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Comment on se-2021-141

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Referee comment on "Postglacial strain rate – stress paradox, example of the Western Alps active faults" by Juliette Grosset et al., Solid Earth Discuss., https://doi.org/10.5194/se-2021-141-RC2, 2022

Please find enclosed my review of Grosset, Mazzotti and Vernant, "Postglacial strain rate - stress paradox, example of the Western Alps active faults". The manuscript analyzes the response of the Western Alps region to the deglaciation of the latest ice sheet covering the region. The authors use a simple model of glacial isostatic adjustment (GIA) to estimate stress and strain in the Earth and compare that to GNSS data and earthquake focal mechanisms. This is an interesting study which goes all the way to the slip directions in the earthquakes to compare how the stress induced by GIA affects current day seismicity. I think this a very worth while study, however, there are issues with the GIA modelling and the fault stability estimates that need further work. I therefore recommend major revision.

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Main comments:
1. Modelling GIA stress and strain.
(a)The thin plate/viscous mantle approach used for the modelling is a significant simplification of the GIA modelling problem and does not take into account stress redistribution due to the mantle (e.g. Wu, 1992; Steffen et al. 2015). Even for a relatively small ice sheet, such as the Alpine in this study, the mantle will be invoked (e.g. Arnadottir et al., 2009 used a more complex GIA model for current deglaciation in Iceland), especially for the elastic plate thicknesses found in the manuscript, with a best fit Te of 10 - 20 km. How large this effect is depends on the ice sheet configuration, the elastic parameters including Te and the viscosity of the mantle, but also the depth of interest in the model. At seismogenic depths in a 10 km thin plate it is not unlikely that the mantle stress redistribution is rather important. The authors should evaluate this by comparing to a more realistic GIA simulation tool.

(b) Write out the parameters used to calculate the flexural parameter and the relaxation time, i.e. Young's and shear modulus, viscosity etc. How large is the model domain and what are the boundary conditions, which are important for stress estimates?

(c) There is very little description of the ice model, it is not even included in its entirety in Figure 3. What is the temporal behaviour of the ice sheet (plot ice volume and maximum ice thickness through time) and how is it implemented in the model? Do you use the full ice sheet? How do you start the ice model? A full load in equilibrium at LGM will not capture the transient behaviour of the GIA response, as it is unlikely that the Earth is in flexural equilibrium at the LGM.

(d) Extracting the GIA induced stress field from the top of the elastic plate does indeed give you a maximum stress signal, but it is not very realistic as the earth model almost certainly is too stiff near the surface, not taking near-surface fracturing into account. Also, I guess earthquakes in the region rarely occur in the uppermost 1-2 kilometers? With best fitting GIA models of Te 10 - 20 km, and seismicity down to 15 km depth, it is unclear to me why the near-surface stress field should be the most appropriate to use. On the contrary, below 10 km in a 20 km elastic plate stresses go from compressive to tensile.

(e) The model domain contains significant topography, from the Mediterranean to Mont Blanc. Therefore probably also a significant root. I guess that affects the flexure of the area. It would be nice with some discussion of this.

2. GIA and fault stability.
The Coulomb Failure Stress, CFS, is widely used when estimating how a stress change affects faults, promoting or demoting stability. However, using the change in CFS (D_CFS) with shear and normal stresses estimated from some external process, like GIA in this case, may lead you wrong. Unless the shear and normal stress changes occur in the directions of the pre-existing shear and normal stresses, the full stress tensor has to be taken into account. As the GIA induced stresses are significantly smaller than the in-situ stress even at LGM, at depths of more than 1-2 km, it is unlikely that the GIA stresses change the directions of the in-situ principal stresses, so the effect of the combined stress field needs to be considered, see e.g. Lund et al. (2009). This is of course tricky if you do not know the what the stress field without the GIA component looks like. Since the present day GIA stresses are very small compared to the in-situ stress it would have been interesting to see the focal mechanisms, or even better a stress inversion of the focal mechanisms, to get an idea of the current stress field. This issue needs to be addressed, and discussed, as it affects the results of section 4. As an example, for the Belledonne fault GIA predicts reverse faulting while the mechanisms show strike-slip. So GIA does not drive seismicity on its own, but perhaps GIA adds that extra bit of stress that pushes the fault into instability? Such that the seismic activity is larger than it would have been without GIA. Or, oppositely lower?

Further, on line:

15: Reference for "plate tectonics cannot be the main source of SCR seismicity." That is not generally correct.

16: Need to define "recent", as today's seismicity in Fennoscandia is very much tectonics driven (e.g. Bungum et al, 2010) whereas the late/end-glacial was very much influenced by GIA.

18: Add Wu et al., 1999 or Lund et al. 2009 for Fennoscandia.

19: "Rapid decay in 103 - 105 yr"? Please explain what you mean, and give a reference. The timing of the Fennoscandian postglacial earthquakes are very uncertain and associated with the time just be fore ice retreat from a location, during ice retreat and just after, at the various locations. This gives a span of at least 1,000 years for the about a dozen ruptures, perhaps more as the exact time of ice free conditions are uncertain.

20: The Pärvie earthquake may have bee as large as Mw 8.0 (Lindblom et al., 2015).

41: You should comment on Keiding et al. (2015) who did a similar study for Fennoscandia. And also had problems reconciling the GNSS data, GIA and seismicity.

62, 66: Not sure if there is a problem with my pdf-viewer, but there is a different sign than a decimal dot in 1.2. Aha, it should be a hyphen?

66: Figure 3a shows the vertical velocities, which is perhaps not a good indicator of the size and variation in horizontal velocities, making up the strain rate field. How large are the uncertainties in the velocities, and propagated to your strain rates?

85: "wm" ? OK, I see. Write it in italics.

116 and Fig 3: Please add the outline of the maximum ice sheet to Fig 3a as well. How well does the current vertical GNSS velocities agree with the ice edge and the concept of a forebulge?

118: 50 MPa of horizontal compression under a 2 km (18 MPa) thick ice? That is a very high number.

120: GIA in Fig 3C.

122: The difference between GNSS and GIA strain rates in Fig 3 could be shown with for example bow tie plots, which would make the comparison much easier.

139: Indicate that you discuss present time(?).

143: Maximum horizontal GIA stress?

146-147: With DeltaCFS you should use Delta_tau and Delta_sigma_n, and therefore also the change in shear stress and the change in normal stress.

158: "...predicted rates are compared..."

206-209: This sentence is a little unclear. The ice adds a large vertical stress, the lithosphere slowly flexes inducing horizontal stresses. The increase in average stress increases fault stability. The rapid melting of the ice, compared to the Earth's rebound, decreases vertical stress faster than horizontal stress, resulting in an induced reverse stress state. Combined with a pre-existing reverse stress state, in a similar direction as in Fennoscandia, the process destabilizes faults. See Lund et al. (2009). Then we have the added action of strain accumulation during 50 - 60 kyr of ice cover, which adds to the horisontal stress/strain.

Figures:

3) Indicate that this is present time for 3c. The arrows in 3c are virtually impossible to see, and even the ones in 3b are difficult in many areas. Perhaps have different scales in b and c, with a large legend and the caption pointing out the difference? A factor of 2 difference could make the comparison easier? As you show vertical velocities in 3a, perhaps point out that you show horizontal strain rates. Add a scale bar to the figures, as the text explicitly talks about 90 km half-width filtering and 150-200km wavelength signals.

4 and 5) Add that this is the present day stress field. It would be good to have the extent of the ice sheet on these maps as well.

A3) The symbols are very difficult to see, even at 300% magnification on my screen.

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