Short Visit Grant ☒ or Exchange Visit Grant ☐

(please tick the relevant box)

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online <u>within one month of the event</u>. It will be published on the ESF website.

<u>*Proposal Title*</u>: Towards multi-scale ice sheet modelling

<u>*Application Reference N°*</u>: 7392

1)   Purpose of the visit

The response and contribution of large ice sheets to a changing climate is one of the greatest issues in contemporary climate research. In particular, knowledge of the deformation mechanisms of polar ice is of crucial importance to predict the flow of polar ice sheets and hence their contribution to global sea level rise (Vaughan et al. 2013).

Identification of the deformation mechanisms that are active in polar ice and determination of their proportionate occurrence is a significant contribution to the improvement of ice sheet flow models (Faria et al. 2014). The flow law mainly used in current ice sheet models (Glen's flow law), was derived empirically from laboratory deformation tests. The major challenge of this project is to combine the results from ice fabric measurements, microstructural modelling and homogenization procedures into a generalized flow law for polar ice flow. This new theory will pave the way for a new generation of anisotropic ice sheet models and may help us to refine the interpretations of studies of ice-core physical properties.

The theoretical approach shall combine concepts from thermodynamics, continuum mechanics, materials science, and continuous diversity that can be applied to microstructure modelling (Faria 2006a,b; Faria et al. 2006). One great challenge of this project is to extract from experimental observations the necessary information to derive appropriate mathematical expressions for the theory. This theoretical-numerical-experimental interaction is essential to help developing a new micro-macro approach to ice sheet modelling with input from observational results.

The aim of the visit was to discuss data and discuss recent progress of the theoretical approach. We have reviewed observational results of ice fabrics derived from deep ice cores from Antarctica (EDML) and Greenland (NEEM) to improve our understanding of the micromechanical mechanisms in polar ice, aiming for a new theory of ice microstructure evolution.

2) Description of the work carried out during the visit

The Applicant arrived in Bremerhaven in the evening of the first day (26 August 2015). Scientific meetings took place at AWI Bremerhaven on 27 and 28 August 2015.

The second day (27 August 2015) was marked by intensive meetings, which started with a plan of activities for the two remaining days. The Applicant was introduced to two recent members of AWI's Glaciology Section, Ina Kleitz (masters student at the University of Halle) and Johanna Kerch (PhD student at the University of Heidelberg). The students presented their research activities to the Applicant, both covering different aspects of observations and modelling of multiscale ice sheet flow.

Ms. Kleitz presented the initial results of her inter-comparison of microstructure and micro-Raman analyses of polar ice samples from a deep ice core from Greenland (NEEM core, 740 m depth). Besides corroborating the known anti-correlation between impurity content and mean grain size (e.g. Gow and Williamson, 1976, Faria et al. 2010), she has been trying to make a more precise identification of the chemical species involved in this correlation, and the potential consequences for the rheology of polar ice. We concluded that the results from the circa 300 micro-chemical measurements already performed are promising, but many more measurements are necessary in order to draw statistically significant conclusions.

Ms. Kerch presented the partial results of her study of cm-scale variations of lattice preferred orientations (LPOs) in a cold Alpine ice core from Colle Gnifetti (72 m deep; Swiss-Italian border). She explained that, for such type of ice core, a wide range of parameters is necessary for describing the microstructure of such a cold Alpine ice core, including grain sizes, grain orientations, c-axis orientations, grain misorientations, grain-boundary shapes, and others. Additionally, we discussed the results of a pilot study of LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) on Alpine ice, which focused on the spatial concentration of impurities (viz. inside grains or at grain boundaries). She found a high concentration of impurities at grain boundaries, with decays rapidly towards the center of the grain. We analyzed the possible causes of such a concentration gradient, including surface and bulk diffusion, as well as grain boundary migration, in accordance with the "core—mantle" grain paradigm (Faria et al. 2009).

Another activity during this second day was a seminar presentation by Dr. Florian Ziemen (Max Planck Institute for Meteorology, Hamburg). He spoke about the current implementation of tracers into PISM (Parallel Ice Sheet Model), in order to follow particle paths through the ice sheet during ice-sheet flow numerical simulations. It is hoped that this approach may allow the calculation of accumulated strain and stress tensor components along the way.

The meetings continued in the afternoon with Dr. Weikusat presenting some recent ice micromechanics numerical simulations carried out by her former PhD student Maria Gema Llorens, using the Elle—FFT (Fast Fourier Transform) model (Lebensohn, 2001). These simulations have been designed to study the mechanisms and evolution of strain-induced c-axis rotation, strain localization, and dynamic recrystallization in polycrystalline ice aggregates. These simulations suggest that dynamic recrystallization has a strong influence on the resulting microstructure. The strain-induced anisotropy (LPOs) developed in the ice aggregate produces strain localization, which can be masked by dynamic recrystallization. This result corroborates the theoretical study by Faria and Kipfstuhl (2005), who asserted that it is usually not possible to recognize the real amount of deformation in polar ice by simply looking at the shapes and sizes of grains.

The second day finished with a discussion about a manuscript recently submitted by Dr. Daniela Jansen and collaborators on fold formation in polar ice. Shear-induced folding is a widespread phenomenon in the deeper parts of polar ice sheets (NEEM Community Members 2013), but the mechanisms that first trigger these flow instabilities in polar ice sheets are still not fully understood (Alley et al. 1997). During the meeting we discussed possible mechanisms, including the one proposed by Dr. Jansen and others in their manuscript. The Applicant called the attention of the Authors to the link between their model and an old theoretical hypothesis put forward by Azuma and Goto-Azuma (1996), and explained how their model could provide the "sought-after initial mechanism" that was missing in previous studies.

In the third and last day of the visit (28 August 2015), discussions about fold formation continued, and moved to the consequences of such processes for the large-scale flow of ice sheets. The competition between large-scale horizontal simple shear and vertical compression has been revisited, as well as the relevance or irrelevance of competence contrasts between adjacent layers (hypothetically caused, e.g., by grain-size or impurity-content contrasts).

These hypotheses led us to recall some grain-size sensitive models used to explain the flow of natural ice (e.g. Cuffey et al. 2000; Goldsby and Kohlstedt, 2001). In particular, we discussed the characteristics and consequences of a composite flow law of the type proposed by Herwegh et al. (2005), adapted to the case of polar ice. We have also revised the significance of the many polynomial flow laws for ice proposed in the literature (e.g. Lliboutry 1969; Colbeck and Evans 1973; Hutter et al. 1981; Smith and Morland 1981; Azuma et al. 2000; Pettit and Waddington 2003).

The visit finished with an action plan for the near future, described in Sect. 4.

3) Description of the main results obtained

The main results have already been mentioned within their respective contexts in Sect. 2, and are summarized here:

•   The combination of stratigraphy, microstructure, and micro-Raman analyses seems to be a promising approach to investigate the role of impurities in the mechanical properties of polar ice. The drawback of this approach is that a large number of laborious Raman analyses must be carried out in order to draw statistically significant conclusions.

•   A pilot study of impurity distribution in ice using LA-ICP-MS suggests that impurities might concentrate at grain boundaries, at least in cold Alpine ice. These observations must however be corroborated by more extensive studies.

•   As predicted theoretically by Faria and Kipfstuhl (2005), recent full-field numerical simulations of ice flow confirm that dynamic recrystallization may mask the traces of strain localization, making the recognition of the real amount of deformation in polar ice by simply looking at the shapes and sizes of grains an impossible task.

•   According to Dr. Jansen and others, the formation of kink bands may be a possible trigger of folding in deep polar ice regions with flow dominated by simple shearing.

•   Recent observations reinforce the hypothesis that micro-mechanical processes on the grain scale may give rise to large scale flow phenomena through the action of multi-scale interactions, as proposed by Faria et al. (2009).

4)   Future collaboration with host institution (if applicable)

Collaboration between the Applicant and the host institution will continue through joint research and publications (cf. Sect. 5).

It has been agreed that Dr. Jansen should visit the Applicant in Bilbao in 2016 for developing further the concepts towards a multi-scale ice sheet model.

5)   Projected publications / articles resulting or to result from the grant (ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)

The following publications are expected to derive from this visit:

1.   "Small-scale disturbances in the stratigraphy of the NEEM ice core: observations and numerical simulations" by D. Jansen, M.-G. Llorens, J. Westhoff, F. Steinbach, S. Kipfstuhl, P.D. Bons, A. Griera and I. Weikusat. Submitted to The Cryosphere.

2.   "Micro-deformation and recrystallisation of polar ice" by I. Weikusat, S.H. Faria and others. To be submitted to Proceedings of the Royal Society of London A.

6)   Other comments (if any)

References:

Alley, R.B., Gow, A.J., Meese, D.A., Fitzpatrick, J.J., Waddington, E.D., Bolzan, J.F. (1997) Grain-scale processes, folding, and stratigraphic disturbance in the GISP2 ice core. J. Geophys. Res., 102(C12): 26819—26830

Azuma, N., Goto-Azuma, K. (1996) An anisotropic flow law for ice-sheet ice and its implications. Ann. Glaciol. 23: 202—208

Azuma, N., Wang, Y., Yoshida, Y., Narita, H., Hondoh, T., Shoji, H.,Watanabe, O. (2000) Crystallographic analysis of the Dome Fuji ice core. In: Hondoh, T. (Ed.) Physics of Ice Core Records. Sapporo: Hokkaido University Press. 45—61

Colbeck, S.C., Evans, R.J. (1973) A flow law for temperate glacier ice. J. Glaciol. 12(64): 1—86

Cuffey, K.M., Conway, H., Gade, A., Hallet, B., Raymond, C.F., Whitlow, S. (2000) Deformation properties of subfreezing glacier ice: role of crystal size, chemical impurities, and rock particles inferred from in situ measurements. J. Geophys. Res. 105(B12): 27895—27915

Faria, S.H. (2006a) Creep and recrystallization of large polycrystalline masses. Part I: general continuum theory. Proc. Roy. Soc. London A462(2069): 1493–1514

Faria, S.H. (2006b) Creep and recrystallization of large polycrystalline masses. Part III: continuum theory of ice sheets. Proc. Roy. Soc. London A462(2073): 2797–2816

Faria, S.H., Kipfstuhl, S. (2005) Comment on "Deformation of grain boundaries in polar ice" by G. Durand et al. Europhys. Lett. 71(5): 873–874

Faria, S.H., Freitag, J., Kipfstuhl. S. (2010) Polar ice structure and the integrity of ice-core paleoclimate records. Quat. Sci. Rev. 29: 338–351

Faria, S.H., Kipfstuhl, S., Azuma, N., Freitag, J., Hamann, I., Murshed, M.M., Kuhs,W. (2009) The multiscale structure of Antarctica. Part I: inland ice. Low Temp. Sci. 68: 39-59

Faria, S.H., Kremer G.M., Hutter K. (2006) Creep and recrystallization of large polycrystalline masses. Part II: constitutive theory for crystalline media with transversely isotropic grains. Proc. Roy. Soc. London A462(2070): 1699–1720

Faria, S.H., Weikusat, I., Azuma, N. (2014) The microstructure of polar ice. Part I: highlights from ice core research. J. Struct. Geol. 61: 2—20

Goldsby, D.L., Kohlstedt, D.L. (2001) Superplastic deformation of ice: experimental observations. J. Geophys. Res. 106: 11017—11030

Gow, A.J., Williamson, T. (1976) Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd Station. Geol. Soc. Am. Bull. 87: 1665—1677

Herwegh, M., de Bresser, J.H.P., ter Heege, J.H. (2005) Combining natural microstructures with composite flow laws: an improved approach for the extrapolation of lab data to nature. J. Struct. Geol. 27: 503–521

Hutter, K., Legerer, F., Spring, U. (1981) First-order stresses and deformations in glaciers and ice sheets. J. Glaciol. 27(96): 227—270

Lebensohn, R.A. (2001) N-site modeling of a 3D viscoplastic polycrystal using Fast Fourier Transform. Acta Materialia 49: 2723—2737

Lliboutry, L. (1969) The dynamics of temperate glaciers from the detailed viewpoint. J. Glaciol. 8(53): 185—205

NEEM Community Members (2013) Eemian interglacial reconstructed from a Greenland folded ice core. Nature 493(7433): 489–494

Pettit, E.C., Waddington, E.D. (2003) Ice flow at low deviatoric stress. J. Glaciol. 49(166): 359—369

Smith, G.D., Morland, L. (1981) Viscous relations for the steady creep of polycrystalline ice. Cold Reg. Sci. Technol. 5(2): 141—150

Vaughan, D.G. and 13 others (2013) Observations: Cryosphere. In: Stocker, T.F. and 9 others (Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge: Cambridge University Press. 317—382