Title: The western Andes at ~20–22°S: A contribution to the quantification of crustal shortening and kinematics of deformation
Author(s): Tania Habel et al.
MS No.: egusphere-2022-629
MS type: Research article

General comments:

In this manuscript Habel et al. constrain the timing and quantify the amount of tectonic shortening in a part of the Western Andes in northern Chile. They processed high-resolution satellite images, field observations, updated geological and structural maps in order to confront this dataset to numerically-modeled balanced cross-sections of the study area.

As it has never been done before, results and discussions are of a great interests for the community working on the Andes. The Western Cordillera is often mentioned in the literature, but the shortening has never been quantified accurately. Results, based on the study of pluri-kilometer geological objects, partially fill the data gap regarding shortening rates and timings of (re)activation of structures in the Western Cordillera. These data allow to better frame the deformation of the Western Andes and should be taken into account in future attempts to restore Andean shortening rates.

I particularly appreciated the topic, the scientific approach and the efforts of the authors in order to reach their scientific objectives. This work is worth publishing. Results are discussed and satisfactorily confronted to the literature already published. I have detailed in the sections below a few points of science to clarify.

However, the presentation of the manuscript still needs some work. It is sometimes difficult to follow the reasoning. For instance, some parts of the results are interpretations and some interpretation sections include reporting of results. Some sentences are difficult to follow (especially figure captions). I would suggest to shorten them (please see detailed comments below). Some significant information are missing and some less relevant are available. The presentation of the supplementary document is quite different from the manuscript. I advise authors to homogenize the presentation.

I am not native English speaker but some of the vocabulary and grammar seem to be incorrect. I have indicated errors I was able to identify, but I advise authors to have the manuscript proofread by a specialized company or a native English-speaking colleague if possible.

I recommend a round of minor revision, especially to fix presentation issues.

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Review criteria:

1. *Does the paper address relevant scientific questions within the scope of SE?*

→ Yes. The understanding of the timing and the quantification of deformation in the Andean Western Cordillera is of a great interest for the geological community working in the Andes. Methods, results and discussion definitely fit with the scope of Solid Earth journal.

2. *Does the paper present novel concepts, ideas, tools, or data?*

→ Yes, new ideas and data are presented in this manuscript.

3. *Are substantial conclusions reached?*

→ Yes. Results have been satisfactorily analyzed, discussed, and conceptualized. The conclusions are of importance for a better understanding of the building of the Central Andes.

4. *Are the scientific methods and assumptions valid and clearly outlined?*

→ Overall, yes. Some information about the cross-section restoration modeling process are missing. Please see detailed comments below.

5. *Are the results sufficient to support the interpretations and conclusions?*

→ Yes. Results were satisfactorily exploited to support authors' statements. The limitation associated to the results were clearly discussed.

6. *Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?*

→ Overall, yes. Some information about the modeling process are still missing.

7. *Do the authors give proper credit to related work and clearly indicate their own new/original contribution?*

→ Yes.

8. *Does the title clearly reflect the contents of the paper?*

→ Yes. The title should be even more assertive by showing that the shortening of the Western Andes estimated in this study is not so negligible at the scale of the entire Andes.

9. *Does the abstract provide a concise and complete summary?*

→ Yes, the abstract is complete.

10. *Is the overall presentation well-structured and clear?*

→ No, it needs a considerable amount of work, especially in the organization of the results, interpretation and discussion sections.

11. *Is the language fluent and precise?*

→ No, Some paragraphs are difficult to follow. I advise authors to have the manuscript proofread by a native English-speaking colleague if possible and refer to technical corrections below.

12. *Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?*

→ Yes.

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?

→ Yes. Parts of the manuscript and figures should be clarified. Please see detailed comments below. Paragraphs have to been clarified and shorten by removing redundant information.

14. Are the number and quality of references appropriate?

→ Yes, the state of the art is almost complete and authors' results are satisfactorily confronted with the literature available in the discussion.

15. Is the amount and quality of supplementary material appropriate?

→ Yes. Some parts need to be clarified. Please see detailed comments hereafter.

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Specific comments / Scientific questions and issues:

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L22-24: I do not think that the authors can say that the shortening of the Western Andes is "negligible" even at the scale of the entire range. The study area only represents approximately 1/5 in width of the Western Cordillera; Authors should expect higher shortening for the Western Cordillera. Taking into account the authors' maximum shortening estimate, it could represent 15% of total shortening integrated to the entire Andes. Authors should be a bit more assertive about this important result because most of the deformation of Western Cordillera is hidden.

L61-62: How much shortening has been estimated in the thrust belt framed by San Ramon fault ? Authors should add this information (if available) in order to compare it with their results. Is this tectonic shortening thick or thin-skinned, or both in Santiago de Chile area?

L100: The Eastern Cordillera and the Cordillera Oriental are the same… The Cordillera Oriental is not the Interandean zone. The nomenclature should be clarified here. The Interandean zone is a transition zone between the Eastern cordillera and the Subandean zone with a specific tectonic style and specific geological units involved (Kley, 1996).

L107-115: Authors should also discuss paleo-altimetry estimates in this paragraph, which is (at least partly) linked to the deformation. Please see Sundell et al. (2019) and others for instance. In this section, authors should also mentioned the Bolivian Orocline bending that affected the area, to highlight potential relationships with the migration of the deformation eastward (Müller et al., 2002; for instance).

L125: Why is the structural organization become more complex southward? Please consider to add a short explanation here.

L226: Are variations in stratigraphic thicknesses have been taken into account (error computation in shortening estimates)? And if yes, how? Does it affect significantly the shortening estimates?

L237-243: Authors should consider to briefly detail here what was the set of parameters explored for cross-section restoration? Even if it is available in the supplementary document. Also, what were the criteria to define the best solution of the forward modeling approach? Authors should had this significant information in this paragraph.

L574-582: This part should be in the method section. Not in the discussion. Furthermore, authors should had first-order missing information here, such as:

- Briefly describe what are parameters investigated (trishear).
- What were criteria to define the "best-fitting model". Are specific metrics used? if qualitative only, which parameters have been taken into consideration? Authors should describe a bit more the methodology.

L585-586: Are there errors on cumulative shortening estimates? Did the authors test other modeling setups with similar results (or close results), which also satisfies the present-day geometry of the structures.

L692-696: Exhumation and uplift are different. Authors should not compare it directly. I did not find the information about the amount of uplift related to the shortening modeling. Authors should explain how uplift has been computed and what is the value of uplift taken into account for comparison.

L790-795: Authors should briefly explain hypothesis dealing about the deformation transfer from west to east in the frame of their discussion.

Supporting information

Text S1: How many forward models have been run? Information partly appear in the caption of Table S1, but it has to be written in the text also (in the supplementary and in the manuscript). How was the range of parameters explored? How the authors decided to sample the range of parameters in order to cover the parameter space in the most representative way. Authors should add these information.

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Technical corrections:

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L12/L14/L45: "western Andes" should be written "Western Andes" with a capital letter (w). Authors should check it in the entire manuscript.

L14-15: "Our results […] regional data". Authors should consider to rework this sentence that is difficult to follow. I think the part "once our […] regional data" is not necessary.

L45: Authors should consider to add a reference (e.g. Jaillard et al., 2000; Jaillard & Soler, 1996) to justify Andean mountain-building initiation.

L47-49: Authors should considered to cite only 2 or 3 articles here, in order to focus on the most relevant papers that deal with Andean deformation migration. Some of the papers cited here do not deal exclusively with this topic.

L49-53: This sentence is too long and difficult to follow. I suggest to shorten it.

L50-51: To justify previous studies in the "various cordilleras to the east" authors should consider to cite Gérard et al. (2021) to support their statements.

L57: "locations" instead of "localities" maybe?

L67: "onset" instead of "start" maybe?

L69: Authors should refer to Figure 1 to help the reader. "blanketing Cenozoic deposits and volcanics".

L73: Authors should briefly describe here what kind of quantitative data have been processed.

L86-115: This state of the art is quite complete but, it is too difficult to follow. In order to be clearer, I would suggest to start the geological framework from the full Andes' scale and then to focus on the study area. That is to say, to keep L86-90 as it is. Then to put L97-115 in a row and next, focusing on the study area (L90-96).

L91-92: "elevation" instead of "altitude". Please check throughout the manuscript.

L95-96: Merge "Figure 1" into the bracket located before. For instance: (…Atacama Bench; Figure 1). Please check throughout the manuscript.

L98: Authors do not need to quote "following here the terminology of …" I would suggest just to cite the literature. It will be easier to read.

L118-119: Authors usually described units from west to east before. Here it is reversed. I suggest to keep this west-east logic, it will be easier for the reader.

L124: Please add the city of Calama on Figure 1.

L149-153: These sentences are confusing. Please consider to rework this section. There are too many comas.

L150: Where are located these Sierras on Figure 1? Sierra del Medio and Sierra de Moreno? Authors should consider to add these information on Figure 1.

L189: Authors should add a reference for "European Pléiades satellites images".

L191: A space is missing between "2" and "m".

L249-251: This is a paragraph for a discussion. Authors should consider to put this section in the interpretation/discussion section and not in the result section.

L254-255: “The first order […] units”. Authors do not need to introduce figures like in a book chapter or in a thesis or report. Just to smoothly integrate it in the text to argue their points. This observation is valid for other sections in the manuscript.

L255-256: To my opinion, and this is valid for the entire manuscript, it would be easier for the reader if authors should refer to the exact figures in the supplementary document (in line with their statements; Figure S1 for instance) instead of just reporting that there is supplementary material here and there.

L314-315: Authors should not introduce figures at the beginning of sections, just integrate it in the text, according to their statements. It will be easier to read.

L395: The section 4.1.3 is an interpretation section. Authors must not merged results and interpretation this way. 4.1.3 part has to appear later in the manuscript. Authors should consider to had this section in the Discussion/Interpretation section.

L416: Same comment as above. Authors cannot present results and interpretations from Pinchal area and then present results and interpretations from Quebrada Blanca. The organization of the sections has to be reviewed. Authors should present all observations, stratigraphic, tectonic and modeling results for both area; and then interpret and discuss it later in the manuscript. Parts of section 4.2 has to be transferred in a distinct interpretation section (section 6 for instance, with new sub-sections for Quebrada Blanca and for Pinchal).

L417-418: In order to get straight to the point, these introductory sentences are not necessary. It makes the reading difficult with unnecessary information. Authors should simply refer to figures and tables to support their statements.

L418: There is an issue in results presentation. Authors should not refer to table 1 (presenting shortening values computed from cross-section restoration) before figures presenting cross-sections restoration/line-length balancing (Figure 11). It is very difficult to follow.

L425: For this assumption, authors should consider to add a reference to support their point.

L453: Results for Quebrada Blanca area should appear before interpretations from Pinchal area.

L525: Similar comment from above. Parts of this section are interpretations, and it should appear in a distinct and independent section later in the manuscript to avoid merging results and interpretation in the same section.

L554: It is not necessary to refer to previous sections: “section 4.1”. Authors should remove this information.

L567: Section 6.2 is a mix between trishear method, results, interpretation and discussion. Results should appear earlier in the manuscript. Authors should review the structure of the manuscript.

L574-582: This part should be in the method section. Not in the discussion.

L617: “elevation” instead of “altitude”.

L797-802: There are too many information here. Authors should consider to shorten this part to focus on first-order information.

L798: Authors may add “Chilean” before “Andes” to help the reader.

L855: The bibliography is not homogeneous. Some titles are in capital letters, typos are present. Please fix issues.

Figures

Figure 1:

- The text in the figure caption is not very clear. Authors should consider to rework the caption with smallest sentences.
- Authors should consider to add the topographic cross-section location on the geological map.
- Authors should consider to add major tectonic features location on the topographic cross-section to identify potential relationships between faults and topography.
- Cordillera Domeyko appears in the caption but does not appear on the geological map. Please add it.
- To simplify the caption, authors should remove abbreviation explanation for ABT, WAT, WATS, Cz, Mz, Px-Pc as it is already written in the figure. Or delete the abbreviation in the figure et keep it in the caption.
- In the inset, authors should consider to add an arrow to show the direction of convergence (Nazca vs. South American plate).

Figure 2:

- Labels “a” and “b” are on the figure but not in the caption. What is the difference between the two pictures ? Authors should maybe select one picture to avoid repetition of information.
- Figures 2 and 3 could be merged.

Figure 3:

- Approximative thicknesses of units should be indicated on the figure. Even if the log is not scaled.
- In the caption: “By analogy to regional description”. Please cite the literature here.

Figure 4:

- It would be maybe better to call figure 4 before. At the beginning of section 4, to better organize this section.
- Authors do not need to add information twice (in the figure + in the caption). Field picture locations for instance.

Figure 5:

- Authors should not repeat three times “Figure 4” in the caption. It represents a repetition of the same information. It is difficult to read… I suggest to find a way to shorten these sentences.
- There are some French words in the figure: “Cisaillement, Schisosité”. Please translate it.

Figure 7:

- L385/389: In the caption, the word "violet" should be replaced by "purple"?
- Authors should indicate dip marks of strata on the pictures to help the reader.

Figure 10:

- This figure is not well structured. Authors should add a symbol (on the figure) to show the relationship between picture a and b. Authors should also find a way to remove blank space at bottom right of the figure.

Figure 11:

- This Figure and associated results have to be presented before in the result section. Not in an interpretation part.
- L596-603: This text is not needed in the figure caption and should be written in the main text, otherwise the caption is too hard to follow.
- Parts of the caption are already displayed on the figure. To shorten the caption, authors should consider to remove duplicate information.

Supporting information

The style of the supplementary document is quite different from the manuscript. I advise authors to homogenize the presentation. English has to be proofread. In the manuscript, authors should refer to the exact figure label to clarify the text. Generally, figure captions should be shorten in order to optimize them.

Section (1)

- Figure S14 appears before Figure S13 in the text. Authors should check the order.
- Figures S15 and S16 are not introduced. Authors should consider to add this information.

Figure S4: Aguilef et al. 2019 citation in the caption is not referenced in the bibliography at the end of the supplementary document.

Figure S11: In the figure, authors should correct "bancs" into "bed" or "strata". And "Calcareous" into "Limestone".

Figure S14: I do not see "view directions" on the map. "Field picture" information appears twice in the legend and in the caption. To help the reader, authors should remove one of this information. "Quebrada" is not only Chilean but used in all the Andes. Authors should write "Spanish word for…". This latest observation is also valid for Figure 4.

Text S1: Some of the information presented here have to be written in the method section of the manuscript to help the reader. Please see detailed comments above.

Table S1: This table should be in the method section of the main manuscript. In the caption, authors should remove unnecessary parts (Best results […] Allmendinger, 2002) and add them instead in the text S1, or even in the manuscript.

Data Set S1: Parts of this text (although nice) are not appropriate for publication in a scientific journal. Although I love to imagine geologists in the field under a beautiful starry night, this is not required here. Authors must remain factual.

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Benjamin Gérard

References cited in this review letter

Gérard, B., Robert, X., Audin, L., Valla, P. G., Bernet, M., & Gautheron, C. (2021). Differential Exhumation of the Eastern Cordillera in the Central Andes: Evidence for South-Verging Backthrusting (Abancay Deflection, Peru). *Tectonics*, *40*(4), 1–29. https://doi.org/10.1029/2020TC006314

Jaillard, E., & Soler, P. (1996). Cretaceous to early Paleogene tectonic evolution of the northern Central Andes (0-18 degrees S) and its relations to geodynamics. *Tectonophysics*, *259*(2), 41–53. https://doi.org/10.1016/0040-1951(95)00107-7

Jaillard, E., Hérail, G., Monfret, T., Diaz-Martinez, E., Baby, P., Lavenu, A., et al. (2000). Tectonic evolution of the Andes of Ecuador, Peru, Bolivia and northermost Chile. *Tectonic Evolution of South America*, 481–559.

Kley, J. (1996). Transition from basement-involved to thin-skinned thrusting in the Cordillera Oriental of southern Bolivia. *Tectonics*, *15*(4), 763–775. https://doi.org/10.1029/95TC03868

Müller, J. P., Kley, J., & Jacobshagen, V. (2002). Structure and Cenozoic kinematics of the Eastern Cordillera, southern Bolivia (21°S). *Tectonics*, *21*(5), 1-1-1–24. https://doi.org/10.1029/2001tc001340

Sundell, K. E., Saylor, J. E., Lapen, T. J., & Horton, B. K. (2019). Implications of variable late Cenozoic surface uplift across the Peruvian central Andes. *Scientific Reports*, *9*(1), 1–12. https://doi.org/10.1038/s41598-019-41257-3