Response to comments pointed out by Andres Tassara on the manuscript "Forearc density structure of the overriding plate in the northern area of the giant 1960 Valdivia earthquake" (se-2021-53)

We sincerely appreciate the detailed review and comments of the Dr. Andres Tassara (https://doi.org/10.5194/se-2021-53-RC2). To provide a complete response, we write all original comments in black and our responses in blue. The corresponding changes in the text were included in the new submitted version of the manuscript.

The authors

This paper presents a gravity-based model of the subduction zone anatomy along a segment of the Chilean margin that coincides with the greatest slip patch of the giant Valdivia 1960 earthquake. The authors attempt to interpret their resulting density model in terms of the geological structure of the margin and to discuss the implications of their findings for our comprehension of seismogenic processes leading to the largest earthquake ever recorded.

The work has scientific merit, although the density model is not particularly new (other papers have been published with the topic in the studied area) and the interpretations and conclusions will probably have a moderate impact in the community. This potential impact could be improved if a) more details are offered regarding some methodological aspects that are obscure in the present version (and therefore inhibit a clear interpretation of the results), b) the quality and clarity of figures and text could be augmented, and c) a deeper and complete interpretation can be developed. I expand points a and c below. I also provide a list of many idiomatic points (mostly orthographic and grammar typos and errors) that I identified through the text; this list is not complete, and the authors should take care and be sure that a revised version of the manuscript must have no errors like these in order to be accepted.

- Gaps in methodology.

I found that section 3 Data and Methods is oversimplified and some important gaps can be identified that you should fill in order to provide a better basis for the further interpretation of results. This is a list of my main concerns associated to line numbers on the original pdf.

135-136. Specify the model of the Lacoste&Romberg gravimeter used for the study. What do you mean with "with a digital upgrade provided by ANID-FONDECYT project No11170047"?

R.- We corrected as: "The gravity acquisition was made using A Lacoste & Romberg G-411 gravimeter, with a digital upgrade (http://www.gravitymeter-repair.com) funded by ANID-FONDECYT project Nº11170047"

134-140. More details about the processing of gravity data could be useful. How do you ensure that the new data are leveled with the old data compilation? Do you applied any further procedure to correctly merge the satellite data, marine data, old land data and your newly acquired data? Just putting all together as it was provided by different sources could create large problems with different data levels that must be solved before modeling!

R.-. The spatial coverages of different gravity databases (satellite, marine, and onshore) present areas of interception (Fig. 2) where can be compared to determine the average gravity differences (constant shifts). These shifts were used to generate a merged database levelling all data to the values observed in the new acquired data. More details were included in the new version of the manuscript.

171-173, 175-176. It seems that information provided in lines 171-173 regarding the size and geometry of the 3D inversion grid, is in contradiction with information provided in lines 175-176. Please clarify this point.

R.-. First paragraph refers to the mesh size and second paragraph refers to the "length scale parameters" of the UBC-GIF GRAV3D v3.0 software (Li and Oldenburg 1998). The point is clarified in the new version of the text.

Instead of gr/cc please use gr/cm3 in the entire text (which is the correct use of metric units in the SI)

R.-. changed in the new version.

You mention that "…greater densities than the background below 7500 m depth." What is the background density and its value?

R.-. The modeling of residual gravity provides contrasts of density respecting to the background density. Theoretically, above the reference level considered to perform the Bouguer Correction (0 m respecting to ellipsoid in this case), the background density is equal to the reference density (or reduction density), i.e. 2.67 gr/cm3 in this case. To clarify the point, we include the value in the corresponding sentence.

Section 3.2.1. Too few specifications about the method associated with forward gravity modeling. Please provide more information about the basics of the GravGrad modeling scheme of Maksymowicz et al. (2015) and its specific application to the study region, including the original geometry of each section, downward extent, background density structure, how densities of different bodies are assigned and validated, how the constraint information is incorporated into the model, are the geometries of the bodies modified interactively?

R-. The basics of the GravGrad modeling scheme is largely explained in Maksymowicz et al. (2015), but we include some modification in the section 3.2.1 to clarify the interactively model procedure. On the other hand, details on the independent information used to constraint the model is listed in the section 3.3.1. Note that in the new version we corrected the section numbers.

Section 3.2.2 3D gravity inversion. I am confused with the target of this model, mostly with the depth of the 3D model and what are you trying to obtain. In addition, with the confusing information noted in lines 171 to 176 regardinf the spatial extend of the inversion space, it is not clear what is the maximum depth of the model, it seems to be only few kilometers below Earth surface? If this is the case, can you please justify the application of this tool considering that you are interested in the crustal-to-lithospheric scale structure of the subduction zone?

R-. As is pointed in the introduction, this work aims to study the forearc density structure at regional scale by 2D forward modeling and, at local scale, by 3D density inversion of onshore data. Then, we are interested not only in the crustal-to-lithospheric scale, but also in the upper crustal density structure below the sedimentary units of central depression, where few geophysical or geological drilling campaigns has been performed.

While the regional models provide a possible solution of the density structure of the subduction zone (under the available independent constraints), the 3D local inversion can be seen as an automatic solution (independent of the forward 2D method) of the upper crust density contrast bodies (above ~20 km depth according to the results) which explain the gravity anomalies respecting to a regional linear trend, i.e. deeper anomalies (at lower crusts and mantle, for instance) are mostly contributing to regional linear trend at the scale of 3D local study. To show this approximate depth limit (~20 km), new version of supplementary material presents 3D views with the model density obtained to 50km of depth. It is important to highlight that the 3D inversion method is completely different numerical approach to 2D forward method, but the obtained density structure is similar (at common depths), which reinforce the modeled characteristics of density distribution in the upper crust.

324-325. How is defined the base of the inversion model at 20 km depth? This is not clear in section 3.2.2 3D gravity inversion, where it seems that the maximum depth is something larger than 7.5 km, but 20 km looks like too deep for this kind of model. Please clarify.

R-. The inverted space (The 3D mesh) has 67x80x102 blocks (in X, Y, Z direction), and vertically, the cell size gradually grows from 100 to 1500 m, reaching 70 km in depth (see section 3.2.2 and its modifications). In this inverted space, the 3D inversion algorithm founds anomalies to ~20 km in depth (see Figure 7). Which means that deeper anomalies are mostly contributing to regional linear trend, as was mentioned before. This idea was included in the new version of the manuscript.

349-365. How do you justify the spatial extend and the resolution of the model? Is there resolution and/or sensitivity test that allows to trust the model results??? This point is important and critical to be solved in a new version of the paper.

R- The spatial resolution of the model is restricted to space discretization mesh, which have 3000 m x 3000 m size (horizontal) and vertically gradually grows from 100 to 1500 m, in accordance with the developer's recommendation (https://www.eoas.ubc.ca/ubcgif/iag/sftwrdocs/technotes/faq.htm). On the other hand, the horizontal spacing (3000 m x 3000 m) of inverted gravity grid (and space mesh) was selected to generate a regular input data signal whit similar spacing than the average spacing of available measurements. Then, density anomalies with sizes at the order of the horizontal and vertical discretizing cannot be considered, which is the case of our interpretation where we only describe and analyze the main observed anomalies and trends, much larger than model discretizing. Numerical experiments were developed to observe the sensitivity of the solution under the variation of parameters and data, some of them are show in the new version of the supplementary material. This analysis indicated that main interpreted characteristics of the solution remains unaltered under variations of scale length parameters, and the introduction of artificial noise in the input gravity data. Beyond these numerical considerations, as in any gravity inversion, the presents not uniqueness in the solution, which is an important methodological reason to use independent model methodologies (2D forward and 3D inversion, in this case) and contrasting the results with independent available and new geophysical constrains. Finally, some modifications were included to give more details of the density inversion (section 3.2.2).

- Improve quality and clarity of interpretations and discussion.

Sections 4 and mostly 5 need some improvement in terms of the description, interpretation and discussion of results that for some cases is too confusing. The discussion would benefit from a clear separation of different points, like the geological nature of dentiy anomalies and influence of crustal structure on megathrust seismogenesis.

255-260. Please explain how the gravimetric lineaments were identified; is this just a visual exercise? You would need to justify these identifications, which seems to be quite whimsical. Is it really necessary to include these lineaments? Perhaps a good description of how the recognized (published) crustal faults and geologic lineaments correlate with gravity is a better idea in this case.

R- These lineaments were visually interpreted, which in our opinion is a valid procedure to provide a qualitative description of the gravity signal. Similar qualitative exercise is often used in bathymetric/topographic, earth magnetic field, gravity and seismic studies, and other geophysical/geological analysis to highlight linear features in the signal that could be related (or not) with hidden structures and other geological features at depth. To make easier this qualitative interpretation, it is a common practice to generate set of derivative filters of the original signal to highlight short wavelength features. A set of figures with the interpreted gravity lineaments and derivative filters is presented in the new version of the supplementary material (first derivative to the west, first de first derivative to the north, directional derivative to the northeast, slope gradient and analytical signal).

In the Figure 3b the interpreted gravity lineaments are drawing with dotted lines on the CBA grid and Figure 3a shows also the CBA grid without these interpreted features in order to facilitate the direct evaluation of our interpretation by the reader. Regarding the relation of interpreted gravity lineaments with structure published in the zone we explicitly state that "The gravity lineaments confirm the location of fault zones previously identified at the surface (SERNAGEOMIN, 2003; Melnick and Echtler, 2006), suggesting their continuity through the forearc and, in some cases, their seaward extension (e.g., Valdivia-Futrono lineament, VFL in Fig. 3b)". In fact, published fault and structures and their names are presented in Figure 3 (blue lines). The clear relation between previously identified crustal faults with some of the interpreted gravity lineaments is the primary reason to show this qualitative interpretation, because some of these lineaments could be confirmed (or not) as crustal structures in future works. In the new version of the text, we explicitly clarify the visual/qualitative type of this interpretation.

280-289. Note that the CBA high called H1 in Fig 3a does not appear in P1, but the modeled density high called H1 in Fig. 4 is present in all the profiles: it is confusing to use the same nomenclature for gravity and density anomalies in this case, perhaps it is better to change these names.

R- We agree, in the new version of the manuscript L1, L2 and H1 were maintained for gravity anomalies and D1 and D2 were used for density anomalies.

292-295. Why a high-density anomaly shall be related to the volcanic arc? I would expect the opposite since magmatic bodies and the entire plumbing system underneath volcanoes should have a much lower density than the country rock. Please explain this.

R- We agree. The phrase is confusing because we originally use the volcanic arc as a geographic reference for the roughly location of D2 (or H2 in the original text). D2 is a deeep feature in the upper crust, and then, it is not necessarily related to the plumbing system, location of magma bodies and structural of the upper portion of the crust. However, we observed that "LOFS approximately correlates with the western limit of D2 in profiles P1_Toltén, with the eastern limit of D1 in profile P2_Unión and with the eastern border of D2 at profiles P4_LLanquihue and P5_Chepu", which in fact in suggests an structural relation between the deep geometry of the high density anomalies (D1 and D2) and LOFS, which in turns, have a close relation with active volcanic systems in the region (Lara and Folguera, 2006; Sánchez et al., 2013; Díaz et al., 2020). On the other hand, the results of 3D model show that "Most of quaternary volcanoes are located in zones with negative density contrast below 5 km depth (Fig. 6). The upward migration of magmas should generate local weakening zones in the overriding plate, and consequently, the continental crust in the active volcanic zone should present pervasive fracturing, fluid migration and lower density". In the new version of the manuscript, we change this paragraph including references for the relation between LOFS and the active volcanic arc.

Are you sure Contreras-Reyes et al. (2008 and 2010) mention that the age of the paleo-acreccionary prism is Mesozoic to Tertiary? The metamorphic complexes in the region are of clear Late Paleozoic to Triassic age.

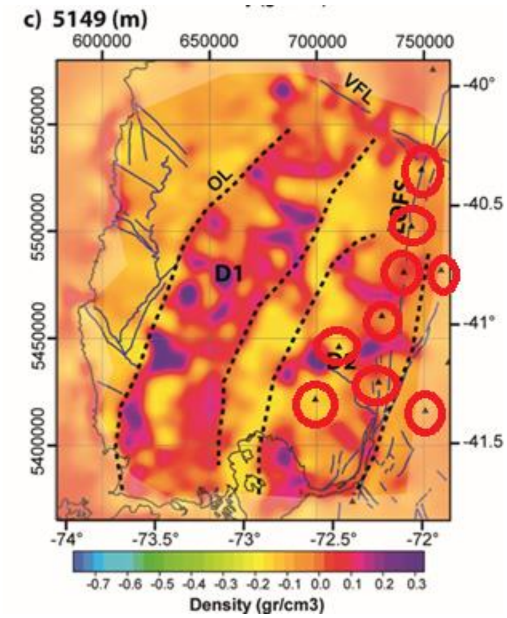
R- This paragraph refers to the middle wedge unit (MWU), seaward from outcrops of Paleozoic-Early Mesozoic accretionary complex (WS/ES). The eastern portion of MWU should be the offshore continuation of WS/ES, however the western portion of MWU could be formed by a younger "paleo-accretionary prism" (Jurassic age as is suggested by Contreras-Reyes et al., 2008) which even could include younger basal accreted material, coeval with Miocene erosional phase (Contreras-Reyes et al., 2010). On the other hand, and as is indicated in the text, there are not direct information (boreholes) to confirm the age of the continental basement in the western portion of MWU.

444-454. For the discussion about the geological nature of the H1 anomaly you should consider Plissart et al. (2019; https://doi.org/10.1016/j.lithos.2019.03.023) and references there in, which shows that the metamorphic basement associated to the WS south of 39ºS includes a great proportion of mafic and ultramafic (serpentinites) rocks that were incorporated inside a subduction channel during the Carboniferous. As H1 gravity anomaly in Fig. 3 extend southward into the Chiloe island where only Late Paleozoic metamorphic rocks has been described (i.e. no Devonian intrusive rocks related to the Chaitenia island arc), one could imagine that H1 (both gravity and density anomalies) are mostly related to the dominance of these lithologies. However, it is important to consider the evolutionary interpretation of Plissart et al. (2019) because they actually link the occurrence of these (ultra)mafic rocks to the creation of an island arc and backarc region disconnected to the main Gondwana margin during the Devonian, similar to the original idea of Herve et al. further south. This could support your interpretation, but you should complement the argumentation already exposed in this section.

R- We agree, the evolutionary interpretation of Plissart et al. (2019) is relevant for the discussion and was included in the new version of the manuscript.

456-457. I don´t see the supposed correlation between volcanoes and negative density contrast in Fig. 6; please mark clearly the volcanoes in this figure and provide actual values of density contrast to judge about it. This is also in contradiction with what is exposed in lines 292-295, i.e. a correlation between high density and the presence of the volcanic arc and LOFZ. Please clarify.

R- As was mentioned before, D1 and D2 are crustal anomalies, not necessarily associated to shallow magmatic system below the active volcanoes, but their limits could be related to deep geometry of LOFS, which in turn have some control on the active volcanism in the region. Al lower scale, active volcanoes are located in zones with low density contrast (in general < 0.0 gr/cm3), inside de D2, as is observed in figure 6 (see red ellipses below).



480-481. A better reference for the Melinka earthquake in terms of describing the physical properties of the forearc is Moreno et al. (2018; https://www.nature.com/articles/s41561-018-0089-5). This discussion about the nature of seismic segments along the Valdivia earthquake segment could benefit from including findings and ideas of Molina et al. (2021).

R- Moreno et al. (2018) and Molina et al (2021) were referenced in the new version of the manuscript.

Minor points

27-28. Include Molina et al. (2021)

R- Molina et al (2021) were referenced in the new version of the manuscript.

31-. Reference is Tassara (2010). Add Molina et al. (2021)

R- Corrected in the new version

34-. Include Molina et al. (2021)

R- Molina et al (2021) were referenced in the new version of the manuscript.

50-. Replace “Fithermore” by “Furthermore”

R- Corrected

54-. Replace “at the south of…” by “southward of…”

R- Corrected

Fig. 1. Colors of geologic units are somehow masked by topography; perhaps you can either choose a color table with grey tones for topo/bathy (changing colors for metamorphic units in this case), or to use topo/bathy only in B along with the potential trace of basement domains, leaving in A the geology, structures, slip, fracture zones. By the way, the dashed outline in B is very usefulness and awkward, please remove it.

R- Fig.1 was improved according to the suggestions of reviewers.

67-. Solve "Schematic map of map of basement…"

R- Corrected

72-. Put "cm/yr" in "convergence rate (6.6 cm, Angermann, 1999)"

R- Corrected

85-. Replace "fiction" by "friction"

R- Corrected

88-. Replace "…three mayor trenches parallel morphoestructural units…" by "…three mayor trench-parallel morphoestructural units…"

R- Corrected

105-107. Rephrase this sentence, it is awkward.

R- Rephrased as: "This paired metamorphic belt is observed continuously at the CC, but the width of their outcrops varies along the margin (see Fig. 1a). Between ~38°S and 40ºS, and southward of ~ 41.5ºS, outcrops of WS are observed eastward, near the western limit of PC. Thus, between ~40ºS to ~ 41.5ºS, the eastern limit of these units is not defined due to the presence of the CD deposits and could form most of the forearc basement or it could be confined near the coast."

119-. Replace "Devonic" by "Devonian"

R- Corrected

120-. Replace "Ch in Fig. 1b" by "Ct in Fig. 1b"

R- Corrected

121-. Remove "Ch in Fig. 1b" (is already indicated in line 120).

R- Corrected

120-121. A good and updated reference for this is Rapela et al. (2021, https://doi.org/10.1016/j.gr.2021.04.004)

R-Rapela et al. (2021) was referenced in the new version of the manuscript

127-. Replace "include:" by "includes:"

R- Corrected

147-. Replace "schema" by "scheme"

R- Corrected

149-. Replace "…it should be modelling considering…" by "…it should be modelled considering…"

R- Corrected

165-. Replace “3.2.1 3D gravity inversion” by “3.2.2 3D gravity inversion”

R- Corrected

172-. Replace “…blocks (in X, Y, Z direction), respectively.” by “…blocks (in X, Y, Z direction, respectively).”

R- Corrected

195-. Replace “3.2.1 Available geophysical information” by “3.3.1 Available geophysical information”

R- Corrected

210-. Replace “3.2.1 Electromagnetic methods to constrain gravity measurements” by “3.3.2 Electromagnetic methods to constrain gravity measurements”

R- Corrected

Figure 3. Replace “Grvimetric Lineaments” by “Gravimetric Lineaments” in the legend of the figure.

R- Corrected

Figure 4. This is a bit confusing, and you could consider some of the following suggestions: 1) Put each gravity profile with the corresponding density profile, so one can appreciate the correlation between anomalies and the modeled density structure. 2) Try to separate or identify the original CBA from the modeled anomaly, since in the current Fig. 4a is impossible to recognize it. 3) Use a different name for H1 and H2 because it is confused with H1 of Fig. 3a although they are not the same. Fig 4d has a problem with numbers in the x-axis, please correct it.

R- This figure was designed to allow a direct comparison of all density models in a single image. If we add individual panels with gravity data above profiles it is necessary to greatly reduce the scale of each panel, which in our opinion, is not convenient for model comparison. Then, we prefer to maintain the design of the figure (correcting the errors), but also including individual figures with corresponding gravity panels in the new version of the supplementary material.

281-282. Replace “… and increase to deep” by “…and increase downwards”

R- Corrected

291 and elsewhere. Please do not use “before” and/or “after” to refer to east-west locations with respect to a given feature, better use westward or eastward!

R- Corrected in the new version of the manuscript.

292-. Replace “important toconsider” by “important to consider”

R- Corrected

Figure 5. Please include the original CBA and the regional field obtained as a polynomial representation that is extracted from the observed CBA in order to get the residual CBA.

R- Fig. 5 is highlighting the input data of 3D inversion (RBA) and the final fitting between observed and modeled data. As the regional trend (not inverted) is only a single plane, we include its equation and a figure with CBA, RBA and linear regional trend in the supplementary material.

349-. What is the DC? Do you mean CD I guess.

R- Corrected

385-. Replace “see and interpretative schema at Fig. 8a” by “see an interpretative scheme at Fig. 8a”

R- Corrected

393-. Replace “bangs et al., (2020)” by “Bangs et al. (2020)”.

R- Corrected

429-. Is there any specific references for this supposed west-dipping reverse fault that puts CC in tectonic contact with CD??

R- This sentence was removed in the new version. Few lines above (and also in section 4.1) we include the references:

Melnick, D. and Echtler, H. P.: Morphotectonic and geologic digital map compilations of the south-central Andes (36–42°S), In: Oncken, O., Chong, G., Franz, G., Giese, P.,Götze, H.-J., Ramos, V.A., Strecker, M., Wigger, P. (Eds.), The Andes – Active Subduction Orogeny. Frontiers in Earth Science Series, Vol. 1. Springer-Verlag, Berlin, Heidelberg, New York, pp. 565–568, 2006.

Hackney, R., Echtler, H., Franz, G., Götze, H. J., Lucassen, F., Marchenko, D., Melnick, D., Meyer, U., Schmidt, S., Tašárová, Z., Tassara, A., and Wienecke, S.: The Segmented Overriding Plate and Coupling at the South-Central Chilean Margin (36-42°S), In:Oncken, O., et al. (Ed.), The Andes-Active Subduction Orogeny, Frontiers in Earth Sciences. Springer-Verlag, Berlin, Heidelberg, New York, pp. 355–374, 2006.

Encinas, A., Sagripanti, L., Rodríguez, M.P., Orts, D., Anavalón, A., Giroux, P., Otero, J., Echaurren, A., Zambrano, P. and Valencia, V.: Tectonosedimentary evolution of the Coastal Cordillera and Central Depression of south-Central Chile (36°30′-42°S), Earth-Science Reviews,Volume 213,103465, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2020.103465. 2021.

430-. Remove one of both “depth” in the sentence “the depth contact between CC domain and H1 at depth”

R- Corrected

449-. Please close the parenthesis after “(Hervé et al., 2016; 2018”

R- Corrected

466-. Replace “intreseismic deformation” by “interseismic deformation”

R- Corrected

468-. Please provide relevant reference for this sentence.

R- We referenced to Scholz, 1998; Perfettini, H., and Avouac, 2004; Tassara, 2010; Moreno et al., 2018 and Im et al., 2020 in this paragraph.

469-. Replace “fractured and or metamorphic” by “fractured and/or metamorphic”

R- Corrected

474-. Replace “…should modified the…” by “…should modify the…”

R- Corrected

490-. This is also observed by Molina et al. (2021) and you can used to reinforce this idea. In this line please replace “This siggests oversaturate fluid…” by “This suggests that over-saturated fluid…”

R- Corrected.

494-. Replace “Several authors have siggested” by “Several authors have suggested”

R- Corrected