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The Cryosphere Discussions

Interactive comment on "Layer disturbances and the radio-echo free zone in ice sheets" *by* R. Drews et al.

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Thanks for your interest and your suggestions concerning this paper. In the following your comments will be cited in ".." and the corresponding response is printed in bold.

"Figure 1, indicates the abrupt change from numerous reflector horizons to none. This image is too small to adequately convey the completeness of the change from numerous reflectors to the EFZ spatially. I recommend using two figures separating either by profile or pulse length."

We agree that the figures appear too small. We will use two figures. For the time being one can zoom in the Figures in the online version of the manuscript to see

more detail.

"It would also be pertinent and useful, given the limited literature on the subject, to include an RES profile from another location, previously published, to illustrate the nature of the EFZ in diverse settings. For example the RES profile from near Vostok could provide a compliment indicating that the EFZ is not related to bed topography as it exists over mountainous basal areas and Lake Vostok. This would also illustrate that the EFZ is not dependent on a specific flow setting, for example at a flow divide versus along a flow line.“

For clarity: EDML is not a flow divide in the sense of divide flow, as the along-divide component is around 0.7 m/a (so flank flow), and the across-divide flow is much smaller. Fujita showed a transition from divide to flank flow at Dome Fuji: no EFZ near Dome F and an EFZ develops when flank flow sets in. The RES profile near/over lake Vostok discussed in Siegert and Kwok (2000) is certainly a candidate for an EFZ over a lake. However, it has to be kept in mind that the ice over the lake is advected there and that the internal layers obtain their characteristics further upstream, as illustrated by Leonard et al. (2004, doi: 10.1029/2004GL021102). Possibly an EFZ forms upstream of the lake, e.g. in a region of considerable shear, and is then advected over the lake. In the Siegert and Kwok paper it is not finally established whether the loss of internal layering around 3 km depth is due to the system sensitivity or due to other physical mechanisms. Therefore we prefer not to include that example. We do have a profile in the vicinity of Dome F which also crosses a subglacial lake (referred to as M2011 by Siegert et al. (2005)) along the flow line and where the EFZ can partly be identified. In case the reviewers and the editor argue along the same line, we can include the attached image (see Fig. 1 in this document). This profile also illustrates that the EFZ onset may sometimes be objective. In the attached example it depends on whether the small reflections in Trace 365 below 2000 m are considered to be laterally coherent or not. If they are considered to be laterally

disturbed, the onset starts at 2000 m. If not, no EFZ can be identified.

"The authors refer to Fujita's (2006) identified sequence of 4 radio echo zones: the density driven near surface zone, the conductivity zone, the COF zone, and last the EFZ zone. In Figure 3 it would be nice to see the bracketed delineation of these various zones not just the EFZ."

In Fujita (1999) the four zones are identified with a two-frequency experiment, because reflection coefficients of the conductivity driven zones are frequency dependent, whereas the ones of density and COF are not. Density and COF zones are kept apart with the absence of aligned COF in shallower ice and the near constant density in deeper ice. Siegert and Kwok (2000) derive the zones from the characteristic of signal attenuation. We agree that these zones exist but we don't know where to set the boundaries in our example as only a single frequency is available and the shape of signal attenuation needs more analysis. However, from multi-polarization data in a nearby experiment (Eisen 2006) we think that a COF zone exists above the EFZ. Moreover, a strict categorization is misleading, as reflections from density and conductivity can occur at similar depth ranges, and also for COF and conductivity, actually for the same reflection signal (see discussion by Eisen et al., 2007). The physical origin of a horizon depends on relative importance of either reflection mechanism.

"The case has been made that a change in COF can cause an internal reflecting horizon and did cause the last substantial reflecting horizon (Eisen et. al., 2007). More attention needs to be paid to COF changes or lack thereof in the EFZ. A COF reflector would represent a change in the stress and strain history occurring along some plane. That no such reflector horizon, or very few anyway, occur in the EFZ suggests a zone with no significant COF planes. Would not the COF either be relatively consistent or completely incoherent in the EFZ to have no planar reflecting horizon? Siegart and Kwok (2000), note in the Lake Vostok core, that there is abundant crystal alignment at ice depths greater than 2700 m, resulting in ice layers with preferred COF across Lake

Vostok at ice depths greater than 2800 m. An examination of the RES from the Lake Vostok area indicates this depth band coincides with the EFZ. Drews et. al., (2009) and Eisen. al., (2007) note the anisotropic COF below 2040 m. This to me suggests a consistent COF in a bed parallel shear dominated environment as noted by Pettit (2007)."

Coherent COF changes of considerable magnitude and spatial size are necessary to create laterally continuous reflection horizons, not only certain types of alignment. We agree that changing COF at the EFZ's upper boundary (also observed for example in Fujita 1999) needs more attention, but a direct connection has not been made yet. The measured COF eigenvalues (25 - 50 m spacing) show a transition from a girdle distribution to a single maximum at 2040 m depth (at 2080 a conductivity reflector has been identified). From there on, the COF eigenvalues are relatively consistent (apart from 2375 m depth) so we would not expect reflections from changing COF based on the physical properties within the EDML ice core. We think it is correct that we deal with a bed parallel shear and a consistent (single maximum) COF. The relation to Pettit et al. is partly discussed in Eisen et al. 2007.

"It is noted in Figure 2 and in the text that the cloudy bands lose their perfectly parallel nature at the transition to the EFZ and are often folded, faulted and tilted. Hence, the upper bound of the EFZ would be the zone where depositional layering loses lateral continuity. In Figure 2 within the EFZ as the authors note most of the layers remain parallel, this suggests the possibility of a different explanation. That COF becomes dominant due to the development of an anisotropic fabric due to crystal growth and reorientation. Do the crystals cross a threshold size large enough to cross the small scale layers-cloudy bands, possibly reducing a coherent reflection from them? As the anisotropy develops at the top of the EFZ the depositional layer properties then are secondary to crystal and crystal fabric properties. What has been observed that makes this explanation less plausible? In either case it is ice sheet flow properties that is causing the loss of reflecting horizons.“

First of all, the question of lateral continuity is very much a question of the spatial scale. Most CBs within the EFZ are parallel (within a vertical 1-m core segment of 10 cm in diameter) and tilted. Towards greater depths the parallel nature becomes more disturbed. The fabric is certainly anisotropic. The crystal size does correlate with the cloudy bands, but at the EFZ onset down to 2300 m, the mean crystal size is around 2-3 mm . This is an order of magnitude smaller than vertical spatial range of the CBs. The large crystals observed at the last interglacial (2300 – 2375 m) are an exception, no significant change in crystal size is observed at 2100 m. Thus it seems not likely that crystal size alone is a primary reason for the EFZ. As mentioned before, the changing COF at 2040 m and the EFZ onset at 2100 m suggests a physical connection (the false bed effect, Pettit et al.) likely related to stress and flow, but details of which still have to be established.

Interactive comment on The Cryosphere Discuss., 3, 307, 2009.

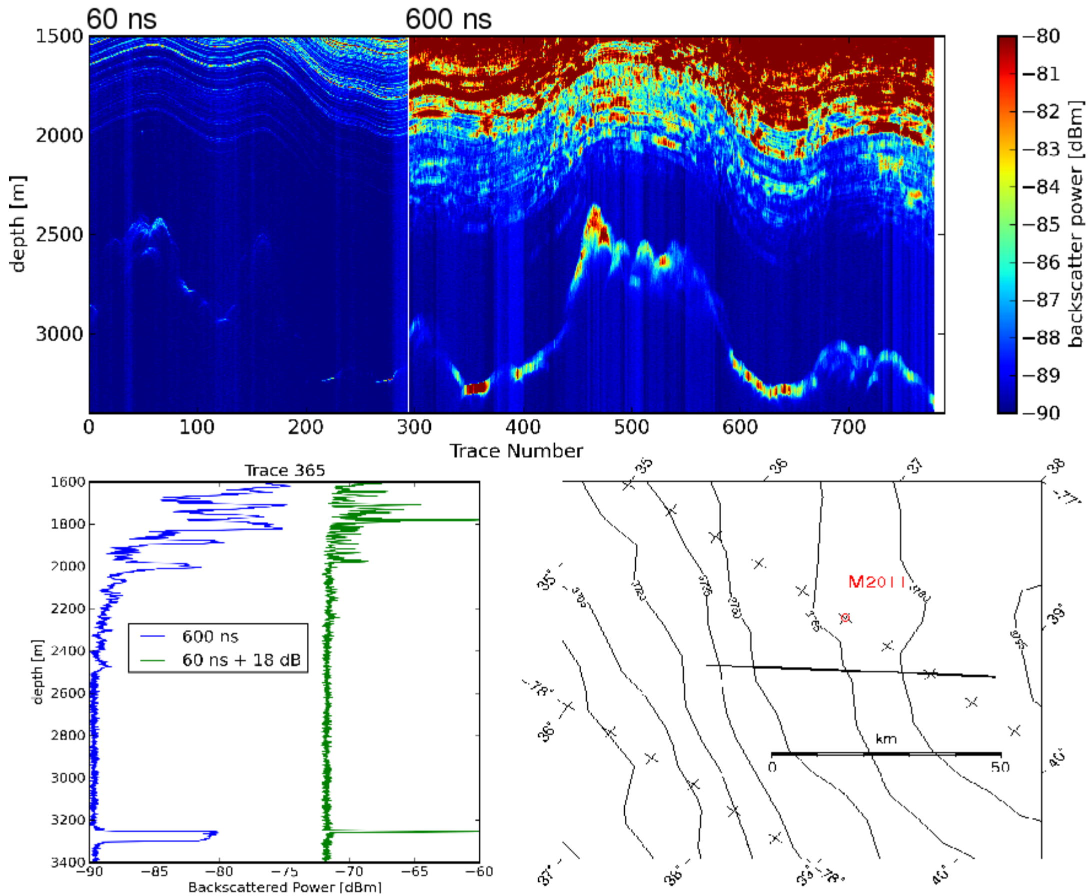
60 ns
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Fig. 1.