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BE-OI

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	X 4 – CNRS	☐ 5 – NERC-BAS	☐ 6 – UU-IMAU
	☐ 7 – NPI	☐ 8 – SU	☐ 9 - UBERN
	☐ 10 – UNIBO	☐ 11 – UCAM	☐ 12 - UCPH
	☐ 13 – ULB	☐ 14 – ULUND	
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EXECUTIVE SUMMARY

The objective of this work package is to determine the glaciological characteristics by completing the geophysical data coverage in the two regions of interest and to select the most promising sites with potential very old ice and good internal layering. The first workshop WP2.1, organized in Grenoble on 13-14 October 2016, aimed at bringing together all the partners to present the state of the art on this topic for both regions of interest Dome C and Dome F. Presentations gave an overview of plans for future surveys, methods to retrieve isochrones and a variety of modelling tools to improve data interpretation.

For Dome C region, a compilation of the existing data was extensively presented including the radar survey performed in January 2016 (UTIG/AAD). A new bedrock map was provided and will be fundamental to understand the potential of the DC region and to serve as boundary condition to ice flow models. Several data/modelling approaches were presented to infer the spatial pattern of basal melting and subglacial lakes. In all the regions surveyed, the isochrones were tracked down to an age of 360 kyears by following them from the EPICA ice core site. Two inverse methods were used to derive basal age and basal melting rate from these dated isochrones. The absolute ages found by these methods differ but the places where age is maximum are the same in both approaches. All these interpretations converge toward a promising zone close to "Little Dome C" 40 km far from Concordia Station. A noticeable result is that the thinner ice locations may not be the best because they display a very poor resolution and the 1.5 Myears isochrone is located very close to the bedrock raising the concern of basal disturbance.

A large part of the discussions included Milestone MS1, the selection of target areas in which the high resolution survey will be performed in the region of Dome C, this Antarctic summer season 2016-2017. With the set of information provided and visualisation of the echo sounding images, we discussed and agreed on the criteria for best candidate patches:

- oldest age in the two modelling approaches that were done so far
- resolution at 1.5 Myears with the same models
- height above the bedrock of the 1.5 Myrs modelled isochrone
- bedrock higher than a water table inferred from subglacial lakes.
- layer continuity and study of the internal layers undulations.

The target area for the high resolution survey was broadly defined during the workshop and was refined in the following weeks before the departure of the team to Concordia. The first priority is a 5 km x 7 km patch close to "Little Dome C", this patch could be extended depending on available time (second priority). We also defined a "north patch" of interest, 15 km from Concordia station were the ground based radar may be tested before the Italian traverse arrives.

Most of available data and modelling results are included in a geo-referenced database that can be used in the field. A preliminary version was provided to the team that will do the ground based survey in Dome C. After some improvement, this database will be circulated among the partners.

1. Introduction

To retrieve an ice core record going back to 1.5 million years, the requirements are well identified (Fisher et al 2013) selecting central regions with relatively thin ice. According to these criteria, the regions of Dome C and Fuji Dome could feature very good candidates. A dedicated ice-core drilling is however done in only one location and we know that the conditions can considerably change at the scale of a few kilometres or even less. To determine precisely which are the most promising sites inside these regions, it is necessary to improve the spatial coverage but also to acquire complimentary measurements to determine certain key characteristics (geothermal heat flux for instance). Finally, analysis of the data require a variety of methods and modelling, because these data are heterogeneous and very often do not provide information on the deepest part of the ice sheet where modelling must be used to extrapolate. Our approach is based on several steps: airborne radar survey with a resolution of a few kilometres is followed by data analysis and modelling in order to define patches of particular interest. Then it is possible to deploy ground based measurements within these selected patches to perform high horizontal resolution survey. The ground-based measurements include various types of radar, precise positioning of stakes and fast drillings tools (task 3.1, RAID, RADIX, WP3).

In the region of Dome C, airborne radar data were acquired by our external partners University of Texas (UTIG) and Australian Antarctic Division (AAD). With the logistical mini-traverse (Subtask 1.1.1), the ground-based survey will be done in December 2016-January 2017(Subtask 2.1.2). The ultimate test will be a drilling with the instrument SUBGLACIOR (WP3, Subtask 3.1.2) planned during the season 2017-2018, and the decision of where to do this drilling will be taken in November 2017 (Milestone MS4). The activity in the dome Fuji region lags the activities at Dome C in time by one year, the airborne radar survey being planned during the summer season 2016-2017 (Subtask 2.2.1).
The purpose of the workshop WP2.1, held in Grenoble 13-14 October 2016, was to bring together all the partners concerned with this work package, present the present state of data, interpretation, methods and modelling as well as the survey plans for the coming years for both regions of interest. A major objective was to discuss the selection of target area in which the high-resolution survey will be performed in the region of Dome C, this summer season 2016-2017 (Milestone MS1).

2. Methodology

The meeting was held over the October 13 th and 14 th 2016. Formal presentations (see annexes) were given to introduce the discussions. The presentations were grouped to address the following topics:

- State of the art for Dome Fuji region and plans
- Methods to track isochrones and related uncertainties
- Dome C area. Interpretation of existing data
- Projects for the coming field season.

For the Dome C region, a compilation of the existing data was presented including the radar survey performed in January 2016 (UTIG/AAD). Interpretation of the radar data with several

approaches was also presented. Most of these results are included in a preliminary version of a database under the form of a georeferenced databas (QGIS project) that can be used in the field and was indeed provided to the people going to Dome C to do the ground based survey. This QGIS project is initially based on the project Quantarctica.

3. Results and Discussion

The main results and discussions focussed on:

- *Pre-site airborne survey at Dome Fuji:* The existing data coverage with respect to ice thickness and thus bedrock topography is rather coarse, apart from in the direct vicinity, where our Japanese cooperation partners performed groud-based radar measurements in the past. Moreover, the existing airborne radar data from Sovies/Russian survey, dated back to the 1960s and ‘70s have a high uncertainty in geolocation. As the output uncertainty from numerical models relies considerably on the availability of bedrock topography data, it was decided that a regional survey with coarser flightlinespacing on the order of 10 km is most suitable. This was in accordance with discussions of the BE-OI partners NPI and AWI at a workshop in Japan at NIPR in the end of September 2016.

- *Comparing the methods to track isochrones and the related uncertainties.* This tracking was done manually for the UTIG/AAD radar survey (by Marie Cavitte), but several automatic or semi automatic methods were proposed and there is now a set of data that could be used for an intercomparison of these methods. Additionally two independent traveltime—age-depth conversions were proposed (Marie Cavitte, UTIG, Anna Winter, AWI) and their comparison indicates a very good agreement.

- *Inferring glaciological characteristics (bedrock, basal hydrology) from radar echo sounding*. A new bedrock map was provided (Young et al, submitted). This preliminary data is fundamental to understand the potential of the DC region and to serve as boundary condition to ice flow models. Another output of the radar survey is a map of subglacial lakes. Although there are many lakes, a large zone exists were no lake was detected. Moreover, interpolating hydraulic head at the observed lake locations to infer an apparent water table (if it exists) and where the water may pool and where it does not (bedrock above the table). Another work was presented (O. Passalacqua, LGGE) on inverse modelling of geothermal flux from radar reflectivity (Italian data) and a map of basal melting was proposed. Both works agree on the fact that there is a rather “safe” zone for Old Ice as far as subglacial hydraulic/thermal condition is concerned.

- *Modelling basal age by inversion of the tracked isochrones.* In all regions surveyed, the isochrones were tracked down to 360 kyears by following them from the EPICA drilling site. Two inverse methods were used to derive basal age and basal melting rate

from these dated isochrones. The absolute ages found by these methods differ but the places where age is maximum are the same in both approaches. They confirm the "safe" zones derived from hydrology/temperature approaches. An important result is that the thinner ice locations may not be the best because they display a very poor resolution and the 1.5 Myrs isochrones is located very close to the bedrock raising the concern of basal disturbance.

- *Discussing the layer patterns in radar echo sounding images.* Most of the images could be visualized on demand during the discussion. Each consist in a radar image on which the tracked isochrones are superimposed. (see Figure 1).

With this set of information, criteria for best candidate patches were discussed. We agreed on the following ones:

- oldest age in the two modelling approaches that were done so far
- resolution at 1.5 Myrs with the same models
- height above the bedrock of the 1.5 Myrs modelled isochrone
- bedrock higher than a water table inferred from subglacial lakes.
- layer continuity and study of the internal layers undulations.
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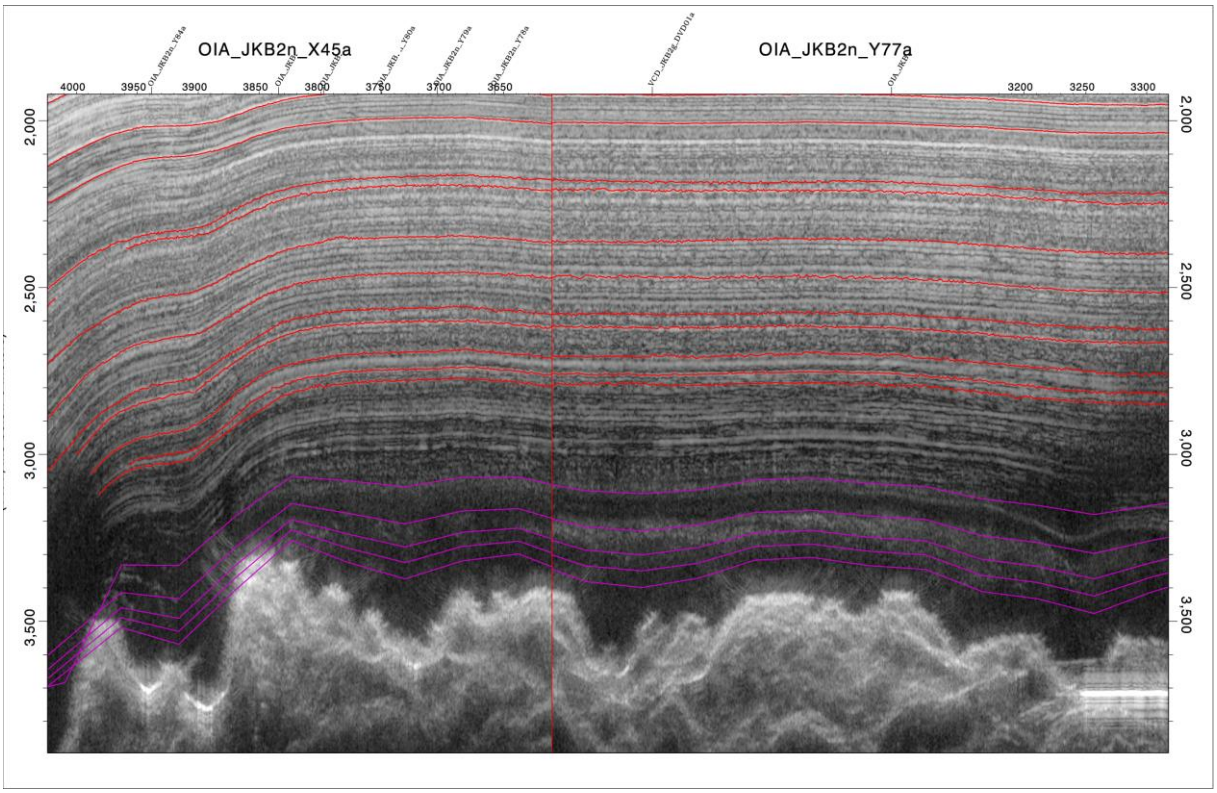

Figure 1. Echo sounding image (UTIG/AAD) with superimposed isochrones. Vertical scale 100 units = 84 m. In red the isochrones dated by following them from the EPICA site, the deepest one is 360 kyears old. In purple the modelled isochrones at 600, 800, 1000, 1200, 1500 kyears.This image is composite: on the left the flight line, X45, is along the X direction (along the ice divide), on the right of the flight Y77 is along the

Y direction. The red vertical line is the crossing of the lines. There was an agreement among the workshop participants that this area is promising and the selected priority target is framed around it. (Work in progress, Marie Cavitte and Fred Parrenin personal communication, use only internally in the BE-OI project).

The target area for the high-resolution survey was broadly defined during the workshop. It was refined in the weeks following the workshop by interactions between BAS, LGGE and UTIG in order to provide the tools necessary for the field work: way points, relative positions of the various instruments, UTIG echo sounding precise geolocation to compare with the ground based radar DELORES. All these data were embedded in the QGIS project.

A 5 km x 7 km patch close to "Little Dome C" was defined as a first priority (40 km from Concordia station in the Vostok direction). If there is time during the mini-traverse, this survey will be extended (second priority). Moreover, because there was a logistic opportunity in December to test DELORES before the arrival of the Italian traverse, we defined a third zone of interest, 15 km north of Concordia station (opposite to Little Dome C). The age modelling is promising also for this zone but the uncertainty on the dating is substantially larger than in the Little Dome C area. The various selected areas are displayed on the map on figure 2

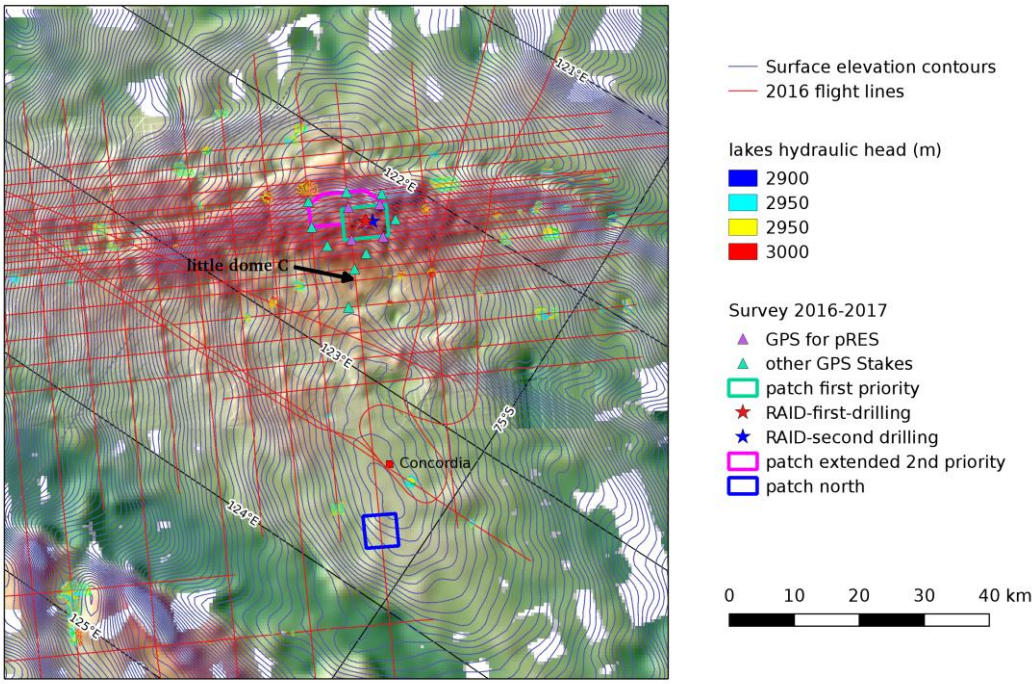

Figure 2. Map of Dome C region and the selected patches for 2016-2017 field season survey. Background is bedrock elevation (Young et al. Submitted). Lake positions courtesy D. Young (UTIG).

4. Conclusion and Outlook

- The analysis of available data indicate that there are promising places where we can expect to find very old ice beyond 1 Myrs in age. These places are close to Little Dome C, 40 km far from Concordia station. At this stage of the study, it is more difficult to assess the quality of the record for the deepest layers and we hope that the ground-based survey will decrease this uncertainty. In any case the higher horizontal resolution of the coming survey and the additional measurements (ApRES, temperature in the RAID borehole) will allow to refine the site selection for SUBGLACIOR.

- According to the task objectives, two target areas were defined for ground based activities during the 2016-2017 field season (see Figure 2).

- A database for the Dome C area is being built and will be circulated among the partners after some grooming. Participants involved in the high-resolution survey have received a preliminary (but functional) version for availability on site in the field.

- Modelling and analysis methods were developed or refined. This is a work in progress and the new skills will soon be applied for the interpretation of the ground-based data to be acquired soon as well as for the decision to be made in November 2017 concerning the location of SUBGLACIOR drilling.

The workshop was also a great opportunity for stimulating discussions that should result in enhanced collaborations between the partners. Moreover, several young scientists participated and had a crucial input, indicating that a new generation of researchers is building up in this field.

5. References

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Anna Winter, Daniel Steinhage, Emily J. Arnold, Donald D. Blankenship, Marie G. P. Cavitte, Hugh F. J. Cor, John D. Paden, Stefano Urbini, Duncan A. Young, and Olaf Eisen. Comparison of measurements from different radio-echo sounding systems and synchronization with the ice core at Dome C, Antarctica, The Cryosphere, in press.

Young, D. A., Roberts, J. L., Ritz, C., Frezzotti, M., Quartini, E., Cavitte, M. G. P., Tozer, C. R., Steinhage, D., Urbini, S., Corr, H. F. J., Van Ommen, T., and Blankenship, D. D.:

High resolution boundary conditions of an old ice target near Dome C, Antarctica, The Cryosphere Discuss., doi:10.5194/tc-2016-169, in review, 2016.

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Quantarctica: A free GIS package for Antarctica http://quantarctica.npolar.no

QGIS: A Free and Open Source Geographic Information System
http://www.qgis.org/en/site

6. Acronyms

ApRES : phase radar developed by partner NERC-BAS
DELORES. Ground base radar system developped and operated by partner NERC-BAS
QGIS: an open source software (geographical information system).
Quantarctica: A QGIS project with many Antarctic maps.
RADIX. Rapid acces drilling tool developped by Partner UBERN
RAID. Rapid access drilling tool developed by partner NERC-BAS
SUBGLACIOR. Rapid acces drilling and probe developed by partner CNRS

7. List of presentations

Welcome and Introductions
- Olaf Eisen (AWI, project coordinator) general status BE-OI and Catherine Ritz (LGGE) Objectives of the workshop

State of the art for Dome Fuji region and plans
- Olaf Eisen (AWI): overview Dome Fuji survey
- Nanna Karlsson (AWI): Dome F Field Season 2016/17
- Kenny Matsuoka (NPI): Radar survey plans in the Dome Fuji area during the 2017/18 and 2018/19 seasons at DF

Methods to track isochrones and related uncertainties
- Anna Winter (AWI) Radio-echo sounding measurements around EPICA Dome C and synchronization with the Ice Core
- Marie Cavitte (UTIG). Tracking the isochrones from UTIG radar. Results and uncertainty assessment
- Jason Roberts (AAD) Internal layers via the Radon Transform
- Hugh Corr (BAS) A random walk approach to following internals
- Hugh Corr (BAS) Measurements of vertical strain rate by pRES at Concordia

Dome C area. Interpretation of existing data
- Duncan Young (UTIG). High-resolution subglacial hydrology of a potential old ice target near Dome C, Antarctica
- Brice Van Liefferinge (ULB) Stochastic modelling of basal temperature of divide area over the last 1.5 Myears

- Olivier Passalacqua (LGGE). Geothermal heat flux and basal melt rate in the Dome C region inferred from radar reflectivity and thermal modelling
- Fred Parrenin (LGGE) Modelling basal age by inversion of isochrones.
- Olivier Passalacqua (LGGE), Marie Cavitte (UTIG), Fred Parrenin (LGGE), Catherine Ritz (LGGE) On going work based on the isochrones

Projects for the coming field season.
- Rob Mulvaney (BAS). 2016/2017 season RAID-DTS system , Delores (ground based radar) and ApRES
- Luca Vittuari (UNIBO). Extending the GNSS strain net of Dome C.

8. Participants:

Catherine Ritz, Frédéric Parrenin, Olivier Passalacqua, Olivier Gagliardini, Fabien Gillet-Chaulet, Jérôme Chappellaz, Olivier Alemany, Eric Lefebvre (LGGE, France)
Olaf Eisen, Frank Wilhelms, Nanna Karlsson, Anna Winter (AWI-Bremerhaven, Germany)
Robert Mulvaney Hugh Corr (BAS, UK)
Massimo Frezzotti (ENEA, Italy)
Pascal Morin, Doris Thuillier (IPEV, France)
Jason Roberts (AAD-CRC, Australia)
Dorthe Dahl-Jensen (CIC, Denmark)
Jakob Schwander (University of Bern, Switzerland)
Frank Pattyn, Brice Van Liefferinge (ULB, Belgium)
Duncan Young, Marie Cavitte (UTIG, USA)
Luca Vittuari (UNIBO, Italy)
Stefano Urbini (INGV, Italy)
Kenny Matsuoka (NPI, Norway)