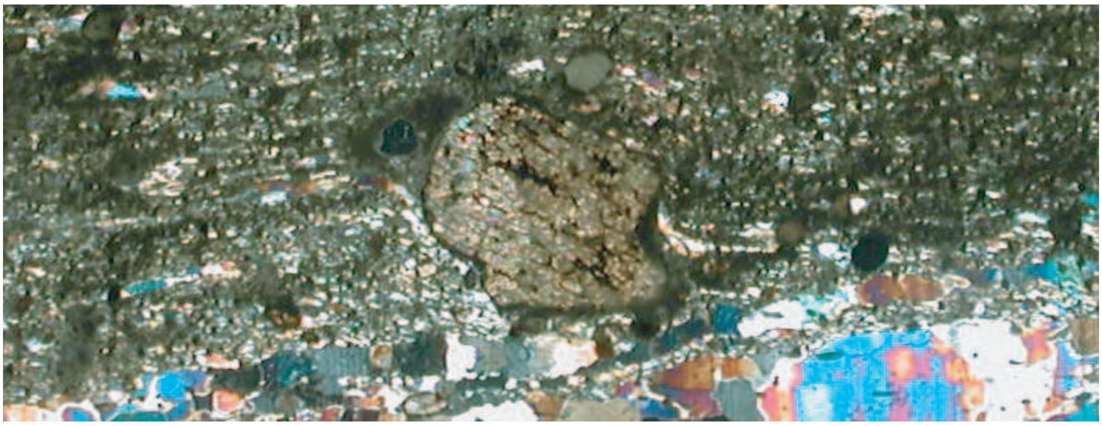
Structural and Geochemical Analysis of Basal Ice from Taylor Glacier, Antarctica:

On the Role and Behaviour of the Interstitial Fluid Phase

SAMYN Denis



A dissertation submitted in partial fulfillment of
the requirements for the degree of

Docteur en Sciences

Laboratoire de Glaciologie,
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Chairs of Supervisory Committee: Prof. R. Souchez and R. Lorrain
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The jury committee of this thesis was composed of the followings:

- **Prof. J.-L. Tison**, Committee Chair;
- **Prof. B. Hubbard**, Invited Member (Univ. Aberystwyth, U.K.);
- **Prof. R. Souchez**, Promotor;
- **Prof. R. Lorrain**, Promotor;
- **Prof. F. Pattyn**, Secretary.

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`Basal ice does not suffer deformation; it enjoys it.`

(Wink to Rob Knipe, 1982; quoted in Groshong, 1988)

Foreword

General

For many of us, glaciers are perceived as forming in remote regions of the Earth and as having a passive role in Earth's dynamics. Glaciers would then belong to 'another part of the world', distant from the main centres of human civilization. The reality is however different. The evidence is growing that close interactions exist between the cryosphere and the other spheres of the global environmental system. Fluctuations in one of these spheres around the Earth would accordingly have the potential to directly affect the dynamics of (an)other(s). Thence, since life - and more particularly humankind - is widespread all over the planet, and since environmental changes can be global, ice matters are of crucial importance for world's populations and ecosystems.

Glaciological studies have known a major expansion those last decades. This is mostly due to the relatively recent awareness that terrestrial ice bodies are outstanding repositories for information about environmental conditions having prevailed in the past. This finding, along with the growing concern for a possible man-made impact on the current climate state, has driven a surge of interest in figuring out how ice sheets interact with climate and what to expect in the future. The recession of local glaciers observed during the last fifty years has focused attention on the possible contribution of large ice sheets to global sea level rise. The Antarctic ice sheets were for example to melt away completely, this would cause a mean sea level rise of about 60 m taking account of the isostatic rebound of the continent. The East Antarctic Ice Sheet is considered as very stable and is expected to act as a freshwater sink in a warmer climate due to increased precipitation, but the West Antarctic Ice Sheet could possibly be dynamically unstable due to its sub-sea-level sole and thus cause unpredictable and drastic environmental changes.

Deep ice cores from polar ice sheets are actually the keystones of glaciology as well as of many Earth Science disciplines because they enclose, along periods of time up to several hundred millennia, paleo-records of temperature, precipitations, chemistry and gas composition of the lower atmosphere, volcanic eruptions, solar variability, sea surface productivity, anthropogenic emissions, and a variety of biogeochemical indicators. These pieces of informations have proven to be invaluable in our understanding of terrestrial climate processes and for testing theories that can predict future climatic changes. The reliability of ice cores is based on the postulate that ice sheets and glaciers are depositional environments that preserve the temporal sequence of atmospheric precipitations. This postulate is true in first approximation for most of the ice column. But difficulties generally arise in the vicinity of the basal zone, where strong interactions exist between the sole of the ice body and its effective bed. However, the disadvantages resulting from the occurrence of basal ice processes in terms of palaeo-climatic reconstruction may turn into significant advantages as regards geomorphic reconstruction. Geochemical and structural analyses of the basal zone of various types of glaciers and ice sheets have indeed brought crucial information on how ice reacts to environmental changes materialized by e.g. fluctuations in impurity content, in meltwater discharge, in ice mass balance, or in temperature. In fact, basal ice studies provide, if one can retrieve it, a 'frozen picture' of the physical state of the ice body. The present work is embodied in this basal ice perspective.

Scope of the study

Central to our understanding of the evolution of terrestrial ice bodies is the knowledge of the flow behaviour of polycrystalline ice. This problem has received much attention in recent years because of its strong connections with the above-referred environmental questions. But large gaps still persist, notably as regards the behaviour of cold ice [1]. This lack of knowledge on ice at cold conditions is simply primarily due to the fact that such conditions are found at present only in remote places of Earth, namely around the poles. Nevertheless, various environmental proxies have revealed that cold conditions have prevailed and have been widespread during significant periods of time over the past hundred millennia. It is thus worth studying cold ice physics in the perspective of reconstructing the palaeo-environmental extension of ancient glaciers and ice sheets. Other fundamental issues that remain unsolved are the relative importance of grain-size dependent vs. grain-size independent deformation mechanisms, the threshold impurity level from which recrystallization is inhibited, or the softening effect of dissolved impurities. These issues are intimately linked within basal ice, espe-

[1] By 'cold' ice is meant ice well below the freezing point. We fix for the remainder of this thesis the arbitrary boundary of $-10\,^{\circ}$C, below which we use this term. This boundary conveniently displays a difference of about an order of magnitude with 'warm', or 'temperate', conditions.

cially at freezing temperatures where slight transient phenomena have a strong impact on the whole rheology. To reconstruct previous - and to assess future - Earth's glacial fluctuations, there is thus a need for an extension of the flow law of ice to the various physical conditions that may have prevailed in past glacial environments. Of major concern in these issues is the growing evidence that liquid water, in all of its forms, plays a major role in ice dynamics. This is not surprising, since the phase transitions of water occur in a very narrow range of temperature as compared to most known solid Earth materials. Recent theoretical and modeling developments have cast light on the potentially significant impact on the cryosphere of the premelt phase - i.e. of the thin liquid films that are normally present at intercrystalline and interfacial boundaries within natural ice. From a physical point of view, these films are for instance assumed to have a large effect on the viscosity of ice by attenuating the internal stress resulting from deformation. From a chemical point view, these films have been proposed to potentially hamper the reliability of deep ice cores in a manner that causes compositional diffusion and advection, along thermal gradients, of the particulate and soluble ice proxies. From a biological point of view, these films have recently been shown to offer a viable medium for micro-organisms at temperatures as low as $-50\,^{\circ}$C, thereby opening new frontiers to the study of the evolution of life on Earth and other icy planets. These examples only provide a restricted overview of the multiple potential effects of the premelt phase and its derivatives on the cryosphere. The present thesis is actually a contribution to a better understanding of the potential lubricating, softening, composition altering and sediment reworking role played by this interstitial liquid phase in the dynamics of cold basal ice.

This work involves, to varying degrees, multi-parametric investigations conducted in the basal zone of Taylor Glacier, an outlet glacier from the East Antarctic Ice Sheet. This glacier is commonly believed to be polythermal and, as such, is an excellent natural laboratory to appraise the above-noted questions. This glacier is all the more interesting that it belongs to a very particular place on Earth: the 'Dry Valleys of McMurdo', which are situated between the Transantarctic Mountains and the Ross Sea. About fifty years of intensive research in the area have revealed that these valleys have a very specific geological and climatic history as compared to the rest of Antarctica. The Dry Valleys actually hold a key position in conjectures related to the crucial problem of potential collapse of the Antarctic Ice Sheet as a result of current global climate change. The present study of Taylor Glacier may thus also be viewed, to some extent, as a piece of this large puzzle that is the understanding of the Antarctic ice-sheet dynamics.

To get access into the basal zone of the glacier, a tunnel was dug from the northern part of the glacier front, revealing an alternance of debris-rich and clean ice layers at the homogeneous temperature of $-15\,°C$. Field work related to the study of this basal zone was made possible through an international collaboration between the Department of Geography of the University of Otago (New Zealand) and the Glaciology Unit of the *Université Libre de Bruxelles* (Belgium). This field work spanned the austral summer of 1999-2000, with Dr S. J. Fitzsimons (Univ. Otago) as P.I. and Prof. R. D. Lorrain (Univ. Brussels) as Co-P.I., under the auspices of *Antarctica New Zealand*. The main purpose of the project was the understanding of the thermal and mechanical processes that operate beneath glaciers from the Dry Valleys. This project also lied within the scope of the *AMICS* [2] program from the Belgian Antarctic Policy, the aim of which was to contribute to a better assessment of the Antarctic Ice Sheet response to climate

[2] ***A****ntarctic ice-sheet dynamics and climatic change:* ***M****odelling and* ***I****ce* ***C****omposition* ***S****tudies.*

changes.

Setup of the thesis

The heading line of this thesis will be to illustrate the possible interactions that may exist at cold conditions between basal ice dynamics, basal ice geochemistry and thin liquid film activity. This will mostly be done by means of micro-structural, gas content (i.e. gas composition and total gas volume) and co-isotopic ($\delta^{18}O$ and δD) analyses. The results obtained by the application of each main type of analysis makes the subject of a distinct chapter.

In **Chapter 1**, basic concepts used in this thesis are briefly outlined. These concepts range from the geological context of Antarctica and the Dry Valleys to the microscopic notion of thin liquid films within ice. This theoretical overview is not meant to be exhaustive; given the resolutely multi-parametric aspect of this work, the idea is foremost to provide a general background on the Dry Valley system as well as of the physico-chemical processes covered.

Chapter 2 is a description of the investigation techniques used in the field as well as in the laboratory. These techniques pertain to the analysis of strain figures as well as of the composition of atmospheric gases and water stable isotopes.

Chapter 3 deals with morphological and kinematical analysis of small-scale deformation structures embedded within debris-rich layers of the basal sequence. Through the application of original cutting techniques and recent theories in structural geology to the study of these structures, we illustrate how the rheological behaviour of cold debris-laden ice is related to that of the premelt phase.

It is shown in **Chapter 4** that interstitial liquid water may alter the gas composition of clean basal ice as a direct result of deformation. This has strong implications for palaeo-environmental reconstruction, since it is commonly believed that the only effect of deformation on the reliability of ice cores is flow mixing. A qualitative scenario is proposed, based on strain localization at structural interfaces and differential redistribution of gases through the premelt phase to account for the gas fractionation observed.

Can the stable isotope composition of ice be altered under cold conditions? Also, how can debris be incorporated at the base of cold glaciers and form extensive basal ice layers such as those observed at Taylor Glacier? These questions are addressed in **Chapter 5**. The results of co-isotopic analyses conducted in the basal sequence at the same resolution as that for the gas analyses do not show the occurrence of bulk fractionation processes, suggesting marked freezing temperatures at the time of formation. This phenomenon is discussed in the light of an isotopic model involving microscopic interactions with the soft bed in the form of upward pore-water flow.

General conclusions are drawn at the end of the work. These are based on the findings of the preceding chapters. We demonstrate the need for multi-parametric analysis in basal ice studies, as well as the important role played by the internal liquid fraction in bedrock/glacier interactions. Additionally, **suggestions** for further research are made.