Geológicos* 57, 171-295.

722 Carracedo, J.-C., Troll, V., 2016. *The Geology of Canary Islands*. Elsevier, Amsterdam, 622 pp.

723 Day, S., Carracedo, J.-C., Guillou, H., 1997. Age and geometry of an aborted rift flank collapse: the San Andres  
724 fault system, El Hierro, Canary Islands. *Geological Magazine* 134, 523-537.  
725 <https://doi.org/10.1017/S0016756897007243>

726 De Blasio, F., Elverhøi, A., 2008. A model for frictional melt production beneath large rock avalanches. *Journal  
727 of Geophysical Research, Earth Surface* 113, F02014. <https://doi.org/10.1029/2007JF000867>

728 Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., Ferri, F., Cocco, M., Shimamoto, T., 2011.  
729 Fault lubrication during earthquakes. *Nature* 471, 494-499. <https://doi.org/10.1038/nature09838>

730 Duffield, W., 1975. *Structure and origin of the Koa'e Fault System, Kilauea Volcano, Hawaii*. United States  
731 Geological Survey, Professional Paper 856, 12 pp.

732 Faber, C., Rowe, C., Miller, J., Fagereng, Å., Neethling, J., 2014. Silica gel in a fault slip surface: field evidence for  
733 palaeo-earthquakes? *Journal of Structural Geology* 69 108-121.  
734 <https://doi.org/10.1016/j.jsg.2014.09.021>

735 Fondriest, M., Smith, S., Candela, T., Nielsen, S., Mair, K., Di Toro, G., 2013. Mirror-like faults and power  
736 dissipation during earthquakes. *Geology* 41, 1175-1178. <https://doi.org/10.1130/G34641.1>

737 Gombert, J., Bodin, P., Savage, W., Jackson, M., 1995. Landslide faults and tectonic faults, analogs? The  
738 Slumgullion earthflow, Colorado. *Geology* 23, 41-44. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1995)023<0041:LFATFA>2.3.CO;2)  
739 [7613\(1995\)023<0041:LFATFA>2.3.CO;2](https://doi.org/10.1130/0091-7613(1995)023<0041:LFATFA>2.3.CO;2)

740 Gómez Sainz de Aja, J., Klein, E., Ruiz García, M., Balcells Herrera, R., Del Pozo, M., Galindo, E., La Moneda, E.,  
741 2010. Mapa Geológico de España, Escala 1:25 000, Valverde (Isla de El Hierro), Hoja N° 1105-II,  
742 Memoria. Instituto Geológico y Minero de España, Madrid, 96 pp.

743 Goudie, A., 2006. The Schmidt hammer in geomorphological research. *Progress in Physical Geography* 30, 703-  
744 718. <https://doi.org/10.1177/0309133306071954>

745 Grasemann, B., Dabrowski, M., 2015. Winged inclusions: pinch-and-swell objects during high-strain simple  
746 shear. *Journal of Structural Geology* 70, 78-94. <https://doi.org/10.1016/j.jsg.2014.10.017>

747 Grasemann, B., Dabrowski, M., Schöpfer, M., 2019. Sense and non-sense of shear reloaded. *Journal of*  
748 *Structural Geology* 125, 200-228. <https://doi.org/10.1016/j.jsg.2018.05.028>

749 Guillou, H., Carracedo, J.-C., Pérez Torrado, F., Rodríguez Badiola, E., 1996. K-Ar ages and magnetic stratigraphy  
750 of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands. *Journal of Volcanology and*  
751 *Geothermal Research* 73, 141-155. [https://doi.org/10.1016/0377-0273\(96\)00021-2](https://doi.org/10.1016/0377-0273(96)00021-2)

752 Han, R., Hirose, T., 2012. Clay-clast aggregates in fault gouge: an unequivocal indicator of seismic faulting at  
753 shallow depths? *Journal of Structural Geology* 43, 92-99. <https://doi.org/10.1016/j.jsg.2012.07.008>

754 Han, R., Hirose, T., Shimamoto, T., Lee, Y., Ando, J., 2011. Granular nanoparticles lubricate faults during seismic  
755 slip. *Geology* 39, 599-602. <https://doi.org/10.1130/G31842.1>

756 Hildenbrand, A., Marques, F., Catalao, J., Catita, C., Costa, A., 2012. Large scale active slump of the  
757 southeastern flank of Pico Island, Azores. *Geology* 40, 939-942. <https://doi.org/10.1130/G33303.1>

758 [Hunt, J.E., Wynn, R.B., Talling, P.J., Masson, D.G., 2013. Multistage collapse of eight western Canary Island](#)  
759 [landslides in the last 1.5 Ma: Sedimentological and geochemical evidence from subunits in submarine](#)

760 [flow deposits. \*Geochemistry Geophysics Geosystems\* 14\(7\), 2159-2181. \[https://doi.org/\]\(https://doi.org/10.1002/ggge.20138\)](https://doi.org/10.1002/ggge.20138)  
761 [10.1002/ggge.20138](https://doi.org/10.1002/ggge.20138)

762 [Hunt, J.E., Cassidy, M., Talling, P.J., 2018. Multi-stage volcanic island flank collapses with coeval explosive](https://doi.org/10.1038/s41598-018-19285-2)  
763 [caldera-forming eruptions. \*Scientific Reports\* 8, 1146. <https://doi.org/10.1038/s41598-018-19285-2>](https://doi.org/10.1038/s41598-018-19285-2)

764 Jaboyedoff, M., Penna, I., Pedrazzini, A., Baroň, I., Crosta, G., 2013. An introductory review on gravitational  
765 deformation induced structures, fabrics, and modeling. *Tectonophysics* 605, 1-12.  
766 <https://doi.org/10.1016/j.tecto.2013.06.027>

767 [Karstens, J., Berndt, C., Urlaub, M., Watt, S.F.L., Micallef, A., Ray, M., Klaucke, I., Muff, S., Klaeschen, D., Kühn,](https://doi.org/10.1016/j.epsl.2019.04.009)  
768 [M., Roth, T., Böttner, C., Schramm, B., Elger, J., Brune, S., 2019. From gradual spreading to catastrophic](https://doi.org/10.1016/j.epsl.2019.04.009)  
769 [collapse – Reconstruction of the 1888 Ritter Island volcanic sector collapse from high-resolution 3D](https://doi.org/10.1016/j.epsl.2019.04.009)  
770 [seismic data. \*Earth and Planetary Science Letters\* 517, 1-13. <https://doi.org/10.1016/j.epsl.2019.04.009>](https://doi.org/10.1016/j.epsl.2019.04.009)

771 Kendrick, J., Lavallée, Y., Ferk, A., Perugini, D., Leonhardt, R., Dingwell, D., 2012. Extreme frictional processes in  
772 the volcanic conduit of Mount St. Helens (USA) during the 2004-2008 eruption. *Journal of Structural*  
773 *Geology* 38, 61-76. <https://doi.org/10.1016/j.jsg.2011.10.003>

774 Kendrick, J., Lavallée, Y., Hess, K.-U., De Angelis, S., Ferk, A., Gaunt, H., Meredith, P., 2014. Seismogenic  
775 frictional melting in the magmatic column. *Solid Earth* 5, 199-208. [https://doi.org/10.5194/se-5-199-](https://doi.org/10.5194/se-5-199-2014)  
776 [2014](https://doi.org/10.5194/se-5-199-2014)

777 Kirkpatrick, J., Rowe, C., White, J., Brodsky, E., 2013. Silica gel formation during fault slip: evidence from the  
778 rock record. *Geology* 41, 1015-1018. <https://doi.org/10.1130/G34483.1>

779 Klimeš, J., Yepes, J., Becerril, L., Kusák, M., Galindo, I., Blahůt, J., 2016. Development and recent activity of the  
780 San Andrés Landslide on El Hierro, Canary Islands, Spain. *Geomorphology* 261, 119-131.  
781 <https://doi.org/10.1016/j.geomorph.2016.02.018>

782 Kurz, M., 1986. In situ production of ~~cosmogenic~~ terrestrial [cosmogenic](#) helium and some applications to  
783 geochronology. *Geochimica et Cosmochimica Acta* 50, 2855-2862. [https://doi.org/10.1016/0016-](https://doi.org/10.1016/0016-7037(86)90232-2)  
784 [7037\(86\)90232-2](https://doi.org/10.1016/0016-7037(86)90232-2)

785 Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth*  
786 *and Planetary Science Letters* 104, 424-439. [https://doi.org/10.1016/0012-821X\(91\)90220-C](https://doi.org/10.1016/0012-821X(91)90220-C)



787 Lavallée, Y., Hirose, T., Kendrick, J., De Angelis, S., Petrakova, L., Hornby, A., Dingwell, D., 2014. A frictional law  
788 for volcanic ash gouge. *Earth and Planetary Science Letters* 400, 177-183.  
789 <https://doi.org/10.1016/j.epsl.2014.05.023>

790 Lavallée, Y., Mitchell, T., Heap, M., Vasseur, J., Hess, K.-U., Hirose, T., Dingwell, D., 2012. Experimental  
791 generation of volcanic pseudotachylytes: constraining rheology. *Journal of Structural Geology* 38, 222-  
792 233. <https://doi.org/10.1016/j.jsg.2012.02.001>

793 Legros, F., Cantagrel, J.-M., Devouard, B., 2000. Pseudotachylite (frictionite) at the base of the Arequipa  
794 Volcanic Landslide Deposit (Peru): implications for emplacement mechanisms. *The Journal of Geology*  
795 108, 601-611. <https://doi.org/10.1086/314421>

796 León, R., Somoza, L., Urgeles, R., Medialdea, T., Ferrer, M., Biain, A., García-Crespo, J., Mediato, J., Galindo, I.,  
797 Yepes, J., González, F., Gimenez-Moreno, J., 2017. Multi-event oceanic island landslides: new onshore-  
798 offshore insights from El Hierro Island, Canary Archipelago. *Marine Geology* 393, 156-175.  
799 <https://doi.org/10.1016/j.margeo.2016.07.001>

800 Liu, C., Lay, T., Xiong, X., 2018. Rupture in the 4 May 2018  $M_w$  6.9 earthquake seaward of the Kilauea East Rift  
801 Zone fissure eruption in Hawaii. *Geophysical Research Letters* 45, 9508-9515.  
802 <https://doi.org/10.1029/2018GL079349>

803 Longpré, M., Chadwick, J., Wijbrans, J., Iping, R., 2011. Age of the El Golfo debris avalanche, El Hierro (Canary  
804 Islands): new constraints from laser and furnace  $^{40}\text{Ar}/^{39}\text{Ar}$  dating. *Journal of Volcanology and*  
805 *Geothermal Research* 203, 76-80. <https://doi.org/10.1016/j.jvolgeores.2011.04.002>

806 López, C., Blanco, M., Abella, R., Brenes, B., Cabrera Rodríguez, V., Casas, B., Domínguez Cerdeña, I., Felpeto, A.,  
807 Fernández de Villalta, M., Del Fresno, C., et al., 2012. Monitoring the volcanic unrest of El Hierro (Canary  
808 Islands) before the onset of the 2011-2012 submarine eruption. *Geophysical Research Letters* 39,  
809 L13303. <https://doi.org/10.1029/2012GL051846>

810 Maddock, R., 1986. Frictional melting in landslide generated frictionites (hyalomylonites) and fault generated  
811 pseudotachylytes: discussion. *Tectonophysics* 128, 151-153. [https://doi.org/10.1016/0040-](https://doi.org/10.1016/0040-1951(86)90316-1)  
812 [1951\(86\)90316-1](https://doi.org/10.1016/0040-1951(86)90316-1)

813 Martin, L., Blard, P.-H., Balco, G., Lave, J., Delunel, R., Lifton, N., Laurent, V., 2017. The CREp program and the  
814 ICE-D production rate calibration database: a fully parameterizable and updated online tool to compute

815 cosmic-ray exposure ages. *Quaternary Geochronology* 38, 25-49.  
816 <https://doi.org/10.1016/j.quageo.2016.11.006>

817 Masch, L., Wenk, H., Preuss, E., 1985. Electron microscopy of hyalomylonites - evidence for frictional melting in  
818 landslides. *Tectonophysics* 115, 131-160. [https://doi.org/10.1016/0040-1951\(85\)90103-9](https://doi.org/10.1016/0040-1951(85)90103-9)

819 Masson, D., 1996. Catastrophic collapse of the volcanic island of Hierro 15 ka ago and the history of landslides  
820 in the Canary Islands. *Geology* 24, 231-234. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1996)024<0231:CCOTVI>2.3.CO;2)  
821 [7613\(1996\)024<0231:CCOTVI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<0231:CCOTVI>2.3.CO;2)

822 Masson, D., Watts, A., Gee, M., Urgeles, R., Mitchell, N., Le Bas, T., Canals, M., 2002. Slope failures on the flanks  
823 of the western Canary Islands. *Earth-Science Reviews* 57, 1-35. [https://doi.org/10.1016/S0012-](https://doi.org/10.1016/S0012-8252(01)00069-1)  
824 [8252\(01\)00069-1](https://doi.org/10.1016/S0012-8252(01)00069-1)

825 McGuire, W., 1996. Volcano instability: a review of contemporary themes. In: McGuire, W., Jones, A., Neuberg,  
826 J. (Eds.), *Volcano Instability on the Earth and Other Planets*. Geological Society of London, Special  
827 Publication 110, 1-23. <https://doi.org/10.1144/GSL.SP.1996.110.01.01>

828 Meletlidis, S., Di Roberto, A., Domínguez Cerdeña, I., Pompilio, M., García-Cañada, L., Bertagnini, A., Benito-Saz,  
829 M., Del Carlo, P., Sainz-Maza Aparicio, S., 2015. New insight into the 2011-2012 unrest and eruption of El  
830 Hierro Island (Canary Islands) based on integrated geophysical, geodetical, and petrological data. *Annals*  
831 *of Geophysics* 58, S0546. <https://doi.org/10.4401/ag-6754>

832 Mitchell, T., Smith, S., Anders, M., Di Toro, G., Nielsen, S., Cavallo, A., Beard, A., 2015. Catastrophic  
833 emplacement of giant landslides aided by thermal decomposition: Heart Mountain, Wyoming. *Earth and*  
834 *Planetary Science Letters* 411, 199-207. <https://doi.org/10.1016/j.epsl.2014.10.051>

835 Moscardelli, L., Wood, L., 2008. New classification system for mass transport complexes in offshore Trinidad.  
836 *Basin Research* 20, 73-98. <https://doi.org/10.1111/j.1365-2117.2007.00340.x>

837 Palumbo, L., Benedetti, L., Bourlès, D., Cinque, A., Finkel, R., 2004. Slip history of the Magnola Fault (Apennines,  
838 Central Italy) from <sup>36</sup>Cl surface exposure dating: evidence for strong earthquakes over the Holocene.  
839 *Earth and Planetary Science Letters* 225, 163-176. <https://doi.org/10.1016/j.epsl.2004.06.012>

840 [Paris, R., Ramalho, R.S., Madeira, J., Ávila, S., May, S.M., Rixhon, G., Engel, M., Brückner, H., Herzog, M.,](#)  
841 [Schukraft, G., Perez-Torrado, F.J., Rodriguez-Gonzales, A., Carracedo, J.C., Giachetti, T., 2018. Mega-](#)  
842 [tsunami conglomerates and flank collapses of ocean volcanoes. \*Marine Geology\* 395, 168-187.](#)  
843 <https://doi.org/10.1016/j.margeo.2017.10.004>

844 Passchier, C., Trouw, R., 2005. *Microtectonics*. Springer, Berlin, 366 pp. <https://doi.org/10.1007/3-540-29359-0>

845 Pouljol, A., Ritz, J.-F., Tahayt, A., Vernant, P., Condomines, M., Blard, P.-H., Billant, J., Vacher, L., Tibari, B., Hni,  
846 L., Koulali Idrissi, A., 2014. Active tectonics of the Northern Rif (Morocco) from geomorphic and  
847 geochronological data. *Journal of Geodynamics* 77, 70-88. <https://doi.org/10.1016/j.jog.2014.01.004>

848 Price, N., Johnson, S., Gerbi, C., West, D., 2012. Identifying deformed pseudotachylyte and its influence on the  
849 strength and evolution of a crustal shear zone at the base of the seismogenic zone. *Tectonophysics* 518-  
850 521, 63-83. <https://doi.org/10.1016/j.tecto.2011.11.011>

851 Protin, M., Blard, P.-H., Marrocchi, Y., Mathon, F., 2016. Irreversible adsorption of atmospheric helium on  
852 olivine: a lobster pot analogy. *Geochimica et Cosmochimica Acta* 179, 76-88.  
853 <https://doi.org/10.1016/j.gca.2016.01.032>

854 Rasa, R., Azzaro, R., Leonardi, O., 1996. Aseismic creep on faults and flank instability at Mount Etna Volcano,  
855 Sicily. In: McGuire, W., Jones, A., Neuberg, J. (Eds.), *Volcano Instability on the Earth and Other Planets*.  
856 Geological Society of London, Special Publication 110, 179-192.  
857 <https://doi.org/10.1144/GSL.SP.1996.110.01.14>

858 Rempe, M., Smith, S., Ferri, F., Mitchell, T., Di Toro, G., 2014. Clast-cortex aggregates in experimental and  
859 natural calcite bearing fault zones. *Journal of Structural Geology* 68, 142-157.  
860 <https://doi.org/10.1016/j.jsg.2014.09.007>

861 Rowe, C., Fagereng, Å., Miller, J., Mapani, B., 2012. Signature of coseismic decarbonation in dolomitic fault  
862 rocks of the Naukluft Thrust, Namibia. *Earth and Planetary Science Letters* 333-334, 200-210.  
863 <https://doi.org/10.1016/j.epsl.2012.04.030>

864 Rowe, C., Griffith, W., 2015. Do faults preserve a record of seismic slip: a second opinion. *Journal of Structural*  
865 *Geology* 78, 1-26. <https://doi.org/10.1016/j.jsg.2015.06.006>

866 Rowe, C., Lamothe, K., Rempe, M., Andrews, M., Mitchell, T., Di Toro, G., Clancy White, J., Aretusini, S., 2019.  
867 Earthquake lubrication and healing explained by amorphous nanosilica. *Nature Communications* 10,  
868 320. <https://doi.org/10.1038/s41467-018-08238-y>

869 Rowe, C., Moore, J., Meneghini, F., McKeirnan, A., 2005. Large scale pseudotachylytes and fluidized cataclases  
870 from an ancient subduction thrust fault. *Geology* 33, 937-940. <https://doi.org/10.1130/G21856.1>

871 Sagy, A., Brodsky, E., Axen, G., 2007. Evolution of fault surface roughness with slip. *Geology* 35, 283-286.  
872 <https://doi.org/10.1130/G23235A.1>

873 Siebert, L., 1984. Large volcanic debris avalanches: characteristics of source areas, deposits, and associated  
874 eruptions. *Journal of Volcanology and Geothermal Research* 22, 163-197. [https://doi.org/10.1016/0377-](https://doi.org/10.1016/0377-0273(84)90002-7)  
875 [0273\(84\)90002-7](https://doi.org/10.1016/0377-0273(84)90002-7)

876 Siebert, L., 1992. Threats from debris avalanches. *Nature* 356, 658-659. <https://doi:10.1038/356658a0>

877 Smeraglia, L., Bettucci, A., Billi, A., Carminati, E., Cavallo, A., Di Toro, G., Natali, M., Passeri, D., Rossi, M.,  
878 Spagnuolo, E., 2017. Microstructural evidence for seismic and aseismic slips along clay-bearing,  
879 carbonate faults. *Journal of Geophysical Research, Solid Earth* 122, 3895-3915.  
880 <https://doi.org/10.1002/2017JB014042>

881 Smith, S., Billi, A., Di Toro, G., Spiess, R., 2011. Principal slip zones in limestone: microstructural characterization  
882 and implications for the seismic cycle (Tre Monti Fault, Central Apennines, Italy). *Pure and Applied*  
883 *Geophysics* 168, 2365-2393. <https://doi.org/10.1007/s00024-011-0267-5>

884 Sorriso-Valvo, M., Gullà, G., Antronico, L., Tansi, C., Amelio, M., 1999. Mass movement, geologic structure, and  
885 morphologic evolution of the Pizzotto-Greci Slope (Calabria, Italy). *Geomorphology* 30, 147-163.  
886 [https://doi.org/10.1016/S0169-555X\(99\)00051-3](https://doi.org/10.1016/S0169-555X(99)00051-3)

887 Széreméta, N., Laj, C., Guillou, H., Kissel, C., Mazaud, A., Carracedo, J.-C., 1999. Geomagnetic paleosecular  
888 variation in the Brunhes period, from the island of El Hierro (Canary Islands). *Earth and Planetary*  
889 *Science Letters* 165, 241-253. [https://doi.org/10.1016/S0012-821X\(98\)00270-2](https://doi.org/10.1016/S0012-821X(98)00270-2)

890 Tesei, T., Carpenter, B., Giorgetti, C., Scuderi, M., Sagy, A., Scarlato, P., Collettini, C., 2017. Friction and scale-  
891 dependent deformation processes of large experimental carbonate faults. *Journal of Structural Geology*  
892 100, 12-23. <https://doi.org/10.1016/j.jsg.2017.05.008>

893 Ui, T., Takarada, S., Yoshimoto, M., 2000. Debris avalanches. In: Sigurdsson, H., Houghton, B., McNutt, S.,  
894 Rymer, H., Stix, J. (Eds.), *Encyclopedia of Volcanoes*. Academic Press, San Diego, pp. 617-626.

895 Ujiie, K., Tsutsumi, A., Kameda, J., 2011. Reproduction of thermal pressurization and fluidization of clay-rich  
896 fault gouges by high-velocity friction experiments and implications for seismic slip in natural faults.  
897 *Geological Society of London, Special Publication* 359, 267-285. <https://doi.org/10.1144/SP359.15>

898 Urgeles, R., Canals, M., Baraza, J., Alonso, B., 1996. The submarine El Golfo debris avalanche and the Canary  
899 debris flow, west Hierro Island: the last major slides in the Canary Archipelago. *Geogaceta* 20, 390-393.

900 Urgeles, R., Canals, M., Baraza, J., Alonso, B., Masson, D., 1997. The most recent megalandslides on the Canary  
901 Islands: the El Golfo debris avalanche and the Canary debris flow, west El Hierro Island. Journal of  
902 Geophysical Research, Solid Earth 102, 20305-20323. <https://doi.org/10.1029/97JB00649>

903 Verberne, B., De Bresser, J., Niemeijer, A., Spiers, C., [Matthijs de Winter, M.D.](#), Plümpner, O., 2013.  
904 Nanocrystalline slip zones in calcite fault gouge show intense crystallographic preferred orientation:  
905 crystal plasticity at subseismic slip rates at 18-150°C. Geology 41, 863-866.  
906 <https://doi.org/10.1130/G34279.1>

907 [Walter, T.R., Haghighi, M.H., Schneider, F.M., Coppola D, Motagh, M., Saul, J., Babeyko, A., Dahm, T., Troll, V.R.,](#)  
908 [Tilmann, F., Heimann, S., Valade, S., Triyono, R., Khomarudin, R., Kartadinata, N., Laiolo, M., Massimetti,](#)  
909 [F., Gaebler, P., 2019. Complex hazard cascade culminating in the Anak Krakatau sector collapse. Nature](#)  
910 [Communications 10, 4339. https://doi.org/10.1038/s41467-019-12284-5](#)

911 Weidinger, J., Korup, O., Munack, H., Altenberger, U., Dunning, S., Tippelt, G., Lottermoser, W., 2014. Giant  
912 rockslides from the inside. Earth and Planetary Science Letters 389, 62-73.  
913 <https://doi.org/10.1016/j.epsl.2013.12.017>

914 Zimmermann, L., Avice, G., Blard, P.-H., Marty, B., Füre, E., Burnard, P., 2018. A new all-metal induction furnace  
915 for noble gas extraction. Chemical Geology 480, 86-92. <https://doi.org/10.1016/j.chemgeo.2017.09.018>

916 **Figure captions**

917

918 **Figure 1** A shaded topographic and bathymetric relief map of El Hierro, Canary Islands, overlain by a  
919 geological map simplified from Ancochea et al. (2004). The inset shows an aerial image of the  
920 studied fault outcrop. SAL: San Andrés Landslide.

921

922 **Figure 2** (A) General view of the San Andrés Fault outcrop showing the location of each sampling site. The-  
923 numbers in parentheses following after COS samples 1-5 indicate the estimated exposure ages in  
924 ka. (B) Detailed view of the fault outcrop which shows a series of conspicuous vertical or  
925 subvertical slickenlines and the whitish layer adorning the recently exposed parts of its surface; (C)  
926 Contact between the footwall (left) and the hanging wall (right); (D) Detailed view of the oxidised  
927 rock visible in the footwall of the fault which reflects the presence of fine grained Fe-oxides and Fe-  
928 hydroxides. (E, F) Samples used for microstructural analysis: (E1) hand sample MSA1 shows  
929 slickenlines composed of the whitish layer - note the dashed line parallel to the slickenlines; (E2)  
930 closeup view of the slickenlines, (E3) rock slab used to extract thin sections shows the whitish layer  
931 that covers the cataclasite and breccia. The black rectangles mark the positions of Figures 5-6; (F1)  
932 core sample MSA2 drilled perpendicular to the fault surface shows large clasts in the breccia and  
933 white layer - red dashed line highlights the orientation of the slickenlines; (F2) rock slab shows the  
934 gradual increase in oxidation of the breccia towards the fault surface; (F3) thin section shows the  
935 sharpness of the slip surface and the barely-visible white silica layer. The black rectangle marks the  
936 location of Figure 7.

937

938

939 **Figure 3** Structural analysis of the surface of the San Andrés Fault outcrop conducted on the basis of a  
940 remotely sensed UAV DTM. (A) Slope gradient map giving a ground plan view presented in inverted  
941 greyscale and showing distinct sets of striations and elongated bumps. (B) Slope gradient map  
942 giving a fault perpendicular view presented in inverted greyscale and visualised in three  
943 dimensions (for reference see the right hand part of the fault in (A)). (C) Orientation of the fault  
944 surface Stereoplot of the structural geological measurements and the striations revealed by the

945 morphostructural analysis of the UAV DTM. [The stereoplot is in azimuthal projection of the lower](#)  
946 [hemisphere while the different coloured arrows represent distinct sets of striations and elongated](#)  
947 [protrusions.](#)

948  
949 **Figure 4** The interpolated R-values obtained through Schmidt hammer sampling on the San Andrés Fault.  
950 The size of the [proportional plots/black dots](#) illustrates the rock hardness at each of the test sites.

951  
952 **Figure 5** Photomicrographs [and BSE images](#) of rocks from the San Andrés Fault, sample MSA1. First area  
953 presented (aA) under plane polarised light, (bB) under cross polarised light, (cC) as a sketch, (dD) in  
954 [BSEbackscattered mode](#), and (e-E-F) in elemental maps. These show tectonic breccia (TB) covered  
955 by a cataclastic layer (CL) which is, in turn, covered by a silica layer (SL). The cataclasite cuts both  
956 the tectonic breccia and a zeolite vein (Z) and has preserved P-foliation and a winged inclusion. The  
957 boundary between the silica layer and the adjacent cataclastic layer is sharp with high interference  
958 bands, characteristic of recrystallisation. The area is rotated during analysis and the sense of shear  
959 is marked on the sketch. Second area presented (gG) under plane polarised light, (hH) under cross  
960 polarised light, (iI) as a sketch, (jJ) in [BSEbackscattered mode](#), and (k-K-L) in elemental maps. These  
961 show tectonic breccia (TB) with zeolite veins (Z) covered by a thinner cataclastic layer (CL) and a  
962 thicker silica layer (SL). The fault slip surface is subhorizontal with a top-to-right shear direction.  
963 The boundary between the cataclastic layer and the silica layer is marked by high intensity bands of  
964 recrystallised material. The silica layer preserves clast-cortex aggregates (CCA) and flow bands (FB)  
965 along with parallel P- and Y- shears. The elongated void was most probably a clast-cortex aggregate  
966 lost during preparation of the sample.

967  
968 **Figure 6** Photomicrographs [and BSE images](#) of rocks from the San Andrés Fault, sample MSA1. Area  
969 presented in (aA) under plane polarised light, (bB) under cross polarised light, (cC) under cross  
970 polarised light using a gypsum tint plate, (dD) in [BSEbackscattered mode](#), and (eE) as a sketch.  
971 These show tectonic breccia (TB) covered by a silica layer (SL). The tectonic breccia was cut during  
972 deformation which resulted in truncated clasts (TC) while the silica layer preserves clast-cortex  
973 aggregates (CCA), a cataclastic sublayer (CL), and flow bands (FB). These flow bands show a positive

974 birefringence, in contrast to the rest of the silica layer, as evidenced by the second order blue  
975 interference colour in (eC). The rectangles in (dD) indicate regions highlighted in (f-iF-l): (fF) new  
976 crystals growing in a void surrounded by ultrafine grained to amorphous matrix, (gG) a large clast-  
977 cortex aggregate with a complex cortex and elongated clast in its core, (hH) a lensoid of reworked  
978 cataclasite, and (iI) two smaller clast-cortex aggregates and new crystals growing in the void. The  
979 fault slip surface is horizontal with a top-to-right shear direction.

980  
981 **Figure 7** Photomicrographs [and BSE images](#) of rocks from the San Andrés Fault, sample MSA2. Area  
982 presented in (aA) under plane polarised light, (bB) under cross polarised light using a gypsum tint  
983 plate, and (cC) as a sketch. These show a large truncated clast (TC) in the tectonic breccia (TB) cut  
984 by cataclasite (CL) and covered by a silica layer (SL) which has flow bands (FB) and clast-cortex  
985 aggregates (CCA). The rectangle in (aA) indicates the region highlighted in (d-fD-F). In (d-fD-F)  
986 elemental maps show P-foliation in the cataclastic layer along with clast-cortex aggregates and  
987 flow bands in the silica layer. Dashed lines highlight characteristics presented in the sketch. The  
988 fault slip surface is horizontal with a top-to-right shear direction.

989  
990 **Figure 8** A [proposed conceptual](#) model for the development of the San Andrés Fault system over the last  
991 550 ka based on Day et al. (1997), Carracedo et al. (1997), Széreméta et al. (1999), León et al.  
992 (2017), and the findings presented herein. The uppermost labels denote the main geological events  
993 to have taken place on El Hierro, i.e. rotation and volcanism, while those beneath denote the  
994 supposed age ranges for each of the giant landslides. The proposed timing of activity on the San  
995 Andrés Fault is presented underneath the timeline: the first slip event is associated with the  
996 formation of the cataclasite while the second slip event is associated with the formation of the  
997 silica layer. [The time axis depicts shows thousands of years before present.](#)

998  
999 **Figure 9** A [proposed conceptual](#) model for the development of the surface of the San Andrés Fault. Prior to  
1000 slip a tectonic breccia, of basaltic origin, hosted zeolite veins, as shown in green. During the first  
1001 slip event the tectonic breccia was sheared and a foliated cataclasite formed, as shown in red.



1002                    During the second slip event both the host rock and foliated cataclasite were sheared and a silica  
1003                    layer formed with clast-cortex aggregate and flow bands, as shown in blue.

1004 **Table captions**

1005

1006 **Table 1** Results of the cosmogenic  $^3\text{He}$  exposure dating for five samples obtained from the San Andrés  
1007 Fault.

1008

1009 **Supp. Tab. A** Chemical composition of the five samples obtained from the San Andrés Fault for cosmogenic  
1010  $^3\text{He}$  exposure dating (COS1 - COS5).

1 **Volcanic edifice slip events recorded on the fault plane of the San Andrés Landslide, El Hierro, Canary Islands**

2

3

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21 **Abstract:** Volcanic flank collapses often result in giant debris avalanches that are capable of travelling tens of  
22 kilometres across the ocean floor and generating tsunamis that devastate distant communities. The San Andrés  
23 Landslide on El Hierro, Canary Islands, represents one of the few places in the world where it is possible to  
24 investigate the landslide mass and fault planes of a volcanic collapse structure. In this study, a new conceptual  
25 model for the development of this enormous slump is presented on the basis of structural geological and  
26 geomorphological measurements, petrological and microstructural analyses, and cosmogenic radionuclide  
27 dating. Structural geological and geomorphological measurements indicate that the fault plane records two  
28 distinct events. Petrological and microstructural analyses demonstrate that a thin layer of frictionite covers the  
29 surface of the fault in contact with an oxidised tectonic breccia that transitions into the underlying undeformed  
30 basanite host rock. This frictionite comprises a heterogeneous cataclastic layer and a translucent silica layer  
31 that are interpreted to represent two separate slip events on the basis of their architecture and crosscutting  
32 relationships. Cosmogenic  $^3\text{He}$  dating reveals a maximum exposure age of  $183\pm 17$  ka to  $52\pm 17$  ka. Arguments  
33 are presented in support of the idea that the first slip event took place between 545 ka and 430 ka, prior to  
34 significant clockwise rotation of El Hierro, and the second slip event took place between 183 ka and 52 ka,  
35 perhaps in association with one of the giant debris avalanches that occurred around that time. This is the first  
36 time that more than one slip event has been recognised from the fault plane of the San Andrés Landslide. It is  
37 also believed to be the first time a silica layer resulting from frictional melt has been described in a volcanic  
38 setting.

39

40 **Keywords** volcanic collapse; frictionite; cataclasis metamorphism; silica layer; cosmogenic radionuclide  
41 dating; Canary Islands

42 **1. Introduction**

43 Gravitational slope failures generate geological structures at a range of scales that are similar or identical to  
44 those that result from tectonic processes (Jaboyedoff et al., 2013). Consequently, faults generated as a result of  
45 large slope failures are often analogous to their tectonic counterparts (Gomberg et al., 1995). Some of the  
46 largest slope failures on Earth are represented by volcanic flank collapses on oceanic islands – these events are  
47 so enormous that they are also comparable to the largest mass movements on Mars (Blahůt et al., 2019). The  
48 processes that lead to volcanic flank collapses on oceanic islands are not well understood despite their  
49 potential to generate catastrophic tsunamis (Paris et al., 2018; Walter et al., 2019). In part this situation reflects  
50 the dearth of events as volcanic flank collapses are estimated to have only occurred four times a century for  
51 the past five hundred years (Siebert, 1992). Volcanic flank collapses on oceanic islands are usually represented  
52 by debris avalanches (*sensu* Ui et al., 2000), which displace huge volumes of rock and create amphitheatre  
53 shaped calderas (Siebert, 1984). Such debris avalanches localise shear deformation along thin sliding surfaces  
54 at the base of the displaced mass (De Blasio and Elverhøi, 2008). These events are triggered by a range of  
55 factors which can be broadly categorised as seismogenic or magmatic (McGuire, 1996). Therefore, while  
56 huge debris avalanches may occur in other settings, volcanic flank collapses on oceanic islands are especially  
57 dangerous due to the interminable nature of the potential triggering events, i.e. volcanic tremors and related  
58 seismicity, coupled with the adjacency of an extremely high risk impact environment, i.e. seawater. The run-up  
59 heights of consequent tsunami waves may exceed 100 m (Karstens et al., 2019; Walter et al., 2019).  
60 Occasionally, volcanic collapses are represented by creeping or slumping but only a small number of studies  
61 have focused on these processes. Examples come from Mount Etna in Sicily (Rasa et al., 1996), Pico Ridge in the  
62 Azores (Hildebrand et al., 2012), San Andrés in the Canary Islands (Blahůt et al., 2017), and Hilina Slump in the  
63 Hawaiian Islands (Liu et al. 2018).

64

65 During landslide emplacement, flash heating may occur along thin shear layers to produce frictional melt,  
66 referred to as frictionite or landslide pseudotachylyte (Masch et al., 1985; Maddock, 1986; Legros et al., 2000;  
67 Lavallée et al., 2012; Mitchell et al., 2015). Frictionite is a subtype of pseudotachylyte, *sensu lato*, which is  
68 generated at the base of landslides, as opposed to pseudotachylyte, *sensu stricto*, which is generated in greater  
69 depths with higher pressure and temperature conditions (Maddock, 1986). Frictionite tends to have  
70 thicknesses of between one and three centimetres and develops parallel or subparallel to the dip of the

71 landslide (Weidinger et al., 2014). Indicators of frictionite include significant grain size reduction, evidence for  
72 fluidised flow, and the presence of amorphous material. Other types of cohesive fault rocks, such as  
73 microbreccias and cataclasites, are common during the emplacement of large landslides. Cataclasites typically  
74 show grain size reduction, compared to the host rock, with development of foliation. To accurately assess the  
75 hazard relating to volcanic flank collapses it is crucial to be able to estimate the strength and velocity of the  
76 landslide. Fast slip along shallow faults can be inferred by the presence of devitrified material observed in  
77 pseudotachylytes, clast-cortex aggregates (Smith et al., 2011; Han and Hirose, 2012; Rempe et al., 2014), silica  
78 layers (Kirkpatrick et al., 2013; Faber et al. 2014), and other type of fault rock architecture. Pseudotachylytes  
79 and frictionites are ultrafine-grained rocks, with the presence of partial melt. Clast-cortex aggregates comprise  
80 of a central clast enclosed within a layer, or concentric layers, of material akin to the matrix (e.g. Anders et al.,  
81 2010; Rowe et al., 2012). Silica layers are composed of translucent silica with microstructures that exhibit flow  
82 banding, armoured clasts, and extreme comminution compared to adjacent rocks (Kirkpatrick et al., 2013;  
83 Faber et al., 2014). These fault rock structures are not common – they are known to occur in a range of tectonic  
84 settings but have not been reported in relation to volcanic flank collapses. The first report of frictionite at the  
85 base of a landslide was described from the Köfels landslide in the Austrian Alps (Masch et al., 1985) while the  
86 first report of frictionite at the base of a landslide in a volcanic environment was described from the Arequipa  
87 volcanic landslide deposit in Peru (Legros et al., 2000). Furthermore, volcanoes tend to be basic in composition  
88 and silica layers are not expected to form in predominantly basic environment.

89

90 Reconstruction of past volcanic failures in their source areas is extremely rare as there is usually no material to  
91 study and/or the main scarp has since been covered by younger eruptions. For that reason, the majority of  
92 studies have focused on the sedimentological properties of these failures (e.g. Hunt et al., 2013). Until recently,  
93 it has been assumed that the volcanic flank collapses occur as one major event that displaces hundreds of cubic  
94 kilometres of rock. However, new research suggests that at least some of these collapses occurred in multiple  
95 stages (Hunt et al., 2013, 2018; León et al., 2017). Such findings may have serious implications for the  
96 calculated frequency of such hazards and reopens questions about the possible reactivation of apparently  
97 inactive structures. The San Andrés Landslide on El Hierro in the Canary Islands represents one of the few  
98 places in the world where it is possible to investigate the fault planes and landslide mass of a volcanic collapse  
99 structure. This study integrates a range of structural geological and geomorphological measurements,

100 petrological and microstructural analyses, and cosmogenic nuclide dating in order to reconstruct the  
101 developmental history of this huge slope failure. Data have been obtained - directly or indirectly - from the  
102 surface of the fault plane while samples were collected from both the fault plane itself and an adjacent gully  
103 perpendicular to the footwall. Our hypothesis states that this landslide is not the result of a single event, as  
104 proposed by Day et al. (1997), but instead results from a number of successive events spanning a protracted  
105 period. This hypothesis is not straightforward to address as unambiguous evidence for multiple slip events  
106 along a single fault is difficult to elucidate due to problems associated with overprinting and weathering.  
107 Nonetheless, on the basis of previously published research and the results obtained during this study, it has  
108 been possible to propose a new conceptual model for the development of the San Andrés Landslide.

109

## 110 **2. Geological setting**

### 111 *2.1 The island of El Hierro*

112 El Hierro is an active volcanic edifice that constitutes the smallest and youngest of the Canary Islands (Figure 1).  
113 Its oldest subaerially exposed rocks are represented by the Tiñor Unit, with a maximum age of 1.12 Ma (Guillou  
114 et al., 1996), which form the northern and northeastern parts of the island. This unit is thought to have  
115 developed rapidly until around the time of the Tiñor debris avalanche at 0.88 Ma (Carracedo et al., 2001).  
116 Thereafter, the rocks of the El Golfo-Las Playas Unit, with a maximum age of 0.55 Ma (Guillou et al., 1996),  
117 capped much of the Tiñor Unit and infilled the scarp area of the Tiñor debris avalanche (Carracedo et al., 2001).  
118 Its youngest subaerially exposed rocks are represented by the Rift Series, with a maximum age of 0.16 Ma  
119 (Guillou et al., 1996). Over the past 33 000 years onshore eruptions have reoccurred approximately once every  
120 1 000 years (Becerril et al., 2016a). The latest, ongoing phase of volcanism began around 2.5 ka (Carracedo et  
121 al., 2001). Recently a period of intense seismic activity spanned from July 2011 (López et al., 2012) to 2014  
122 (Benito-Saz et al., 2017). During this period an offshore eruption started on 10 October 2011 and finished in  
123 March 2012 (Meletlidis et al., 2015). A more detailed description of the geology of island has recently been  
124 presented elsewhere (Carracedo and Troll, 2016).

125

126 The flanks of El Hierro have hosted a number of enormous gravitational slope failures which have contributed  
127 to the development of its characteristic three-point star morphology (Figure 1). Until now, seven debris  
128 avalanches have been identified: Tiñor (< 880 ka), Las Playas I (545-176 ka), Las Playas II (176-145 ka), El Julan

129 (> 158 ka), El Golfo A (176-133 ka), El Golfo B (87-39 ka), and Punta del Norte of unknown age (Masson, 1996;  
130 Urgeles et al., 1996, 1997; Carracedo et al., 1999, 2001; Masson et al., 2002; Longpré et al., 2011; Becerril et al.,  
131 2016b; Carracedo and Troll, 2016; León et al., 2017; Blahůt et al., 2018a). The volumes of these debris  
132 avalanches vary between 50 km<sup>3</sup> and 234 km<sup>3</sup>, which makes them average from the known volcanic slope  
133 failures (for additional morphometric characteristics, see Blahůt et al., 2019). In addition, a large slump, sensu  
134 Moscardelli and Wood (2008), or a deep seated gravitational slope deformation, sensu Sorriso-Valvo et al.  
135 (1999) or Agliardi et al. (2001), is located on the southeast flank of the volcanic edifice. This feature, the San  
136 Andrés Landslide, is defined by a group of pronounced faults which represent landslide detachment planes.  
137 While its volume has not been determined, the deformed toe is visible around 18 km off coast at a depth of  
138 more than 3 km (Becerril et al., 2016b). Similar features have been described from other volcanic islands  
139 including the Azores (Hildenbrand et al., 2012) and the Hawaiian Islands (Duffield, 1975). It has previously been  
140 proposed that the San Andrés Landslide is an anchored block associated with the debris avalanche Las Playas I  
141 (Day et al., 1997).

142

## 143 2.2 *San Andrés Landslide*

144 The San Andrés Landslide has developed in the volcanic rocks of the Tiñor Unit. This unit comprises three  
145 distinct subunits (Gómez Sainz de Aja et al., 2010): the basal subunit is represented by relatively thin, 20-40 cm,  
146 steeply dipping lava flows; the intermediate subunit, which forms the majority of the unit, is represented by  
147 thicker, up to 4 m, shallow dipping lava flows; while the uppermost subunit is represented by emission vents  
148 with well-preserved craters and associated lavas. The broad arcuate and presumably listric fault system which  
149 defines the boundaries of the slope deformation to the northeast is terminated to the southwest by an  
150 escarpment associated with the giant debris avalanche Las Playas II. Previously the San Andrés Landslide has  
151 been interpreted as either an aborted collapse structure (Day et al., 1997) or a deep seated gravitational slope  
152 deformation (Klimeš et al., 2016).

153

154 It has been reasoned that the fault system must have developed at some point between 545 ka and about 261-  
155 176 ka (Day et al., 1997). If correct, this implies that the collapsed landslide mass has remained anchored  
156 during each of the subsequent giant debris avalanches on El Hierro (Carracedo and Troll, 2016). Support for the  
157 notion of protracted inactivity is provided by the presence of younger lavas crossing the fault without



158 displacement and the presence of scree covering lava flows as old as 145 ka in the gully of Las Playas  
159 (Carracedo et al., 1997). However, recent research is starting to challenge these arguments. The step-like  
160 structure of the incised gullies in the collapsed mass, together with records of progressive creep along its main  
161 detachment plane, in the order of  $0.5 \text{ mm} \cdot \text{a}^{-1}$ , suggests that the landslide mass may be moving steadily to the  
162 east and southeast (Klimeš et al., 2016; Blahůt et al., 2017, 2018b).

163

164 The part of San Andrés Fault system investigated in this study is exposed along a narrow road which traverses  
165 the Barranco de Tiñor ( $27^{\circ}47'18.82''\text{N}$ ,  $17^{\circ}55'19.04''\text{W}$ ). This outcrop is situated at c. 490 m asl, has a length of  
166 c. 70 m, and dips between  $65^{\circ}$  and  $75^{\circ}$  to the SE (Figure 2). The fault zone has a total thickness of between one  
167 and two metres. Both the footwall and hanging wall rocks comprise basaltic lavas of the Tiñor Unit with a few  
168 thin intercalated lapilli beds and soil horizons (Carracedo et al., 1997). No indurated breccia is present on the  
169 hanging wall. Its eastern section has only been uncovered relatively recently as a result of road construction  
170 and is distinguished by its whitish surface. This part of the fault surface hosts well-preserved slickenlines, which  
171 range in size from several millimetres to metre scale surface undulations. Detailed petrographic examinations  
172 of the fault rocks have been published previously (Day et al., 1997).

173

### 174 **3. Methods**

#### 175 *3.1 Field data and structural analyses*

176 Structural analyses of the surface of the San Andrés Fault plane incorporated structural geological field  
177 measurements alongside the interrogation of a high resolution digital terrain model (DTM). This DTM was  
178 constructed on the basis of photogrammetric imagery obtained from an unmanned aerial vehicle (UAV) and  
179 processed using the commercial software Agisoft PhotoScan (Agisoft LLC, 2014). The accuracy of terrain models  
180 constructed following this approach is directly comparable to those constructed on the basis of laser scanning  
181 (Balek and Blahůt, 2017). From the photogrammetric point cloud, it was possible to derive two complimentary  
182 slope gradient maps with grid cells of  $2 \times 2 \text{ cm}$ . The first gives a ground plan view of the fault (Figure 3A) while  
183 the second gives a fault perpendicular view (Figure 3B). These maps have been analysed in detail using the  
184 ESRI® ArcGIS applications ArcMap and ArcScene. Slope gradient maps, in contrast to hillshade maps, are  
185 particularly suited for the identification of linear features irrespective of their spatial distribution and

186 orientations. The obtained data were then compared to the structural geological field measurements recorded  
187 on the outcrop.

188

189 Schmidt hammer sampling is used in geomorphological research to estimate rates of weathering and to obtain  
190 information relating to relative exposure ages for rock surfaces on the basis of rebound values, R (Aydin and  
191 Basu, 2005; Goudie, 2006). A total of eighty-eight test sites were sampled on the fault plane using a Proceq  
192 SilverSchmidt ST-PC. Each site was sampled twelve times in a direction perpendicular to its surface. Of these  
193 twelve samples, the uppermost and lowermost values were disregarded, according to standard sampling  
194 protocol, and the remaining ten were used to calculate the rebound value. These R values were processed in a  
195 GIS. Initially, an orthophotograph of the fault scarp had to be created from a set of photoshots. The position of  
196 each test site was recorded on a printed copy of the orthophotograph prior to image rectification in the GIS.  
197 The relative positions of several test sites were measured in the field and used as reference points during  
198 georeferencing. Each test site is represented by a point placed approximately in its centre and then the  
199 calculated R value was added to each test site. Interpolation of these values indicates changes in the relative  
200 surface hardness across the exposed part of the fault scarp. Several interpolation algorithms were tested but  
201 the character of the data led us to select the natural neighbour technique.

202

### 203 3.2 *Petrographic and microstructural analyses*

204 Petrographic analyses of the sampled rocks were performed at the Institute of Rock Structure and Mechanics  
205 CAS and the Institute of Geology CAS in Prague. Optical microscopy was conducted using the polarisation  
206 microscope Leica DMR while chemical analysis of the primary and accessory minerals was conducted using the  
207 electron microprobe CAMECA SX-100. Microstructural investigations have been made through the application  
208 of optical microscopy, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). These  
209 investigations were made at the University of Vienna. Thin sections were cut perpendicular to the shear plane  
210 and parallel to the direction of sliding prior to mechanical polishing to thicknesses of c. 30 µm. Optical  
211 microscopy was conducted using the polarisation microscope Leica DM4500 P with micrographs obtained  
212 under both plane polarised light (PPL) and crossed polarised light (XPL). Selected samples were carbon coated  
213 for SEM. The SEM imaging was conducted using a FEI Inspect S with an accelerating voltage of 10-15 kV for  
214 spot sizes of 5-7. Images were obtained and presented in the back scattered mode (BSE). Element energy

215 dispersive spectroscopy was also conducted to better understand the chemical effects of fault slip. The EDAX  
216 EDS systems were used as an add-on to the FEI Inspect S. Using the TEAM™ Software Suite and Smart Phase  
217 Mapping it was possible to collect spectra and generate phase maps showing elemental distribution and  
218 associated spectra. The EDS operating conditions were 15 kV accelerating voltage for spot size of 5, at  
219 resolution of 514 x 514, dwell 200  $\mu$ s.

220

### 221 3.3 *Cosmogenic radionuclide dating*

222 Cosmogenic radionuclide dating constrains the amount of time a rock has been situated at or near the surface  
223 of the Earth (e.g. Lal, 1991). Normal fault planes represent ideal objects for this dating technique as the  
224 incoming cosmic rays are only able to penetrate the progressively exposed parts of the fault (e.g. Palumbo et  
225 al., 2004). The basaltic lithologies of El Hierro determine that the most suitable cosmogenic nuclide with which  
226 to constrain periods of fault activity is  $^3\text{He}$  (e.g. Kurz, 1986; Poujol et al., 2014). The sampling strategy aimed,  
227 first, to obtain samples from the least eroded parts of the fault and, second, to avoid obtaining samples from  
228 the whitish part of the fault plane as this was known to have been exposed during road construction. Five  
229 samples were collected from two profiles along the footwall (Figure 2). These samples range in thickness from  
230 two to five centimetres and belong to the same basaltic sequence that erupted  $1.05\pm 0.02$  Ma (Carracedo et al.,  
231 2001). Samples were crushed and sieved to isolate fractions of less than 0.25 mm, 0.25-0.5 mm, and 0.5-2.0  
232 mm. Several physical separation techniques including magnetic separation and density separation were used to  
233 isolate pure olivine and pyroxene phenocrysts.

234

235 All helium analyses were performed in the noble gas platform of the Centre de Recherches Pétrographiques et  
236 Géochimiques in Nancy. Samples were fused *in vacuo* at 1600°C for 15 minutes using the new custom designed  
237 metal induction furnace of CRPG (Zimmermann et al., 2018). Typical furnace blanks were  $(1.9\pm 0.6) \times 10^{-19}$  and  
238  $(5\pm 4) \times 10^{-15}$  mol.g<sup>-1</sup> for  $^3\text{He}$  and  $^4\text{He}$ , respectively, which represented an average of 1 % and 0.1 % of the  $^3\text{He}$   
239 and  $^4\text{He}$  concentrations measured in the samples, respectively. The extracted gas then underwent standard gas  
240 purification (Blard et al., 2015). Helium was cryofocused at 8K before being released at 70K and introduced into  
241 the Split Flight Tube mass spectrometer, a Nier source static mass spectrometer optimised for the analysis of  
242 cosmogenic nuclides (Protin et al., 2016). The linearity of the mass spectrometer was carefully established by  
243 analysing standard splits with similar  $^4\text{He}$  pressure to those of the samples. During the one-month analytical

244 period the observed reproducibility of the system was 2 % at 1 $\sigma$ , for both  $^3\text{He}$  and  $^4\text{He}$ . Furthermore, during this  
 245 one-month period, two CRONUS-P pyroxene standards were analysed. These yielded  $^3\text{He}$  concentrations of  
 246  $(4.86\pm 0.14) \times 10^9 \text{ at.g}^{-1}$  and  $(5.01\pm 0.14) \times 10^9 \text{ at.g}^{-1}$ . Both values stand within the internationally recognised  
 247 error limits for this material (Blard et al., 2015). To determine the  $^3\text{He}/^4\text{He}$  ratio of the magmatic component  
 248 step crushing *in vacuo* was conducted on 0.5 mm to 2 mm olivines and pyroxenes obtained from Sample 5III  
 249 (1<sup>st</sup> step: 100 strokes, 1 min; 2<sup>nd</sup> step: 500 strokes, 5 mins; Table 1). Crushing blanks were  $(3\pm 2) \times 10^4$  and  $(7\pm 2)$   
 250  $\times 10^9$  for  $^3\text{He}$  and  $^4\text{He}$ , respectively. This represented 1 % and 4 % of the  $^3\text{He}$  and  $^4\text{He}$  analysed during the  
 251 second crushing step.

252

253 To determine cosmogenic  $^3\text{He}$  concentrations it was necessary to correct the melted  $^3\text{He}$  concentrations  
 254 ( $^3\text{He}_{\text{melt}}$ ) from the nucleogenic ( $^3\text{He}_{\text{nucleo}}$ ) and the magmatic ( $^3\text{He}_{\text{mag}}$ ) components:

255

$$256 \quad ^3\text{He}_{\text{cos}} = ^3\text{He}_{\text{melt}} - ^3\text{He}_{\text{nucleo}} - ^3\text{He}_{\text{mag}}$$

257

258 With:

259

$$260 \quad ^3\text{He}_{\text{nucleo}} = P_{3\text{nuc}} \times T_{\text{eruption}},$$

261

262  $P_{3\text{nuc}}$  is the production rate of nucleogenic  $^3\text{He}$ . In this study, a value of  $6 \times 10^{-3} \text{ at.g}^{-1} \cdot \text{a}^{-1}$  has been used,  
 263 computed using the equations of Andrews (1985) and the chemical composition measured in the phenocrysts  
 264 and bulk rock samples (Supp. Table A). Combined with a value of  $1.05 \pm 0.02 \text{ Ma}$  for  $T_{\text{eruption}}$ , based on the K-Ar  
 265 age of the San Andrés basalt presented in Carracedo et al. (2001), this yielded a value of  $(6 \pm 3) \times 10^3 \text{ at.g}^{-1}$  for  
 266  $^3\text{He}_{\text{nucleo}}$ .

267

268 In theory, the magmatic  $^3\text{He}$  component has to be computed following this equation from Blard and Farley  
 269 (2008):

270

$$271 \quad ^3\text{He}_{\text{mag}} = (^4\text{He}_{\text{melt}} - ^4\text{He}_{\text{rad}}) \times (^3\text{He}/^4\text{He})_{\text{crush}}$$

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With

$${}^4\text{He}_{\text{rad}} = P_{4\text{rad}} \times T_{\text{eruption}},$$

$P_{4\text{rad}}$  being the radiogenic  ${}^4\text{He}$  production rate in the analysed olivines and pyroxenes.  $P_{4\text{rad}}$  is computed using the equations of Blard and Farley (2008) and the U, Th, and Sm concentrations measured in samples COS4-I and COS5-II (Supp. Table A). Using the  $1.05 \pm 0.02$  Ma value for  $T_{\text{eruption}}$ , this yields  ${}^4\text{He}_{\text{rad}}$  theoretical concentrations ranging from  $1.2 \times 10^{12}$  at.g $^{-1}$  to  $4.1 \times 10^{12}$  at.g $^{-1}$ .

Such  ${}^4\text{He}_{\text{radio}}$  concentrations are similar to the total  ${}^4\text{He}$  concentrations measured by fusing the samples, which range from  $6.2 \times 10^{12}$  at.g $^{-1}$  to  $1.36 \times 10^{13}$  at.g $^{-1}$ , for an average of  $(3.3 \pm 4.6) \times 10^{12}$  at.g $^{-1}$ .

Thus the outlined approach for estimating  ${}^4\text{He}_{\text{rad}}$  represents the main source of uncertainty when computing the magmatic  ${}^3\text{He}$  correction and, in turn, the main source of uncertainty when computing the final cosmogenic  ${}^3\text{He}$  concentrations.

Instead, we decided to apply the following approach and compute a minimal and a maximal value for the cosmogenic  ${}^3\text{He}$  concentrations, as follow (Table 1):

$${}^3\text{He}_{\text{cos min}} = {}^3\text{He}_{\text{cos min}} - {}^3\text{He}_{\text{nucleo}} - {}^3\text{He}_{\text{crush mag}},$$

assuming that  ${}^3\text{He}_{\text{crush mag}}$  is the magmatic  ${}^3\text{He}$  concentration from the prolonged crushing  $(4.3 \pm 2.0) \times 10^6$  at.g $^{-1}$

$${}^3\text{He}_{\text{cos max}} = {}^3\text{He}_{\text{cos min}} - {}^3\text{He}_{\text{nucleo}}$$

${}^3\text{He}_{\text{cos min}}$  concentrations range from less than  $2 \times 10^6$  at.g $^{-1}$  to  $(1.19 \pm 0.20) \times 10^7$  at.g $^{-1}$  while  ${}^3\text{He}_{\text{cos max}}$  range from  $(2.22 \pm 2.04) \times 10^6$  at.g $^{-1}$  to  $(2.17 \pm 0.21) \times 10^7$  at.g $^{-1}$ .

301 Finally,  $^3\text{He}_{\text{cos}}$  exposure ages were computed using the CREp calculator ([crep.crgp.cnrs-nancy.fr](http://crep.crgp.cnrs-nancy.fr)), with the world  
302 averaged  $^3\text{He}$  production rate, the standard atmosphere, and the Lal-Stone time dependent model (Martin et  
303 al., 2017). The production rate was computed taking into account the spatial characteristic of the samples,  
304 including self-shielding (Table 1).

305

## 306 **4. Results**

### 307 *4.1 Field data and structural analyses*

308 The NE section of the San Andrés Fault outcrop is morphologically well preserved while its SW section has been  
309 smoothed as a result of weathering and incurred some damage during road construction. In general, the  
310 exposed fault plane is straight with an orientation of approximately 170/70° (dip direction/dip angle). Only  
311 some irregularities can be observed such as two remarkable fault plane undulations protruding from its  
312 surface, with widths of up 4 m, separated by a parallel depression (Figure 3A-B). These irregularities were also  
313 recognised during structural geological measurements. In greater detail, it has been possible to identify  
314 numerous linear features, which have been grouped into three families on the basis of their character and  
315 orientation (Figure 3A-C). First, a family of centimetre to metre scale striations were identified on the basis of  
316 structural measurements and from the slope gradient maps. These striations cover most of the outcrop but are  
317 best preserved on the fault plane undulations. Most commonly, the striations plunge with azimuths of 125° and  
318 131°. Second, a family of smooth elongated undulations and strongly elongated protrusions were also  
319 identified on the basis of structural measurements and from the slope gradient maps. These features are best  
320 seen in the northeastern section of the fault plane. The undulations and protrusions plunge with an azimuth of  
321 111°. Third, a family of very smooth, spatially limited, slightly elongated protrusions were identified from the  
322 fault perpendicular slope gradient map. These are found in the lower SW and upper NE part of the 4 m wide  
323 fault plane undulation as well as at the crest of the other undulation protruding from surface to the NE. The  
324 protrusions plunge with an azimuth of 158°.

325

326 A photomosaic offering a perpendicular view of the fault outcrop overlain by a raster of interpolated R values is  
327 presented on Figure 4. Proportional plots illustrate the spatial variability in rock hardness across the outcrop. In  
328 general, higher R values have been measured on the lower and right side of the fault outcrop than have been  
329 measured on its upper and left side. The highest R values, indicating the least weathering, have been recorded

330 in the lowermost part of the fault outcrop on its right side ( $R > 50$ ). This finding is not surprising given that the  
331 hard whitish surface was exposed only recently during construction of the road. High R values have also been  
332 recorded on the far left side of the fault outcrop ( $R > 40$ ). This finding is more surprising but it can be explained  
333 by several tens of centimetres of erosion on the fault surface and the presence of harder basalt blocks within  
334 the tectonic breccia. Conspicuously low R values have been recorded in a wedge-shaped zone between 23 m  
335 and 26 m ( $R < 25$ ). Here a rather soft gouge material is attached to the fault surface and the vegetation cover  
336 descends much lower than elsewhere – this suggests that chemical and biological weathering processes are  
337 more intense in this area.

338

#### 339 4.2 *Petrographic analyses*

340 The host rock basanites are fine grained basic rocks (samples PET3 and PET4). These rocks contain mainly  
341 pyroxene, plagioclase, olivine, amphibole and volcanic glass, together with the accessory minerals (apatite,  
342 chromite, magnetite, and Ti-magnetite). The pyroxene is represented by diopside. The plagioclases are usually  
343 zoned with a basic core ( $An_{79-83}$ ) and acid rim ( $An_{45-70}$ ). Olivine occurs only in basanites with subordinate  
344 amounts of volcanic glass. The olivine is enriched by forsterite component (75-80 mol. %). The amphibole is  
345 represented by magnesiohornblende to hornblende tschermakite. The texture of the groundmass is mostly  
346 ophitic and gives no indication of a pre-existing preferred fabric orientation. The tectonic breccias sampled  
347 from the fault plane are composed of fragments of volcanic rock (up to several centimetres), cemented by a  
348 very fine grained groundmass containing abundant fragments of the original volcanic rock (millimetres to  
349 centimetres on samples PET1 and PET2). The higher proportion of fine grained Fe-oxides and Fe-hydroxides  
350 imparts a rusty colour of these tectonic breccias. However, the volume of Fe-oxides and Fe-hydroxides is highly  
351 variable, with significant enrichment in the fine grained groundmass of the original volcanic rock. The tectonic  
352 breccias are cross-cut by zeolite veins in a range of orientations and sizes. Frictionite, or landslide  
353 pseudotachylyte, was found in samples obtained directly from the fault plane (Figure 2). This is composed of  
354 relict frictional melt and material similar to tectonic breccia (Figures 5-7).

355

#### 356 4.3 *Microstructural analyses*

357 The NE part of the fault outcrop is covered by a whitish layer which attains a maximum thickness in the order  
358 of several centimetres. Figure 2 shows examples of the whitish layer that overlies the grey cataclasite and

359 microbreccias. In some cases this whitish layer comes into direct contact with tectonic  
360 breccia is highly oxidised (Figure 2D, F). Brecciation intensity increases from the undeformed basanite to the  
361 more deformed breccia, i.e. towards the fault surface. This breccia may be the product of an earlier slip event.  
362 However, here we focus on the cataclasite and the whitish layer, i.e. those layers that overlie the tectonic  
363 breccia. Using optical microscopy, it is possible to differentiate two distinct layers within the frictionite by their  
364 composition and microstructure: a structurally lower cataclasite and a structurally higher silica layer.

365

366 The cataclasite cuts the tectonic breccia while in places it is cut by the silica layer. Contact with the host rock is  
367 characterised by a sharp boundary that is observed in both hand samples and optical micrographs (Figure 6).  
368 Although the cataclasite is grey in hand samples, it is dark brown in optical micrographs (Figure 6A, B) while the  
369 sharpness of the contact is accentuated by the truncation of several clasts (Figures 6 & 7). The main  
370 characteristics of this layer are grain size reduction and P- foliation, terminology of Passchier and Trouw, 2005).  
371 The zones of grain size reduction, in which grain sizes range from c. 10  $\mu\text{m}$  to c. 100  $\mu\text{m}$ , are defined by P- and  
372 Y- shears (Figure 6B, D). A dextral sense of shear is indicated by the P- and Y- shears along with a winged  
373 inclusion visible in the optical micrographs (Figure 6A, B). This finding is consistent with structural observations  
374 made at the outcrop scale. Elemental maps highlight the similarity between the composition of the host rock  
375 and the composition of the cataclasite (Figure 6E, F). Moreover, this similarity is accentuated by the apparent  
376 resemblance in composition of a truncated clast, itself in contact with the cataclasite (Figure 6E, F). A second  
377 cataclasite has a more lensoid shape which is apparently defined by P- and Y- shears (Figure 7). It exhibits  
378 strong P-foliation which is seen most readily in the elemental maps (Figure 7C, E). In addition, cracks within this  
379 layer are parallel to both the Y-shear, and the slip surface, and are filled with silica (Figure 7E).

380

381 The silica layer cuts both the tectonic breccia and the cataclastic layer. The boundary between the silica layer  
382 and the subjacent rocks is a sharp, single line, which crosscuts foliation in the cataclasite and truncates clasts in  
383 the tectonic breccia. The boundary between the cataclasite layer and the silica layer is sometimes marked by  
384 shiny sublayers that parallel the boundary (Figure 6B, H) and exhibit a high interference colour when seen  
385 under cross polarised light with a gypsum tint plate (Figure 5C). There is no indication of mixing between the  
386 cataclasite and the silica layer across the boundary separating these layers. The silica layer appears to be  
387 translucent, white to pale coloured under plane polarised light (Figures 5-7). It is composed of a



388 microcrystalline to amorphous silica matrix with a thickness of c. 250  $\mu\text{m}$  to 350  $\mu\text{m}$ . The architecture varies:  
389 the matrix consists of an inclusionless silica material that develops into complex structures with flow bands  
390 (Figures 5-7), cataclastic sublayers (Figure 5H), and clast-cortex aggregates (Figure 6G, I). Flow bands, which  
391 vary in thickness from c. 25  $\mu\text{m}$  to c. 110  $\mu\text{m}$ , correspond to P- and Y- shears in the cataclastic layer fabric and  
392 are characterised by a change in the amount of Mg (Figure 5L and Figure 6C, D). Cataclasite sublayers form  
393 lenticular shapes (Figure 5H). These sublayers appear to have a similar composition to the cataclasite layer but  
394 with a finer grain size and present evidence of material mixing with the silica layer. Some clasts embedded in  
395 the silica layer have a cortex, or armour, and these are referred to as clast-cortex aggregates. The clast-cortex  
396 aggregates vary in size, from c. 90  $\mu\text{m}$  to 290  $\mu\text{m}$ , complexity, and composition. Those clasts within the  
397 aggregates consist of fragments of adjacent rock (Figure 7G) or silica matrix (Figure 6I). A complex cortex  
398 texture with what appears to be several coatings has been observed (Figure 6G). Elemental maps show that the  
399 cortex composition varies as well (e.g. Figure 6L and Figure 7D, E). It is believed that a significant amount of the  
400 cortex material was lost during preparation of the thin sections (e.g. Figure 6G-I).

401

#### 402 4.4 *Cosmogenic radionuclide dating*

403 Cosmogenic  $^3\text{He}$  exposure ages reveal significant differences between each of the two sampled profiles. Sample  
404 COS1 has yielded a maximum exposure age of  $21\pm 20$  ka while samples COS2 and COS3 have yielded a  
405 maximum exposure age of  $26\pm 18$  ka. Replicates of sample COS4 yielded exposure ages ranging from  $21\pm 19$  to  
406  $61\pm 19$  ka while replicates of sample COS5 yielded exposure ages ranging from  $52\pm 17$  to  $183\pm 17$  ka (Table 1).  
407 These results indicate that movement across the currently exposed portion of the fault plane occurred over a  
408 short period of time as suggested by the fact that there is no gradual decrease in exposure ages from upper to  
409 lower part of the two profiles.

410

411 The right hand profile (samples COS1-3) revealed exposures ages that are below the detection limit i.e. these  
412 were exposed between 0 and 26 ka. These young exposure ages most probably reflect recent exhumation on  
413 the right hand part of the fault owing to the fact that the right hand profile is separated from the left hand  
414 profile by only 6-7 m. Intense erosion of the right hand profile can be excluded as the R values indicate much  
415 greater hardness, i.e. less weathering, here than on the left hand profile.

416

417 The left hand profile (samples COS4 and COS5) revealed exposure ages between 21 and 183 ka. The higher  
418 sample COS4 provides a younger age than the lower sample COS5. Under normal circumstances this should not  
419 be possible – the highest parts of the fault should be exposed before its lower parts – and it suggests that the  
420 higher sample has been subjected to weathering. Consequently sample COS5 offers the most reliable results as  
421 it has neither been affected by weathering nor by recent exhumation. The high variability of computed  
422 exposure ages between the replicate in this sample is due to the considerable uncertainty associated with the  
423 estimate of the magmatic  $^3\text{He}$  component as outlined in Section 3.3. Nonetheless it is believed that the most  
424 recent fault reactivation occurred between the calculated exposure ages of sample COS5 ( $52\pm 17$  to  $183\pm 17$  ka).

425

## 426 **5. Interpretation and discussion**

### 427 5.1 *Landslide displacement direction*

428 Distinct families of linear and elongated features at the fault plane evidence past behaviour of the rock mass  
429 (Sagy et al., 2007). Two major slip events are interpreted to have occurred on the studied fault plane on the  
430 basis of the relative position and general morphology of such features. The older phase is represented by the  
431 family of smooth elongated undulations and strongly elongated bumps, best preserved in the depressions and  
432 flats in the northeastern section of the fault plane, which have a plunge direction of  $111^\circ$ . During this phase the  
433 rock mass moved towards the ESE. The younger phase is represented by the other two families of linear and  
434 elongated features. The onset of this phase is interpreted to have commenced with minor, most probably slow  
435 displacement towards the SSE. Support for this is gleaned from the smooth, spatially limited, elongated bumps  
436 which have a plunge direction of  $158^\circ$ . The displacement rate is then interpreted to have accelerated as the  
437 rock mass moved more towards the SE. Support for this is gleaned from the centimetre to metre scale  
438 striations which cover most of the fault outcrop and have plunge directions of  $125^\circ$  and  $131^\circ$ . The general  
439 appearance of these features is sufficiently similar to assume that they developed during a single slip phase. It  
440 is supposed that this shift in the displacement direction, from the SSE to the SE, can be explained by either a  
441 sudden change in the geometry of the slip surface or a fundamental change in the morphology of the entire  
442 volcanic edifice. It is known that El Hierro underwent a clockwise rotation of  $15^\circ$ , beginning around 440 ka  
443 (Szérméta et al., 1999), and it has been suggested that this rotation could be associated with activity on the  
444 San Andrés Landslide and the debris avalanche Las Playas I (Carracedo, 2008).

445

446 5.2 *Fault related microstructures and dynamic rock reworking*

447 The microstructures seen on the surface of the San Andrés Fault are believed to be a result of fast slip,  
448 associated with frictional heating and partial melting during landslide emplacement. The first line of evidence  
449 for flash heating during flank collapse is observed in both hand samples and polished slabs as heat diffused in  
450 the underlying material: the adjacent host rock and tectonic breccia exhibits increasing level of oxidisation  
451 towards the fault surface. This is similar for pseudotachylytes reported from the Köfels landslide (Masch et al.,  
452 1985) and from the Arequipa volcanic landslide deposit in Peru (Legros et al., 2000). The second line of  
453 evidence comes from the crosscutting relationships between either the host rock or the tectonic breccia and  
454 the deformation layers. All of the observed contacts are sharp and accentuated by multiple truncated clasts.  
455 This type of crosscutting relationship indicates fast displacement and is often considered a strong indication of  
456 a seismic slip (Passchier and Trouw, 2005; Price et al., 2012; Smeraglia et al., 2017). The third line of evidence  
457 comes from the boundary between the silica layer and the adjacent rocks. This boundary is characterised by  
458 shiny bands that exhibit a high interference colour under cross polarised light and a positive optical sign under  
459 cross polarised light using a gypsum tint plate. These bands are tentatively interpreted as recrystallised  
460 material resulting from frictional melting but further analyses are needed to confirm this supposition.

461

462 The cataclastic layer exhibits P-foliation, grain size reduction, and the development of winged clasts in a  
463 heterogeneous matrix. The winged clast presented in Figure 5 resembles those of Grasemann and Dabrowski  
464 (2015) and Grasemann et al. (2019). The foliation developed within this layer is typical of brittle deformation,  
465 with Y- shears parallel to the slip surface, and P-shears inclined relative to the slip surface (i.e. Figure 5I). This  
466 type of foliation cannot be used as an indicator for fast slip as it is recorded in association with both seismic  
467 and creep phenomena (Verberne et al., 2013; Smeraglia et al., 2017). However, unequivocal evidence for fast  
468 slip, instead of progressive creep, is provided by the fact that the contact between the cataclastic layer and the  
469 adjacent rock is sharp and accentuated by multiple truncated clasts. The cataclasite architecture is similar to  
470 those described in other volcanic pseudotachylytes (Lavallée et al., 2012, 2014; Kendrick et al., 2012, 2014) as  
471 well as to that described in seismically deformed limestones (Smith et al., 2011). Therefore, it is necessary to  
472 define this cataclastic layer as frictionite *sensu lato*, as it was almost certainly emplaced during catastrophic  
473 landslide emplacement but there is no decisive proof of flash heating.

474

475 In contrast, the silica layer is defined as frictionite *sensu stricto*, as it is comparable to traditional  
476 pseudotachylytes (e.g. Passchier and Trouw, 2005; Price et al., 2012; Rowe and Griffith, 2015). Here a list of  
477 particularly pertinent features is presented with reference to the identification criteria for deformed  
478 pseudotachylytes (Passchier and Trouw, 2005; Price et al., 2012):

479

480 i. *Crosscutting relationships with sharp layer boundaries.* The silica layer cuts the cataclasite  
481 foliation and the boundaries are accentuated by clast truncation and presence of shiny bands  
482 which have been interpreted as recrystallised material from frictional melting. Analogous  
483 microstructural features have been reported from numerous natural and experimental cases of  
484 seismic slip (e.g. Fondriest et al., 2013; Smeraglia et al., 2017; Tesei et al., 2017).

485

486 ii. *The presence of fragments of host rock.* Fragments of adjacent rock appear as isolated islands and  
487 vary in size, shape, and complexity. The more complex clasts have an encasing cortex, or armour,  
488 and are referred to as clast-cortex aggregates. Typically, those fragments described here have a  
489 volcanic clast in the core, cataclastic material in the rim, and they parallel the foliation. In a  
490 number of senses, they are similar to “armoured clasts” or “accretionary rounded grains” (Anders  
491 et al., 2010; Rowe et al., 2012; Kirkpatrick et al., 2013) and clay-clast aggregates (Boutareaud et  
492 al., 2008; Han et al., 2011). The main differences are the ratio between the clast and the rim and  
493 their composition. The rims described here appear to be wider than previously reported while  
494 they are neither composed of clay nor any other mineral assemblage. Consequently, the clast-  
495 cortex aggregates presented in this study are most readily comparable to the accretionary  
496 rounded grains described from the Corona Heights Fault (Kirkpatrick et al., 2013).

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498 iii. *The presence of an ultra-fine grained matrix.* The silica layer comprises a homogenous silica  
499 matrix, ultra-fine grained to amorphous, which is very similar to silica gel (Kirkpatrick et al., 2013;  
500 Faber et al., 2014) and amorphous nanopowder (Rowe et al., 2019). More detailed studies are  
501 needed in order to measure the amount of water and crystalline material that occurs in this  
502 matrix. The presence of new grains that have grown in the voids or bubbles indicates that at least  
503 some of this matrix must be crystalline.

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iv. *Inherited compositional variations from flow structures.* Flow bands in the silica layer are defined by optical and compositional variations. Optical variations are evident as shiny bands and they can be traced along the whole length of the layer. The flow bands are structurally controlled, as they parallel the P- and Y- shears, and they localise clasts and clast-cortex aggregates as well as Mg-enriched material. Further analyses are needed to fully understand their origin. Similar to these flow bands are the cataclastic sublayers, which are also structurally controlled, but with evidence for the reworking of cataclastic material. This feature, together with presence of clast-cortex aggregates is interpreted as fluidised granular flow reported in many geologic settings (Boutareaud et al., 2008; Anders et al., 2010; Ujiie et al., 2011; Kirkpatrick et al., 2013). Furthermore, fluidised cataclasites have been suggested as a record of seismic slip rates (Brodsky et al., 2009; Rowe et al., 2005).

v. *Differences between the matrix and host rock mineral assemblages.* The most conspicuous difference between the silica layer and the adjacent rocks is in the mineral assemblage. The homogenous silica layer contrasts greatly with the polymineralic cataclasite and the host rock. Even though the silica layer can be assumed to be a product of hydrothermal fluid deposition, the presence of kinematic indicators such as shears and flow bands consistent with observations at the outcrop scale, indicate that the silica layer was formed as a product of frictional slip. Silica has been reproduced in fast slip experiments (e.g. Di Toro et al., 2011; Kirkpatrick et al., 2013; Rowe et al., 2019) and is considered to be a product of frictional wear that weakens the fault, acting as a lubricant (Rowe et al., 2019).

### 5.3 *Conceptual model for the San Andrés Landslide*

A conceptual model for the development of the San Andrés Landslide is proposed here on the basis of the findings presented in this study and age estimates presented elsewhere in the published literature (Figure 8). The first slip event as evidenced by the cataclastic layer is proposed to have occurred between 545 ka and 430 ka. The lower limit for fault activity is defined by the onset of volcanism associated with the El Golfo Series (Guillou et al., 1996) while the upper limit for fault activity is defined by the onset of the clockwise rotation of

533 El Hierro (Széreméta et al., 1999). The second slip event as evidenced by the silica layer is proposed to have  
534 occurred between  $183 \pm 17$  and  $52 \pm 17$  ka based on the presented cosmogenic  $^3\text{He}$  exposure dates. This age  
535 range spans termination of volcanism associated with the El Golfo-Las Playas Unit and the onset of volcanism  
536 associated with the Rift Series at 145 ka (Guillou et al., 1996). The lower limit for fault activity broadly relates to  
537 the probable timing of the debris avalanches El Golfo A, between 176 ka and 133 ka, and Las Playas II, between  
538 176 ka and 145 ka. Moreover, the upper limit for fault activity broadly relates to the probable timing of the  
539 debris avalanche El Golfo B, between 87 ka and 39 ka. Thus, it is believed that the factor, or factors, which  
540 triggered one of these giant debris avalanches may have triggered the second slip event described in this study  
541 but no other data have yet been found to support this hypothesis. In addition, a conceptual model is presented  
542 for the development of the surface of the San Andrés Fault (Figure 9). The developmental model outlined here  
543 is broadly consistent with the findings of Day et al. (1997). In that study, it was suggested that the minimum  
544 age of the San Andrés Fault should be between 250 ka and 150 ka and that the fault could have been active  
545 only for a geologically short period of less than 400 ka. Their assertions are based on a younger undisturbed  
546 lava flow which covers the southern part of the fault.

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## 549 **6. Conclusions**

550 In this study the fault plane of the San Andrés Landslide on El Hierro in the Canary Islands has been investigated  
551 through a combination of geological and geomorphological measurements, petrological and mineralogical  
552 analyses, and cosmogenic  $^3\text{He}$  exposure dating.

- 553 • The fault surface is composed of a striated frictionite which is in contact with a highly oxidised tectonic  
554 breccia. The tectonic breccia transitions into the underlying undeformed basanite host rock.  
555 Microstructural analysis of the frictionite has revealed two distinct layers: a dark heterogeneous  
556 cataclastic layer and a translucent silica layer with a thickness of up to 1 cm.
- 557 • The architecture of the samples and the observed crosscutting relationships suggest that the  
558 cataclastic layer and the silica layer represent two separate slip events associated with seismic rupture  
559 during landslide emplacement. Moreover, the notion of two distinct slip phases is supported by  
560 kinematic markers etched on the fault surface.

561 • This information – coupled with the cosmogenic exposure dating and knowledge about the geological  
562 history of the island – forms basis of a conceptual model for the development of the San Andrés  
563 Landslide. The first slip event, represented by the cataclastic layer, is thought to have occurred  
564 between 545 ka and 430 ka while the second slip event, represented by the silica layer, is thought to  
565 have occurred between  $183 \pm 17$  and  $52 \pm 17$  ka.

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567 This is the first time that more than one slip event has ever been recognised on a single fault plane resulting  
568 from volcanic flank collapse on an oceanic island. It suggests that the possibility of reactivating supposedly  
569 inactive fault structures may be far greater than hitherto assumed. This is a key finding, which may lead to re-  
570 evaluation of the threats related to volcanic islands collapses. Furthermore, it is believed that this is the first  
571 time a silica layer resulting from frictional melt has been described from a volcanic setting.

572

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577

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### 583 **References**

584 Agisoft LLC, 2014. Agisoft PhotoScan User Manual, Professional Edition, Version 1.1. Agisoft LLC, St. Petersburg,  
585 78 pp.

586 Agliardi, F., Crosta, G., Zanchi, A., 2001. Structural constraints on deep seated slope deformation kinematics.  
587 Engineering Geology 59, 83-102. [https://doi.org/10.1016/S0013-7952\(00\)00066-1](https://doi.org/10.1016/S0013-7952(00)00066-1)

588 Ancochea, E., Barrera, J., Bellido, F., Benito, R., Brändle, J., Cebriá, J., Coello, J., Cubas, C., De la Nuez, J., Gómez,  
589 J., 2004. Canarias y el vulcanismo neógeno peninsular. In: Vera, J. (Ed.), *Geología de España*. Sociedad  
590 Geológica de España-Instituto Geológico y Minero de España, Madrid, pp 635-682.

591 Anders, M., Fouke, B., Zerkle, A., Tavarnelli, E., Alvarez, W., Harlow, G., 2010. The role of calcining and basal  
592 fluidization in the long runout of carbonate slides: an example from the Heart Mountain Slide Block,  
593 Wyoming and Montana, U.S.A. *The Journal of Geology* 118, 577-599. <https://doi.org/10.1086/656383>

594 Andrews, J., 1985. The isotopic composition of radiogenic helium and its use to study groundwater movement  
595 in confined aquifers. *Chemical Geology* 49, 339-351. [https://doi.org/10.1016/0009-2541\(85\)90166-4](https://doi.org/10.1016/0009-2541(85)90166-4)

596 Aydin, A., Basu, A., 2005. The Schmidt hammer in rock material characterization. *Engineering Geology* 81, 1-14.  
597 <https://doi.org/10.1016/j.enggeo.2005.06.006>

598 Balek, J., Blahůt, J., 2017. A critical evaluation of the use of an inexpensive camera mounted on a recreational  
599 unmanned aerial vehicle as a tool for landslide research. *Landslides* 14, 1217-1224.  
600 <https://doi.org/10.1007/s10346-016-0782-7>

601 Becerril, L., Ubide, T., Sudo, M., Martí, J., Galindo, I., Galé, C., Morales, J., Yepes, J., Lago, M., 2016a.  
602 Geochronological constraints on the evolution of El Hierro (Canary Islands). *Journal of African Earth*  
603 *Sciences* 113, 88-94. <https://doi.org/10.1016/j.jafrearsci.2015.10.012>

604 Becerril, L., Galve, J., Morales, J., Romero, C., Sánchez, N., Martí, J., Galindo, I., 2016b. Volcanostructure of El  
605 Hierro (Canary Islands). *Journal of Maps* 12, Supplement 1, 43-52.  
606 <https://doi.org/10.1080/17445647.2016.1157767>

607 Benito-Saz, M., Parks, M., Sigmundsson, F., Hooper, A., García-Cañada, L., 2017. Repeated magmatic intrusions  
608 at El Hierro Island following the 2011-2012 submarine eruption. *Journal of Volcanology and Geothermal*  
609 *Research* 344, 79-91. <https://doi.org/10.1016/j.jvolgeores.2017.01.020>

610 Blahůt, J., Rowberry, M., Balek, J., Klimeš, J., Baroň, I., Meletlidis, S., Martí, X., 2017. Monitoring giant landslide  
611 detachment planes in the era of big data analytics. In: Mikoš, M., Arbanas, Ž., Yin, Y., Sassa, K. (Eds.),  
612 *Advancing Culture of Living with Landslides, Volume 3*. Springer, Cham, pp. 333-340.  
613 [https://doi.org/10.1007/978-3-319-53487-9\\_38](https://doi.org/10.1007/978-3-319-53487-9_38)

614 Blahůt, J., Klimeš, J., Rowberry, M., Kusák, M., 2018a. Database of giant landslides on volcanic islands - first  
615 results from the Atlantic Ocean. *Landslides* 15, 823-827. [https://doi.org/10.1007/s10346-018-0967-](https://doi.org/10.1007/s10346-018-0967-3)  
616 [3Blahůt, J., Baroň, I., Sokol, L., Meletlidis, S., Klimeš, J., Rowberry, M., Melichar, R., García-Cañada, L.,](https://doi.org/10.1007/s10346-018-0967-3)



617 Martı́, X., 2018b. Large landslide stress states calculated during extreme climatic and tectonic events on  
618 El Hierro, Canary Islands. *Landslides* 15, 1801-1814. <https://doi.org/10.1007/s10346-018-0993-1>

619 Blahůt, J., Balek, J., Klimeš, J., Rowberry, M., Kusák, M., Kalina, J., 2019. A comprehensive global database of  
620 giant landslides on volcanic islands. *Landslides* 16 (10), 2045-2052. [https://doi.org/10.1007/s10346-](https://doi.org/10.1007/s10346-019-01275-8)  
621 [019-01275-8](https://doi.org/10.1007/s10346-019-01275-8)

622 Blard, P.-H., Balco, G., Burnard, P., Farley, K., Fenton, C., Friedrich, R., Jull, A., Niedermann, S., Pik, R., Schaefer,  
623 J., Scott, E., Shuster, D., Stuart, F., Stute, M., Tibari, B., Winckler, G., Zimmermann, L., 2015. An inter-  
624 laboratory comparison of cosmogenic <sup>3</sup>He and radiogenic <sup>4</sup>He in the CRONUS-P pyroxene standard.  
625 *Quaternary Geochronology* 26, 11-19. <https://doi.org/10.1016/j.quageo.2014.08.004>

626 Blard, P.-H., Farley K., 2008. The influence of radiogenic <sup>4</sup>He on cosmogenic <sup>3</sup>He determinations in volcanic  
627 olivine and pyroxene. *Earth and Planetary Science Letters* 276, 20-29.  
628 <https://doi.org/10.1016/j.epsl.2008.09.003>

629 Boutareaud, S., Calugaru, D.-G., Han, R., Fabbri, O., Mizoguchi, K., Tsutsumi, A., Shimamoto, T., 2008. Clay-clast  
630 aggregates: a new textural evidence for seismic fault sliding? *Geophysical Research Letters* 35, L05302.  
631 <https://doi.org/10.1029/2007GL032554>

632 Brodsky, E., Rowe, C., Meneghini, F., Moore, J., 2009. A geological fingerprint of low viscosity fault fluids  
633 mobilized during an earthquake. *Journal of Geophysical Research, Solid Earth* 114, B01303.  
634 <https://doi.org/10.1029/2008JB005633>

635 Carracedo, J.-C., 2008. *Canarian Volcanoes IV: La Palma, La Gomera, El Hierro*. Editorial Rueda S.L., Madrid, 213  
636 pp.

637 Carracedo, J.-C., Day, S., Guillou, H., Pérez Torrado, F., 1997. *Geology of the island of El Hierro, Canary Islands:*  
638 *stratigraphy, volcanology, and structure*. Excursion Guidebook, International Workshop on Volcanism  
639 and Volcanic Hazards in Immature Intraplate Oceanic Islands, La Palma, 43 pp.

640 Carracedo, J.-C., Day, S., Guillou, H., Pérez Torrado, F., 1999. Giant quaternary landslides in the evolution of La  
641 Palma and El Hierro, Canary Islands. *Journal of Volcanology and Geothermal Research* 94, 169-190.  
642 [https://doi.org/10.1016/S0377-0273\(99\)00102-X](https://doi.org/10.1016/S0377-0273(99)00102-X)

643 Carracedo, J.-C., Rodríguez Badiola, E., Guillou, H., De la Nuez, H., Pérez Torrado, F., 2001. *Geology and*  
644 *volcanology of the western Canaries: La Palma and El Hierro*. *Estudios Geológicos* 57, 171-295.

645 Carracedo, J.-C., Troll, V., 2016. *The Geology of Canary Islands*. Elsevier, Amsterdam, 622 pp.

646 Day, S., Carracedo, J.-C., Guillou, H., 1997. Age and geometry of an aborted rift flank collapse: the San Andres  
647 fault system, El Hierro, Canary Islands. *Geological Magazine* 134, 523-537.  
648 <https://doi.org/10.1017/S0016756897007243>

649 De Blasio, F., Elverhøj, A., 2008. A model for frictional melt production beneath large rock avalanches. *Journal*  
650 *of Geophysical Research, Earth Surface* 113, F02014. <https://doi.org/10.1029/2007JF000867>

651 Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., Ferri, F., Cocco, M., Shimamoto, T., 2011.  
652 Fault lubrication during earthquakes. *Nature* 471, 494-499. <https://doi.org/10.1038/nature09838>

653 Duffield, W., 1975. Structure and origin of the Koahe Fault System, Kilauea Volcano, Hawaii. United States  
654 Geological Survey, Professional Paper 856, 12 pp.

655 Faber, C., Rowe, C., Miller, J., Fagereng, Å., Neethling, J., 2014. Silica gel in a fault slip surface: field evidence for  
656 palaeo-earthquakes? *Journal of Structural Geology* 69 108-121.  
657 <https://doi.org/10.1016/j.jsg.2014.09.021>

658 Fondriest, M., Smith, S., Candela, T., Nielsen, S., Mair, K., Di Toro, G., 2013. Mirror-like faults and power  
659 dissipation during earthquakes. *Geology* 41, 1175-1178. <https://doi.org/10.1130/G34641.1>

660 Gomberg, J., Bodin, P., Savage, W., Jackson, M., 1995. Landslide faults and tectonic faults, analogs? The  
661 Slumgullion earthflow, Colorado. *Geology* 23, 41-44. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1995)023<0041:LFATFA>2.3.CO;2)  
662 [7613\(1995\)023<0041:LFATFA>2.3.CO;2](https://doi.org/10.1130/0091-7613(1995)023<0041:LFATFA>2.3.CO;2)

663 Gómez Sainz de Aja, J., Klein, E., Ruiz García, M., Balcells Herrera, R., Del Pozo, M., Galindo, E., La Moneda, E.,  
664 2010. Mapa Geológico de España, Escala 1:25 000, Valverde (Isla de El Hierro), Hoja N° 1105-II,  
665 Memoria. Instituto Geológico y Minero de España, Madrid, 96 pp.

666 Goudie, A., 2006. The Schmidt hammer in geomorphological research. *Progress in Physical Geography* 30, 703-  
667 718. <https://doi.org/10.1177/0309133306071954>

668 Grasemann, B., Dabrowski, M., 2015. Winged inclusions: pinch-and-swell objects during high-strain simple  
669 shear. *Journal of Structural Geology* 70, 78-94. <https://doi.org/10.1016/j.jsg.2014.10.017>

670 Grasemann, B., Dabrowski, M., Schöpfer, M., 2019. Sense and non-sense of shear reloaded. *Journal of*  
671 *Structural Geology* 125, 200-228. <https://doi.org/10.1016/j.jsg.2018.05.028>

672 Guillou, H., Carracedo, J.-C., Pérez Torrado, F., Rodríguez Badiola, E., 1996. K-Ar ages and magnetic stratigraphy  
673 of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands. *Journal of Volcanology and*  
674 *Geothermal Research* 73, 141-155. [https://doi.org/10.1016/0377-0273\(96\)00021-2](https://doi.org/10.1016/0377-0273(96)00021-2)

675 Han, R., Hirose, T., 2012. Clay-clast aggregates in fault gouge: an unequivocal indicator of seismic faulting at  
676 shallow depths? *Journal of Structural Geology* 43, 92-99. <https://doi.org/10.1016/j.jsg.2012.07.008>

677 Han, R., Hirose, T., Shimamoto, T., Lee, Y., Ando, J., 2011. Granular nanoparticles lubricate faults during seismic  
678 slip. *Geology* 39, 599-602. <https://doi.org/10.1130/G31842.1>

679 Hildenbrand, A., Marques, F., Catalao, J., Catita, C., Costa, A., 2012. Large scale active slump of the  
680 southeastern flank of Pico Island, Azores. *Geology* 40, 939-942. <https://doi.org/10.1130/G33303.1>

681 Hunt, J.E., Wynn, R.B., Talling, P.J., Masson, D.G., 2013. Multistage collapse of eight western Canary Island  
682 landslides in the last 1.5 Ma: Sedimentological and geochemical evidence from subunits in submarine  
683 flow deposits. *Geochemistry Geophysics Geosystems* 14(7), 2159-2181. [https://doi.org/](https://doi.org/10.1002/ggge.20138)  
684 [10.1002/ggge.20138](https://doi.org/10.1002/ggge.20138)

685 Hunt, J.E., Cassidy, M., Talling, P.J., 2018. Multi-stage volcanic island flank collapses with coeval explosive  
686 caldera-forming eruptions. *Scientific Reports* 8, 1146. <https://doi.org/10.1038/s41598-018-19285-2>

687 Jaboyedoff, M., Penna, I., Pedrazzini, A., Baroň, I., Crosta, G., 2013. An introductory review on gravitational  
688 deformation induced structures, fabrics, and modeling. *Tectonophysics* 605, 1-12.  
689 <https://doi.org/10.1016/j.tecto.2013.06.027>

690 Karstens, J., Berndt, C., Urlaub, M., Watt, S.F.L., Micallef, A., Ray, M., Klauke, I., Muff, S., Klaeschen, D., Kühn,  
691 M., Roth, T., Böttner, C., Schramm, B., Elger, J., Brune, S., 2019. From gradual spreading to catastrophic  
692 collapse – Reconstruction of the 1888 Ritter Island volcanic sector collapse from high-resolution 3D  
693 seismic data. *Earth and Planetary Science Letters* 517, 1-13. <https://doi.org/10.1016/j.epsl.2019.04.009>

694 Kendrick, J., Lavallée, Y., Ferk, A., Perugini, D., Leonhardt, R., Dingwell, D., 2012. Extreme frictional processes in  
695 the volcanic conduit of Mount St. Helens (USA) during the 2004-2008 eruption. *Journal of Structural*  
696 *Geology* 38, 61-76. <https://doi.org/10.1016/j.jsg.2011.10.003>

697 Kendrick, J., Lavallée, Y., Hess, K.-U., De Angelis, S., Ferk, A., Gaunt, H., Meredith, P., 2014. Seismogenic  
698 frictional melting in the magmatic column. *Solid Earth* 5, 199-208. [https://doi.org/10.5194/se-5-199-](https://doi.org/10.5194/se-5-199-2014)  
699 [2014](https://doi.org/10.5194/se-5-199-2014)

700 Kirkpatrick, J., Rowe, C., White, J., Brodsky, E., 2013. Silica gel formation during fault slip: evidence from the  
701 rock record. *Geology* 41, 1015-1018. <https://doi.org/10.1130/G34483.1>

702 Klimeš, J., Yepes, J., Becerril, L., Kusák, M., Galindo, I., Blahůt, J., 2016. Development and recent activity of the  
703 San Andrés Landslide on El Hierro, Canary Islands, Spain. *Geomorphology* 261, 119-131.  
704 <https://doi.org/10.1016/j.geomorph.2016.02.018>

705 Kurz, M., 1986. In situ production of terrestrial cosmogenic helium and some applications to geochronology.  
706 *Geochimica et Cosmochimica Acta* 50, 2855-2862. [https://doi.org/10.1016/0016-7037\(86\)90232-2](https://doi.org/10.1016/0016-7037(86)90232-2)

707 Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth  
708 and Planetary Science Letters* 104, 424-439. [https://doi.org/10.1016/0012-821X\(91\)90220-C](https://doi.org/10.1016/0012-821X(91)90220-C)

709 Lavallée, Y., Hirose, T., Kendrick, J., De Angelis, S., Petrakova, L., Hornby, A., Dingwell, D., 2014. A frictional law  
710 for volcanic ash gouge. *Earth and Planetary Science Letters* 400, 177-183.  
711 <https://doi.org/10.1016/j.epsl.2014.05.023>

712 Lavallée, Y., Mitchell, T., Heap, M., Vasseur, J., Hess, K.-U., Hirose, T., Dingwell, D., 2012. Experimental  
713 generation of volcanic pseudotachylytes: constraining rheology. *Journal of Structural Geology* 38, 222-  
714 233. <https://doi.org/10.1016/j.jsg.2012.02.001>

715 Legros, F., Cantagrel, J.-M., Devouard, B., 2000. Pseudotachylite (frictionite) at the base of the Arequipa  
716 Volcanic Landslide Deposit (Peru): implications for emplacement mechanisms. *The Journal of Geology*  
717 108, 601-611. <https://doi.org/10.1086/314421>

718 León, R., Somoza, L., Urgeles, R., Medialdea, T., Ferrer, M., Biain, A., García-Crespo, J., Mediato, J., Galindo, I.,  
719 Yepes, J., González, F., Gimenez-Moreno, J., 2017. Multi-event oceanic island landslides: new onshore-  
720 offshore insights from El Hierro Island, Canary Archipelago. *Marine Geology* 393, 156-175.  
721 <https://doi.org/10.1016/j.margeo.2016.07.001>

722 Liu, C., Lay, T., Xiong, X., 2018. Rupture in the 4 May 2018  $M_w$  6.9 earthquake seaward of the Kilauea East Rift  
723 Zone fissure eruption in Hawaii. *Geophysical Research Letters* 45, 9508-9515.  
724 <https://doi.org/10.1029/2018GL079349>

725 Longpré, M., Chadwick, J., Wijbrans, J., Iping, R., 2011. Age of the El Golfo debris avalanche, El Hierro (Canary  
726 Islands): new constraints from laser and furnace  $^{40}\text{Ar}/^{39}\text{Ar}$  dating. *Journal of Volcanology and  
727 Geothermal Research* 203, 76-80. <https://doi.org/10.1016/j.jvolgeores.2011.04.002>

728 López, C., Blanco, M., Abella, R., Brenes, B., Cabrera Rodríguez, V., Casas, B., Domínguez Cerdeña, I., Felpeto, A.,  
729 Fernández de Villalta, M., Del Fresno, C., et al., 2012. Monitoring the volcanic unrest of El Hierro (Canary

730 Islands) before the onset of the 2011-2012 submarine eruption. *Geophysical Research Letters* 39,  
731 L13303. <https://doi.org/10.1029/2012GL051846>

732 Maddock, R., 1986. Frictional melting in landslide generated frictionites (hyalomylonites) and fault generated  
733 pseudotachylytes: discussion. *Tectonophysics* 128, 151-153. [https://doi.org/10.1016/0040-](https://doi.org/10.1016/0040-1951(86)90316-1)  
734 1951(86)90316-1

735 Martin, L., Blard, P.-H., Balco, G., Lave, J., Delunel, R., Lifton, N., Laurent, V., 2017. The CREp program and the  
736 ICE-D production rate calibration database: a fully parameterizable and updated online tool to compute  
737 cosmic-ray exposure ages. *Quaternary Geochronology* 38, 25-49.  
738 <https://doi.org/10.1016/j.quageo.2016.11.006>

739 Masch, L., Wenk, H., Preuss, E., 1985. Electron microscopy of hyalomylonites - evidence for frictional melting in  
740 landslides. *Tectonophysics* 115, 131-160. [https://doi.org/10.1016/0040-1951\(85\)90103-9](https://doi.org/10.1016/0040-1951(85)90103-9)

741 Masson, D., 1996. Catastrophic collapse of the volcanic island of Hierro 15 ka ago and the history of landslides  
742 in the Canary Islands. *Geology* 24, 231-234. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1996)024<0231:CCOTVI>2.3.CO;2)  
743 7613(1996)024<0231:CCOTVI>2.3.CO;2

744 Masson, D., Watts, A., Gee, M., Urgeles, R., Mitchell, N., Le Bas, T., Canals, M., 2002. Slope failures on the flanks  
745 of the western Canary Islands. *Earth-Science Reviews* 57, 1-35. [https://doi.org/10.1016/S0012-](https://doi.org/10.1016/S0012-8252(01)00069-1)  
746 8252(01)00069-1

747 McGuire, W., 1996. Volcano instability: a review of contemporary themes. In: McGuire, W., Jones, A., Neuberg,  
748 J. (Eds.), *Volcano Instability on the Earth and Other Planets*. Geological Society of London, Special  
749 Publication 110, 1-23. <https://doi.org/10.1144/GSL.SP.1996.110.01.01>

750 Meletlidis, S., Di Roberto, A., Domínguez Cerdeña, I., Pompilio, M., García-Cañada, L., Bertagnini, A., Benito-Saz,  
751 M., Del Carlo, P., Sainz-Maza Aparicio, S., 2015. New insight into the 2011-2012 unrest and eruption of El  
752 Hierro Island (Canary Islands) based on integrated geophysical, geodetical, and petrological data. *Annals*  
753 *of Geophysics* 58, S0546. <https://doi.org/10.4401/ag-6754>

754 Mitchell, T., Smith, S., Anders, M., Di Toro, G., Nielsen, S., Cavallo, A., Beard, A., 2015. Catastrophic  
755 emplacement of giant landslides aided by thermal decomposition: Heart Mountain, Wyoming. *Earth and*  
756 *Planetary Science Letters* 411, 199-207. <https://doi.org/10.1016/j.epsl.2014.10.051>

757 Moscardelli, L., Wood, L., 2008. New classification system for mass transport complexes in offshore Trinidad.  
758 *Basin Research* 20, 73-98. <https://doi.org/10.1111/j.1365-2117.2007.00340.x>

759 Palumbo, L., Benedetti, L., Bourlès, D., Cinque, A., Finkel, R., 2004. Slip history of the Magnola Fault (Apennines,  
760 Central Italy) from <sup>36</sup>Cl surface exposure dating: evidence for strong earthquakes over the Holocene.  
761 Earth and Planetary Science Letters 225, 163-176. <https://doi.org/10.1016/j.epsl.2004.06.012>

762 Paris, R., Ramalho, R.S., Madeira, J., Ávila, S., May, S.M., Rixhon, G., Engel, M., Brückner, H., Herzog, M.,  
763 Schukraft, G., Perez-Torrado, F.J., Rodriguez-Gonzales, A., Carracedo, J.C., Giachetti, T., 2018. Mega-  
764 tsunami conglomerates and flank collapses of ocean volcanoes. Marine Geology 395, 168-187.  
765 <https://doi.org/10.1016/j.margeo.2017.10.004>

766 Passchier, C., Trouw, R., 2005. Microtectonics. Springer, Berlin, 366 pp. <https://doi.org/10.1007/3-540-29359-0>

767 Poujol, A., Ritz, J.-F., Tahayt, A., Vernant, P., Condomines, M., Blard, P.-H., Billant, J., Vacher, L., Tibari, B., Hni,  
768 L., Koulali Idrissi, A., 2014. Active tectonics of the Northern Rif (Morocco) from geomorphic and  
769 geochronological data. Journal of Geodynamics 77, 70-88. <https://doi.org/10.1016/j.jog.2014.01.004>

770 Price, N., Johnson, S., Gerbi, C., West, D., 2012. Identifying deformed pseudotachylite and its influence on the  
771 strength and evolution of a crustal shear zone at the base of the seismogenic zone. Tectonophysics 518-  
772 521, 63-83. <https://doi.org/10.1016/j.tecto.2011.11.011>

773 Protin, M., Blard, P.-H., Marrocchi, Y., Mathon, F., 2016. Irreversible adsorption of atmospheric helium on  
774 olivine: a lobster pot analogy. Geochimica et Cosmochimica Acta 179, 76-88.  
775 <https://doi.org/10.1016/j.gca.2016.01.032>

776 Rasa, R., Azzaro, R., Leonardi, O., 1996. Aseismic creep on faults and flank instability at Mount Etna Volcano,  
777 Sicily. In: McGuire, W., Jones, A., Neuberg, J. (Eds.), Volcano Instability on the Earth and Other Planets.  
778 Geological Society of London, Special Publication 110, 179-192.  
779 <https://doi.org/10.1144/GSL.SP.1996.110.01.14>

780 Rempe, M., Smith, S., Ferri, F., Mitchell, T., Di Toro, G., 2014. Clast-cortex aggregates in experimental and  
781 natural calcite bearing fault zones. Journal of Structural Geology 68, 142-157.  
782 <https://doi.org/10.1016/j.jsg.2014.09.007>

783 Rowe, C., Fagereng, Å., Miller, J., Mapani, B., 2012. Signature of coseismic decarbonation in dolomitic fault  
784 rocks of the Naukluft Thrust, Namibia. Earth and Planetary Science Letters 333-334, 200-210.  
785 <https://doi.org/10.1016/j.epsl.2012.04.030>

786 Rowe, C., Griffith, W., 2015. Do faults preserve a record of seismic slip: a second opinion. Journal of Structural  
787 Geology 78, 1-26. <https://doi.org/10.1016/j.jsg.2015.06.006>

788 Rowe, C., Lamothe, K., Rempe, M., Andrews, M., Mitchell, T., Di Toro, G., Clancy White, J., Aretusini, S., 2019.  
789 Earthquake lubrication and healing explained by amorphous nanosilica. *Nature Communications* 10,  
790 320. <https://doi.org/10.1038/s41467-018-08238-y>

791 Rowe, C., Moore, J., Meneghini, F., McKeirnan, A., 2005. Large scale pseudotachylytes and fluidized cataclases  
792 from an ancient subduction thrust fault. *Geology* 33, 937-940. <https://doi.org/10.1130/G21856.1>

793 Sagy, A., Brodsky, E., Axen, G., 2007. Evolution of fault surface roughness with slip. *Geology* 35, 283-286.  
794 <https://doi.org/10.1130/G23235A.1>

795 Siebert, L., 1984. Large volcanic debris avalanches: characteristics of source areas, deposits, and associated  
796 eruptions. *Journal of Volcanology and Geothermal Research* 22, 163-197. [https://doi.org/10.1016/0377-](https://doi.org/10.1016/0377-0273(84)90002-7)  
797 [0273\(84\)90002-7](https://doi.org/10.1016/0377-0273(84)90002-7)

798 Siebert, L., 1992. Threats from debris avalanches. *Nature* 356, 658-659. <https://doi.org/10.1038/356658a0>

799 Smeraglia, L., Bettucci, A., Billi, A., Carminati, E., Cavallo, A., Di Toro, G., Natali, M., Passeri, D., Rossi, M.,  
800 Spagnuolo, E., 2017. Microstructural evidence for seismic and aseismic slips along clay-bearing,  
801 carbonate faults. *Journal of Geophysical Research, Solid Earth* 122, 3895-3915.  
802 <https://doi.org/10.1002/2017JB014042>

803 Smith, S., Billi, A., Di Toro, G., Spiess, R., 2011. Principal slip zones in limestone: microstructural characterization  
804 and implications for the seismic cycle (Tre Monti Fault, Central Apennines, Italy). *Pure and Applied*  
805 *Geophysics* 168, 2365-2393. <https://doi.org/10.1007/s00024-011-0267-5>

806 Sorriso-Valvo, M., Gullà, G., Antronico, L., Tansi, C., Amelio, M., 1999. Mass movement, geologic structure, and  
807 morphologic evolution of the Pizzotto-Greci Slope (Calabria, Italy). *Geomorphology* 30, 147-163.  
808 [https://doi.org/10.1016/S0169-555X\(99\)00051-3](https://doi.org/10.1016/S0169-555X(99)00051-3)

809 Széreméta, N., Laj, C., Guillou, H., Kissel, C., Mazaud, A., Carracedo, J.-C., 1999. Geomagnetic paleosecular  
810 variation in the Brunhes period, from the island of El Hierro (Canary Islands). *Earth and Planetary*  
811 *Science Letters* 165, 241-253. [https://doi.org/10.1016/S0012-821X\(98\)00270-2](https://doi.org/10.1016/S0012-821X(98)00270-2)

812 Tesei, T., Carpenter, B., Giorgetti, C., Scuderi, M., Sagy, A., Scarlato, P., Collettini, C., 2017. Friction and scale-  
813 dependent deformation processes of large experimental carbonate faults. *Journal of Structural Geology*  
814 100, 12-23. <https://doi.org/10.1016/j.jsg.2017.05.008>

815 Ui, T., Takarada, S., Yoshimoto, M., 2000. Debris avalanches. In: Sigurdsson, H., Houghton, B., McNutt, S.,  
816 Rymer, H., Stix, J. (Eds.), *Encyclopedia of Volcanoes*. Academic Press, San Diego, pp. 617-626.

817 Ujiie, K., Tsutsumi, A., Kameda, J., 2011. Reproduction of thermal pressurization and fluidization of clay-rich  
818 fault gouges by high-velocity friction experiments and implications for seismic slip in natural faults.  
819 Geological Society of London, Special Publication 359, 267-285. <https://doi.org/10.1144/SP359.15>

820 Urgeles, R., Canals, M., Baraza, J., Alonso, B., 1996. The submarine El Golfo debris avalanche and the Canary  
821 debris flow, west Hierro Island: the last major slides in the Canary Archipelago. *Geogaceta* 20, 390-393.

822 Urgeles, R., Canals, M., Baraza, J., Alonso, B., Masson, D., 1997. The most recent megalandslides on the Canary  
823 Islands: the El Golfo debris avalanche and the Canary debris flow, west El Hierro Island. *Journal of*  
824 *Geophysical Research, Solid Earth* 102, 20305-20323. <https://doi.org/10.1029/97JB00649>

825 Verberne, B., De Bresser, J., Niemeijer, A., Spiers, C., De Winter, M.D., Plümper, O., 2013. Nanocrystalline slip  
826 zones in calcite fault gouge show intense crystallographic preferred orientation: crystal plasticity at  
827 subseismic slip rates at 18-150°C. *Geology* 41, 863-866. <https://doi.org/10.1130/G34279.1>

828 Walter, T.R., Haghghi, M.H., Schneider, F.M., Coppola D, Motagh, M., Saul, J., Babeyko, A., Dahm, T., Troll, V.R.,  
829 Tilmann, F., Heimann, S., Valade, S., Triyono, R., Khomarudin, R., Kartadinata, N., Laiolo, M., Massimetti,  
830 F., Gaebler, P., 2019. Complex hazard cascade culminating in the Anak Krakatau sector collapse. *Nature*  
831 *Communications* 10, 4339. <https://doi.org/10.1038/s41467-019-12284-5>

832 Weidinger, J., Korup, O., Munack, H., Altenberger, U., Dunning, S., Tippelt, G., Lottermoser, W., 2014. Giant  
833 rockslides from the inside. *Earth and Planetary Science Letters* 389, 62-73.  
834 <https://doi.org/10.1016/j.epsl.2013.12.017>

835 Zimmermann, L., Avicé, G., Blard, P.-H., Marty, B., Füre, E., Burnard, P., 2018. A new all-metal induction furnace  
836 for noble gas extraction. *Chemical Geology* 480, 86-92. <https://doi.org/10.1016/j.chemgeo.2017.09.018>



837 **Figure captions**

838

839 **Figure 1** A shaded topographic and bathymetric relief map of El Hierro, Canary Islands, overlain by a  
840 geological map simplified from Ancochea et al. (2004). The inset shows an aerial image of the  
841 studied fault outcrop. SAL: San Andrés Landslide.

842

843 **Figure 2** (A) General view of the San Andrés Fault outcrop showing the location of each sampling site. The  
844 numbers in parentheses after COS samples 1-5 indicate the estimated exposure ages in ka. (B)  
845 Detailed view of the fault outcrop which shows a series of conspicuous vertical or subvertical  
846 slickenlines and the whitish layer adorning the recently exposed parts of its surface; (C) Contact  
847 between the footwall (left) and the hanging wall (right); (D) Detailed view of the oxidised rock  
848 visible in the footwall of the fault which reflects the presence of fine grained Fe-oxides and Fe-  
849 hydroxides. (E, F) Samples used for microstructural analysis: (E1) hand sample MSA1 shows  
850 slickenlines composed of the whitish layer - note the dashed line parallel to the slickenlines; (E2)  
851 closeup view of the slickenlines, (E3) rock slab used to extract thin sections shows the whitish layer  
852 that covers the cataclasite and breccia. The black rectangles mark the positions of Figures 5-6; (F1)  
853 core sample MSA2 drilled perpendicular to the fault surface shows large clasts in the breccia and  
854 white layer - red dashed line highlights the orientation of the slickenlines; (F2) rock slab shows the  
855 gradual increase in oxidation of the breccia towards the fault surface; (F3) thin section shows the  
856 sharpness of the slip surface and the barely-visible white silica layer. The black rectangle marks the  
857 location of Figure 7.

858

859

860 **Figure 3** Structural analysis of the surface of the San Andrés Fault outcrop conducted on the basis of a  
861 remotely sensed UAV DTM. (A) Slope gradient map giving a ground plan view presented in inverted  
862 greyscale and showing distinct sets of striations and elongated bumps. (B) Slope gradient map  
863 giving a fault perpendicular view presented in inverted greyscale and visualised in three  
864 dimensions (for reference see the right hand part of the fault in A). (C) Orientation of the fault  
865 surface and the striations revealed by the morphostructural analysis of the UAV DTM. The

866 stereoplot is in azimuthal projection of the lower hemisphere while the different coloured arrows  
867 represent distinct sets of striations and elongated protrusions.

868

869 **Figure 4** The interpolated R-values obtained through Schmidt hammer sampling on the San Andrés Fault.  
870 The size of the black dots illustrates the rock hardness at each of the test sites.

871

872 **Figure 5** Photomicrographs and BSE images of rock from the San Andrés Fault, sample MSA1. First area  
873 presented (A) under plane polarised light, (B) under cross polarised light, (C) as a sketch, (D) in BSE,  
874 and (E-F) in elemental maps. These show tectonic breccia (TB) covered by a cataclastic layer (CL)  
875 which is, in turn, covered by a silica layer (SL). The cataclasite cuts both the tectonic breccia and a  
876 zeolite vein (Z) and has preserved P-foliation and a winged inclusion. The boundary between the  
877 silica layer and the adjacent cataclastic layer is sharp with high interference bands, characteristic of  
878 recrystallisation. The area is rotated during analysis and the sense of shear is marked on the sketch.  
879 Second area presented (G) under plane polarised light, (H) under cross polarised light, (I) as a  
880 sketch, (J) in BSE, and (K-L) in elemental maps. These show tectonic breccia (TB) with zeolite veins  
881 (Z) covered by a thinner cataclastic layer (CL) and a thicker silica layer (SL). The fault slip surface is  
882 subhorizontal with a top-to-right shear direction. The boundary between the cataclastic layer and  
883 the silica layer is marked by high intensity bands of recrystallised material. The silica layer  
884 preserves clast-cortex aggregates (CCA) and flow bands (FB) along with parallel P- and Y- shears.  
885 The elongated void was most probably a clast-cortex aggregate lost during preparation of the  
886 sample.

887

888 **Figure 6** Photomicrographs and BSE images of rock from the San Andrés Fault, sample MSA1. Area  
889 presented in (A) under plane polarised light, (B) under cross polarised light, (C) under cross  
890 polarised light using a gypsum tint plate, (D) in BSE, and (E) as a sketch. These show tectonic  
891 breccia (TB) covered by a silica layer (SL). The tectonic breccia was cut during deformation which  
892 resulted in truncated clasts (TC) while the silica layer preserves clast-cortex aggregates (CCA), a  
893 cataclastic sublayer (CL), and flow bands (FB). These flow bands show a positive birefringence, in  
894 contrast to the rest of the silica layer, as evidenced by the second order blue interference colour in

895 (C). The rectangles in (D) indicate regions highlighted in (F-I): (F) new crystals growing in a void  
896 surrounded by ultrafine grained to amorphous matrix, (G) a large clast-cortex aggregate with a  
897 complex cortex and elongated clast in its core, (H) a lensoid of reworked cataclasite, and (I) two  
898 smaller clast-cortex aggregates and new crystals growing in the void. The fault slip surface is  
899 horizontal with a top-to-right shear direction.

900

901 **Figure 7** Photomicrographs and BSE images of rock from the San Andrés Fault, sample MSA2. Area  
902 presented in (A) under plane polarised light, (B) under cross polarised light using a gypsum tint  
903 plate, and (C) as a sketch. These show a large truncated clast (TC) in the tectonic breccia (TB) cut by  
904 cataclasite (CL) and covered by a silica layer (SL) which has flow bands (FB) and clast-cortex  
905 aggregates (CCA). The rectangle in (A) indicates the region highlighted in (D-F). In (D-F) elemental  
906 maps show P-foliation in the cataclastic layer along with clast-cortex aggregates and flow bands in  
907 the silica layer. Dashed lines highlight characteristics presented in the sketch. The fault slip surface  
908 is horizontal with a top-to-right shear direction.

909

910 **Figure 8** A conceptual model for the development of the San Andrés Fault system over the last 550 ka based  
911 on Day et al. (1997), Carracedo et al. (1997), Széreméta et al. (1999), León et al. (2017), and the  
912 findings presented herein. The uppermost labels denote the main geological events to have taken  
913 place on El Hierro, i.e. rotation and volcanism, while those beneath denote the supposed age  
914 ranges for each of the giant landslides. The proposed timing of activity on the San Andrés Fault is  
915 presented underneath the timeline: the first slip event is associated with the formation of the  
916 cataclasite while the second slip event is associated with the formation of the silica layer. The time  
917 axis depicts thousands of years before present.

918

919 **Figure 9** A conceptual model for the development of the surface of the San Andrés Fault. Prior to slip a  
920 tectonic breccia, of basaltic origin, hosted zeolite veins, as shown in green. During the first slip  
921 event the tectonic breccia was sheared and a foliated cataclasite formed, as shown in red. During  
922 the second slip event both the host rock and foliated cataclasite were sheared and a silica layer  
923 formed with clast-cortex aggregate and flow bands, as shown in blue.

924 **Table captions**

925

926 **Table 1** Results of the cosmogenic  $^3\text{He}$  exposure dating for five samples obtained from the San Andrés  
927 Fault.

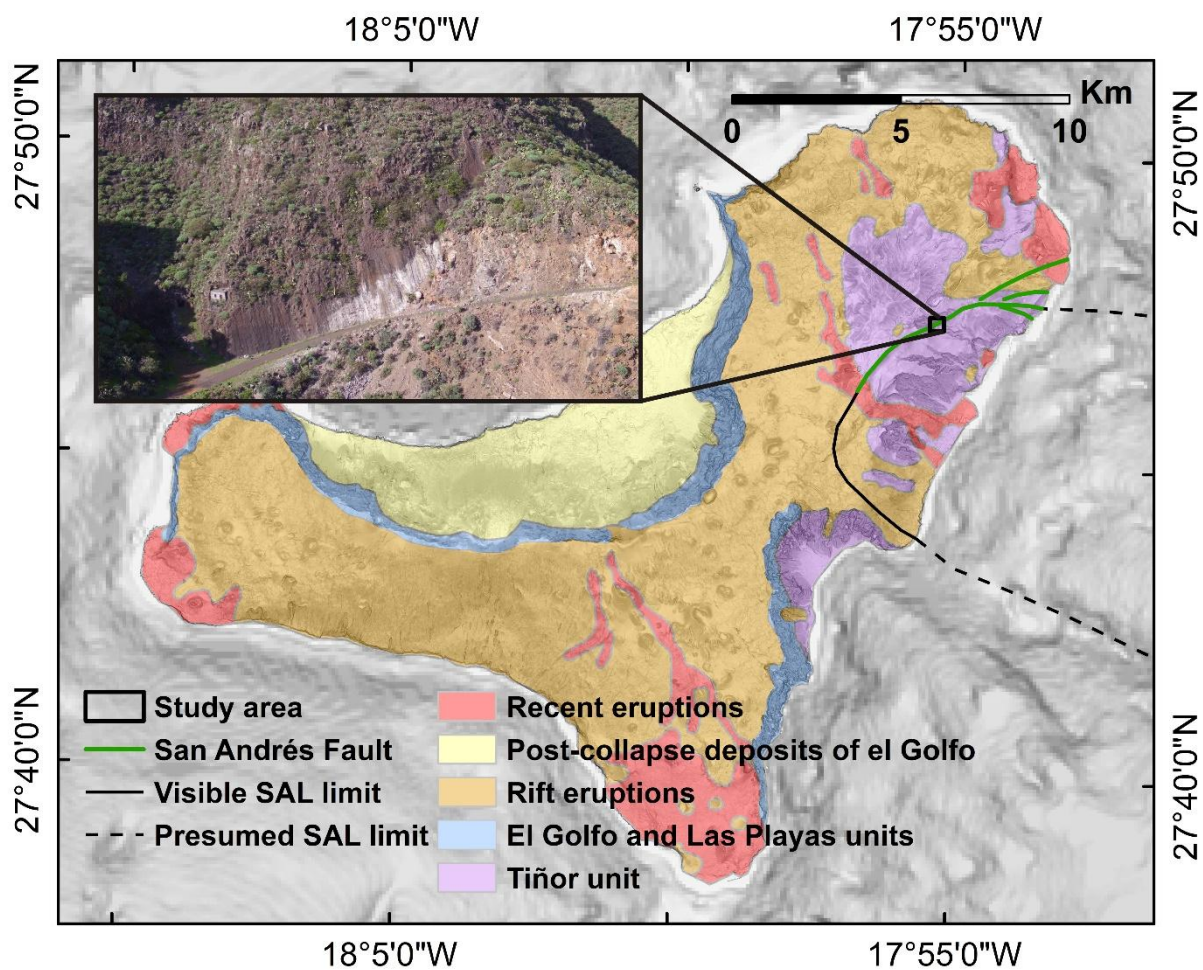
928

929 **Supp. Tab. A** Chemical composition of the five samples obtained from the San Andrés Fault for cosmogenic  
930  $^3\text{He}$  exposure dating (COS1 - COS5).

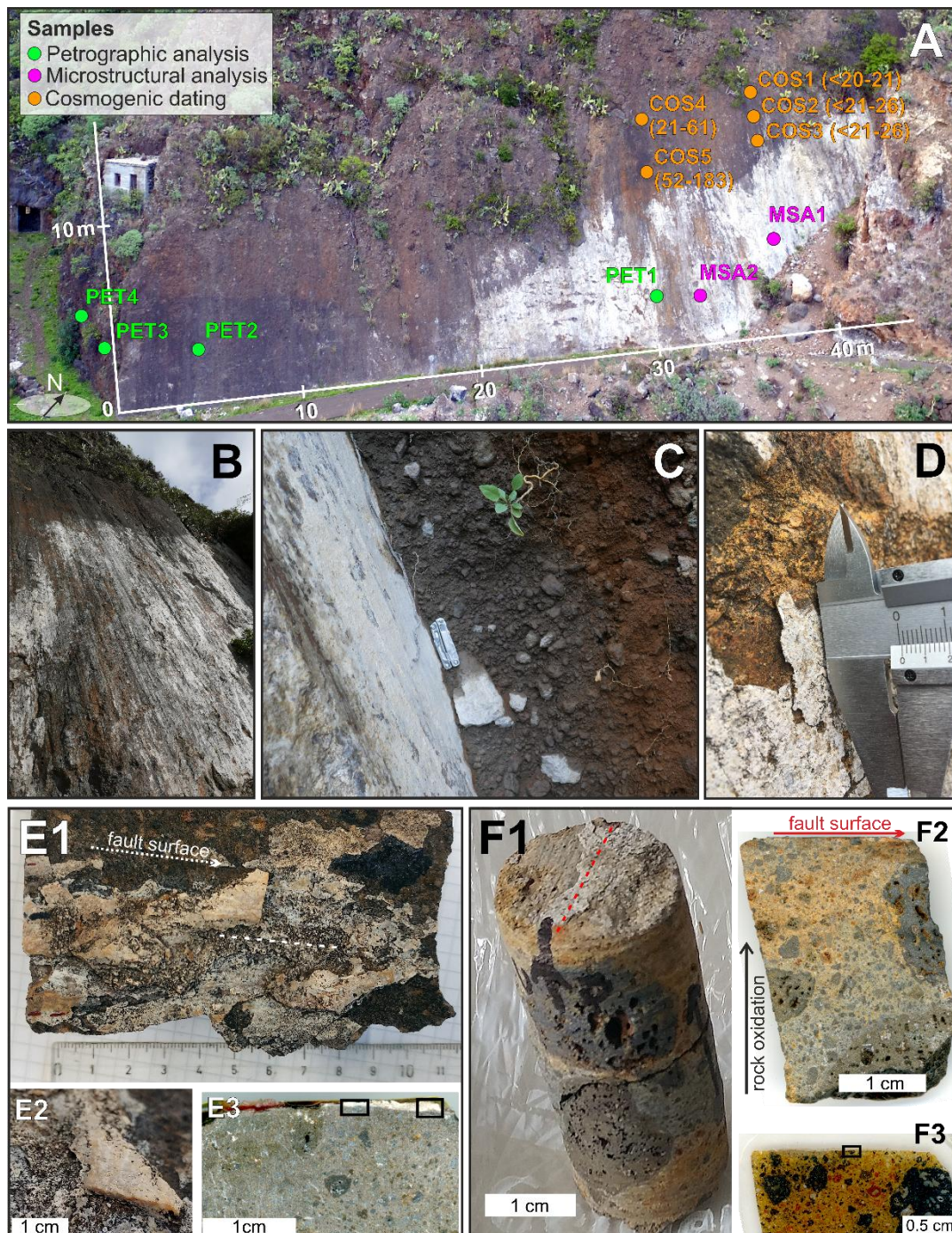
**Table 1**  
[Click here to download Table: Blahut et al. 2019 - Tectonophysics Table.pdf](#)

Sample	Size (mm)	Extraction method	Mass (g)	$^3\text{He}_{\text{melt}}$ ( $10^6 \text{ at.g}^{-1}$ )	$^4\text{He}_{\text{melt}}$ ( $10^{12} \text{ at.g}^{-1}$ )	$^3\text{He}_{\text{cos min}}$ ( $10^6 \text{ at.g}^{-1}$ )	$^3\text{He}_{\text{cos max}}$ ( $10^6 \text{ at.g}^{-1}$ )	Dip slope (°)	Local scaling factor	Minimal exposure (ka)	Maximum exposure (ka)
COS5-III	0.5 - 1	1 min vacuum crushing / 100 strokes	0.5	0.195 ± 0.096	0.014 ± 0.001						
COS5-III	0.5 - 2	5 min vacuum crushing / 500 strokes	0.5	4.27 ± 0.16	0.36 ± 0.01						
COS-1	0.5 - 2	Furnace 1700°C / 15 min	0.1182	2.22 ± 0.39	13.62 ± 0.21	< 2	2.22 ± 2.04	75	0.68	< 20	21 ± 20
COS-2 and 3	0.2 - 2	Furnace 1700°C / 15 min	0.1206	2.95 ± 0.39	0.62 ± 0.02	< 2	2.95 ± 2.04	67	0.75	< 21	26 ± 18
COS - 4I	0.2 - 2	Furnace 1700°C / 15 min	0.3007	6.46 ± 0.25	2.05 ± 0.03	2.19 ± 2.02	6.46 ± 2.02	71	0.7	21 ± 19	61 ± 19
COS - 4II	0.2 - 2	Furnace 1700°C / 15 min	0.2089	7.13 ± 0.32	1.21 ± 0.02	2.85 ± 2.03	7.13 ± 2.03	65	0.78	24 ± 17	60 ± 17
COS - 5II	0.25 - 0.5	Furnace 1700°C / 15 min	0.2097	10.48 ± 0.37	1.99 ± 0.03	6.21 ± 2.03	10.48 ± 2.03	65	0.78	52 ± 17	88 ± 17
COS - 5III	0.5 - 2	Furnace 1700°C / 15 min	0.1939	16.16 ± 0.48	1.63 ± 0.03	11.88 ± 2.06	16.16 ± 2.06	65	0.78	100 ± 17	136 ± 17
COS - 5III	0.5 - 2	Furnace 1700°C / 15 min	0.2606	21.75 ± 0.53	2.16 ± 0.04	17.47 ± 2.07	21.75 ± 2.07	65	0.78	147 ± 17	183 ± 17
Age of lava eruption: (1.05 ± 0.02) Ma											
All sample are a mixture of pure olivines and pyroxenes											
Ra = $1.384 \times 10^{-6}$											

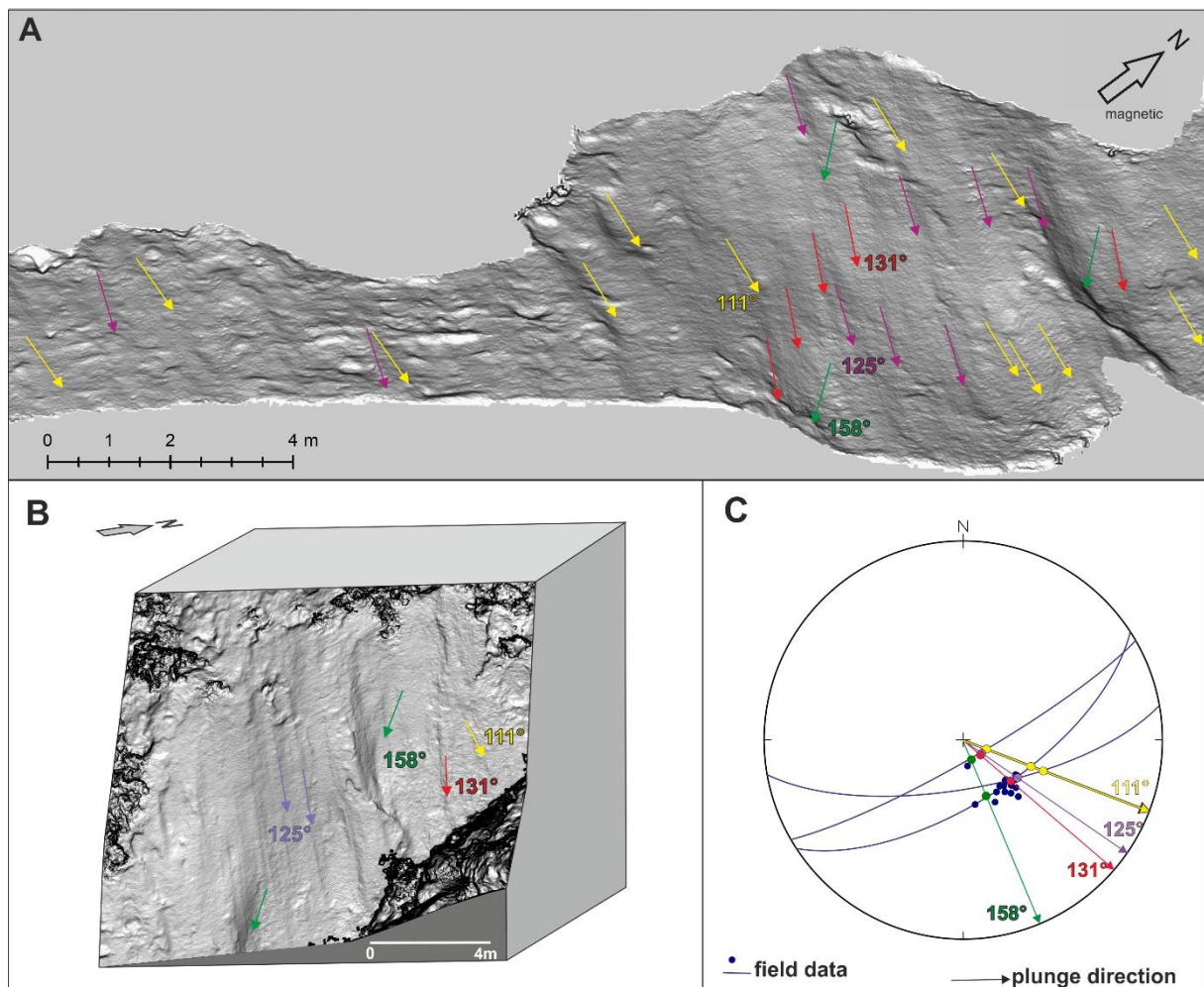
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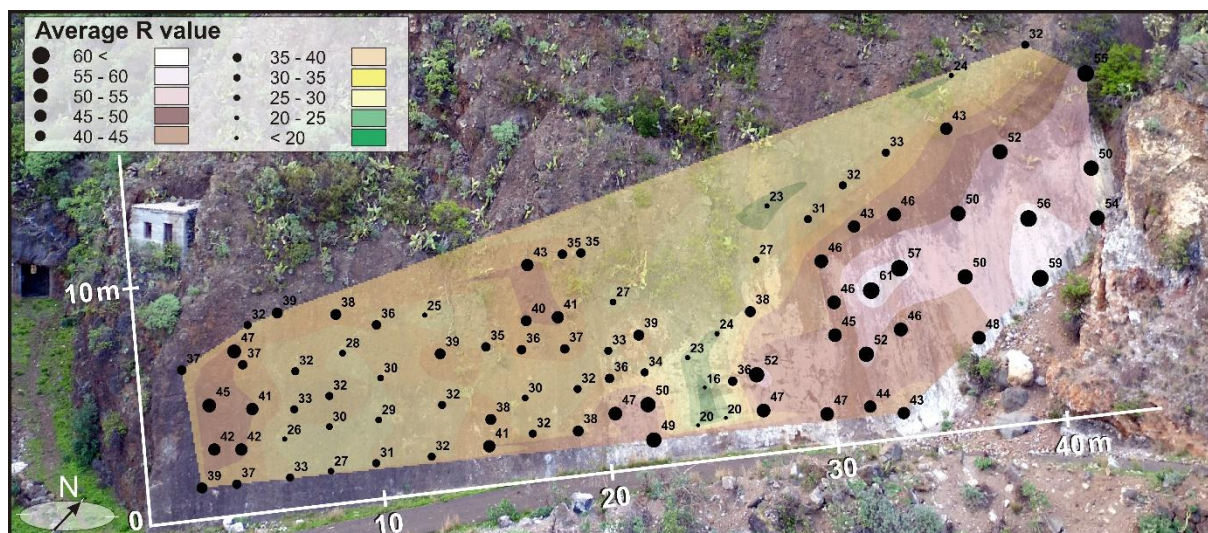


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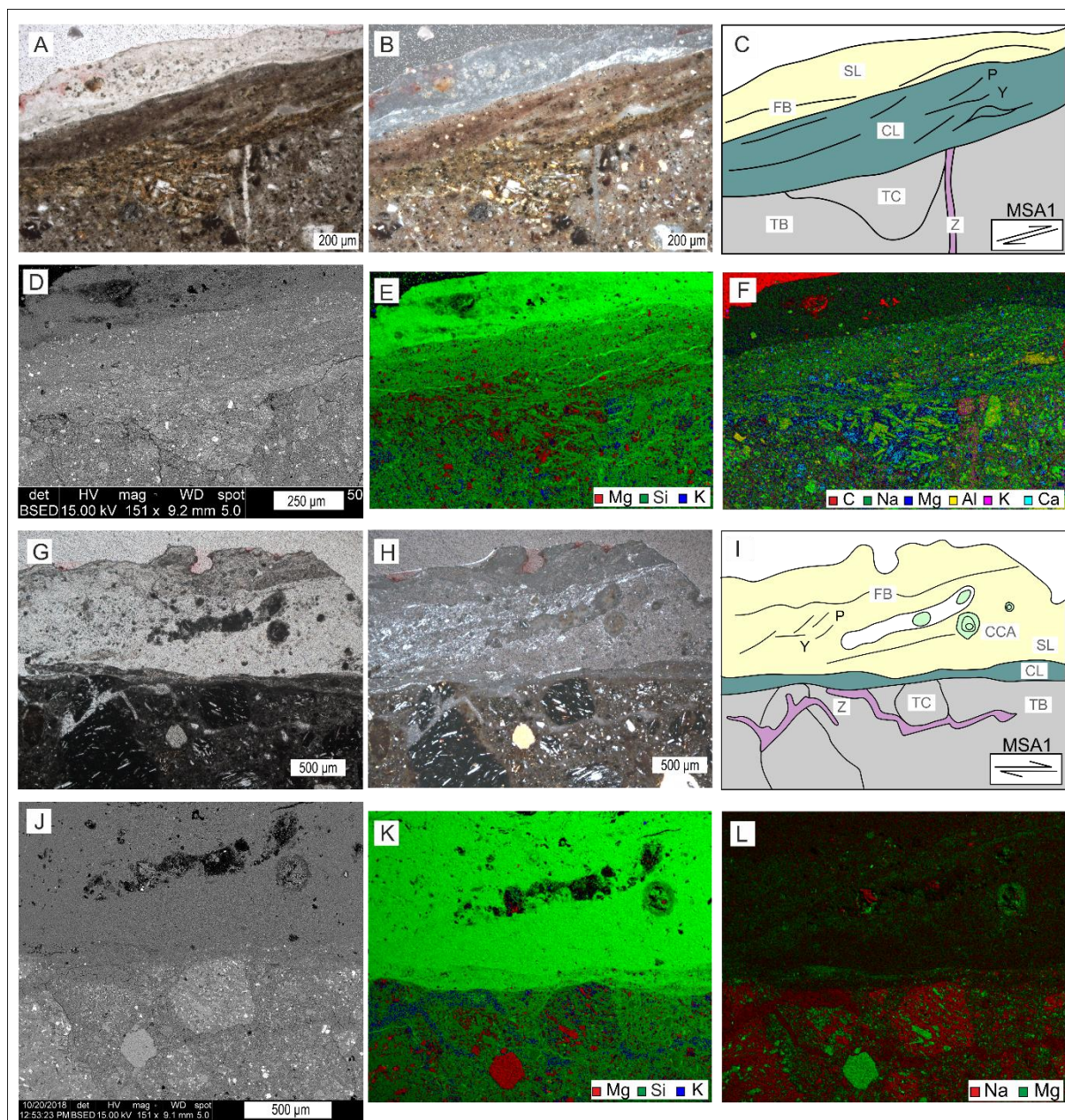
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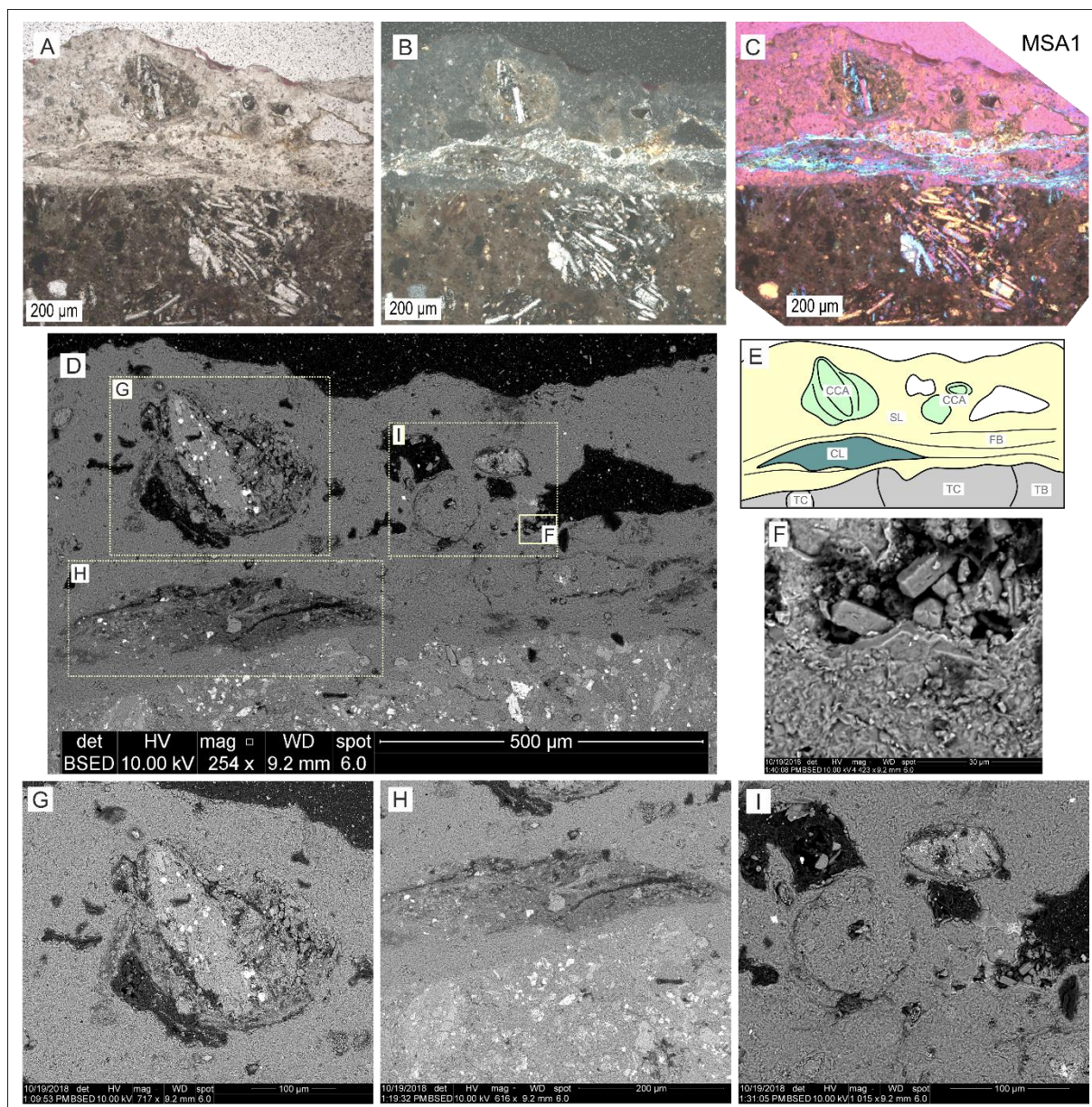


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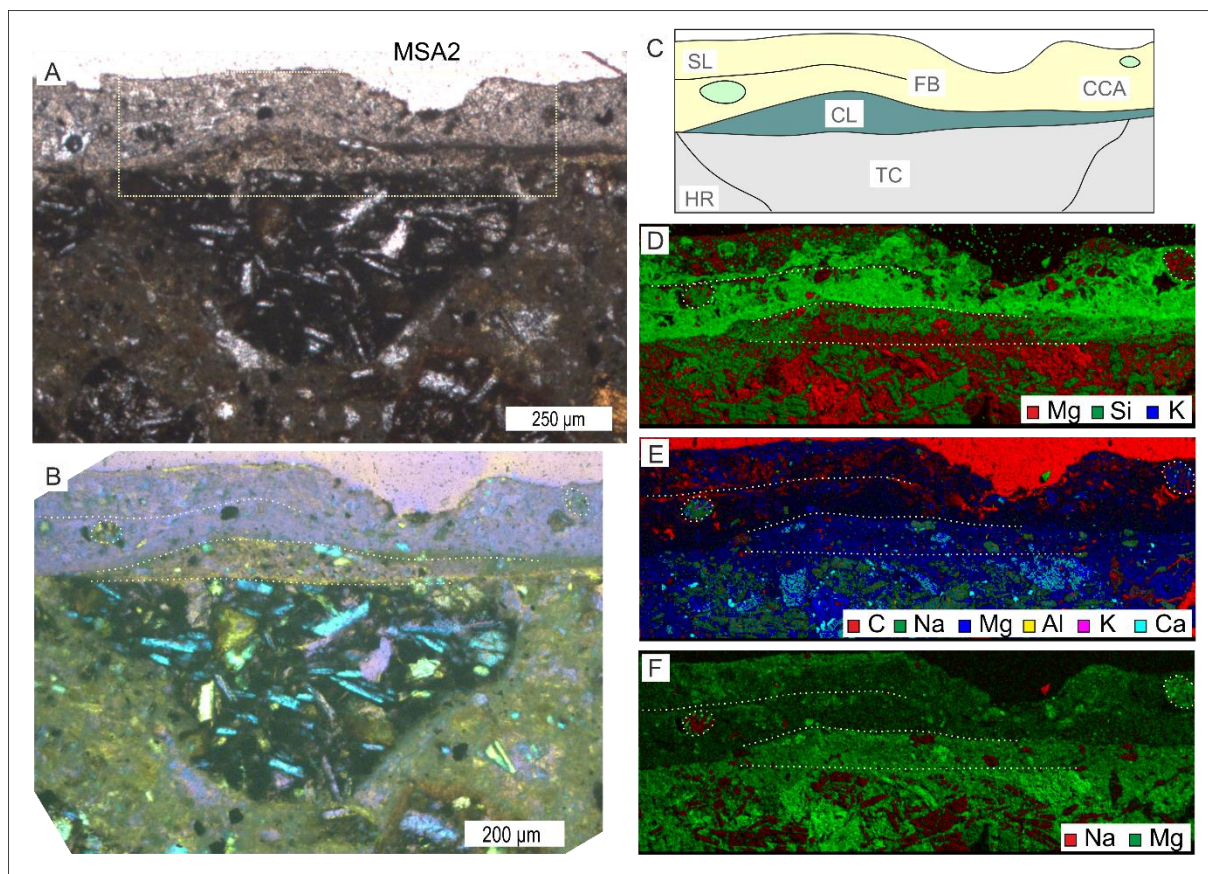
The size of the black dots illustrates the rock hardness at each of the test sites.



**Figure 5** Photomicrographs and BSE images of rock from the San Andrés Fault, sample MSA1. First area presented (A) under plane polarised light, (B) under cross polarised light, (C) as a sketch, (D) in BSE, and (E-F) in elemental maps. These show tectonic breccia (TB) covered by a cataclastic layer (CL) which is, in turn, covered by a silica layer (SL). The cataclasite cuts both the tectonic breccia and a zeolite vein (Z) and has preserved P-foliation and a winged inclusion. The boundary between the silica layer and the adjacent cataclastic layer is sharp with high interference bands, characteristic of recrystallisation. The area is rotated during analysis and the sense of shear is marked on the sketch. Second area presented (G) under plane polarised light, (H) under cross polarised light, (I) as a sketch, (J) in BSE, and (K-L) in elemental maps. These show tectonic breccia (TB) with zeolite veins (Z) covered by a thinner cataclastic layer (CL) and a thicker silica layer (SL). The fault slip surface is subhorizontal with a top-to-right shear direction. The boundary between the cataclastic layer and the silica layer is marked by high intensity bands of recrystallised material. The silica layer preserves clast-cortex aggregates (CCA) and flow bands (FB) along with parallel P- and Y- shears. The elongated void was most probably a clast-cortex aggregate lost during preparation of the sample.

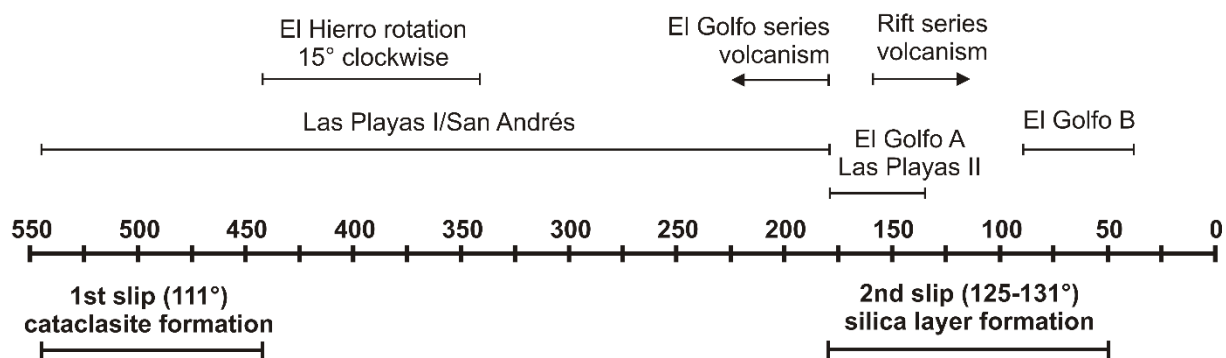


**Figure 6** Photomicrographs and BSE images of rock from the San Andrés Fault, sample MSA1. Area presented in (A) under plane polarised light, (B) under cross polarised light, (C) under cross polarised light using a gypsum tint plate, (D) in BSE, and (E) as a sketch. These show tectonic breccia (TB) covered by a silica layer (SL). The tectonic breccia was cut during deformation which resulted in truncated clasts (TC) while the silica layer preserves clast-cortex aggregates (CCA), a cataclastic sublayer (CL), and flow bands (FB). These flow bands show a positive birefringence, in contrast to the rest of the silica layer, as evidenced by the second order blue interference colour in (C). The rectangles in (D) indicate regions highlighted in (F-I): (F) new crystals growing in a void surrounded by ultrafine grained to amorphous matrix, (G) a large clast-cortex aggregate with a complex cortex and elongated clast in its core, (H) a lensoid of reworked cataclasite, and (I) two smaller clast-cortex aggregates and new crystals growing in the void. The fault slip surface is horizontal with a top-to-right shear direction.

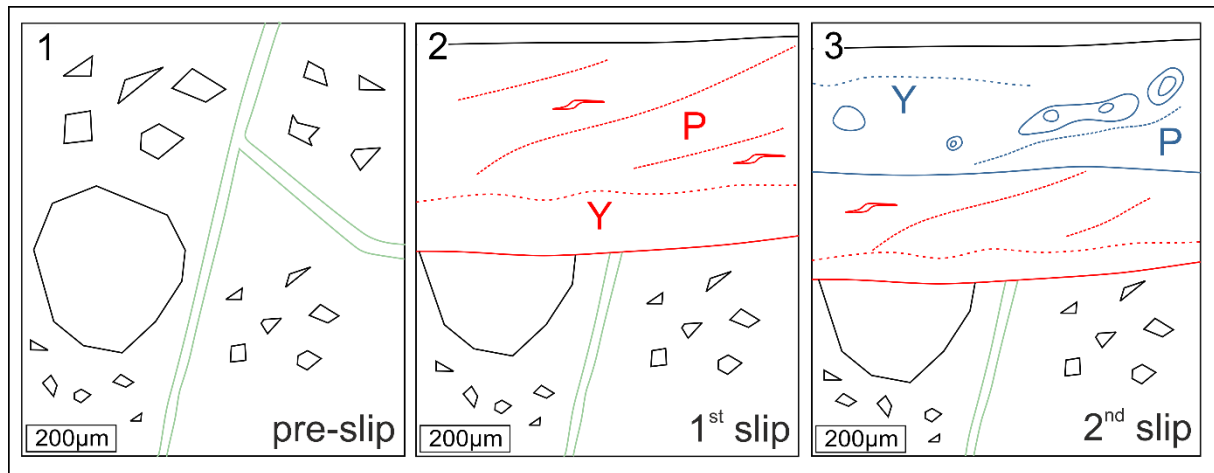


**Figure 7** Photomicrographs and BSE images of rock from the San Andrés Fault, sample MSA2. Area presented in (A) under plane polarised light, (B) under cross polarised light using a gypsum tint plate, and (C) as a sketch. These show a large truncated clast (TC) in the tectonic breccia (TB) cut by cataclasite (CL) and covered by a silica layer (SL) which has flow bands (FB) and clast-cortex aggregates (CCA). The rectangle in (A) indicates the region highlighted in (D-F). In (D-F) elemental maps show P-foliation in the cataclastic layer along with clast-cortex aggregates and flow bands in the silica layer. Dashed lines highlight characteristics presented in the sketch. The fault slip surface is horizontal with a top-to-right shear direction.

Figure 8 (with caption below and on the same page)



**Figure 8** A conceptual model for the development of the San Andrés Fault system over the last 550 ka based on Day et al. (1997), Carracedo et al. (1997), Szérméta et al. (1999), León et al. (2017), and the findings presented herein. The uppermost labels denote the main geological events to have taken place on El Hierro, i.e. rotation and volcanism, while those beneath denote the supposed age ranges for each of the giant landslides. The proposed timing of activity on the San Andrés Fault is presented underneath the timeline: the first slip event is associated with the formation of the cataclasite while the second slip event is associated with the formation of the silica layer. The time axis depicts thousands of years before present.



**Figure 9** A conceptual model for the development of the surface of the San Andrés Fault. Prior to slip a tectonic breccia, of basaltic origin, hosted zeolite veins, as shown in green. During the first slip event the tectonic breccia was sheared and a foliated cataclasite formed, as shown in red. During the second slip event both the host rock and foliated cataclasite were sheared and a silica layer formed with clast-cortex aggregate and flow bands, as shown in blue.

**Supplementary Table**

[Click here to download Supplementary material for online publication only: Blahut et al. 2019 - Tectonophysics SuppTable.pdf](#)

## \*Credit Author Statement

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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