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The Multiscale Structure of Antarctica
Part II: Ice Shelves

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To G.

You wait. Everyone has an Antarctic.

T. Pynchon, [42]

Abstract: Polar ice masses, including grounded (inland) ice, ice shelves, icebergs and sea ice, constitute an essential part of the global climate system. They interact with the hydrosphere and the atmosphere, and, if persisting through millennia, serve as archives of the past climate of Earth. Currently, significant efforts in climate reconstructions are being undertaken, serving as a basis for climate predictions into the future. It has been argued in Part I of this work that more attention should be given to interactions between structures on distinct scales (multiscale structural interactions), which seem to play a decisive role in the structure–form–environment interplay (SFEI) in grounded polar ice. As ice shelves play an equally important role in the global climate, the present article is devoted to the description of the multiscale structure of ice shelves.

Key words: multiscale structure, ice shelves, global climate, ice cores, cross-disciplinary modelling

1 Introductory remarks

Beyond this flood a frozen continent
Lies dark and wilde, beat with perpetual storms
Of whirlwind and dire hail, which on firm land
Thaws not, but gathers heap, and ruin seems
Of ancient pile, all else deep snow and ice.

J. Milton, [33]

Polar ice masses constitute an essential part of the global climate system and comprise grounded (inland) ice, ice shelves, icebergs, sea ice and frozen subglacial landforms. We use the term *grounded ice* (or: *inland ice*) when referring to a large mass of meteoric (freshwater) ice covering an extensive region of solid land, while simultaneously allowing for the presence of subglacial lakes and channels. An *ice shelf* is a large mass of meteoric and marine (sea-water) ice which is floating on the ocean while being attached to and fed by inland ice. The terminology *ice sheet* here implies that a system consisting of grounded ice *plus* ice shelves is considered. Presently, we will not be dealing with icebergs, sea ice and subglacial landforms.

Ice sheets have, from a modelling point of view, received increased attention in the context of reconstructions of the past and predictions of the future climate on Earth. However, the latter statement is not relating in equal parts to *grounded ice* and *ice shelves*: grounded ice has been in the focus of theoretical modelling, numerical simulation and field work, as reflected in particular by the many deep ice cores drilled in Greenland and Antarctica, such as NGRIP, GISP2, Vostok, Dome Fuji, EPICA-DML, EPICA-Dome C, Law Dome and others. From what has been observed in the cores (together with radar data and field surveys), it transpired that a fundamental reorganization of the modeling strategy would be advantageous, with the introduction of a new kind of modelling, not for the entire inland ice itself, but for its intrinsic structures. Several aspects of this new branch of inland ice modelling, here called *multiscale structural modelling*, have been discussed in Part I of this text.

The present Part II is the continuation of [10] and focuses on multiscale structural interactions in ice *shelves*, of which most are fringing the Antarctic continent. While ice shelves have received considerable attention in determining their role in the hydrological cycle and the formation of Southern Ocean water masses [16, 22, 30, 37, 55], insufficient effort has been spent on analysing their inherent structures which are prevailing and interacting with each other on different scales – this is in sharp contrast to the investigation of the intrinsic structure of the grounded ice they are connected to. Consequently, literature documenting the scarce data concerning the multiscale structure of ice shelves is also rare. For the present article, it thus seemed appropriate to first collect references focusing on the multiscale structure of ice shelves, however, we must admit that a thorough review must be postponed to a forthcoming occasion.

2 Early descriptions of ice shelves

> *It was on just such a winter night, too, that Scott read his interesting paper on the Ice Barrier and Inland Ice which will probably form the basis for all future work on these subjects. The Barrier, he maintained, is probably afloat, and covers at least five times the extent of the North Sea with an average thickness of some 400 feet [...]. According to the movement of a depot laid in the* Discovery *days the Barrier moved 608 feet towards the open Ross Sea in 13.5 months.*
>
> A. Cherry-Garrard, [5]

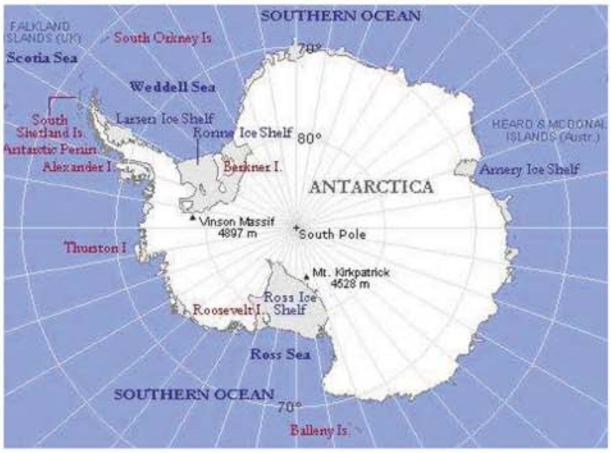

Figure 1: *Map of Antarctica, showing in particular the locations of the Ross Ice Shelf, the Filchner–Ronne Ice Shelf, the Amery Ice Shelf and the Larsen Ice Shelf. From mapsofworld.com.*

In Part I [10], the role of grounded polar ice masses has been highlighted with special focus on their intricate structure-form-environment-interplay (SFEI). Here, emphasis is on the role of ice *shelves*. Today's largest ice shelves, namely the Filchner–Ronne Ice Shelf, the Ross Ice Shelf and the Amery Ice Shelf, cover an area of approximately 1.1×10^6 km^2, cf. Figure 1. Most ice shelves are confined in bays, others are attached to the coast on only one side and very rarely a tunnel-like structure occurs. Few ice shelves exist in the Canadian High Arctic around Ellesmere Island. Ice shelves form where meteoric, inland ice flows off the Antarctic continent onto the sea to (we quote Thomas [49])

> '[...] produce rather flat slabs of floating ice which, for the theoretician, are the simplest of all large ice masses.'

Unfortunately, the just cited classification, which actually reads like an invitation to investigate and model ice shelves analytically and numerically, remained unrecognized by most theoreticians which had the required tools – rooting in applied mathematics and numerical analysis, fluid dynamics and rheology – at hand. Tragically, also the experimentalists paid little attention to ice shelves per se but rather regarded their flat, relatively uncrevassed surface as (cf. again [49])

> '[...] excellent highways for surface access to the heart of Antarctica, particularly so for the early attempts to reach the South Pole.'

Back in the mid 19$^{\text{th}}$ century, ice shelves have been effective barriers to the conquest of the South Pole, which was soon to become man's last remaining challenge on Earth's surface: when James Clark Ross first sighted the ice shelf named after him on January 9, 1841, he called the ice mass the 'Great Ice Barrier'.

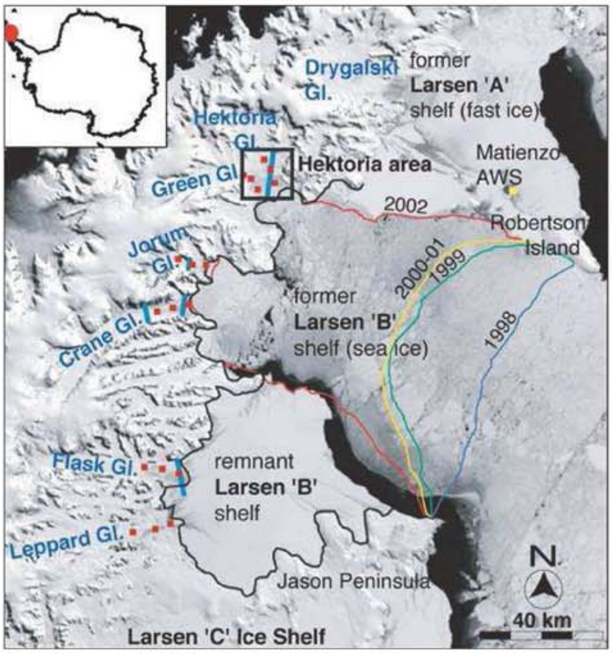

Figure 2: *Map of the Larsen Bay / Larsen Ice Shelf region. From Nasa Goddard Space Flight Center, www.nasa.gov/centers/goddard/earthandsun.*

Until the mid 20$^{\text{th}}$ century, the description of ice shelves remained limited to some spot observations from early Antarctic explorers and logbooks from whalers from the late 19$^{\text{th}}$ century. More detailed descriptions of Antarctic ice shelves became available from expeditions undertaken at the turn of the last century: in 1902, Otto Nordenskjöld[1] and his field party crossed and described, among others, the site of the Larsen A Ice Shelf (which was called Larsen Bay by Nordenskjöld, cf. also Figure 2), while in 1922, Wright & Priestly [60] added an immense contribution to the knowledge of ice shelves at that time with their report on glaciological results of Scott's last expedition (the Terra Nova expedition, 1910–1913). Regardless of the strenuous extremes encountered during the expedition, Cherry-Garrard's diary [5] (published later as the novel *The worst journey in the world* and from which the citation at the beginning of the section is taken) proves that achieving scientific progress and gaining an

[1] Nordenskjöld was the first to introduce the terminology 'ice shelf' as a substitute for the term 'barrier' suggested by Ross.

enhanced understanding of Antarctica was one of the major aims of the expedition.

For more than 25 ensuing years, ice shelves disappeared from the stage of science to re-enter it with the Norwegian–British–Swedish 1949–1952 expedition to the Maudheim Ice Shelf, followed by an international cast acting on the Filchner Ice Shelf and the Ross Ice Shelf during the International Geophysical Year 1957–1958.

Receiving sufficient attention neither from modelers nor from field parties, ice shelves were thus for a long time doomed to play a minor role in attempts to understand the global climate system. As a matter of fact, inland ice alone has been believed to represent the action of the cryosphere in ocean-atmosphere global circulation models (OAGCM) adequately for decades.

Today, ice shelves are clearly recognized as vital elements of the global climate system. They are intermediators of an intricate interplay between the ocean, the atmosphere and the inland ice. Exchange processes occurring at the bottom of ice shelves are important both for the formation of Southern Ocean water masses and for the coupling between ice sheets and the world ocean [16, 30, 37], while their high albedo affects the global radiation balance.

The detection, description and analysis of the multiscale structure of ice shelves is however, still in its infancy. There exists just a handful of publications describing some essential structural features on the micro- and macroscale, but a systematic study of these structures and their multiscale interactions is lacking. The longing for such a systematic study is in a certain sense comparable with the learning of negative numbers described in the quotation at the beginning of the next section.

3 Macrostructure of ice shelves

Do you know what the foundation of mathematics is? The foundation of mathematics is numbers. If anyone asked me what makes me truly happy, I would say: Snow and ice and numbers. And do you know why? Because the number system is like human life. First you have the natural numbers. The ones that are whole and positive. The numbers of a small child. But human consciousness expands. The child discovers longing, and do you know what the mathematical expression is for longing? The negative numbers. The formalization of the feeling that you are missing something. [Continues in the next section].

P. Høeg, [21]

Until recently, the behavior of large ice masses, be they grounded or floating, has been described using concepts of ordinary continuum mechanics, cf. e.g. [40, 52]. 'Ordinary' is here used to indicate that the material is assumed to be homogeneous. In other words, in ordinary continuum thermo-mechanical descriptions ice is treated as a single constituent continuum, whose mechanical response may be coupled to its actual thermal state. Indeed: if such a simplification is considered to be an acceptable approximation of the situation encountered in ice shelves, the latter might be a good candidate for 'the simplest of all large ice masses.'

Yet, it is obvious that ice shelves are a counter-example of a homogeneous, single-constituent continuum: Being exposed to direct interactions with the feeding inland ice, the atmosphere and the ocean, ice shelves generally consist of at least two layers, viz. meteoric and marine ice, and this is still a very coarse description, seeing that vertical structures, like those deriving from crevasses filled with frozen seawater and sediment inclusions, are also quite frequent. The upper layer of meteoric ice is nourished by the flow of the connected inland ice and precipitation in the form of snow. The lower layer consists of marine ice that is formed by melting and freezing processes at the ice-ocean interface on the one hand and accretion of frazil ice from the underlying ocean on the other hand. As reported by Jenkins [29], sea water frozen on the ice shelf base can form a layer up to 350 m thickness, rendering the marine layer thicker than the overlying layer of fresh, meteoric ice.

The large-scale layered structure of ice shelves is typically established from analyzing cores that have either been drilled to a certain depth into the ice shelf or penetrated through its entire thickness. Unfortunately, a terminology reflecting this difference is not commonly established. In the context of this article, we shall refer to those cores that have been drilled through the ice shelf as 'deep cores'. In doing so, we adopt the terminology used for (deep-)cores drilled as close as possible to the bottom of grounded inland ice.

For the Ronne Ice Shelf, bottom accumulation in its central part, leading to a marine layer of ice traced along a distance of 350 km, has been detected by electromagnetic reflection profiling data and deep core drilling, cf. e.g. [8, 9, 37, 50] from the mid 1980s on. Indeed, the deep core B13, drilled by a group from the Alfred Wegener Institute in 1989-1990 revealed the Ronne Ice Shelf, at $76°58'S$ $52°16'W$, to have a thickness of roughly 240 m, of which the bottom 80 m are marine ice.

As the marine and the meteoric layers have, among others, different mechanical properties, a continuum description reflecting the physically observable structures should account for a multi-component material rather than a homogeneous, single-component one. Moreover, as melting and freezing processes take place at least at the ice shelf-ocean interface, phase change processes should be accounted for. In other words: thermomechanical coupling is significant and should be reflected in models describing the overall behavior of ice shelves.

Thermomechanical coupling is also important in regard of the flow law, which describes the viscosity of ice as a function of temperature. Moreover, thermal effects play a significant role in the subglacial thermal organization of inland ice: the onset of sliding of grounded ice is made possible only when the ice-bed interface is at the melting point.

Figure 3: *'Dirty ice' at the seaward front of a tidewater glacier in Alaska. Sediment that has previously been deposited on the glacier surface or that has been accumulated on the latter by melting of ice containing rock material and detritus, initially gives rise to horizontal structures in the ice. Subsequent flow-associated deformation of the ice results in tilted bands of dirty ice, which are clearly visible at the glacier tongue, where the glacier terminates in a fjord. Due to the action of the tides, crevasses which can partly be filled with sea- and possibly also meltwater, develop at the front of the glacier. Photograph: N.K.*

Admittedly, the (derivation of the) governing equations of thermomechanically coupled multi-layered ice shelves may seem intimidating at first sight, especially for scientists stemming from fields other than mathematical physics. Despite this, Vaughan & Arthern [51] plead for an unbiased input of both high quality (field) data and high quality theoretical models to eventually achieve an accurate reproduction and, in a next step, prediction of the behaviour of ice shelves by means of advanced, i.e. multiscale numerical models, cf. [51]:

> 'The accuracy (or *skill*) that can be achieved by predictive models rests as much on the quality of data available for testing as it does on the insightful representation of the physical processes.'

As far as the loss and gain of mass associated with phase changes in ice shelves is concerned, the above mentioned 'insightfulness' allows the modeller to neglect phase change effects on the *macroscopic* scale: the majority of mass loss (ablation) in and around the Antarctic continent takes place as breaking off of icebergs at the seaward front of the ice shelves (calving), while mass loss due to melting at the ice shelf-ocean interface and/or the ice-atmosphere interface can be neglected in many circumstances.

Calving of icebergs brings us, indirectly, to another structure that is prevailing in many ice shelves: the presence of sediment layers in the ice, cf. Figure 3. Sediment can either be entrained into large ice masses at their bottom (namely when the creeping ice scratches and abrades particles from the bedrock which is supporting the grounded ice), or it is deposited on the ice surface at the lateral margins of an embayed ice shelf or a valley glacier in the form of e.g. moraines.

The dynamical redistribution of sediment and debris within the McMurdo Ice Shelf, which is outstanding among Antarctic ice shelves in that it has significant surface ablation, minimal calving and large accumulation of surface debris, has recently been investigated in [11].

But why are (dynamical) sedimentological properties of ice shelves so important? In the global climate modelling context, a description of the sediment entrained, transported and deposited by ice shelves is required e.g. for comparison with off-shore sedimentary record to support the conjecture that catastrophic discharge of icebergs from the Laurentide Ice Sheet and its fringing ice shelves caused major Late Quaternary climatic perturbations [24].

Indeed, as detected first by Heinrich, cf. [15], marine sediment cores taken from the North Atlantic sea floor exhibit layers with abundant coarse-grain lithic fragments indicating detrital material transport from the bedrock underlying the Laurentide Ice Sheet to the North Atlantic by calving icebergs. Six major pulses of such ice-rafted sedimentation mark North Atlantic sediment cores between 14.000 and 70.000 YBP in the last glaciation, and the corresponding outbursts of icebergs from the Laurentide Ice Sheets are known as Heinrich-events.

A diagnostic (e.g. a reconstructive) modelling of ice rafted sedimentation originating from the Laurentide Ice Sheet requires, among others, an understanding of how much ice is needed to carry the debris volume deposited at the seafloor and detected in the marine sediment cores. Yet, observations of debris/ice-volume ratios for icebergs are scarce, and as Greve & MacAyeal have pointed out [14], 'an estimate for this ratio of 1/1000 (10 m of dirty ice in a 100m thick iceberg with the debris concentration of dirty ice at 1%) would require 10^5 km^3 of ice to transport the debris contained in each Heinrich layer'.

Moreover, the mechanisms of calving must be understood in more detail: calving can appear as a rather continuous discharge of small icebergs into the sea as well as the rapid disintegration of a large part of an ice shelf observed e.g. from 1986 to the mid 1990s at the Larsen A ice shelf floating on the Weddell Sea close to the Antarctic Peninsula, cf. Figure 4. In both circumstances, internal oscillations at varying frequencies, transmitted to the ice shelf from the connected inland ice, are likely to govern the calving mechanism to a large extend. The mentioned oscillations (also referred to as 'internal forcing') are suspected to result from different flow behavior of ice as triggered by switches in the basal boundary conditions. Investigations of the subglacial thermal organization of grounded ice including frozen bed conditions, temperate bed conditions or the extension of these mere boundary conditions to the modelling of subglacial landforms would shed more light on these issues.

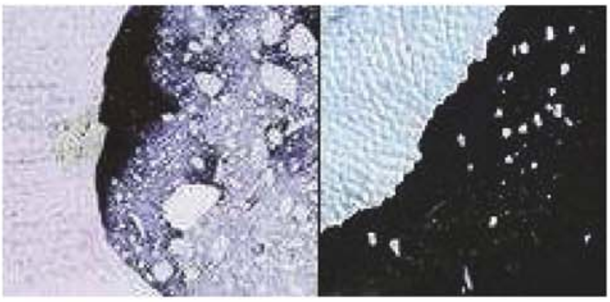

Figure 4: *Satellite images of Larsen Ice Shelf (left) and iceberg B10 from the Ross Ice Shelf (right). From www.nasa.gov/centers/goddard/earthandsun.*

However, it is not only the inland ice which, by mass drainage to the connected shelf, affects the latter: strong (and, from a modelling point of view poorly understood and thus often ignored) feedback mechanism are acting by virtue of which the ice shelves, acting as plugs holding the grounded ice in place, actually control the dynamics, and therefore the system response time, of upstream inland Antarctic ice [2].

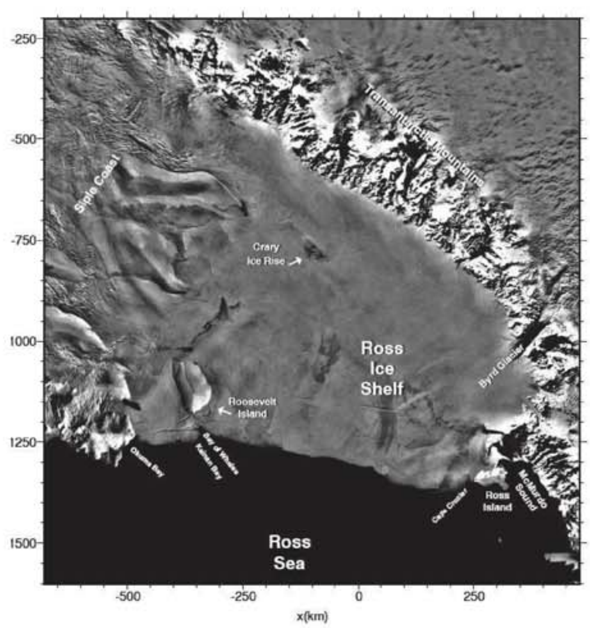

Figure 5: *Satellite image of the Ross Ice Shelf and Crary Ice Rise. Modified from www.nasa.gov/centers/goddard/earthandsun.*

Physically, one such feedback mechanism is provoked when an ice shelf runs aground locally, slows down and tends to increase in thickness. If the grounded area surpasses a certain threshold value, the grounded ice shelf is no longer sliding over its bed, but starts to flow around it. In such cases, the ice overlying the grounded area is referred to as an ice rise[2], cf. Figure 5, and is governed by the same flow patterns as inland ice.

The increase in ice thickness above the grounded area typically implies an advance of the grounding line (which is the location where the inland ice becomes afloat) and thus an extension of the inland ice. Upstream from an ice rise, large pressure ridges may form which pronouncedly exceed often observed undulations on the ice shelf surface with typical wavelengths of 1-10 km and wave heights in the range of 1-5 m. In some cases, these surface waves are aligned at 45° to the direction of the main ice flow, indicating localized shear zones as occurring e.g. between the bulk of an ice shelf and an immersed, fast flowing ice stream (such as Ice Stream B (Whillans Ice Stream) in Antarctica, see Figure 6.)

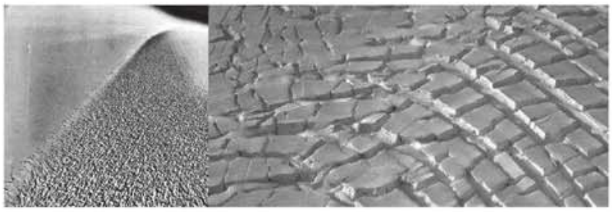

Figure 6: *Satellite image of Ice Stream B, Antarctica (left), close view of the crevasses (right). From www.photo.antartica.ac.uk (British Antarctic Survey)*

The influence of such strong shear is however not only visible at the surface in the form of crevasses: the shear exerted macroscopically induces, at the microscopic level, a change in the microstructure of the ice polycrystal, which is chiefly characterized by a reorientation of the main crystallographic axes (viz. the c-axis) of the ice crystallites, leading to the formation of a strong crystallographic texture (also called 'fabric' in the glaciological literature, cf. [10]). If the genesis and evolution of the microstructures in natural polycrystalline ice masses were known in detail, their interaction with the bulk of ice and the environment could be investigated and analysed to gain deep insight into the SFEI that challenges polar research in cross-disciplinary fashion.

Despite the fact that

1. the layered structure of most ice shelves involving marine ice, meteoric ice as well as 'dirty' ice resulting from the inclusion of sediment and debris has been confirmed in many observations,

2. the behavior and stability of ice shelves and their connected inland ice is governed by mutual, feedback-dominated interaction,

3. in the vicinity of ice rises, ice shelf flow patterns and grounded ice flow patterns exist for which dominating effects take place on scales that differ from each other,

4. the genesis and evolution of the ice microstructure and its interaction with macroscopic bulk features of the shelf are observed,

the modelling of ice shelves is just about to overcome their oversimplification as single-phase continua in an idealized surrounding.

[2]Ice shelves sliding across sufficiently small grounded areas give rise to ice rumples, governed by ice shelf flow patterns.

4 Microstructure of ice shelves

And human consciousness expands and grows even more, and the child discovers in-between spaces. Between stones, between pieces of moss on the stones, between people. And between numbers. And do you know what that leads to? It leads to fractions. Whole numbers plus fractions produce the rational numbers. And human consciousness doesn't stop there. It wants to go beyond reason. It adds an operation as absurd as the extraction of roots. And produces irrational numbers. It's a form of madness. Because the irrational numbers are infinite. They can't be written down. They force human consciousness out beyond the limits. And by adding irrational numbers to the rational numbers, you get real numbers. [Continues in the next section].

P. Høeg, [21]

Since the mid 20$^{\text{th}}$ century, the multiscale structure of ice shelves has been analysed on several occasions and included measurements of density variations, crystal size, c-axis orientation, impurity content in ice, oxygen isotopes as well as the determination of firn stratigraphy and the detection of marine layers.

However, those microstructural features which have become a major issue in the modelling of grounded ice dynamics – e.g. the consideration of flow-induced anisotropy in attempts to improve the reconstructions of the past climate of Earth – are by far less investigated in ice shelves than in inland ice.

Recent deep ice cores playing a key role in climate reconstructions, as described in [38], e.g. the EPICA cores, the GISP2 core, the NGRIP core and the Dome Fuji cores, have absorbed virtually all available logistic, financial, and man-power support on inland ice research rather than on ice shelves. Consequently, there are only a few ice cores that have been drilled through the entire thickness of ice shelves and we are currently aware of three such cores: The first ice shelf deep core has been drilled through the Ross Ice Shelf in 1958, another one followed taken from the Amery Ice Shelf in 1969-1970 while in 1989-1990, the deep core 'B13' was obtained from the Ronne Ice Shelf.

The drilling project on the Ross Ice Shelf, conducted at a site less than 3 km from its seaward edge, proved it to be approximately 260 m thick. The corresponding deep core provided insight into the physical and structural property changes which accompany the mass transfer of snow and ice as its particles move along their 'path' from the top of the ice shelf towards its bottom.

The analysis of the core revealed, on a meso- and macroscopic scale, respectively, the occurrence of sediment layers at various depths and the complete absence of a marine layer at the bottom of the seaward edge of the Ross Ice Shelf. On a microscopic scale, the crystalline structure as observable in the core has been investigated with focus on size and shape of grains, size and shape of gaseous inclusions, crystallographic c-axis orientation and their variations with depth, cf. [12].

The Amery Ice Shelf core, recovered at site 'G1' about 60 km from the front of the shelf, was 315 m long and exhibited a layered structure: the top 70 m contained snow accumulated on top of the shelf, between 70 m and 270 m a layer of meteoric ice originating from the connected Lambert Glacier drainage basin was detected, and the bottom layer, ranging from 270 m down to 315 m, was identified as marine ice that had formed due to freezing of sea water at the shelf-ocean interface. While this macroscopic classification of the Amery Ice Shelf as a three-layered structure is not surprising, a considerable step towards the recognition of the multiscale structure in ice shelves has been made in 1976 by Wakahama & Budd ([54]): they identified, from the microstructure of the ice core, the very same 3-layer structure observed macroscopically.

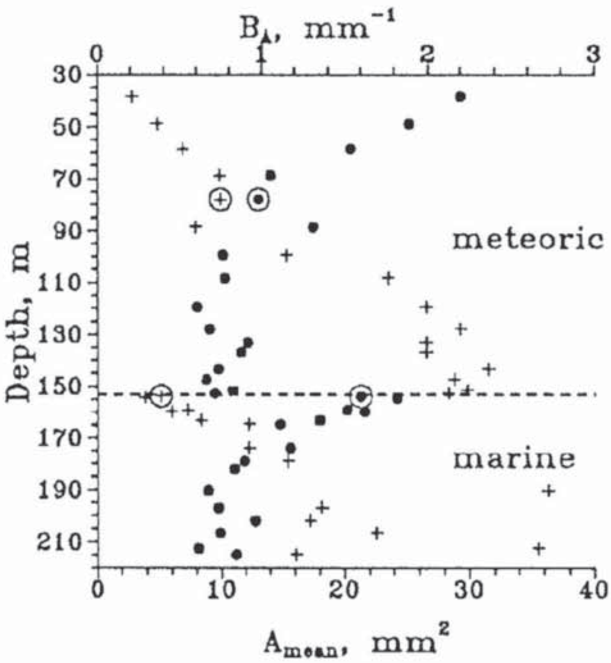

Figure 7: *Profile of the grain boundary density, B_A, plotted as black circles versus the depth of core B13. B_A is defined as the length of grain boundaries per unit area. From [8], where further information can be found.*

A detailed analysis of the multiscale structure of ice shelves, based on data available from the deep core 'B13' taken on Ronne Ice Shelf in 1989-1990, has been given by Eicken and others [8]. Macroscopically, the core 'B13', drilled at a distance of roughly 30 km from the seaward front of the Ronne Ice Shelf, confirmed the 2-layer structure of the ice shelf: at the drill site, the uppermost 160 m consisted of meteoric ice, while the bottom 80 m are marine ice. Moreover, sediment layers have been detected mainly in the marine layer. Microscopically, the analysis of textural characteristics of marine and meteoric ice revealed a correlation between sediment concentration and grain-boundary density, leading the authors to suggest that sediment inclusions may possibly inhibit grain growth and dynamic recrystallization.

Thus, the grain-boundary density is a key textural parameter, cf. Fig. 7. In addition, the grain boundary density is influenced by thermal processes: in the marine layer, an observed increase in grain boundary density (corresponding to a decrease in grain size) is in part explained by the thermal history the marine layer has experienced.

Cores which extend only to a certain depth of an ice shelf appear to have been drilled more frequently, yet the results obtained entered the literature databases seldomly. A counterexample is the report on an isotopic analyses conducted for a 100 m core from Filchner–Ronne Ice Shelf [13]. The remaining available articles based on ice core analysis focus almost exclusively on macroscopic features such as the presence or absence of marine layers [31, 34, 39, 47, 48, 61]. Within the AMISOR (Amery Ice Shelf Ocean Research) project, access holes of 370 m depth and 480 m depth, respectively, have been drilled through the Amery Ice Shelf in 2001 and 2002. Measurements were made in the ocean beneath the shelf through both holes, and instruments were left in place to continue measurements over several years, cf . [1].

Summarizing the above, the properties of ice shelves have first been investigated from a macroscopic point of view, and were later analyzed with a focus on their inherent microscopic structure. While we tried to reflect this historical development in the organization of Sect. 3 and the present Sect. 4, it is obvious from the end of Sect. 4 that an isolated consideration of either microscopic or macroscopic features is not reflecting the physical processes (characterized by feedback mechanism, coupling mechanism and other agents) taking place in ice shelves.

Structures, each prevailing at their own scale, interact with each other and demand to be accounted for – just as it is done, with considerable lead, for grounded ice – if sustainable progress in ice shelf modelling, reflecting their intertwined role with other cryosphere subsystems and the global climate system, shall be achieved.

5 Modelling of ice shelves

> *It doesn't stop. It never stops. Because now, on the spot, we expand the real numbers with the imaginary ones, square roots of negative numbers. These are numbers we can't picture, numbers that normal human consciousness cannot comprehend. And when we add the imaginary numbers to the real ones, we have the complex number system. The first number system in which it's possible to explain satisfactorily the crystal formation of ice.*
>
> P. Høeg, [21]

In the modelling of ice shelves, various aspects have to be considered and range from the consideration of

1. the layered structure of ice shelves, accounting for marine and meteoric ice, to

2. the coupling of thermal and mechanical processes, which is especially important at temperatures close to the melting point. Further,

3. the connection of ice shelves to their attached inland ice, the stability of which is likely to be governed essentially by the ice shelves, as well as

4. the presence of (fast flowing) ice streams, draining mass especially from the West Antarctic Ice Sheet into the Ross Ice Shelf have to be accounted for. Finally,

5. the formulation of an evolution equation for the seaward front of ice shelves, leading to an improved modelling of calving processes

remains one of the great challenges of modern glaciology.

The importance of a coupled modelling of grounded ice and ice shelves, especially with a focus on the stabilizing role of ice shelves, controlling the dynamics of their attached inland ice by acting as a 'plug', has been pointed out in [56].

Accounting for coupling between grounded ice flow (dominated by shearing induced by tangential traction at the bed-ice interface) and ice shelf flow (a plug-type flow dominated by longitudinal stresses in the absence of significant tractions at the ice shelf-ocean interface) allows an understanding of the dynamics of the grounding line, separating grounded and floating ice. Indeed, over thousand of years, migration of the grounding line can be considerable: the grounding line of the Ross Ice Shelf has been estimated to have retreated nearly 1300 km since the last glacial maximum (LGM), 21.000 YBP [7]. Theoretical modeling of the transition zone between grounded ice and an ice shelf is currently an active field of research, and debates concerning the formulation of the 'correct' boundary conditions are going on [6, 17, 20, 46, 58], complemented by first numerical implementations. Three-dimensional, time-dependent thermomechanically coupled models for inland ice and connected ice shelves, rooting in continuum mechanical foundations and simplified by the application of the Shallow Ice Approximation[3] (SIA), have been developed for the entire Antarctic Ice Sheet, cf. [27, 28, 43, 44, 45] and for the West Antarctic Ice Sheet, cf. [41, 23].

The occurrence of different types of flow regimes, namely relatively slow inland ice flow which is essentially due to ice deformation (creep), fast ice flow in the region of ice streams, and ice shelf flow, makes the coupled modeling of systems involving these different flow regimes a difficult task from a theoretical and numerical point of view.

Focusing on ice shelves alone, continuum thermodynamical models ultimately accounting for the presence of marine and meteoric ice, the transitions surface between those types of ice, the presence of a liquid phase with varying brine concentration and an appropriate scaling reflecting the properties of ice shelf geometry and ice

[3]The Shallow Ice Approximation (SIA) is a thin-film approximation applied to the Stokes equations of grounded ice dynamics: if the latter are properly non-dimensionalised with the use of an aspect ratio characterising the difference of vertical and horizontal length scales, their zeroth order perturbation expansion renders the equations of the SIA [26].

shelf flow (the Shallow Shelf Approximation SSA), have been derived in [35, 36, 57].

An expansion of the governing equations of ice shelf flow that goes beyond retaining the zeroth order terms in the perturbation expansion has been presented in [3] for layered ice shelves, and it is only with such a refined theory that the interaction and feedback mechanisms which are exerted upon the ice shelf while it flows across an ice rise can be captured. Such a higher order Shallow Shelf Approximation SSA has counterparts derived in the context of scaling grounded ice masses: the longitudinal stress approximation (LSA, cf. [4, 53]) and the formal expansion of the SIA to the next higher order equations, which are then second order in the aspect ratio parameter and which are simply called Second Order Shallow Ice Approximation (SOSIA) equations. The LSA has recently been advocated as a balanced compromise between the SIA and the SOSIA [19].

If implemented into numerical codes, the complexity of advanced continuum mechanical models respecting the presence of meteoric and marine ice in shelves typically requires a de-coupling of the thermomechanical problem by e.g. specifying a temperature profile as available from deep-cores drilled through a shelf, cf. [25].

A subsequent coupling of the just described ice shelf models to separately implemented inland ice models is likely to be successful only if some kind of homogenization is employed for the transition zone, i.e. in the vicinity of the grounding line:

1. Firstly, the scalings typically employed (SIA and SSA) differ from one another such that e.g. a matched asymptotics approach borrowed from the discipline of perturbation theory in mathematical physics could be used to render the transition of SIA into SSA a smooth process. The treatment of longitudinal stress coupling on ice dynamics is an important aspect when coupling inland ice and ice shelf models: the back-pressure, generated by the ice shelf and transmitted to the connected inland ice, is suspected to play a major role concerning the stability of the West Antarctic Ice Sheet [18].

2. Secondly, marine ice is not present in grounded ice so that consequently, a coupled inland ice/ice shelf model must be able to capture the transition of a multiphase continuum (with marine and meteoric ice as major constituents) to a single phase continuum (consisting of meteoric ice only).

At present, two topics are not considered satisfactorily in the modelling of ice shelves: The first is the description of the evolution of the ice shelf front: knowledge of the evolution of the calving rate as a function of the ice shelf thickness at the seaward front, the ocean wave stress, the ocean temperature and probably other factors is mandatory to perform realistic simulations of disintegrating ice sheets. Second, the interaction of grounded ice with its bed is to date in most cases reduced to the prescription of a mere boundary condition. However, subglacial bed deformation, induced by the overlying ice, is likely to result in bed slope changes especially at the inland ice margin and in the landward region of the grounding line [59], affecting thus the stability or instability of ice sheets with consequences that are still to be investigated.

6 Conclusions

We came to probe Antarctic's mystery, to reduce this land in terms of science, but there is always the indefinable which holds aloof yet which rivets our souls.

D. Mawson, [32]

Certainly, the above description of relevant topics in ice shelf modelling is neither representative nor comprehensive – repeating our statement made it Part 1 [10] 'it may be biased by our interests and the availability of particular publications'. Yet, we expect that this selection illustrates not only the advances that have already been achieved in the modelling of ice shelves, but also the future developments that are likely to be soon undertaken.

The biggest step, namely the recognition of the need for coherent multiscale structural modelling and the development of appropriate frameworks and theories is currently being undertaken. It is metaphorically reflected in and illustrated by the citations[4] preceding Sections 4 and 5, where we learned how much knowledge of the number system is necessary before one can eventually turn to a satisfactory description of the crystal formation of ice. It is now a pressing issue to push forward theoretical modelling in the spirit of mathematical physics, e.g. provided by a multiphase continuum thermodynamic theory. Testing of the former against field data and/or experimental data as well against numerical results, derived from models which in many instances still await their implementation, is then, naturally, the next step that has to be taken. We hope that research in the near future addresses some of the open problems mentioned in Sections 4 and 5, and thus enhance our understanding of the complex processes taking place around the Antarctic continent and affecting Earth's climate.

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[4]The statement the the complex number system is the first one in which the crystal formation of ice can be described satisfactorily is true if 'first' has a chronological connotation. The complex number system has been introduced in the mid 18^{th} century, while matrix calculus and the theory of quaternions, providing elegant and powerful tools in the description of crystalline structures and symmetries, have only been introduced in the mid 19^{th} century.

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