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REPLY

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Reply to comment by Hampel et al. on “Stress and fault parameters affecting fault slip magnitude and activation time during a glacial cycle”

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This article is a reply to comment by *Hampel et al.* [2015] doi:10.1002/2014TC003772.

Key Points:
- Differences between glacially induced fault models shown
- Glacially induced fault models have to include the entire mantle for ice sheets >100 km
- Importance of stress migration from the mantle to the lithosphere described

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Hampel et al. [2015, hereinafter Ha15] recently commented on our study [*Steffen et al.*, 2014a], which investigates the effect of stress and fault parameters on fault slip magnitude and activation time during a glacial cycle using a newly developed two-dimensional glacial isostatic adjustment (GIA)-fault model [*Steffen et al.*, 2014b]. In summary, Ha15 criticize the following parts of our study stating “*(1) that Steffen et al.* [2014a] *describe our modeling approach in a misleading way, (2) that they do not mention the specific results (e.g., regarding the amount and timing of fault slip) of our studies anywhere in their article despite the similarity of the topic of their article, and (3) that the content and layout of Steffen et al.’s Figure 1 closely resembles two figures previously published in our studies but they do not cite the source (they, however, introduced conceptual errors concerning the glacial-interglacial stress evolution into their figure)* .”

We appreciate the comment by Ha15 as it gives us the opportunity to discuss and describe the differences between our model and Hampel et al.’s model in greater detail than in *Steffen et al.* [2014a] and earlier publications. We show that comparison between the results of both model approaches is not feasible.

Due to the many issues raised by Ha15, we extract specific comments by Ha15 in conjunction to those above and also rephrase their statements so that we can address them in more detail:

1. Hampel et al.’s Earth model neglects the important effects of viscoelasticity in the mantle on GIA and stress migration.
2. The applied plate-motion velocities in Hampel et al.’s model control the fault slip.
3. The load models in Hampel et al. are not suitable for GIA studies.
4. The models of Hampel et al. have only limited direct observational support.
5. According to Ha15, the density of the crust in our models is wrong.
6. According to Ha15, we do not cite Hampel et al.’s studies as source of Figure 1 in *Steffen et al.* [2014a].
7. According to Ha15, Figure 1 in *Steffen et al.* [2014a] has conceptual errors: the Mohr circle during glaciation has to become smaller and cannot exceed the line of failure after glaciation.
8. According to Ha15, we apply our results to the Pärvie fault and omitted a comparison of our results with those by *Turpeinen et al.* [2008].
9. According to Ha15, we do not provide a sufficient comparison between our results and those obtained by Hampel et al.
10. We will correct several statements in Ha15.

Before we deal specifically with these items, we briefly introduce the GIA process and its relation to fault activation as well as the two modeling approaches.

The GIA process, which is the Earth’s response to ice loading and unloading events during glacial cycles as well as the associated changing ocean loads on its surface, is known to affect Earth’s shape, potential, rotation and stress [*Steffen and Wu*, 2011]. Changing stresses induced by the GIA process led to the reactivation of faults near the end of the last glaciation, ~10,000 years ago, resulting in large earthquakes [*Lagerbäck*, 1978; *Johnston*, 1996; *Lagerbäck*, 1992; *Arvidsson*, 1996; *Lagerbäck and Sundh*, 2008; *Lund*, 2015]. These are found in northern Scandinavia, with the Pärvie fault being the largest [*Lagerbäck and Sundh*, 2008]; similar faults are also found in the British Isles [*Stewart et al.*, 2001], Germany [*Brandes et al.*, 2012, 2015] and North America [*Fenton*, 1994]. Early studies of the link between GIA and intraplate earthquakes are based on differential stress [e.g., *Spada et al.*, 1991], which led to the conclusion that GIA induces earthquakes during glacial loading. *Johnston* [1987] was the first to correctly use the Mohr-Coulomb theory for the study of faulting; he showed that the presence of glacial load actually suppresses earthquakes. However, it remained unclear how a fault can become unstable near the end of deglaciation, if it was originally in a stable state before the start of glacial cycles. Using Mohr-Coulomb theory and a viscoelastic Earth with background tectonic stress and overburden pressure, *Wu and Hasegawa* [1996a] explained the underlying mechanism that led to rupture and showed that the predicted timing of GIA-induced earthquakes is in reasonable agreement with the observed data. However, their model uses a simplified representation of faults as virtual faults that are optimally oriented. The concept of virtual fault means that no fault surface is included in the model, and therefore, its presence does not affect the stress distribution. Moreover, while their model predicts that GIA-induced stress is available to reactive faults, it cannot predict the amount of fault slip nor its slip history.

An important contribution of *Hetzel and Hampel* [2005] and subsequent papers is the introduction of fault geometries in the model that are actually able to slip. Their model combines processes of three different time scales. First, they apply velocities at the sides of the models to simulate plate motion that induces tectonic stress on the fault and leads to a constant fault motion related to the applied plate motion velocity (more on this below). This process occurs over time-scales of millions of years. Second, a load cycle of several 10,000 years is applied to the model, which changes the slip velocity of the fault. Third, the much faster slip after unloading is interpreted as induced earthquake activity.

The major difference between the models of Hampel et al. and GIA models is the model geometry. While GIA models include a depth range down to the core-mantle boundary (CMB), Hampel et al.'s model extends, in general, to ~100 km depth. In contrast to most GIA models, the effects of the mantle are simulated by applying certain boundary conditions at the bottom of their lithospheric-mantle (see below).

Steffen et al. [2014b] introduce a new approach that is based on a well-established GIA model [*Wu*, 2004]. We combine the GIA model with a fault surface to investigate the fault slip and fault activation time during a glacial cycle. Our model is referred to as the GIA-fault model below. Instead of plate-velocity, applied at the model boundaries, tectonic stress is input directly into the model to keep the fault at the stability limit. Hence, there is no need to run the model for a dedicated time to induce steady state fault slip. This also means that there is no fault slip or earthquake in the GIA-fault model before glaciation. During/after deglaciation, the change in slip rate is considered important by Hampel et al., as the timing of rapid increase is deemed to represent "the timing of fault slip" that might trigger earthquakes, whereas the calculated slip is, in fact, continuous. In contrast, slips are instantaneous in the GIA-fault model of *Steffen et al.* [2014a, 2014b, 2014c], provided that all conditions for slip initiation are met. Hence, it is possible that for certain parameters the fault in the GIA-fault model does not move at all, but it is also possible that it slips several times in cases when sufficient stress is built up again.

After having introduced the two approaches, we now provide a detailed discussion of Ha15's concerns.

1. Hampel et al.'s Earth Model Neglects the Important Effect of Viscoelasticity in the Mantle on GIA and Stress Migration

   In Hampel et al.'s models, the sublithospheric mantle is represented by lithostatic pressure, elastic foundation, and dashpots at the bottom of the lithosphere. Without the dashpots, these boundary conditions give instantaneous support to the load, the crust and the lithosphere, and prevent them from sinking into an inviscid mantle. (The elastic foundation mimics the buoyancy restoring force at the bottom of the lithosphere.) The dashpot is intended to mimic the delayed response due to mantle viscosity. However the viscosities of the dashpots used are from 10^{17} to 10^{20} Pa s [*Turpeinen et al.*, 2008; *Hampel et al.*, 2009, 2010], corresponding to relaxation times of about a few months to a century, and are thus too short to explain the observed relaxation of the mantle which typically takes thousands of years, according to sea level data, near the centers of rebound in Fennoscandia and Laurentia. It is not acceptable to take the viscosity of the asthenosphere, whose existence is questionable under the old cratons below the centers of rebound, and use its value to represent the viscosity for the whole mantle. Even if the proper viscosity is assigned to the dashpot, these simple boundary conditions are not able to model the load-induced shear stresses in the mantle that drive mantle flow and thus the GIA process.

   In addition, the models of Hampel et al. neglect the upward migration of stresses from the mantle to the lithospheric crust during and after the glacial cycle. This stress migration, which takes thousands of years, occurs due to the relaxation of the viscoelastic mantle in response to surface loading: as is well known, all viscoelastic materials behave like elastic solids if the duration of the applied stress is short compared to the Maxwell time of the material (i.e., the ratio of the viscosity over the shear modulus of the material). When the stress duration exceeds the Maxwell time, then the viscoelastic material starts to flow and behaves like a viscous fluid. Since the lithosphere is colder than the mantle, its viscosity and Maxwell time are much higher than that in the hot mantle. For example, consider the application of a load with size comparable to the Laurentian ice sheet. Immediately after the loading, the whole viscoelastic Maxwell mantle behaves elastically, which means the whole mantle supports the load elastically, and the stress will be spread broadly over the whole mantle (in a way similar to equation (3) below). However, when the load duration exceeds the Maxwell time of the mantle, but not the Maxwell time of the lithosphere, then the load will be supported elastically by the lithosphere and also partially by buoyancy force in the relaxed “fluid” mantle. Since the lithosphere is much thinner than the mantle, higher stress will concentrate in the lithosphere as the viscoelastic mantle relaxes. In other words, the stress from the mantle has migrated upwards into the lithosphere. Finally, as the viscoelastic part of the lithosphere starts to relax, then there will be further upward migration and concentration of the stress in the top part of the lithosphere.

For modeling the stress, the important question is how deep must the mantle be in a model for a given ice sheet? The answer, as will be shown below, depends on the horizontal dimension of the ice sheet. For example, the mantle down to at least 1100 km depth must be included for the Fennoscandian ice sheet, while the whole mantle down to the CMB must be included for the Laurentian ice sheet. To find the answer more precisely, one needs to compute the sensitivity kernel and determine the peak and depth extent of the kernel due to a specific load applied at the Earth’s surface [*Mitrovica and Peltier*, 1991; *Wu*, 2006]. A simple, rule-of-thumb relation exists for an elliptical load on a flat-Earth half-space. Let the vertical displacement w at depth z ($z < 0$) be given by [*Cathles*, 1975, equation (III-13)]:

$$w \sim (kz-1)e^{kz}, \tag{1}$$

with k the wave number for an elliptical load with characteristics lengths of L and M [*Cathles*, 1975, Appendix VI, equation (10)]:

$$k = 1.7\sqrt{\frac{1}{L^2}+\frac{1}{M^2}}. \tag{2}$$

The shear stress profile S is proportional to [*Cathles*, 1975, equation (III-13)]

$$S \sim -kz\,e^{kz}, \tag{3}$$

and the shear energy (sensitivity kernel) is represented by

$$E \sim S^2. \tag{4}$$

Using equation (4) with equation (3) together with $x = kz$ results in

$$E \sim x^2 e^{2x}, \tag{5}$$

which reaches the maximum for E at $x = -1$ (note that we discuss only depth, thus $x < 0$), thus at a depth of $z = -\frac{1}{k}$. For Scandinavia for example, one can assume that the elliptical load, here the Weichselian ice sheet, has minimum lengths L and M of 1400 km and 800 km, respectively, which gives a peak value of sensitivity at about 408 km depth. This is significantly below the base of the lithosphere. Half of the peak value is reached at about $z = -2.08/k \sim 850$ km, a quarter still at about $z = -2.68/k \sim 1100$ km depth. Larger load width further increases these depth values. Therefore, the mantle plays a major role in the energy and stress generation of the GIA process.

A load size such as 400 km (for both L and M) as used in *Hetzel and Hampel* [2005] would give maximum sensitivity in about 166 km depth, half the peak sensitivity at 346 km, which are both much larger than the used model depth of 100 km. Even for a 200 km wide load, the half-peak is at 173 km depth and that is already outside Hampel et al.’s model. Only for a small load with 100 km width or less, the effect of the mantle can be neglected, but then we leave the major field of GIA, because the response of such a load is due to the viscoelastic relaxation of the lower crust and lithosphere and not the mantle.

A comparison of Hampel et al.’s approach to the approach by *Wu* [2004] was presented by *Hampel et al.* [2009] in Figure A2. However, the small differences obtained within the comparison turned out to be

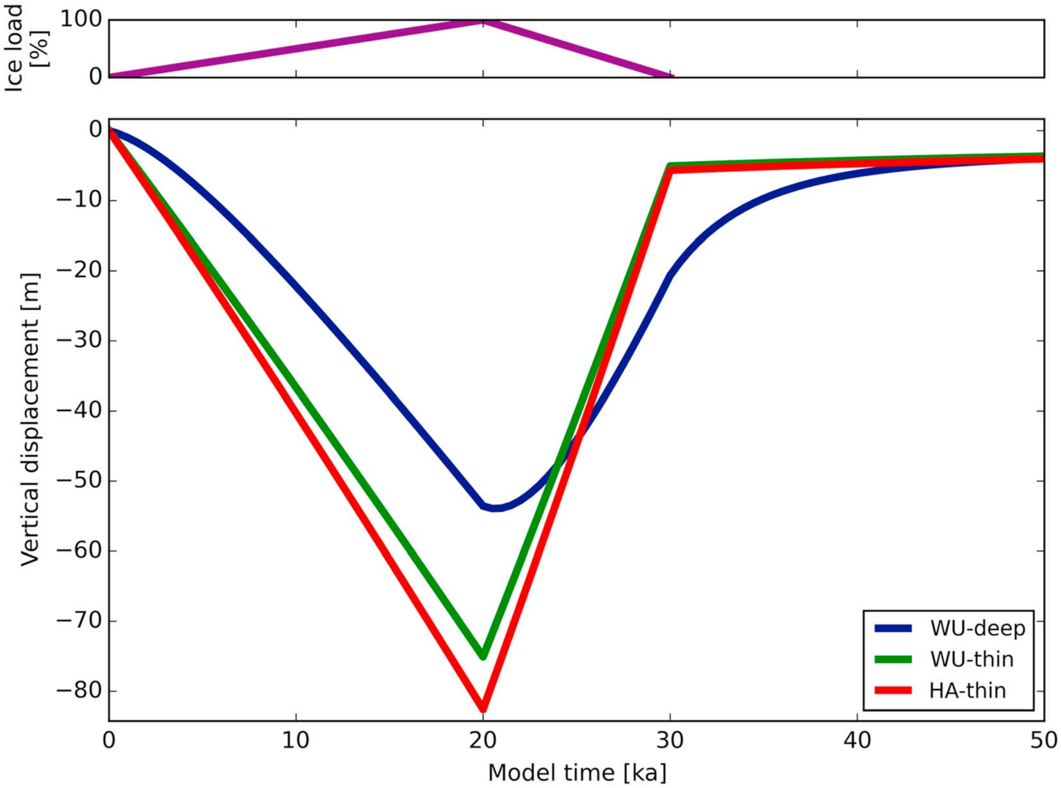

Figure 1. Vertical displacement at the surface for a point beneath the ice sheet center (ice-load width: 200 km, ice-load thickness: 500 m). The same models as in *Hampel et al.* [2009] are used (Model HA-thin and Model WU-thin). Additionally, the model following the approach by *Wu* [2004] is extended to a depth of 2891 km (Model WU-deep). The time distribution of the load is presented in the upper part of the figure.

good only for a 100 km thick crust-lithospheric model. If the viscoelastic effect of the mantle needs to be included, then the differences are much larger. This is illustrated in Figure 1, which shows the vertical displacement over time as in Figure A2 of *Hampel et al.* [2009]. First, we use the same 100 km thick models as in *Hampel et al.* [2009] for this comparison. The models do not include a fault structure and only the GIA process is presented. We will call the model by Hampel et al. HA-thin and the thin (100 km) model using the approach after *Wu* [2004] WU-thin. The displacements of HA-thin and WU-thin differ only by about 7.5 m at maximum loading, i.e., 10% difference, but they also exhibit elastic rebounding during the entire deglaciation and an abrupt change in rebound velocity when the ice is gone. This is not verified by observations and cannot be expected to be correct. Hence, a model such as WU-thin is not used in GIA studies. Such studies use a model that includes the mantle down to CMB depth at 2891 km. The comparison of such a deep model using the approach by *Wu* [2004], we call this model WU-deep in Figure 1, shows a much larger difference of about 30 m (or 54%) to HA-thin. Additionally, the rebound behavior of WU-deep is able to explain sea level curves and other GIA observations. The models of *Steffen et al.* [2014a, 2014b, 2014c] are based on WU-deep and thus include the full effects of the viscoelastic mantle.

2. The Applied Plate-Motion Velocities in Hampel et al.'s Model Control the Fault Slip

   Hampel et al. initiate fault slip by applying convergent or divergent plate velocities between 1 and 5 mm/yr at the sides of the model. After a certain amount of time (which is often not specified in their studies, but all load processes appear to start after one million years, see *Hetzel and Hampel* [2005]), the stress starts to build up and propagate from the sides to the fault, which eventually starts to slip at a steady rate in the absence of any applied load (e.g., Figure 2b in *Hampel and Hetzel* [2006]). The application or removal of glacial load alters the slip rate at the fault but the applied plate motion plays a major part in their fault slip.

In contrast, no plate velocity is applied to the models of *Steffen et al.* [2014a, 2014b, 2014c], whereas the tectonic stress maintains the fault close to the stability limit before the glacial cycle begins. Consequently, fault slip that is induced near the end of deglaciation is only due to the relaxation of the rebound stresses. This is in contrast to the results by Hampel et al., as fault slip is always a consequence of applied plate velocities and a relaxation of load-induced stresses. In addition, it remains unclear if Hampel et al. perform a stress transformation as needs to be done when using finite element software (e.g., ABAQUS) that solve a different equation of motion than that of GIA [see *Wu*, 2004; *Steffen et al.*, 2014b].

3. The Load Models in Hampel et al. Are Not Suitable for GIA Studies

As discussed in equation (1), the 100 km thick crust-lithospheric model of Hampel et al. is only strictly valid for loads with horizontal dimensions smaller than about 100 km. Ice loads of such size are too small for most GIA studies. In addition, for their study of slip along thrust faults [*Turpeinen et al.*, 2008; *Hampel et al.*, 2009], the whole loading and unloading period in their model lasts only 20 to 30 ka, which is very short compared to the 100 ka glacial growth period and 10 ka deglacial period revealed in deep-sea-sedimentary-core data [*Hays et al.*, 1976]. In Figure 10 of *Hampel et al.* [2009], a longer loading period of 50 ka was used for a load with size comparable to the Scandinavian ice sheet; however, the neglect of mantle viscoelasticity renders their results ambiguous.

The short time-span of the loads used may be useful for some special loads. However, *Kaufmann and Amelung* [2000] show the differences between short-term load changes in Lake Mead and the GIA process in the estimation of viscosity and sensitivity of data.

4. The Models of Hampel et al. Have Only Limited Direct Observational Support

The model predictions of Hampel et al. involve slip history (or total displacement versus time) and stress. However, stress magnitudes are not directly observed over time and are thus not well constrained. As to the slip history, their models predict the steady state slip rate is on the order of 0.2 mm/a; such a slip rate may be able to generate some “background earthquakes” continuously. The questions are as follows: (a) is there any observational support for such rate? (b) what background earthquake magnitudes and rates are consistent with such steady state slip rate and do they agree with the observations? During the unloading cycle, Hampel et al.’s thrust model predicts a slip rate that is faster than the steady state slip rate; however, the slip is still over a time scale of a few thousand years and not a seismogenic time-scale of a few seconds or minutes. Furthermore, there are many direct observables for GIA, such as sea levels, GPS data, gravity-rate-of change, Earth ’s spin rate, and true polar wander, but to our knowledge Hampel et al. have not yet demonstrated that their model is compatible with such observations.

In addition, *Hampel et al.* [2009] found that the viscosity parameters in the viscoelastic layers required for normal and thrust faults are different. The viscosity in the lower crust is 2 orders of magnitude smaller for the thrust model than for the normal model, but five orders of magnitude higher in the lithospheric mantle. This poses a major difficulty in explaining how normal faults can be reactivated as thrusts as in northern Europe [e.g., *Brandes et al.*, 2012, 2015].

In contrast, the ice and Earth models used in *Steffen et al.* [2014a, 2014b, 2014c] are more realistic and their 3-D model predictions can readily explain all the GIA observations, in addition to the observed stress rotation [*Wu*, 1996], the timing of GIA-induced earthquakes (also predicted by Hampel et al. models) and magnitude of glacially induced fault slip (or earthquake magnitude). Also, our models predict instantaneous fault slips (single events) near the end of deglaciation, while Hampel et al.’s results exhibit continuous creeping (strictly speaking, aseismic behavior). In addition, our models can explain how normal faults can be reactivated as thrusts.

5. According to Ha15, the Density of the Crust in Our Models is Wrong

Our density is calculated as volume average over all densities in the upper 40 km from PREM [*Dziewonski and Anderson,* 1981] and implemented in a way that the buoyancy boundary condition of the first layer is met, see *Wu* [2004]. This is in agreement with the majority of GIA studies involving Earth models, see, e.g., *Spada et al.* [2011]. We remark that one has to be careful when calculating the density from PREM, as the first layer of 0 – 3 km with a density of 1020 kg/m^3 (as mentioned in Ha15) represents the ocean.

6. According to Ha15, We Do Not Cite Hampel et al.'s Studies as Source of Figure 1 in *Steffen et al.* [2014a]

   Figure 1 in *Steffen et al.* [2014a] has been modified from *Wu and Hasegawa* [1996b] and *Wu* [1998a, 1998b]. Similar figures were also presented by *Quinlan* [1984], *Johnston* [1987], *Muir-Wood* [2000], *Stewart et al.* [2000], and *Chung* [2002].

7. According to Ha15, Figure 1 in *Steffen et al.* [2014a] Has Conceptual Errors: The Mohr Circle During Glaciation Has to Become Smaller and Cannot Exceed the Line of Failure After Glaciation

   Figure 1 in *Steffen et al.* [2014a] is a sketch (which is stated in the caption) and intended to briefly illustrate the concept of fault stability and Mohr's circle, so that the reader can easily understand the results of *Steffen et al.* [2014a]. We note that for an elastic lithosphere over a viscoelastic mantle, time is required to build up and decay the flexural stress, so Figure 1b can be well explained to show the situation soon after loading. Moreover, the size of the Mohr Circle is controlled by ice sheet thickness and size, location of the load, the elastic modulus and viscosity of the Earth, etc., simply all influencing parameters that can be tested; thus, one cannot insist that the Mohr circle becomes smaller during glaciation. Because Ha15 use small ice loads and neglect the viscoelastic stress in the mantle, it is problematic to generalize their finding to large ice sheets with the full effects of mantle viscoelasticity included.

   In general, the line of failure can be exceeded by the Mohr Circle [e.g., *Barton et al.*, 1995] as the failure law depends on several parameters. In investigations of GIA-induced faults, fault activation after deglaciation depends on the dip angle of the fault (such a figure has already been shown in *Wu and Hasegawa* [1996a]). Only in the optimally oriented case failure would result if the failure law is valid.

8. According to Ha15, We Apply Our Results to the Pärvie Fault and Omitted a Comparison of Our Results with Those of *Turpeinen et al.* [2008]

   We strongly disagree with this comment. We transform our fault slips into earthquake magnitudes by applying two different equations. As one equation is a function of fault length, we took the length of the longest glacially induced fault known to date, which is the Pärvie fault, to obtain a maximum magnitude estimate. The length is applied in all investigated cases. There is no comparison to the Pärvie fault per se as indicated by Ha15, and thus a comparison to *Turpeinen et al.* [2008] is superfluous. The discussion of the next point is also applicable here.

9. According to Ha15, We Do Not Provide a Sufficient Comparison Between Our Results and Those Obtained by Hampel et al.

   In the above, we have shown that the two model approaches have totally different physical background, and that Hampel et al.'s approach is not generally applicable for GIA investigations. Also, our results are instantaneous fault slips (single events), while Hampel et al.'s results exhibit continuous seismic or aseismic creep. Hence, the results of both studies are not really comparable. Last but not least, we would like to highlight that we so far only used a two-dimensional model with thrust-fault mechanism in a parameter study. It is far from clear why our results should be compared with three-dimensional models that apply normal-fault mechanism for selected regions in the world.

10. We Will Correct Several Statements in Ha15

    Ha15 write that "Steffen et al.'s description gives the reader the impression that our models did not contain viscoelasticity at all." The details are already discussed in point (1). The main point is that dashpots do not adequately represent viscoelastic stress and its upward migration. Our paper states that Hampel et al. "neglect the effect of the viscoelastic mantle," which does not imply that some simple form of viscoelasticity is not included.

    Ha15 write that they "actually compute the amount of postglacial fault slip." We have checked all publications by Hampel et al. again, but, to the best of our knowledge, could not see postglacial fault slip that resulted from an earthquake rather than accumulated creep.

    Ha15 claim that they were the first "to explain why earthquakes were triggered by the melting of ice sheets." As discussed earlier, many researchers have suggested the relationship between glacial rebound and intraplate earthquakes more than 40 years ago, but their arguments were mostly based on differential stress and not on Mohr-Coulomb theory of fault activation. *Johnston* [1987] was the first to use Mohr-Coulomb theory and show clearly that ice loads suppress earthquakes. *Wu and Hasegawa* [1996a, 1996b] were the first to explain clearly, using Mohr-Coulomb theory, that the removal of ice loads lead to fault reactivation and also predict the timing of postglacial earthquakes. *Arvidsson* [1996] and *Grollimund and Zoback* [2001]—just to name a few, have also written about the relationship between glacial rebound and intraplate earthquakes before *Hetzel and Hampel* [2005].

Ha15 state that their models "showed that after a short period of intense faulting, slip accumulation and hence seismic activity decreased markedly in Scandinavia." All results presented by Hampel et al. show a further fault slip accumulation after unloading has finished, implying that glacially induced faults are still moving at the surface, which is not observed [*Mantovani and Scherneck*, 2013].

1. Conclusion

We have shown the differences between the methods by Hampel et al. and Steffen et al. within the field of glacially induced fault modeling and major discrepancies were documented. For loads of small enough horizontal dimension (<100 km) so that the presence of the mantle can be neglected, then the method of Hampel et al. may be adequate, but that would be mostly for nonglacial types of loading. However, for typical ice loads where the viscoelastic mantle needs to be included and where GIA observations must be explained, then the method of Hampel et al. is not adequate for GIA-induced fault modeling as the inclusion of the full viscoelastic effects of the mantle is a necessity. This is included in the models outlined in *Wu* [2004], which are the foundation for the GIA-fault model introduced by *Steffen et al.* [2014b].

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