# Answer to the reviews on “Tectonic and climatic controls on the Chuquibamba landslide (western Andes, southern Peru)” by A. Margirier et al.


**A. Margirier et al.**

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Comments given by the two referees are repeated in bold for clarification purposes. We join the corrected manuscript after our answer.

**OVERALL COMMENTS:**

***Anonymous referee 1 (AR1):***

1) **“There are several additional statements the authors make that seem to go beyond what they can reasonably conclude from currently available data (although if more references would be available to back up those statements, then they may be fine). “**

→ We changed some of our statements in which we were over interpreting the available data. We reorganize the text by removing some sentences to focus our discussion on the studied Chuquibamba landslide and we add some references to reinforce them.

2) “**The referencing and organization of the manuscript can be improved.”**

→ We added the references cited by AR1.

→ We changed the organization of the manuscript, and restructured the paragraphs according to the two anonymous referees point of view: we gathered the dispersed geomorphic description in the “geomorphological setting” part.

3) “**The authors should clarify their statements or provide better support.”**

→ Adding references, improving figures and re organizing the text makes it clearer.

***Anonymous referee 2 (AR2):***

1) “**There is little clarity on the new data regarding their presentation and structure, and the scope thereof. I believe that a proper reorganization of information, with a good exploitation of the data, can highlight the understanding of landslides in this part of the Andes.”**

→ We improved and reorganized the text according to the two anonymous referees comments: we corrected unclear sentences and we did gather the geomorphological descriptions in a single paragraph.

2) "**The dispersion of geomorphological data in context, method and results, suggest that they were obtained in the research. If so, they should be showed as a result, placing in the geomorphological context only the framework that was already published and indicating the used geomorphologic methods. If you do not want to exploit this aspect, then place everything in the geomorphological setting.**"

→ We gathered all our geomorphological data in the same part (geomorphological setting) and we made a better distinction between our data and those issued from the literature, citing sources.

3) **"Whereas ages are the main results of the work, better treatment of the numbers is needed. The text ages and figures do not always agree among themselves and with the Table. It is important to correct this point to avoid confusion in future cites."**

→ We checked in detail all our ages, either in the text, figures and the tables. In the text and the figures, we now only indicate the ages calculated with an erosion rate of 0.21 mm/ka. We took in account this point and corrected the ages from the figure 5. We do now highlight the $^{10}$Be ages by removing the geomorphological description from the results part.

4) **The fact that large earthquakes do not trigger landslides is mentioned isolated in the summary, without linking it to the results. However, the results dedicated an entire paragraph indicating that landslides could be triggering by seismicity; without arguments supporting this possibility. I suggest improving this point in the results and summary.**

→ We improved the discussion, rewriting some sentence to make it clearer, citing new references. But in the absence of historical seismic data for ~100 ka, it's not possible to discuss 150yrs seismic cycles. Finally, we cannot conclude on the seismic triggering of the last debris-flow during the Ouki event. The main outcome of this paper is that a wet event seems to be necessary to trigger a large landslide.

**LINE-SPECIFIC ANSWERS:**

AR2, p. 1130, l. 14: **The point (i) in the abstract is very general. Be more specific.**

→ Ok, we took this remark in account and focused on this point.

AR1, p. 1130, l. 24: **McPhillips et al. (2014, Nature Geoscience) seems to be an appropriate reference to add to this list (or alternatively to line 25), particularly as it relates to the possible seismic triggering of landslides.**

→ Ok, we had this reference line 25.

AR1 / AR2, p. 1132, l. 2-4: **This unit is quite well dated by Thouret et al. (2007), so it wouldn't hurt to mention the specific age range that they report. / The Huaylillas Ignimbrite is not well defined; its probable age is not mentioned. Explain more.**

→ Ok, we add the age of the ignimbrite after Thouret et al. (2007).

AR1, p. 1132, l. 19: **This sentence should be restructured, because there are many studies that have now documented climatic fluctuations on the Altiplano over those timescales; is there a reason you mention Placzek specifically? If so, please state why, otherwise provide at least a representative list of the paleoclimate studies that have been done close to the field area.**

→ Ok, we change the sentence and add some critical references. At first, we mentioned Placzek et al. (2006, 2013) specifically because this study was the first to document climate fluctuations for such a long period in our study area: they documented climate fluctuations during the last 130 ka.

AR1, p. 1132, l. 20-22: **To be fair, the study by McPhillips et al. (2014, Nature Geoscience) should also be mentioned, because they reported a very different interpretation in one of the areas where Steffen was working.**

→ Ok, we add McPhillips et al. (2014).

AR1, p. 1132, section 2.2: **The results of the study by Roperch et al. (2006, Tectonics) could be useful to add to this description.**

→ We are not convinced this study is relevant at our time scale and for this local description.

AR1, p. 1133, l. 1-2: **To be more precise, Schildgen et al. (2009) stated that the uplift that occurred between 14 and 2.2 Ma was accommodated by normal faulting and monoclinal warping, but that doesn't necessarily mean that normal faulting did not continue afterwards (or did not start earlier). Rewriting could be as simple as changing "the Tertiary episode" to "a Tertiary episode", the latter of which doesn't exclude the possibility of later faulting.**

→ Ok, we rewrite the sentence as suggested by the reviewer.

AR1, p. 1133, l. 2-3: **After reading the whole paragraph, I understand that the authors are talking about a strike-slip system, but calling them "rather vertical faults acting as thrust with punctual normal apparent movements" here is confusing as a technical description… This implies that the kinematics have changed over time, but I don't think that is what the authors are trying to say (?). Perhaps there are near-vertical faults with both apparent thrust and normal offsets, which vary laterally according to the fault orientation (transpression versus transtension)?**

→ Ok with the reviewer, and we clarify the text by using the term "strike-slip fault".

AR2, p. 1133, l. 3: **A comma is missing after 'However'**

→ Ok, we add the comma.

AR2, p. 1133, l. 25-26: **The age of Huaylillas Ignimbrite is mentioned here. Why not before?**

→ Ok, taken in account, we add the age in a previous paragraph.

AR2, p. 1133, l. 22: **It is not mentioned exactly where is located the megafan, although it is a very important feature of the study.**

→ Ok, we add the location of the megafan in the text.

AR2, p. 1134, l. 2: **Here, the Huaylillas volcanic unit is mentioned. It is the ignimbrite? If so, I suggest using the same name to avoid confusions.**

→ Yes, it is the ignimbrite; we change the name to avoid confusions.

AR2, p. 1134, l. 3: **The Megafan Acoy is again mentioned as if it was the first time. It should be all together before, to avoid confusions.**

→ Ok, we completely reorganize the geomorphological setting part, we gathered the Acoy megafan description in a single paragraph.

AR1, p. 1134, l. 9-12: **This material would be better placed at the end of the previous section, because it describes results from another study, not the "Sampling strategy and methods" of this paper.**

→ Ok, we move this paragraph in the geomorphological setting.

AR2, p. 1134, l. 9-12: **The Megafan Acoy is again mentioned as if it was the first time. It should be all together before, to avoid confusions.**

→ Ok, we gather the Acoy megafan description in the same single paragraph.

AR2, p. 1134, l. 18-24: **The description of the specific research is scarce. Can you explain more?**

→ We describe here the classical sampling strategy for TCN surface exposure dating, we are not convinced that the text need to be more detailed.

AR1, p. 1134, l. 21-24: **I guess that an explanation for how a quartz pebble can be used to estimate the erosion rate on rhyolite blocks that are higher in elevation and subject to higher rainfall will come later, but for now, I'm skeptical.**

→ As regional erosion rates are scares (Hall et al., 2012; Kober et al. 2007), we sampled the closest available surface from the Chuquibamba landslide to provide another individual erosion rate. Additionally, this new erosion rate is in agreement with those calculated by Hall et al. (2012) for southern Peru (~0.3 mm/ka) or by Kober et al. (2007) for the western escarpment in northern Chile (rhyolitic Oxaya formation; 0-0.5 mm/ka).

AR1, p. 1135, l. 11-24: **Why not include this basic description of the morphology in section 2.3, where there is already some description of the geomorphology? This way, the results section could move directly into the cosmogenic data, instead of first reviewing more aspects of the morphology.**

→ We change the organization of the text and we gather our geomorphological results in the geomorphological setting part as suggested by the reviewers 1 and 2.

AR1, p. 1136, l. 2-7: **There should at least be a caveat here that one would expect a quartz pebble to yield a lower erosion rate compared to rhyolite blocks. I think the assumption of low erosion is reasonable, but the authors should be a bit more careful in this argument.**

→ We definitely agree with this statement. Indeed, as we should expect a higher erosion rate in rhyolite block than in quartz pebble, we looked for this lower pediment surface in order to calculate the erosion rate and discuss any eventual difference. In such an arid environment, and for 100kyrs time scales, our erosion rate is compatible with those calculated by Hall et al. (2012) for the southern Peru and by Kober et al. (2007) for the Oxaya ignimbrite in the western escarpment of the northern Chile.

AR2, p. 1136, l. 8: **Ages in the text do not match those of Figure 5a and 5b.**

→ Ok, we change the ages in the figures 5a and 5b (those ages were calculated with zero erosion whereas we displayed the ages calculated with an erosion rate of 0.21 mm/ka in the manuscript).

AR2, p. 1136, l. 20-21: **There is a link between the climate event and the megafan. What kind of relationship?**

→ Ok, we change the sentence to detail and explain the causal link between the Ouki climatic event and the Acoy megafan (Steffen et al., 2010).

AR1, p. 1137, l. 1: **It's a reduction of the normal stress (or a reduction in shear strength, but certainly not a reduction in shear stress) due to hydrostatic pressure that typically leads to landsliding; Strasser and Schlunegger referred to decreased friction along a basal shear plane. To quote Ritter, Kochel, and Miller: "A body of material on a slope will remain in equilibrium (stable) as long as the sum of the applied shear stresses does not exceed the sum of the shear strength of the slope materials."**

→ Ok, we modify the text as suggested.

AR2, p. 1137, l. 7-9: **It is suggested that an increase of pore pressure in the Huaylillas Ignimbrite by climate event triggered the megafan, but this is not well argued. What are the mechanical and lithological characteristics of the ignimbrite that let you make this proposal? Moreover, it is not establish directly that the age of the ignimbrite is correlated with the age of the climate event.**

→ The Huaylillas ignimbrite sheets are welded to strongly welded (Thouret et al., 2007) and interlayered with tuff. It suggests strong internal porosity variations in this unit but no geotechnical study of the Huaylillas ignimbrite is available.

AR1, p. 1137, l. 7-9: **Sounds reasonable, but then why would the later wet events not have triggered additional landslides?**

→ Ok, we add a sentence to explain this point: for us the Ouki event is the last event strong enough (in duration or/and intensity) to trigger landslides in the arid western Andean flank.

AR1, p. 1137, l. 15: **Can this generalization really be applied to all landslides? More evidence is needed to back that up, although it seems to be reasonably demonstrated in this case.**

→ Ok, we refocused the discussion on the Chuquibamba landslide and then we add some references to suggest the important role of the tectonic fracturing in preconditioning landsliding in the arid Western Cordillera.

AR2, p. 1137, l. 11-16: **Similarity is suggested in the proposal on the flow direction of sliding Chuquibamba over other in northern Chile. In the case of Chile landslide it flowed towards the SW, perpendicular to structures; but here appears instead (maybe I'm**

**wrong) that megafan flowed parallel to the structures probably favored by the incision of the river Majes. Should put flow lines of the megafan in Fig.3a to clarify this point?**

→ We clarify in the text and discuss this point in the landscape evolution paragraph, pointing out the source of the megafan and detailing the succession of events in such a context. However we don't add any additional information on figure 3a as the Acoy megafan is highlighted in red.

AR1, p. 1137, l. 19-20: **Not clear what the authors are trying to say here; both subduction earthquakes and El Nino events were linked to debris flows? The "succession in time" phrase is confusing. The authors might consider referencing McPhillips et al. (2014, Nature Geoscience) here.**

→ Ok, we change the sentence to clarify the text and we quote McPhillips et al. (2014).

AR1, p. 1137, l. 20-24: **Not being able to exclude a seismic triggering (Lines 22-23) is quite far from "a likely link" (Lines 20-21). The authors should decide what interpretation they would like to make; I suggest deleting the sentence on lines 20-21, because they have not established any link between the recurrence of seismicity and landslide triggering.**

→ Ok, we delete the sentence lines 20-21 as suggested.

AR2, p. 1138, l. 4: **Now you are talking about a Huaylillas paleosurface. Which one? It was never before been described. What is it? It is the roof of the Huaylillas Ignimbrite? It is the roof of the Huaylillas Formation?**

→ Yes, it is the weathered roof of the Huaylillas ignimbrite. We change the sentence and add a description of this surface in the geological context.

AR1 / AR2, p. 1138, l. 19: - **Not clear what is meant by "permits new destabilizations"; are more recent mass movements sourced from that region? Is there a reason for that? / - The phrase 'This last debris-flow permits new destabilizations that enlarge the system' seems very ambiguous. Destabilization of what? Which system? hillsides, valleys, slopes?**

→ Ok, we change the sentence.

AR1, p. 1138, l. 19-24: **This should be a separate paragraph, but "perfectly preserved" should be replaced with "well preserved". It seems dangerous to assume that over the 100 kyr history of exposure, there has been no rainfall, particularly considering that the deposit is interpreted to have been mobilized during a past wet phase. Overall, I'm not convinced that these final lines add anything useful to the discussion; the impact of aridity on surface preservation has already been stated a couple times previously.**

→ Ok, we remove this part.

AR1 / AR2, p. 1139, l. 2-7: - **This is not a very effective paragraph for a conclusions section; it represents a fairly standard set of statements that can be applied to any study that measures TCNs in quartz from arid environments (of which there are many). / - I think that this paragraph does not add much to the conclusion.**

→ Ok, we remove this paragraph.

AR1, p. 1139, l. 10-11: **Text needs to be tightened: the triggering of the debris flow is favored, not the debris flow itself. Also, what part of the results presented favors the climatic triggering? If only the age (i.e., a coincidence in timing), then that should be stated directly.**

→ Ok, we improve this sentence. Both the age of the debris-flow deposit and the Acoy megafan emplacement (with other debris-flow deposits in its stratigraphy) during the Ouki event favors the climatic triggering, we clarify this point in the text.

AR2, p. 1139, l. 11-12: **You mentioned again that the triggering by seismicity but the arguments are lacking.**

→ We improve the discussion on a potential seismic triggering of the debris-flow. But considering our results and the absence of historical earthquake catalog for this period (~100 ka) we can't conclude on this point.

AR2, p. 1139, l. 15: **Now you talk about the hillslope processes and fluvial erosion, but before the discussion about these topics was ambiguous. Discuss earlier properly.**

→ We are suggesting further potential implications and opening the discussion rather than developing arguments about the hillslope processes. This is part of the conclusion and as R1 did not argue on that specific point, we would like to keep this in place.

AR1 / AR2, p. 1139, l. 19-23: - **These sentences would be more appropriate in the discussion, particularly as they provide some of the broader regional context that is currently missing from the discussion. This argument in general though would benefit from references to any studies that may have attempted to quantify the amount of material mobilized in landslides from recent large earthquakes. Are there none from southern Peru or northern Chile? Without these, it is difficult to have much confidence in the dominance of climatic triggering, as the authors themselves point out that a seismic triggering cannot be ruled out. / - Here there is a discussion not mentioned before, place it on the discussion item.**

→ Ok, we place it in the discussion as suggested. There is no study, which quantify the amount of material mobilized in landslides triggered from a recent large earthquake but Lacroix et al.

(2013) demonstrated that in Peru during and after Pisco earthquake (Mw8), no important landslide were triggered along the Andean front. Similarly, no study reported major impact on landsliding of the Arequipa Mw8.5 event, and thus we base our statement on the fact that in the arid western Andean Cordillera none of the recent large earthquake triggered an important landslide.

AR1, p. 1139, l. 24-25: **This statement needs to be supported, but I don't recall that it was brought up earlier in the discussion.**

→ Ok, we add a reference and add this point in the discussion.

AR2, p. 1139, l. 24-26: **You talk about a strong tectonic control / climate on landslide. I think a better discussion about the tectonic control is lacking. There are still uncertainties (at least for me) in the Huaylillas Ignimbrite regard to its geomorphological features… and apparently is very important. You should have a good figure (map/geomorphologic image?) of the ignimbrite location. In addition, there are inaccuracies in the flow direction of Megafan Acoy to support the affirmation in these lines. Improving Fig. 3a is essential at this point.**

→ The map of the figure 1 clearly shows the ignimbrite location (in yellow). We improve the Acoy megafan description and location in the geomorphological setting.

AR1, p. 1139, l. 27-28: **This sentence should be deleted, not only because grammatically it's incorrect, but also because it appears to add nothing to the conclusions.**

→ Ok, we delete the sentence as suggested.

**EDITORIAL COMMENTS/CORRECTIONS**

→ We took in account, agree and correct all the typos and spelling mistakes the reviewer 1 point out. We thank AR1 for his help on editing the manuscript.

→ We only keep the notation $^{10}$Be-ka for the $^{10}$Be ages because this notation indicates that the ages can be posteriorly refined and re calculated in case of a refinement of the production rate. This convention is known and used by at least a part of the $^{10}$Be community (e.g. Gosse et al., 1995; Bigot-Cormier et al., 2005; Delunel et al., 2010).

**TABLE AND FIGURES**

AR2, fig. 1: What is the rectangle at the top of the figure?

→ We remove it.

AR2, fig. 2c: **The symbology of structures is lacking.**

→ Ok, we add the faults symbology in the legend.

AR2, fig. 3a: **It is not well understood what are the Megafan, T1 and T2, there is a bad relationship with the legend. Improve the legend, the lineaments are not indicated. This figure is fundamental to understanding the manuscript, data presentation and discussion. However, it is unclear for a reader not familiar with the area.**

→ Ok, we change the legend (for the Acoy megafan, T1 and T2) to improve the readability. We indicate the lineaments in the legend.

AR2, fig. 3b: **The image resolution is not good enough to review the morphological features.**

→ It's probably linked with the downsizing of the Figures for editorial purposes. We provide the full resolution for this figure.

AR2, fig. 3c: **I think this image is underexploited in the text.**

→ Ok, we referenced this figure more carefully in the text (now 3 citations).

AR2, fig. 4: **Verify that the ages in this figure match the text and table.**

→ The ages in this figure match those from the text and table.

AR2, fig. 5: **The ages are used in the text are different from those used in Fig. 5.**

**Make coherent.**

→ Ok, we change the ages according to the text and table 1 (erosion = 0.21 mm/ka).

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# Tectonic and climatic controls on the Chuquibamba landslide (Western Andes, southern Peru)

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## Abstract

The contribution of landslides to the Quaternary evolution of relief is poorly documented in arid contexts. In southern Peru and northern Chile, several massive landslides disrupt the arid Western Andean front. The Chuquibamba landslide, located in southern Peru, belongs to this set of large landslides. In this area, the Incapuquio fault system captures the intermittent drainage network and localizes rotational landslides. Seismic activity is significant in this region with recurrent Mw9 subduction earthquakes; however, none of the latest seismic events have triggered a major landslide. New terrestrial cosmogenic dating of the Chuquibamba landslide provides evidence that the last major gravitational mobilization of these rotational landslide deposits occurred at ~102 ka, during the Ouki wet climatic event identified on the Altiplano between 120 and 98 ka. Our results suggest that wet events in the arid and fractured context of the Andean forearc induced these giant debris-flows. Finally, our study highlights the role of tectonics and climate on (i) the localization of large Andean landslides in the Western Cordillera and on (ii) the long-term mass transfer to the trench along the arid Andean front.

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# 1 Introduction

In active mountain ranges, landslides are an important process in long-term erosion and thus contribute to the geomorphologic evolution of relief (Korup *et al.*, 2007). Despite their importance in terms of hazards, landslide maps remain rare (Guzzetti *et al.*, 2012) and information on the type, age or distribution of individual landslides is often lacking. Only a few publications deal with landslide triggering and/or evolution in arid contexts such as the western Andean flank, where several gigantic scarps disrupt the forearc piedmont (Audin and Bechir, 2006; Pinto *et al.*, 2008; Strasser and Schlunegger, 2005; Wörner *et al.*, 2002; Mather *et al.*, 2014; Crosta *et al.*, 2015). In contrast, because of the potential seismotectonic trigger (Keefer, 1984 and 2002; McPhillips *et al.*, 2014), landslide triggering along subduction active margins has been studied for a number of years, but most previous studies focused on humid climatic settings (Taiwan, New Zealand, Papua New Guinea, Japan; Meunier *et al.*, 2008; Hovius *et al.*, 2011). In southern Peru, the topographic gradient (average slope of 4% between the coast and the Western Cordillera), the crustal seismotectonic activity and the aridity of the forearc region has been directly linked to the Andean uplift and the subduction of the Nazca plate for the last 25 Myrs at least (Devlin *et al.*, 2012; Alpers and Brimhall, 1988; Dunai *et al.*, 2005). However, the Quaternary tectonic crustal activity and its role in the localization of landslides along the Western Andean Escarpment has never been explored in southern Peru and northern Chile. As a consequence, numerous questions remain concerning the importance of giant landslides in slope erosion relative to other nonseismic agents of erosion such as climatic forcing.

The "Chuquibamba landslide" is a large complex zone of imbricated landslides (about 80 km$^2$) affecting the Western Andean Cordillera in southern Peru. It belongs to the Andean arid piedmont, where most of the geomorphic markers are well preserved from erosion/transport processes (Hall *et al.*, 2008). This study of the Chuquibamba landslide aims to explore the links between seismotectonic activity and abrupt climatic changes on the triggering and development of large landslides. In this paper, we map out the area and characterize the tectonic and geomorphological settings, use Terrestrial Cosmogenic Nuclides (TCN) to date pertinent markers of the last debris-flow event and document the evolution of the landslide area.

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## 2 Context

### 2.1 Geologic and climatic setting of Chuquibamba region

The Andean Pacific arid front comprises different morphological units: the Coastal Cordillera 0-1000 m above sea level (asl), the Pacific Piedmont 1000-1500 m asl and the Western Cordillera 1500-6000 m asl. In southern Peru, the Western Cordillera corresponds to a Jurassic to Cretaceous volcanic arc (Atherton *et al.*, 1985) (Fig. 1). These magmatic and volcano-sedimentary rocks are emplaced within a Precambrian to Paleozoic basement. During the Eocene to Neogene, volcano-sedimentary deposits of the Moquegua group were overlain onto the Western Cordillera. This group is partly covered by the Huaylillas ignimbrite, produced during the Neogene volcanism and dated at 14.3-12.7 ($^{40}Ar/^{39}Ar$; Thouret *et al.*, 2007). The top of this ignimbrite forms a weathering surface. The Moquegua group and Huaylillas ignimbrite reach a maximum of 1500 m thick (Thouret *et al.*, 2007; Gunnell *et al.*, 2010). Some volcano-sedimentary rocks were deposited on the coastal plains during the late Neogene.

The Western Cordillera and Pacific Piedmont are incised, perpendicular to the NW-SE striking Andean range, by 1 to 3 km-deep canyons (Tosdal *et al.*, 1984; Gunnell *et al.*, 2010; Hartley and Evenstar, 2010). This area is affected by Quaternary tectonic deformation mainly expressed in the Western Cordillera by an active fault system striking parallel to the range (Sébrier *et al.*, 1985; Hall *et al.*, 2008, 2012) (Fig. 2). The piedmont region is exposed to extremely low denudation rates ranging from 0.1-1 mm $ka^{-1}$ in the coastal desert and Pacific piedmont to 1-46 mm $ka^{-1}$ in the Western Cordillera (values obtained for Quaternary time-scale by TCN dating; Hall *et al.*, 2008; Kober *et al.*, 2007) due to the arid climatic conditions since at least the Neogene (Mortimer, 1980; Alpers and Brimhall, 1988; Dunai *et al.*, 2005; Rech *et al.*, 2006). Along the Andes, the active subduction and crustal seismic activity largely control the geomorphologic evolution of the forearc (Keefer, 1994; Keefer and Moseley, 2004; Audin *et al.*, 2006; Tavera *et al.*, 2007; Perfettini *et al.*, 2010). Moreover, the Altiplano has been the target of many paleoclimatic investigations (Thompson *et al.*, 1998, 2000; Cross *et al.*, 2001; Baker *et al.*, 2001; Placzek *et al.*, 2006, 2013) that highlighted climate fluctuations for the last 130 ka. Steffen *et al.* (2009, 2010) as well as Carretier *et al.* (2013) highlighted the contribution of these wet climatic events to mass transport in major canyons from the Altiplano to the Pacific coast. In contrast, McPhillips *et al.* (2014) questioned the impact of the climatic fluctuations on landsliding and thus on erosion rate.

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## 2.2 Fault geometry and kinematics

In southern Peru, the Incapuquio fault zone has a strong geomorphic imprint on the Andean range (Huaman, 1985, Sébrier *et al.*, 1985). Based on microtectonic studies Sébrier *et al.* (1985, 1988) and Schildgen *et al.* (2009) identified different kinematic episodes. Sébrier *et al.* (1985, 1988) defined major Tertiary and Early Quaternary compressional phases and a minor Late Quaternary episode of normal faulting. However, Schildgen *et al.* (2009) proposed that a Tertiary episode of strike slip and normal faulting occurred between 14 and 2.2 Ma. However relocated microseismicity (Grange *et al.*, 1984) and teleseismic data (Devlin *et al.*, 2012) demonstrate the present-day reverse and strike slip components on the Lluta fault segment and more regionally for the Incapuquio fault system in the Arequipa region (Fig. 2). The Neogene surface and Quaternary drainage network are also affected by these fault segments (Fig. 3). Channel orientations and captures evidence a sinistral strike-slip component along an extrado graben (Fig. 3c). These Quaternary kinematics are coherent with the vertical geometry of the fault plane imaged at depth (20 km) by the distribution of crustal earthquakes (Fig. 2b) and focal mechanisms (Fig. 2c) (Mw<5; <20 km, Grange *et al.*, 1984; Devlin *et al.*, 2012). Local reverse and normal apparent surface movements are known to occur along major strike-slip fault or flower structure as for the forearc of northern Chile (Victor *et al.*, 2004) and southern Peru (Hall *et al.*, 2012). The present-day main sinistral strike-slip kinematics of the Incapuquio fault system demonstrated by the seismicity is compatible with normal apparent displacements as observed by Schildgen *et al.* (2009) and Sébrier *et al.* (1985, 1988).

## 2.3 Geomorphological setting

The Chuquibamba landslide is located in the Majes river catchment, along the Western flank of the Andes, between 1000 and 4000 m asl (Fig. 1). The Chuquibamba landslide comprises an imbricated set of rotational landslides, a debris-flow deposit and, in the lower area, a megafan and alluvial terraces (Fig. 3a). Upstream, the rotational landslides remobilize the thick Huaylillas ignimbrite formation fractured by the long lasting tectonic activity of the Incapuquio fault system. The total volume mobilized for Chuquibamba landslide is estimated to reach ~40 $km^3$. These imbricated rotational landslides correspond to a succession of 3 head scarps (Fig. 3b). The scar of the rotational landslides, cutting the Huaylillas weathering surface, delimits the landslide area (Fig. 3b) and form an elongated amphitheater trending in the NW-SE direction. This direction does not fit with the overall southwest dipping topographic slope, but rather corresponds to the structural trend of active faults (Fig. 3a).

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**Déplacé vers le bas [2]:** The total volume mobilized for Chuquibamba landslide is estimated to reach ~40 $km^3$.

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**Déplacé vers le bas [3]:** The debris-flow remobilizes the rotational landslides deposits.

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**Supprimé:** The debris-flow deposit is composed of mixed angular clasts, breccias and numerous meter-size boulders (Fig. 4a) entrapped in

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Moreover, several fault planes control the shape of the poly-lobed rotational landslides (Fig. 3b).

The base of the cirque (2900 m asl) is formed by smooth, sub-horizontal surfaces (Fig. 3b). These surfaces likely correspond to former lateral landslide deposits re-incised by the river after the initiation of the Chuquibamba landslide.

The debris-flow remobilizes the rotational landslides deposits. It consists of mixed angular clasts, breccias and numerous meter-size boulders embedded in a thin volcanic matrix (Fig. 4a), reworked from the Huaylillas ignimbrite. The debris-flow deposit displays a smooth and 100 meters-scale ondulated surface (Fig. 4a). In its upper part, the debris-flow rests directly on the basement (Fig. 4a); but 30 km downstream of the head scarp, in the vicinity of the Majes River (900 m asl), the debris-flow overlays the Acoy megafan (Fig. 3a).

The megafan, located downstream of the Chuquibamba village at the outlet of the Rio Grande, is about 100 meters thick and 8 kilometers long (Fig. 3a). Its stratigraphy indicates both a response to multiple phases of sediment production and surface erosion in the Rio Grande and fluvial incision in the Majes Canyon (Steffen *et al.*, 2010). Steffen *et al.* (2010) described an alternation of sheet flood units and debris-flow deposits, and a typical clast- to matrix-supported fabric. OSL dating places the Acoy megafan formation between 107.0 ± 5.0 ka (base) and 101.6 ± 4.9 ka (top) (Steffen *et al.*, 2010). Two levels of alluvial terraces (T1, T2) have been identified in the Majes canyon in the vicinity of the megafan. The Acoy megafan and alluvial terraces development has been linked to wetter episodes, identified in sediments of some Altiplano paleolakes (Placzek *et al.*, 2006, 2013), driving the fluctuations of Colca/Majes hydrologic regime (Steffen *et al.*, 2010).

## 3 Sampling strategy and methods

The last debris-flow deposit is perfectly preserved all along the Chuquibamba valley (Fig. 3a). Six meter-scale boulders of rhyolite entrapped in the Acoy megafan and debris-flow surfaces (Figs 4a and 4c) have been sampled. The preserved surface of the boulders (evidenced by desert varnish) indicates minimal post-abandonment erosion; they are well-anchored and sufficiently elevated on the debris-flow surface to minimize the possibility of post-depositional movement and potential covering by surficial material. In order to provide additional constrain on the regional erosion rate and consequently improve the exposure age

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**Supprimé:** Two levels of alluvial terraces (T1, T2) and a megafan (Acoy megafan) have been identified downstream of Chuquibamba village in the Majes canyon (Fig. 3a). Their

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**Supprimé:** The Chuquibamba debris-flow deposit overlays the Acoy megafan in Majes valley (Figs 3a and 4b). The megafan is about 100 meters thick and 8 kilometers long (Fig. 3a). OSL dating situates the Acoy megafan formation between 107.0 ± 5.0 ka (base) and 101.6 ± 4.9 ka (top) (Steffen *et al.*, 2010). Its stratigraphy indicates both a response to multiple phases of sediment production and surface erosion in the Rio Grande and Majes catchments.

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**Déplacé vers le haut [5]:** Steffen *et al.* (2010) described an alternation of sheet flood units and debris-flow deposits, and a typical clast- to matrix-supported fabric.

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determination, we also sampled the closest surface from the landslide: the Pampa Jahuay (quartzite pebble) in the pediplains 60 km southeast of Chuquibamba (Fig. 1 and Table 1).

Sample preparation was conducted at the Institut des Sciences de la Terre (ISTerre, Grenoble). As the rhyolitic samples contained enough quartz, we extracted *in-situ* produced beryllium-10 ($^{10}$Be) using the chemical procedures developed by Brown *et al.* (1991) and Merchel and Herpers (1999). The AMS $^{10}$Be measurements were performed at the ASTER AMS French national facility (CEREGE, Aix en Provence). Analytical uncertainties include uncertainties associated with AMS counting statistics, AMS external error (1%), standard reproducibility and chemical blank measurements ($^{10}$Be/$^{9}$Be blank = $1.60 \pm 0.72 \times 10^{-15}$). External uncertainties include 6% uncertainty in the production rate and 8% uncertainty in the $^{10}$Be decay constant. Exposure ages were calculated using the online Cronus Calculator (Balco *et al.*, 2008). Results are computed using the time dependent scaling scheme of Lal (1991) modified by Stone (2000).

## 4 TCN dating

In the debris-flow deposit and Acoy megafan samples, the $^{10}$Be concentrations are relatively consistent and range from $6.67 \pm 0.28 \times 10^5$ to $1.38 \pm 0.08 \times 10^6$ atoms per gram of quartz (at g$^{-1}$ qtz) (Tab. 1). The high $^{10}$Be content of the sample ($1.33 \pm 0.02 \times 10^7$ at g$^{-1}$ qtz, 11A28) collected from the Pampa Jahuay suggests an extremely low erosion rate lasting at least for the last 2 million years in the southern Peruvian forearc (1.9 ± 0.3 My). The computed erosion rate (0.21 ± 0.05 mm ka$^{-1}$) agrees with rates published by Hall *et al.* (2012) for the South Peru and, by Kober *et al.* (2007) for Chile (Oxaya formation). These results support the hypothesis of an insignificant erosion of the sampled boulders of the debris-flow deposit. TCN exposure ages deduced from debris-flow boulders (with an erosion rate of 0.21 mm ka$^{-1}$) range from 96.1 ± 8.9 to 108.5 ± 10.2 $^{10}$Be-ka (Tab. 1, Fig. 5). Considering the uncertainties, exposure ages are consistent and suggest a single remobilization event with a weighted average age of 101.9 ± 5.5 ka. The age of the large boulder sampled on the Acoy megafan (Fig. 4) is 105.3 ± 10.2 $^{10}$Be-ka (Tab. 1).

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**Supprimé:** It is important to note that the associated analytical uncertainties are remarkably low (3-6%), probably due to the purity of the quartz mineral, allowing low interferences during AMS measurement and subsequently excellent analytical statistics (Tab. 1).

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## 5 Discussion

### 5.1 Tectonic and climatic forcing on Chuquibamba landslide evolution

The weighted average age of debris-flow boulders indicates a last major debris-flow at 101.9 ± 5.5 ka. The abandonment age of the megafan surface (105.3 ± 10.2 $^{10}$Be-ka; Figs 4 and 5) agrees with the OSL ages published by Steffen *et al.* (2010) (i.e. 107.0 ± 5.0 ka at the base of the megafan and 101.6 ± 4.9 ka near the top). The Ouki wet event has been evidenced from sediments collected in the eponym paleolake located in the higher Bolivian Altiplano (Placzek *et al.*, 2006, 2013). The chronological framework deduced from U-Th dating on carbonates indicates the Ouki deep lake cycle between 120 to 98 ka (Placzek *et al.*, 2006, 2013). Steffen *et al.* (2010) already suggested a correlation between wet time intervals on the Altiplano and sediment aggradation in the Majes Valley. According to Steffen *et al.* (2010), the Acoy megafan recorded two phases of Rio Grande catchment development characterized by landsliding during the Ouki wet climatic event. It indicates that during the megafan emplacement, between 112.0 and 96.7 ka, the Rio Grande permits the sediment transport downstream. Similarly to the Lluta catchment in Chile, landsliding might have been initiated by enhanced precipitation and a reduced friction along a basal shear plane due to increasing hydrostatic pressure in the groundwater (Hoke *et al.*, 2004; Strasser and Schlunegger, 2005). The weighted average age of the last debris-flow deposit (101.9 ± 5.5 ka) also correlates with the Ouki event (120-98 ka). In the Western Andes, other landslides have been associated with wetter climatic conditions such as the older Lluta collapse (North Chile; 18°S; Wörner *et al.*, 2002), yielding a minimum age of 2.5 Ma (Strasser and Schlunegger, 2005), the Tomasiri landslide (South Peru; 17°30'S), dated at 400 ka (Blard *et al.*, 2009) or younger Argentinian landslides which have been associated with the Minchin event (40-25 ka; Trauth *et al.*, 2003; Hermanns and Schellenberger, 2008). We suggest that the debris-flow, which remobilized rotational landslide deposits, was triggered by an increase in the pore water pressure in the Huaylillas Ignimbrite during the Ouki wet climatic event. After this event none of the latest wet climatic event identified on the Altiplano (*e.g.*, Michin, 48-36 ka and Tauca, 26-15 ka) triggered a large landslide or remobilized the Chuquibamba debris-flow. Similarly, in Southern Peru, Keefer *et al.* (2003) identified only cm-scale debris-flows for the last 38 ka. Theses observations are consistent with the preservation of the Chuquibamba debris-flow morphology since its emplacement. We suggest that the Ouki event was the latest event, which duration and intensity permitted to trigger a large landslide in the arid western Andean

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flank (Wörner *et al.*, 2002; Strasser and Schlunegger, 2005; Blard *et al.*, 2009). Moreover, Carretier *et al.* (2013) proposed that the contribution of rare and strong erosive events to the long-term erosion of the Andean range is more than 90% in an arid climatic context. We suggest climatic fluctuations favor landsliding and thus have a great impact on sediment transport and on the western Andean flank morphology.

The link between the tectonic framework, localization, and flow direction of a mega-landslide has already been suggested for the Andean forearc domain (Pinto *et al.*, 2008; Antinao and Gosse, 2009; Mather *et al.*, 2014). As the Chuquibamba landslide is elongated in an NW-SE trend guided by the Incapuquio fault system, we suggest that the localization and geometry of the landslide is mainly controlled by preferential fracturing orientations (Fig. 3b). More broadly, in southern Peru and northern Chile most of the large landslides are located in tectonically fractured regions (Audin and Bechir, 2006; Pinto *et al.*, 2008; Strasser and Schlunegger, 2005; Wörner *et al.*, 2002; Crosta *et al.*, 2015). It suggests that the prefracturation plays an important role in preconditioning landsliding in this arid area.

No relationship between a Mw 8.0 subduction earthquake and a giant landslide has been previously documented in southern Peru (Lacroix *et al.*, 2013) but Keefer *et al.* (2003) point out that the succession in time of subduction earthquakes and El Nino events produces debris-flows in the coastal region (southern Peru). Here, even if the Ouki wet phase seems to predispose the triggering, we can't exclude a contemporaneous seismic triggering (subduction or crustal earthquake) for the Chuquibamba debris-flows. More generally, robust arguments indicating such a correlation for giant-landslides are scarce along the South American margin; other triggering factors (increase of pore pressure, climate change, glacial debuttressing) are usually invoked in addition to a seismic triggering (Keefer, 2002; Pinto *et al.*, 2008).

### 5.2 Landscape evolution and tectono-climatic scenario

We propose a landscape evolution scenario based on geomorphic marker analysis and new TCN ages (Fig. 6). The initial drainage network flowed toward the coast (i.e. in a southerly direction) and incised the roof of the weathered Huaylillas ignimbrite (Fig. 6a). These parallel incisions are still preserved (Fig. 3b, 3c) and sometimes even abandoned. Afterwards, the development of a graben structured by the Incapuquio fault system captured the drainage network along a 110°N trending direction (Fig. 3c) creating a new tributary of the Majes River. Rotational landslides were initiated by slope instability or pore pressure increase at the

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base of the Huaylillas ignimbrite during wet climatic events, as proposed by Hoke *et al.* (2004) and Strasser and Schlunegger (2005) for northern Chile (Fig. 6b). Sliding surfaces of rotational landslides are localized on fault planes and progressively enlarge the valley, as evidenced by the successive rotational landslides scarps (Fig. 3).

The rotational landslides deposits accumulated upstream in the valley (Fig. 6b) and were remobilized by debris-flows during the Ouki event (120-98 ka; Fig. 6c). The accumulation of successive debris-flow and mudflow deposits at the outlet of the Rio Grande during the Ouki event formed the Acoy megafan (Steffen *et al.*, 2010). Finally, at 101.9 ± 5.5 ka, the last major debris-flow sealed the erosion/transport system (Fig. 6c). This pattern, alternating upper slopes destabilizations and its remobilization by debris-flow permits to enlarge the valley (Fig. 6d).

At the present time, the arid climate on the Western flank of the Cordillera preserves geomorphologic features from erosion; the water yield comes only from rivers.

## 6 Conclusions

This study raises the question of the control of local tectonic activity and Altiplano climatic fluctuations on landslide processes in the arid Western Andean front. Indeed, for the Chuquibamba landslide region, the sequence of debris-flows (identified in the Acoy megafan stratigraphy and overlaying its roof) seems to have been favored by the occurrence of a wet climatic event (Ouki event), even if a contemporaneous seismic triggering cannot be excluded. Our results suggest sediment accumulation in the valley during wet periods and incision during dry periods. Wet climatic events then appear to control the growth of the drainage network, participating in regressive erosion and in the creation of new tributaries on the Western Andean front. Our results also show that during wet events in a tectonically fractured region, hillslope processes, rather than fluvial erosion, dictate the evolution of the landscape at the channel head in the arid and high relief area.

As rare and strong erosive events represent the most important contribution to the long-term erosion of the arid Western Cordillera (Carretier *et al.*, 2013), we propose that massive landslides disrupting the arid Western Andean front contribute significantly to long-term erosion of the western escarpment of the Andes. This study also proposes that the Western Cordillera large landslides have been triggered during wet periods. Moreover, in southern

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- A. Margirier 6/3/15 16:43 **Supprimé:** . The debris-flow deposit surface is perfectly preserved; the Rio Grande just incises the debris-flow deposit (~100 m) due to the lack of a significant input of water issuing from the Western Cordillera
- A. Margirier 6/3/15 16:43 **Supprimé:** In an arid context, Terrestrial Cosmogenic Nuclides are the perfect tool to date the exposure of surface older than ~100 ka. In the Peruvian arid piedmont, the
- A. Margirier 6/3/15 16:43 **Déplacé vers le haut [6]:** TCN dating
- A. Margirier 6/3/15 16:43 **Supprimé:** of landslides is theoretically applicable over several hundreds of thousands of years, particularly in this case of gigantic boulder sampling. Additionally our data exemplify that quartz crystals extracted from rhyolites are particularly adapted to TCN dating and open new perspectives for quantitative geomorphologic applications in volcanic areas.
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- A. Margirier 6/3/15 16:43 **Déplacé vers le haut [8]:** Our results suggest sediment accumulation in the valley during wet periods and incision during dry periods.
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Peru and northern Chile, most of the large landslides are located in tectonically fractured regions. We thus suggest a strong regional tectonic and climatic control of the long-term erosion of the arid western Andean front.

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**Supprimé:** In these arid regions, climatic fluctuations have a greater impact on landslide triggering and on sediment transport.

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**Déplacé vers le haut [7]:** Carretier *et al.* (2013) proposed that the contribution of rare and strong erosive events to the long-term erosion of the Andean range is more than 90% in an arid climatic context.

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**Acknowledgments**

This project was supported by the Institut de Recherche pour le Développement (IRD). We acknowledge additional support from Instituto Geologico Mineralogico y Metallurgico del Peru (INGEMMET, Peru). We thank all the staff from the ASTER AMS facility at CEREGE. This work has been carried out in the frame of the Master Thesis of A. Margirier in ISTerre.

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A. Margirier 6/3/15 16:43
**Mis en forme:** Normal, Retrait : Première ligne : 0,05 cm

| Sample | Latitude (°N) | Longitude (°W) | Elevation (m asl) | Production rate (atoms g$^{-1}$ yr$^{-1}$) | | Geomorphic scaling factor (a) | Sample thickness factor (b) | Quartz (g) | $^{9}$Be (mg) | $^{10}$Be/$^{9}$Be (c) | Uncertainty $^{10}$Be/$^{9}$Be (%) | $^{10}$Be concentration (× 10$^{3}$ atoms g$^{-1}$ Qtz) | $^{10}$Be concentration uncertainty (× 10$^{3}$ atoms g$^{-1}$ Qtz) | Erosion rate (m Ma$^{-1}$) | Erosion rate external uncertainty (m Ma$^{-1}$) | Age $^{10}$Be (ka) e = 0 (d) | Age $^{10}$Be internal uncertainty (ka) (e) | Age $^{10}$Be external uncertainty (ka) (f) | Age $^{10}$Be (ka) e = 0.21 m/Ma (d) | Age $^{10}$Be internal uncertainty (ka) (e) | Age $^{10}$Be external uncertainty (ka) (f) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Spallation | Muons | | | | | | | | | | | | | | | | |
| *Blank* | | | | | | | | | | | | | | | | | | | | | |
| BKGRE67 | - | - | - | - | - | - | - | - | 0.486 | 1.604 10$^{-15}$ | 44.74 | 31.374 | 14.036 | - | - | - | - | - | - | - | - |
| *Debris-flow deposit* | | | | | | | | | | | | | | | | | | | | | |
| 11A39 | -15.9294 | -72.5306 | 1315 | 7.15 | 0.27 | 0.99 | 0.98 | 9.54 | 0.291 | 3.998 10$^{-13}$ | 3.10 | 828.574 | 25.748 | - | - | 95.99 | 3.67 | 8.83 | 96.11 | 3.68 | 8.86 |
| 11A40 | -15.5327 | -72.9267 | 1356 | 7.43 | 0.28 | 0.99 | 0.99 | 6.02 | 0.254 | 3.257 10$^{-13}$ | 3.16 | 938.088 | 29.597 | - | - | 102.72 | 4.07 | 9.49 | 102.86 | 4.09 | 9.52 |
| 11A41 | -15.5343 | -72.9245 | 1391 | 7.39 | 0.28 | 0.98 | 0.97 | 5.10 | 0.290 | 2.566 10$^{-13}$ | 3.52 | 992.821 | 34.974 | - | - | 108.29 | 4.85 | 10.17 | 108.46 | 4.87 | 10.2 |
| 11A42 | -15.9145 | -72.5487 | 1543 | 8.40 | 0.29 | 0.99 | 0.98 | 10.98 | 0.292 | 5.468 10$^{-13}$ | 3.44 | 992.144 | 34.175 | - | - | 97.51 | 4.17 | 9.10 | 97.88 | 4.19 | 9.15 |
| 11A43 | -15.8784 | -72.5927 | 1899 | 10.54 | 0.33 | 0.98 | 0.98 | 10.44 | 0.291 | 6.981 10$^{-13}$ | 6.14 | 1375.656 | 84.507 | - | - | 106.7 | 8.30 | 11.42 | 106.87 | 8.34 | 11.46 |
| *Acoy megafan* | | | | | | | | | | | | | | | | | | | | | |
| 11A28 | -16.0091 | -72.4892 | 817 | 5.13 | 0.24 | 1.00 | 0.99 | 9.77 | 0.294 | 3.196 10$^{-13}$ | 4.18 | 666.607 | 27.905 | - | - | 105.1 | 5.55 | 10.15 | 105.26 | 5.57 | 10.19 |
| *Pampa Jahuay* | | | | | | | | | | | | | | | | | | | | | |
| 11A62 | -16.3408 | -72.0840 | 1592 | 8.76 | 0.30 | 1.00 | 0.97 | 19.96 | 0.295 | 1.320 10$^{-11}$ | 1.71 | 13318.936 | 227.531 | 0.21 | 0.05 | 1894.08 | 94.88 | 271.34 | - | - | - |

Table 1. TCN results of the Chuquibamba Valley and the Pampa Jahuay. (a) The topographic scaling factor has been calculated following the method of Dunne *et al.* (1999). (b) The sample thickness correction has been calculated with a 2.7 density factor. (c) AMS (Accelerator Mass Spectrometry) analyses have been carried out at the French AMS facility ASTER. Calibration of $^{10}$Be concentrations were done with NIST Standard Reference Material 4325 which use $^{10}$Be/$^{9}$Be ratio of $2.79 \times 10^{-11}$ and a $^{10}$Be half-life of $1.387 \pm 0.012 \times 10^{6}$ years (Chmeleff *et al.*, 2010; Korschinek *et al.*, 2010). Results have been corrected from the chemical blank ($^{10}$Be/$^{9}$Be blank = $1.60 \pm 0.72 \times 10^{-15}$). Internal uncertainties consider the analytical uncertainties including counting statistics, the instrumental variability (1%), the standard deviation and chemical blank. External uncertainties include 6% uncertainty in the production rate and 8% uncertainty in the $^{10}$Be decay constant. (d) Ages have been computed with Cronus Calculator (Balco *et al.*, 2008) using the time-dependent production rate of Lal (1991) modified by Stone (2000). The production rate calibrate by Kelly *et al.* (in press) on recent time scale in Peruvian Andes is not relevant for this study. For our range of ages (100 ka) geomagnetic variations have to be considered. Ages are presented with the internal (e) and the external uncertainties (f).

A. Margirier 6/3/15 16:43
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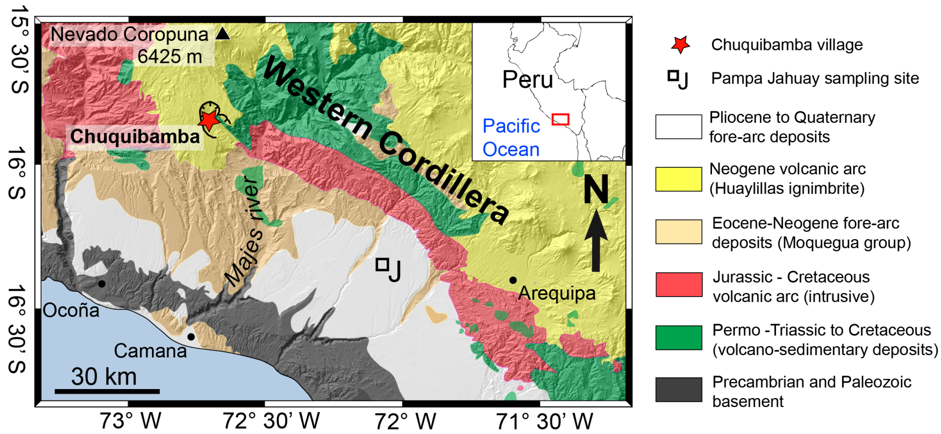


Figure 1. Simplified geological map of South Peru (modified from Roperch *et al.*, 2006; INGEMMET, 2001), showing the Chuquibamba village (red star), the destabilization zone and the Pampa Jahuay sampling site (J). Coordinates are given in WGS 84 longitude and latitude (degrees). Inset shows the study area location within Peru and a part of South America.

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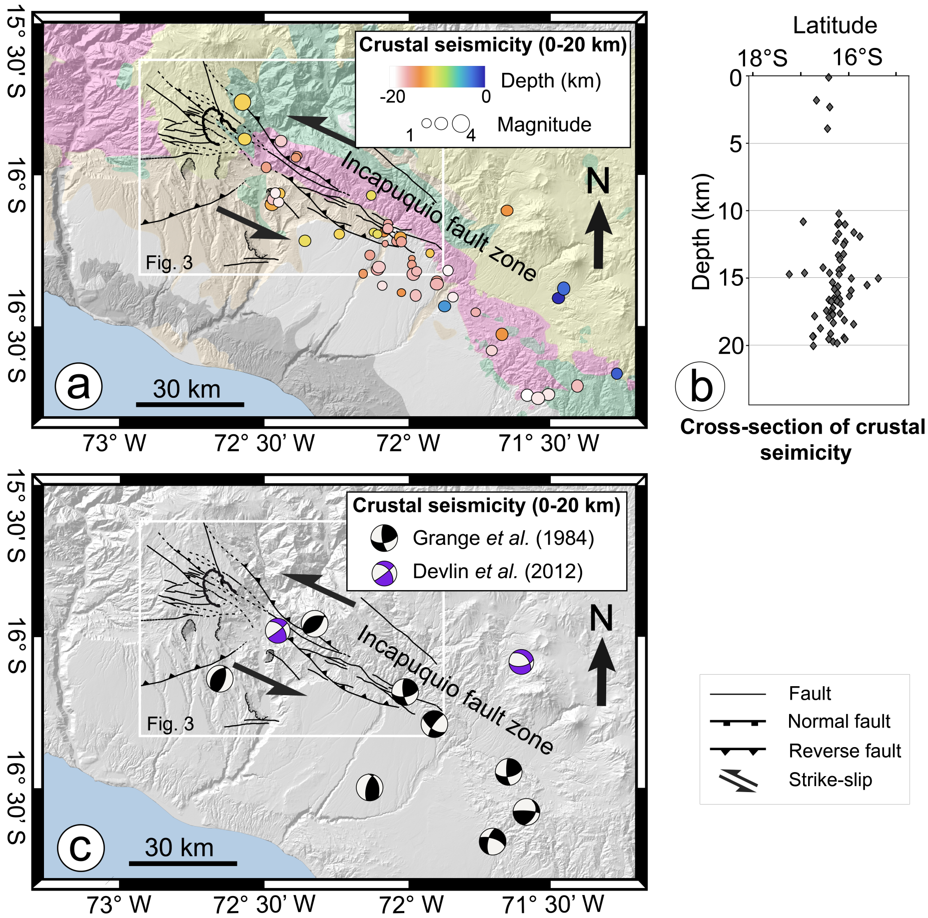


Figure 2. Regional crustal seismicity and focal mechanisms. (a) Crustal seismicity (depth < 20 km) and faults are represented on the geological map of South Peru (modified from Roperch *et al.*, 2006; INGEMMET, 2001). (b) Cross section showing the vertical cluster of earthquakes. (c) Focal mechanisms from Grange *et al.* (1984) and Devlin *et al.* (2012) studies, the kinematic of the Incapuquio fault system is indicated by black arrows.

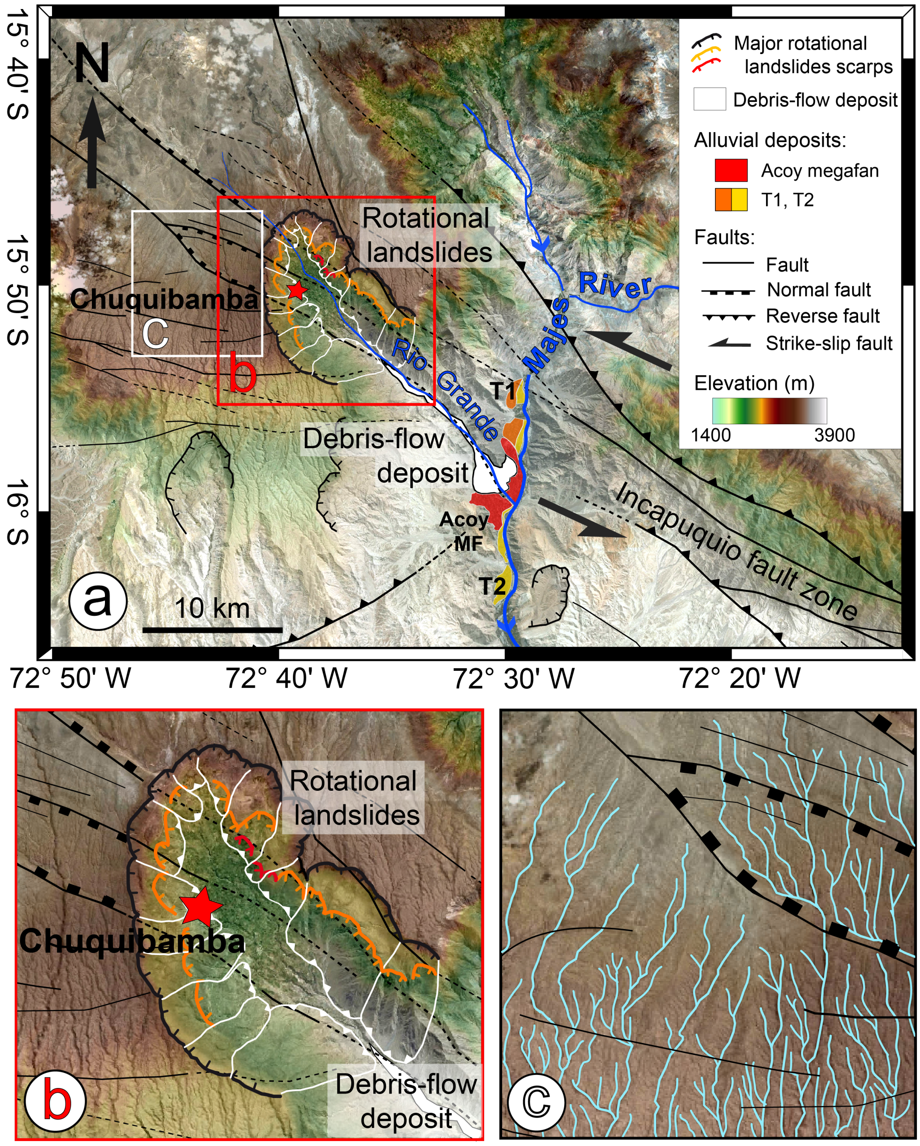


Figure 3. SRTM numerical elevation model overlay by Landsat image of the Chuquibamba destabilization zone. Coordinates are given in WGS 84 longitude and latitude (degrees). (a) Global view of the Chuquibamba area pointing major detachment scarps, debris-flow

deposits, Acoy megafan, alluvial terraces and faults. (b) Zoom on the amphitheater-shaped scar of the rotational landslides showing the different head scarps. (c) Drainage network and faults.

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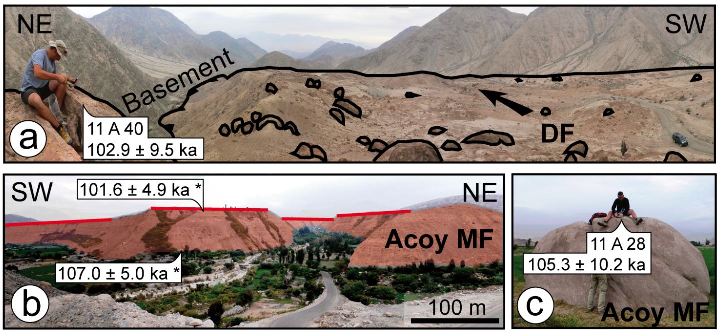


Figure 4. Field photographs showing the debris-flow deposit morphology and the Acoy megafan. (a) Characteristic block sampled on the debris-flow deposit. The arrow indicates flowing direction of the debris-flow. (b) General view of the Acoy megafan (Acoy MF), red lines highlight the top of the terrace. The OSL ages obtain by Steffen *et al.* (2010) for the Acoy megafan are indicated with an asterisk (c) Block sampled on the megafan.

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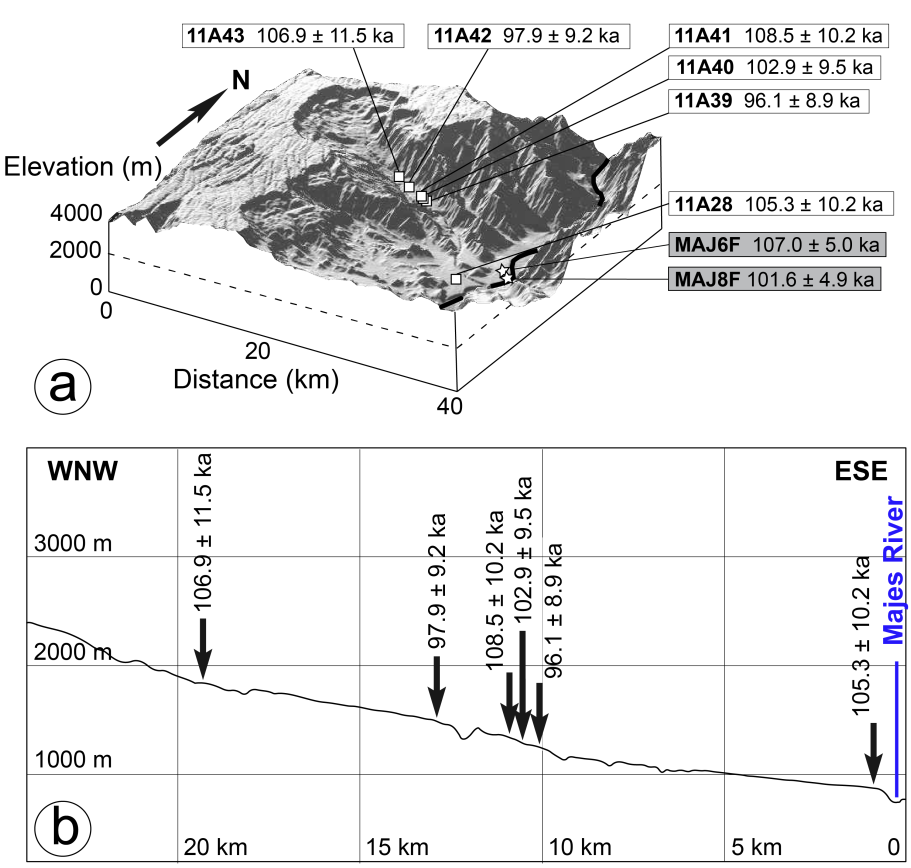


Figure 5. Samples location. (a) Digital elevation model (GeoMapApp, SRTM data, 90 m resolution) of the study area, showing samples location and TCN ages obtained for the debris-flow deposit and the Acoy megafan surface. OSL ages obtained by (Steffen *et al.*, 2010) for the Acoy megafan are noted in grey. (b) Elevation profile locating debris-flow and the Acoy megafan ages.

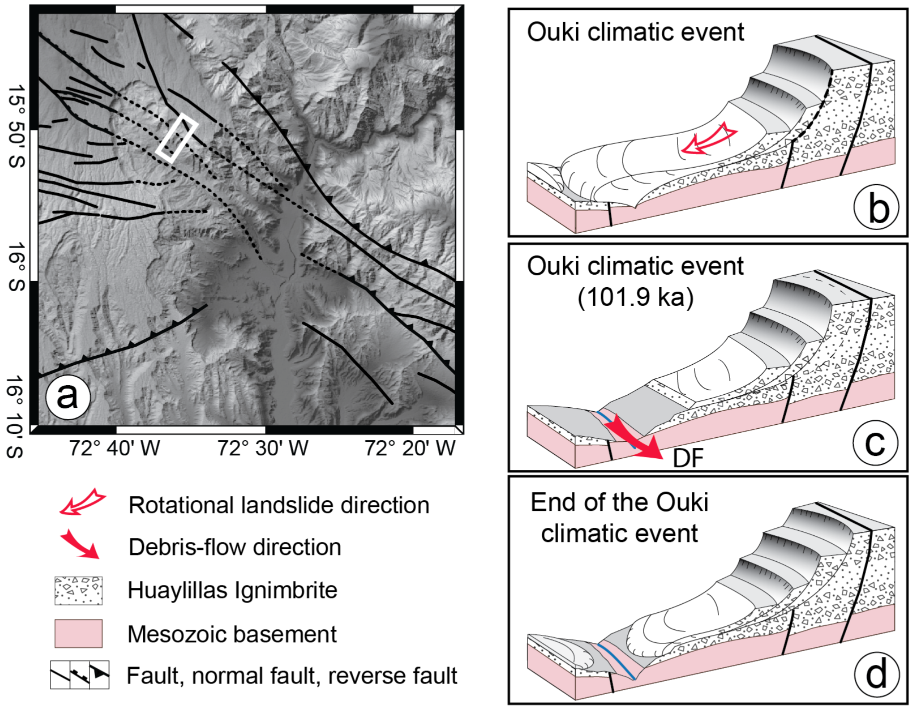


Figure 6. Map and block diagrams of the evolution of the Chuquibamba landslide. (a) SRTM numerical elevation model, the white rectangle localizes the block diagrams. (b) Block diagram showing rotational landslide initiation on the flank of the Chuquibamba Valley during the Ouki wet event. The landslide enlarges the valley and accumulates material at the bottom. (c) The accumulated materials are remobilized by debris-flows during the wetter phases. (d) This remobilization allows new rotational landslides that enlarge the amphitheater shape valley.