Nat. Hazards Earth Syst. Sci. Discuss.,
doi:10.5194/nhess-2016-19-AC2, 2016

Natural Hazards
and Earth System
Sciences
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Discussions

Interactive comment on "Seismic hazard in low slip rate crustal faults, estimating the characteristic event and the most hazardous zone: study case San Ramón fault, in central Andes" *by* Nicolás P. Estay et al.

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Received and published: 3 June 2016

Dear Editor,

We read the G.Vargas referee comments and modified the manuscript incorporating the discussions and precision that he suggests.

Major coments. #1 Page C2

The referee said "My major concern is some apparently contradiction between what the authors show as evidences and what they can conclude, appearing –to me- as a

confusion between fault segmentation and possibilities for large earthquake ruptures. Authors conclude that the fault is segmented, and because of that discard the possibility for an entire rupture connecting different segments between at least the Maipo and Mapocho rivers, as previously proposed (Armijo et al., 2010; Rauld, 2011; Vargas et al., 2014). For example they conclude: "Geophysical and geomorphological evidences suggest that the SRF is segmented into 4 sub-faults that most likely are activated independently. Under this scenario a characteristic earthquake of magnitude Mw = 6.2 – 6.7 is expected." However, previously the same authors state "Although we cannot ruled out a single rupture of the whole FSR segments, our evidences consistently favor the occurrence of a single segment characteristic earthquake, with a rupture length of 10 km." I think this is a major point that can produce confusion especially for people do not familiarized with this specific subject, but more importantly, needs to be more properly argued and discussed in the optic of geologic information as well as historic and past ruptures."

Authors reply: It's necessary to clarify that we do not discard an entire rupture connecting different segments. In fact state explicitly "Although we cannot ruled out a single rupture of the whole FSR segments" (Page #12 line 4). However we are interpreting surface uplift manifestations of the fault as a good indicator of the behavior of the deep faults movements, therefore we asseverate "Our evidences consistently favor the occurrence of a single segment characteristic earthquake, with a rupture length of 10 km" (Page #12 line 4 and 5). Trying to express that the deformation evidence find in this work suggest a not continuously rupture in surface, as we explain in the beginning of the SRF segmentation discussion (section 4.3 Page # 10 Line 25 to Page #11 Line 15, and Figure 9). Therefore we modeled de PGA expected of the most likely scenario consistent with the geomorphologic and geophysics methodologies used in this work.

Major coments. #2 Page C3

The referee said "How can you explain a ca. 5 m of slip at surface along the fault, deduced from direct observations in trenches (Vargas et al., 2014), with only a single

10 km length segment rupture scenario? Please discuss in terms of scale relationship and provide some examples; in the work of Wells and Coppersmith (1994, which you already cited), it looks that slip in the order of 5 m (at surface, it can be more -in average or maximumat depth) are mostly associated to earthquake rupture magnitude in the order of 7 or greater, and not in the order of Mw6.2-6.6 as finally deduced in this work in the case of the corresponding segment 3 (Figure 9). On the contrary, many examples can be cited for surface ruptures along reverse faults connecting different fault segments -some of them partly blind- during large earthquakes (eg. see McCalpin, 2009; Chapter 5; see Nabelek, 1985, in the case of the Mw7.3 El Asnam earthquake)."

Authors reply: At first, an important point of using the Well & Coppermisth (1994) relationships to approximate the Mw magnitude based on the slip is the correlation coefficient "r" for reverse faults. For average slip and maximum slip "r" is 0.38 and 0.28 respectively. Therefore the approximation of magnitude by this law is not precise for reverse faults; however for normal and strike-slip faults the empirical relationships appears to be more representative. A good example of variable behavior of reverse faults is the Mikawa 1945 event, with a 4km of rupture and 1.3 m and 2.5 m of average and maximum slip respectively (Tsuya, 1946; Wesnousky, 2008). Asnam 1980 earthquake is another well analyzed example, with a main displacement of 2.2m, a maximum surface rupture of 6.5m and a likely behavior of two rupture planes of 12km length each one (Yeilding et al. 1980) produced by the same main shock.

Subduction Tohoku 2011 earthquake, although an intraplate event, is other good example of this phenomena. The seismic moment release in this event was bigger than the expected for a ∼500km rupture length earthquake. This was explained for a extremely large slip ∼50m (Susuki et al. 2011) compare with the expected for a subduction event as the 2010 Chilean earthquake with a rupture length of 600km and maximum slip of 17 meters (Tong et al. 2010).

Major coments. #3 Page C3 Finally, I think this paper shows really interesting and novel results supporting the segmentation of this fault system and providing model

results for the case of single segment rupture scenarios, which is –itself- an important contribution. But the worse case scenario that authors proposes, assuming only a single segment rupture (Mw6.2- 6.7), is apparently inconsistent with field observations shown and discussed in previous work, and needs to be better argued. This is a major point taking the emphasis and implications for natural hazard assessment of Santiago city.

Authors reply: At the light of the scarce evidences this is a very arguable point, and that's why we exposed our data interpretation within the discussion section. In fact it is not necessary inconsistent with the previous works because:

1) Fault displacement observed from a paleoseismological study (one trench for a likely 30km fault, Vargas et al. 2014) of 4m it is not necessary inconsistent with a reduced rupture length of 10km (see reply of Major comments #2).

2) Based on empirical evidence, Wesnousky (2008) states that simultaneous rupture of two fault segments separated by less than 3km does not always occur. Therefore, assuming a rupture episode of segments altogether does not necessarily represent the most likely scenario. In addition, Wesnousky (2008) do not have conclusive evidences of propagation rupture for segments close to 3km in reverse faults.

3) The mega-thrust model develop by Armijo et al. (2010) and Rauld (2011) is almost 2D dimension, and do not imply a necessary 30km of length. The folded strata of the Abanico and Farellones units can be produces by several 10 km faults length.

Finally, we try to be responsible with our interpretations, and always we describe our evidence as an interpretation of the fault behavior. The methodologies used in this work observed indirect phenomena influenced by de fault (basement scarp, uplift in the drainage above the fault, and mountain front sinuosity) but not necessary the fault behavior in depth. Therefore, we try to be explicit that the rupture length of the SRF do not has a unique solution, but our evidences are consistence with a segmented rupture. Page #12 Line 4: "Although we cannot ruled out a single rupture of the whole

FSR segments, our evidences consistently favor the occurrence of a single segment characteristic earthquake, with a rupture length of $\sim$ 10 km."

Specific comments #1

Considering the seismic network you installed, please clarify: What's the threshold-magnitude? Were all the stations triggered by each of the events you found? What instruments did you use, broadband, short period, LHZ? What's the depth in boreholes for the installation of seismic stations? Can you provide moment tensor-solutions for the seismic events that you associated to the fault? It could be interesting a more developed discussion of your findings by comparing methodologies and results with those explained in the previous work of Pérez et al. (2014; Natural Hazards); in this last article, authors did a precise location of small events under seismic stations surveyed during ten years, providing moment tensors for those finally associated to the SRF.

Authors reply: We add the following sentence in the Page # 4 line 18

"To achieve the first goal, we deployed a small seismic network of five borehole seismometers with three-component 2 Hz sensors (short period S31f-2.0a of IESE) running in continuous mode during a one year time-window, with a sample rate of 100 Hz. "

Respecting the moment tensor-solution the few stations in our network does not allow the calculation of a moment tensor solution. The seismic events associated with the fault are observed in 3 or 4 of the 5 stations, which explain the huge location erros ($\pm$ 2.5-5 km) see Figure 3.

The difference between the seismicity analysis of Perez et al. (2014) and our work stand in which seismic event assume that can be associated to SRF. We restricted the event to these inside the rupture plane modeled, instead of the Perez et al. (2014) methodology which assume a related event to structure out for about $\sim$5km of the rupture plane modeled by them (which in the 10 year of registration do not have inside events). Our approach integrates different techniques, where seismic results are another line of evidence that reinforce the main conclusions; therefore we think that this specific discussion is beyond the scope of the study.

Sepecifc commets #2

It's not clear if PGA estimations consider or not near-field effects, directivity and stochastic kinematics. Stochastic faulting models are important to predict PGA values. It would be interesting to discuss your findings in the sense of Herrero & Bernard (1994), Lavalle and Archuleta (2003), or even the PAGER from USGS, which suggest the possibility of the different variables to induce errors and artifacts on PGA model results. Please also discuss your methodologies and findings in the optic of previous results for this specific case, already published by Pérez et al. (2014; Natural Hazards)

Authors reply: Using the Chiou & Young (2014) the near-field effects and kinematics are implicit, as we describe in Page #3 Line 7: "We choose the empirical equations for crustal earthquakes (e.g. Sadigh et al. 1997; Chiou & Youngs 2014) to predict the peak ground acceleration (PGA). The robustness of this methodology is grounded on the last decade understanding of the key variables that control the PGA. Principal variables are event magnitude, fault type, hanging wall and site effects (near field effects). We choose the Chiou & Young equation (2014), because their model accounts also for a low slip rate crustal fault, and has an extensive record of different earthquakes worldwide.".

Regarding directional effects, we dismiss this variable because we do not have any moment tensor evidence to model this behavior.

Additionally we add a discussion of the PGA result, and are contrasted with Perez et al. results. Page #12 Line 6:

5.4 PGA results The PGA modeling results are similar to the empirical PGA observed in others reverse earthquake. Examples of these are the Niigata Mw=6.6, 2004 Japan earthquake (Mori & Somerville, 2006); Northridge Mw=6.7 1994 California earthquake

(Porcella et al. 1994); Iwate-Miyagi Nairiku Mw=6.9 2008 Japan earthquake (Cultrera et al. 2013), all with near-epicenter recording stations. The similar PGA suggests that the approximation used in this work is consistent with the empirical evidence.

The range of the PGA values modeled in this work, PGA > 0.3g at distances shorter than 10 km from the fault scarp, are similar to the previous work made at the SRF (Perez et al. 2014) up to 0.2g in the nearby 10km from the fault. Largest values are also similar, PGA = 0.7-0.8g (Perez et al. 2014) and 0.8g in this work. The difference between both results stands on the PGA distribution. In our work we considered the amplification due to sedimentary cover, concentrating larger PGA values at the hanging walls cover by sediments. Whereas in Perez et al. (2014) focus on directional effects, concentrating larger PGA values at the southward fault zone, but neglecting site effects. We are not including directional effects due the lack of reliable focal mechanics.

Despite the differences in the maximum earthquake, Mw=6.9 in the case of Perez et al. (2014) and Mw=6.6-6.7 in our work, the range of PGA values are similar. In addition the largest PGA expected in both studies reaches up to 0.7g, a quite large number that confirm the potential hazardous at the near-field of SRF. As well as occur in faults that caused the Niigata and Northridge earthquakes.

Specific comment # 3

“3. Results from gravimetry are really interesting, I think this is a major contribution for this case of study (SRF). Fault segments can be in partly covered or blind and subsurface geophysics can provides useful indirect observations to complement those made at surface, contributing to unravel the faults. However, it’s an exaggeration to state: “Basement morphology is a useful marker of cumulative faulting. Since SRF has a low slip rate, fault scarp morphology may be modified by deposit and/or erosion surface processes. Thus, we favour the use of gravity profiles and geomorphological measurements instead of scarp topographic analyses.” If you insist, please develop –arguemore in deep this idea that contradicts decades of advancements in paleoseismology and earthquake geology (eg. McCalpin, 2009). Specifically, how can you interpret slip from these profiles? I don’t understand what are the arguments and assumptions supporting slip inferences, please clarify (specifically for the age and then kinematics). The thickness of the sedimentary cover inferred from gravimetry profiles is really small near the fault; It’s possible to discard the influence of previous erosional and depositional processes (transit basin) from the adjacent quebradas, and then the influence on the interpretation of inherited basement morphology, fault segmentation and cumulative slip?”

Authors answers: First we never discredit the paleosesimology study, instead we value this type of work because is the most direct methodology to understand and date past earthquakes. The sentence ““Basement morphology is a useful marker of cumulative faulting. Since SRF has a low slip rate, fault scarp morphology may be modified by deposit and/or erosion surface processes. Thus, we favor the use of gravity profiles and geomorphological measurements instead of scarp topographic analyses.” Point to recognize the value of geophysics and geomorphological techniques confronted to the topographic scarp analyze, but by no means against paleosesimology.

The slip is interpreted by the thickness of the sedimentary cover underneath the fault. That is a numerical approximation of the accumulate slip in the reverse sense of the SRF. In addition, we do not have a control of the time that influenced the sedimentary accumulation. If we want to quantitatively accomplish that task we would require evidences on the starting time for Santiago basin infill. Tentatively we estimate that the sedimentary infill started at least 100kyrs ago.

Finally, an important point that dismisses the influence of the “quebradas”, or deep drainage incisions, is that the gravity profiles nearby the deep incisions always present a gravity anomaly related with the fault activity (see profile L8, L7 at quebrada Apoquindo, and L13 and L14 at quebrada Macul) generating not segment definition dependence to quebradas.

Specific comment # 4

“The contribution of the application of morphometric indexes (SL and SI) is unclear to me. What are the limitations for this kind of analysis in this specific case? For example, could -the indexes you used- have been influenced by landslide deposits present in the area? (Armijo et al. 2010; Rauld, 2011) . . . and by the Maipo and Mapocho rivers in the areas close to?.”

Authors reply: The main contribution of the morphometric indexes is the numeric measure of the accumulative uplift produced by the fault in intermediate and large time scale (Burbank & Anderson, 2001 Cap.9 and 10). Nevertheless, these indexes only give relative uplift information, as has been described in section 3.3 of the N.P Estay et al. (2016) discussion manuscript.

In specific, the contribution of the SL index result is expressed in Page #8 Line 27: “The areas with larger erosion coincide with zones of high SL values. So it is distinguishing, at least in this area, that more SL (surface uplift) means more erosion, therefore more SL means more bedrock uplift”. This means that the high values of SL define high uplift domain along-strike fault.

IS index, is useful to identify difference activity domain under the mountain front, as well we describe in Page #6 line 5-9: “3) Sinuosity Index. Long-term activity of a piedmont fault can be inferred from mountain front sinuosity index (Bull & 5 McFadden, 1977). Low values of this index indicate a fault-controlled landscape (Bull & McFadden, 1977), and the minimum value is 1.00. This index was developed for normal faults, but it has been satisfactorily proven in reverse faults (Casa et al., 2010; Jain & Verma, 2006; Singh & Tandon, 2007; Wells et al., 1988).”

In the manuscript we analyses each methodology separately in sections 4.4 and 4.5, and then a joint interpretation of the results is discusses in the 5.3 section, specifically between Page # 10 line 29 to Page #11 line 17, and the Figure 9 caption.

Specific comment #5

“In Figure 4, please show a map for the location of these profiles. The TEM profile appears over-interpreted. Can you provide more arguments/evidences to interpret all the faults shown in Figure 4b? or at least discuss the limits of this interpretation, eg. see Díaz et al. (2014) for the relationship between direct observations at surface and indirect measurements at subsurface from this same fault system. Figure 4c; please, provide more clear evidences for the presence of the fault, may be a more detailed mapping of the photo: : : It’s really difficult to see/deduce any fault present there.”

Authors reply: We add a supplementary material with the TEM profile location. Regarding the interpretation of the profile, for the spatially relationship with the fault scarp, the most credible interpretation of the vertical conductivity bodies are the presence of fracture saturated rock in the basement. We do not think of another explanation, mainly by the spatially relationship with the fault and the conductivity range (0.8-5 Ohm-m).

We add a supplementary Figure of this outcrop. See sumplementary Figure S2.

Specific comments # 6

“We probably need to be more careful with the use of “characteristic earthquake”. Earthquakes are known to be complex phenomena –even more at crustal scale- and self-organized (Bak et al. 1981, Burridge and Knoppoff 1964). Of course, the most hazardous zone would be defined by the high frequency contain of the earthquake.”.

Authors reply:

We agree with the referee, and we are aware of the not clearly demonstration of this behavior for this fault. The rupture of a fault can have different slip displacement models (as well said Schwartz & Coppersmith, 1984) therefore is necessary to made an specific study to define the best fit model to SRF. However we use this model to have a first order approximation that is a valid strategy taking into account the lack of information.

We add a sentence that explicit this idea.

Page #2 Line 27: “A characteristic earthquake represents a repeating event that accumulates the most important displacement in the fault (Schwartz & Coppersmith, 1984). This model does not necessary fit with all faults and it is not demonstrated for SRF, however the use of this concept can be a useful tool for a first order approximation of the seismic hazard.”

Specific comment #7

“To compare potential effects of an earthquake along the SRF with those observed during the 2010 Mw8.8 Maule subduction earthquake it’s valid, but it would be better to explore also other crustal earthquakes with similar magnitude. It could be interesting to the paper if you can make some comparison with the 1958 Mw 6.9 Las Melosas earthquake (close to Santiago), and with the 1995 Mw 7.0 Kobe Earthquake. Even better, I think the comparison with the Northridge and El Asnam earthquakes are probably nice opportunities to discuss your results. The 1980 Mw7.3 El Asnam earthquake produced a 24 km length rupture along a segmented thrust fault, in partly blind, which generated 3-6.5 m of slip at surface (Nabelek, 1985). The 1994 Mw6.7 Northridge arthquake was associated to a blind fault-rupture which resulted from 3 meters of reverse slip on a 15-kilometer thrust fault that raised the Santa Susana mountains 70 centimeters at surface, generating strong ground motion, with PGA close to 0.9g in some places (USGS, Science, 1994).”

Authors reply: We include a new discussion of the PGA result with some of these events (Northridge, and also Niigata earthquakes). However, to define the construction response and damage effects, is necessary to compare under the same seismic construction norm of Chile (Nch 433), as well is represented by de 2010 Maule earthquake. On the other hand, the Melosa 1958 event have a different construction scenario compared to present-day Santiago. Therefore the Maule 2010 earthquake is the most suitable case to confront our results in terms of PGA. Finally, the Melosa 1958 earthquake confirms that the masonry construction have a high risk to collapse in a cortical events (Alvarado et al. 2009). This led to affirm that “Given this scenario, a

successful mitigation measure must limit the buildings construction in these areas, or at least not allowing the unreinforced masonry buildings.” (Page # 12 line 31). This statement is in agreement with the inferences of other authors at this regard (Barrientos 2004, Alvarado et al. 2009).

Specific comment #8

“Minor comments: -Line 9 &10: Reference is needed for both earthquakes. –Line 20: Please, precise Andersonian regime... Compression in E-W direction? -Title and introduction: Please, can you provide a –tectonic- reference to support that the SRF is located in the “central Andes”? -Since the paper show results from the application of many different geophysical methods, I would recommend to provide some basic concepts at the beginning of each section. -Figures 1 and 3, please cite Armijo et al. (2010) to properly refers or mapping the San Ramón Fault.”

Authors reply: Page 2 Line 9 &10: “Some examples are the Nepal earthquake Mw = 7.8 on 25 April 2015, with more than 1500 deaths and 10000 wounded (USGS); and in the Andes, the Mw = 6.2 earthquake on 26 January 1985 in Mendoza, with 6 deaths and more than 12500 constructions destroyed (USGS).”

Precise Andersonian regime is beyond the scope of the paper. To understand an Andersonian regime see (Anderson, 1951). To be more specific we add "Andersonian stress regime (Anderson, 1951)".

Page 2 Line 13: “This is more difficult when none of these conditions are met. An example of this case is the San Ramón fault (SRF) in southern Andes (Fig. 1)” We change the “central Andes”.

“Since the paper show results from the application of many different geophysical methods, I would recommend to provide some basic concepts at the beginning of each section”. In methodology section we provide the basics concepts to understand each method and its corresponding references.

In Figure 1 we reference to Rauld (2011). In Figure 3, we add the Armijo et al. (2010) reference of the mapping SRF.

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Please also note the supplement to this comment:
http://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2016-19/nhess-2016-19-AC2-supplement.pdf

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Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-19, 2016.

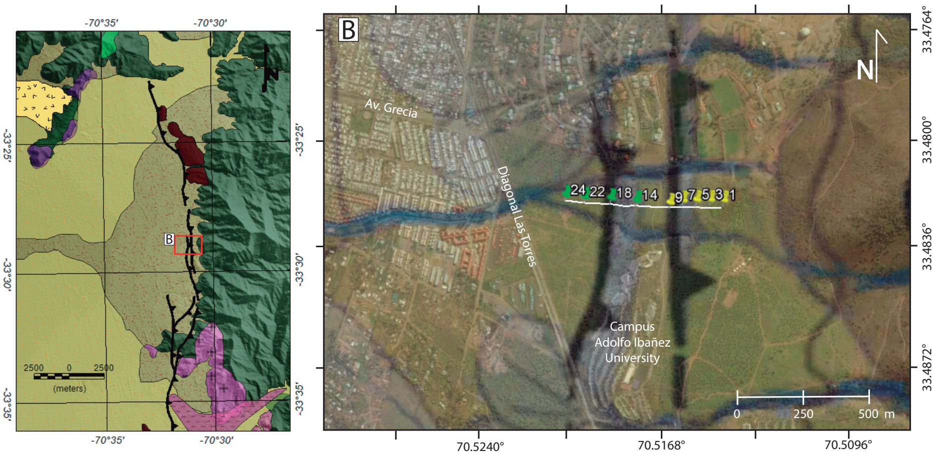

Figure S1. Location of TEM profile. Rigth: Big scale of the location of the profile. The geologic units are the same of the Figure1, in the manuscript. Left: Zoom to the location of the profile. The marks with numbers represent some of the TEM array center. The geologic map behind, is obtain from R.Rauld 2011. The two scarp of the fault can be observe in Figure 4 of the manuscript, by a blue arrow.

Fig. 1. TEM Location

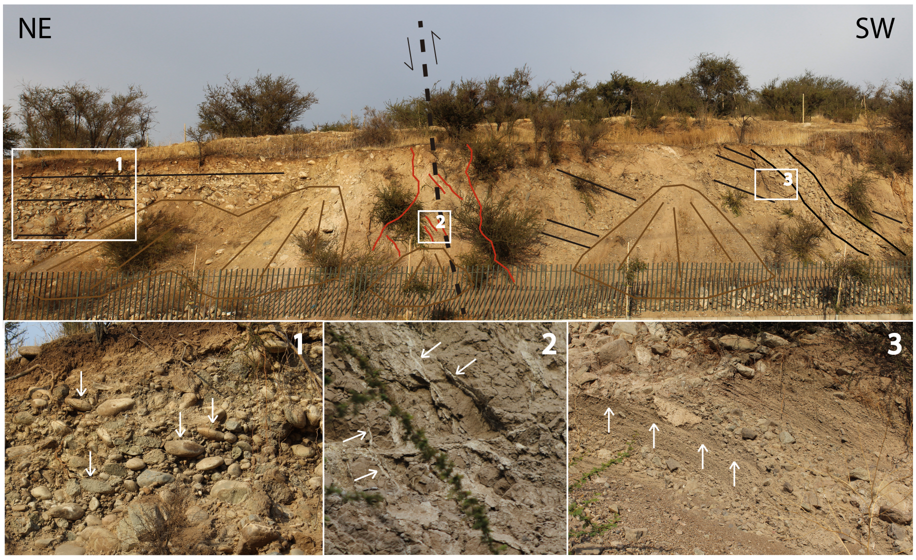

Figure S2. Up the Apoquindo hill outcrop in a better resolution image. Down: 1) The horizontal conglomerate strata with the arrows indicating the imbricated clast that suggest the horizontal actitude. 2) The fault core, mainly of fine soil cutted by white vein pointed by the arrows. 3) The tilting quaternary sediments, dipping againts the natural slope of the zone (sedimentary basin of Santiago has a westward dipping surface, and the rivers flow down from the West to the East).

Fig. 2. Supplementary image (beter quality of Fig 3.c).