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The Multiscale Structure of Antarctica
Part I: Inland Ice

Sérgio H. Faria *†, Sepp Kipfstuhl **, Nobuhiko Azuma ***,
Johannes Freitag **, Ilka Weikusat **, M. Mangir Murshed *, Werner F. Kuhs *

* *GZG, Sect. of Crystallography, University of Göttingen, Göttingen, Germany*
** *Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany*
*** *Dept. of Mechanical Engineering, Nagaoka University of Technology, Nagaoka, Japan*

Abstract: The dynamics of polar ice sheets is strongly influenced by a complex coupling of intrinsic structures. Some of these structures are extremely small, like dislocation walls and micro-inclusions; others occur in a wide range of scales, like stratigraphic features; and there are also those collossal structures as large as megadunes and subglacial lakes. Their significance results from their interactions with the ice-sheet flow and the environment through an intricate *Structure–Form–Environment Interplay* (SFEI). Glaciologists are not unaware of the SFEI issue, as particular details of the problem are well documented in the literature. Nevertheless, many aspects of the SFEI remain unclear and a comprehensive perspective of the problem is missing. Here we present some selected results of a joint investigation of these structures via fieldwork, theoretical modeling, and experiments. The basic strategy is to conceive the Antarctic ice sheet as a heterogeneous system of structured media that interact in a hierarchical fashion via the SFEI. Special emphasis is given to snow and firn structures, interactions between microstructure, stratigraphy and impurities, and the interplay between subglacial structures and the overlaying ice.

Key words: Ice, firn, multiscale modeling, microstructure, recrystallization, stratigraphy, subglacial environment.

1 Glossary

Success is relative:
It is what we can make of the mess we have made of things.

T. S. Eliot [44] (character: Agatha), p. 118.

The choice of a consistent and unambiguous vocabulary for discussing science in a multidisciplinary environment often imposes a terrible dilemma. A typical example is the disparity in the vocabularies used by geoscientists and materials scientists to describe the same microstructural features in polycrystals. In an attempt to be systematic without being completely discrepant with the existing literature, we list below some important definitions and acronyms used throughout the text.

We adopt here a compromise between the vocabulary used by Bunge & Schwarzer [22], Drury & Urai [37], Humphreys & Hatherly [84] and Poirier [119]. It should be noticed that this does *not* always coincide with the terms in vogue in glaciology; and this is done on purpose: we wish to emphasize the need for a more appropriate vocabulary for dicussions with physicists, engineers and materials scientists, by rejecting the oblivious use of vague expressions whose meanings are too often taken for granted or prone to misunderstanding and misuse. The terms adopted here may probably not be the best and ultimate choice for this purpose, but they represent at least an attempt towards clarity.

Clathrate hydrate: Crystalline compound containing guest molecules enclosed in cage-like structures made up of hydrogen-bonded water molecules. When the guest molecules form gas under standard conditions, such compounds are also named *gas hydrates*. In particular, *air hydrates* are formed by atmospheric gases (viz. mainly O_2 and N_2).

Cloudy band: Ice stratum with turbid appearance due to a high concentration of micro-inclusions.

Crystallite: Crystalline domain in a solid polycrystal. Also called *grain*. It should be noticed the difference between crystallites in polycrystalline solids (e.g. iron or ice) and the lose crystals in crystalline granular media (e.g. fine quartz sand or fresh Antarctic snow).

Crystallographic texture: Directional pattern of lattice orientations in a polycrystal (cf. grain stereology). Also called *fabric*, *PLO* (*Preferred Lattice Orientations*), or simply "texture".[1] In particular, a polycrystal with a random distribution

† Corresponding author: sh.faria@geo.uni-goettingen.de

[1] We adopt here the standard nomenclature of materials science [22, 71, 84]. Notice that this is not the definition of "texture" often invoked in the in the glaciological literature. The reason for this choice is convenience: experience shows that it is rather easy for glaciologists to use the term "crystallographic texture" as a synonym for "fabric", whereas it is awkward for most physicists, engineers, and materials scientists to use the term "texture" in the sense frequently employed in glaciology (i.e. as synonym for grain stereology).

of lattice orientations is said to be texture-free (viz. random fabric, no PLO).

Deformation-related structures: Structural features produced and/or affected by deformation, e.g. dislocations, subgrain boundaries, slip bands, stratigraphic folds, etc.

DEP: Dielectric Profiling.

Dislocation wall: Deformation-related structure consisting of dislocations arranged in a two dimensional framework; the precursor of a subgrain boundary (cf. subgrain).

DML: Dronning Maud Land.

Dynamic grain growth (DGG): Class of phenomenological processes of grain coarsening in polycrystals *during deformation*. Several recovery and recrystallization processes may be simultaneously active during DGG, all competing for the minimization of both, the stored strain energy and the grain-boundary energy. The essential feature of DGG (in comparison to other recrystallization processes) is the monotonic increase of the mean grain size with time. Owing to its dynamic nature, however, the diversified kinetics of DGG can generally not be compared with the simple kinetics predicted for normal grain growth (NGG, cf. id.).

ECM: Electrical Conductivity Measurement.

EDC: EPICA-Dome C.

EDML: EPICA-DML.

Elementary structural process: The fundamental operation of structural change via recovery or recrystallization, e.g. grain boundary migration or subgrain rotation. Several elementary processes may combine in a number of ways to produce a variety of *phenomenological structural processes*[2] (cf. id.).

EPICA: European Project for Ice Coring in Antarctica.

Fabric: See *crystallographic texture*.

Firn: Sintered snow that has outlasted at least one summer.

Grain: See *crystallite*.

Grain stereology: Spatial arrangement of grains in a polycrystal, including their sizes and shapes (cf. crystallographic texture).

Grain subdivision: Phenomenological recovery process of formation of new *subgrain boundaries*. It involves the progressive rotation of certain portions of the grain, called *subgrains* (cf. id.), as well as the strengthening of dislocation walls through dislocation rearrangement and migration in regions with strong lattice curvature. If the misorientation across the new subgrain boundary increases with time, grain subdivision may give rise to *rotation recrystallization* (cf. id.).

Inclusion: Locallized deposit of undissolved chemical impurities observed in polar ice, e.g. bubbles, clathrate hydrates, brine pockets, plate-like inclusions, etc.

Megadunes: Wavy snow structure with few kilometers in wavelength and several meters in amplitude, visible from air- and space-borne platforms as alternating bands and supposedly produced by persistent katabatic winds.

Micro-inclusion: Inclusion not larger than a few micrometers, and consequently not clearly identifiable under optical microscope, e.g. dust particles, salt inclusions, microscopic bubbles, etc.

Microshear: Strong, localized shear across a grain that experiences a highly inhomogeneous shear deformation. It culminates with the formation of a new, flat subgrain boundary parallel to the shear plane, called *microshear boundary* (cf. slip bands).

Microstructure: Collection of all microscopic deformation-related structures, inclusions, and the orientation stereology (cf. id.) of a polycrystal.

Migration recrystallization: In full *strain-induced migration recrystallization*. Class of phenomenological recrystallization processes based on the elementary *SIBM* mechanism (cf. id.). If nucleation (cf. id.) is involved in the process, we may call it *nucleated migration recrystallization* (SIBM-N), where the suffix "-N" stands for "new grain". Otherwise, i.e. if the migration of boundaries occurs without formation of new grains, we may call it *ordinary migration recrystallization* (SIBM-O), where the suffix "-O" stands for "old grain".[3]

Multiscale structure: The collection of all sorts of structural features observed in a material body, with emphasis on their interactions. In ice sheets such structural features occur on the (sub-)microscale (e.g. dislocations, air hydrates), on the mesoscale (e.g. cloudy bands) and on very large scales (megadunes, subglacial lakes, etc.). Some of them may appear also in a range of scales (e.g. folds). Most of them are evolving structures that interact with each other as well as with the ice-sheet flow and the environment via SFEI (cf. id.).

NGRIP: North-Greenland Ice-Core Project, also abbreviated as *NorthGRIP*.

Normal grain growth (NGG): Phenomenological recrystallization process of grain coarsening in polycrystals, resulting from "the interaction between the topological requirements of space-filling and the geometrical needs of (grain-boundary) surface-tension equilibrium" [135]. By definition, grain coarsening during NGG is *statistically uniform* and *self-similar*, grain-boundary migration is *exclusively* driven by minimization of the grain-boundary area (and associated free energy), and the grain stereology is close to a configuration of "surface-tension equilibrium" (so-called "foam-like structure"). Owing to these essential features, NGG is generally regarded as a static recrystallization process (cf. recrystallization) taking place before/after deformation (cf. dynamic grain growth). Mathematical and physical arguments strongly suggest that the kinetics of NGG is parabolic with respect to the mean grain radius.[4]

[2] Recovery and recrystallization are complex physical phenomena that are better understood if decomposed in a hierarchy of structural processes or mechanisms, here qualified as "elementary" and "phenomenological." A somewhat similar hierarchical scheme for recrystallization has formerly been proposed by Drury & Urai [37], but with the expressions "elementary/phenomenological process" replaced respectively by "basic process" and "mechanism". We favor here the qualifiers "elementary/phenomenological" (against the "process/mechanism" scheme) because these qualifiers facilitate the visualization of the hierarchy and leave us free to use the terms "process" and "mechanism" as synonyms.

[3] The definition adopted here is based on the concept of "grain-boundary migration recrystallization" originally described in the pioneering work by Beck and Sperry [11]. Notice that this definition is not identical to that used by Poirier [119] or Humphreys & Hatherly [84], and it is also quite distinct from some loose connotations invoked in the glaciological literature. The terms SIBM-N and SIBM-O are not standard in the literature, but they are nevertheless adopted here because they describe quite precisely the kind of information obtained from microscopic analyses of ice core sections. There is unfortunately no one-to-one relation between SIBM-N/SIBM-O and the expressions "multiple/single subgrain SIBM" used e.g. in [84].

[4] As discussed by Smith [135], the interest in NGG comes from the fact that its kinetics depends solely on the properties of the migrating boundaries and is otherwise independent of the medium or its deformation history. This means that the theory underlying the NGG kinetics is not restricted to polycrystals: similar coarsening phenomena are also observed in foams, some tissues, and many other cellular media.

Nucleation: Class of phenomenological recrystallization processes involving the formation of new *nuclei* (viz. tiny strain-free new grains). Two types of nucleation mechanisms can be identified, here called "pseudo-" and "classical nucleation". During *classical nucleation* a cluster of atoms spontaneously form a new nucleus under the action of thermally-activated fluctuations. Despite numerous mentions to it in the glaciological literature, it is currently aknowledged that this mechanism is certainly not relevant for polar ice.[5] During *pseudo-nucleation* a special combination of elementary recrystallization processes (e.g. SIBM, subgrain rotation and growth) takes place *within a small crystalline region* with high stored strain energy, giving rise to a little strain-free new grain called *pseudo-nucleus*.[6] If pseudo-nucleation occurs naturally in polar ice, it most likely happens at grain boundaries and other zones of high stored strain energy, e.g. at air bubbles and solid inclusions.

Orientation stereology: Spatial arrangement of lattice orientations in a polycrystal, i.e. the combination of *grain stereology* and *crystallographic texture*.

Phenomenological structural process: Any combination of elementary structural processes that gives rise to general changes in the structure of the polycrystal (cf. *elementary structural process*). Examples of phenomenological processes are nucleation and grain subdivision.

Plate-like inclusion (PLI): Microscopic, flat cavity with hexagonal symmetry lying on the basal plane of its hosting ice crystallite, i.e. a thin negative crystal. PLIs are usually filled with air, appear in a wide range of temperatures, and are supposed to be produced by some kind of stress relaxation within the ice[7] [98, 105].

Polygonization: Special type of recovery mechanism for the formation of *tilt boundaries*. It is a particular case of grain subdivision (cf. id.), by restricting it to tilting (bending) of crystallographic planes. In ice, polygonization is often used in referrence to the bending of basal planes.

Recovery: Release of the stored strain energy by any thermo-mechanical process of microstructural change other than recrystallization (cf. id.). The qualifiers *dynamic* and *static* denote recovery phenomena occurring *during* and *prior/after* deformation, respectively. Frequently (especially under dynamic conditions), recovery and recrystallization coexist and may even be complementary (e.g. during the development of new subgrain boundaries), so that the distinction between them is sometimes very difficult.

Recrystallization: Any re-orientation of the lattice caused by grain boundary migration and/or formation of new grain boundaries[8] (cf. recovery). The qualifiers *dynamic* and *static* denote recrystallization phenomena occurring *during* and *prior/after* deformation, respectively. Further classification schemes often invoked in the literature include the qualifiers *continuous*/*discontinuous* and *continual*/*discontinual*, used to specify, respectively, the spatial homogeneity and temporal continuity of the recrystallization process. These classifications are, however, not always unique and are therefore of limited use.

Rotation recrystallization: Phenomenological recrystallization process responsible for the formation of new *grain boundaries*. It proceeds from the mechanism of *grain subdivision*, and as such it involves the progressive rotation of subgrains as well as the migration of subgrain boundaries through regions with lattice curvature. Notice that this recrystallization process does not require significant migration of pre-existing grain boudaries, in contrast to migration recrystallization.

SFEI: Structure–form–environment interplay. Generally, the environment influences the form; changes in the form affect the environment; environmental changes act on the structure; the structure modulates the form evolution; the evolving form alters the structure. In the case of glaciers and ice sheets it denotes the interactions between the deforming ice, its multiscale structure, and the environment.

SIBM: See *strain-induced boundary migration*.

SIBM-N/SIBM-O: See *migration recrystallization*.

Slip bands: Series of parallel layers of intense slip activity and high amount of intracrystalline lattice defects (especially dislocations). Slip bands in ice appear always in groups parallel to the basal planes and are indicative of a nearly homogeneous shear deformation of the respective grain (cf. microshear).

Stored strain energy: Fraction of the mechanical energy expended during deformation that is stored in the material in diverse types of intracrystalline lattice defects, e.g. dislocations, stacking faults, subgrain boundaries, etc.

Strain-induced boundary migration (SIBM): Elementary recrystallization process of grain boundary motion driven by minimization of the stored strain energy. It involves the migration of a grain boundary towards a region of high stored strain energy. The migrating boundary heals the highly energetic lattice defects in that region, therefore promoting a net reduction in the total stored strain energy of the polycrystal.

Subglacial structure: Any structural feature underneath the ice, ranging from till and rocks to channels and lakes.

Subgrain: Sub-domain of a grain, delimited by a *subgrain boundary* and characterized by a lattice orientation that is similar, but not identical, to that of the rest of the grain. In ice, the lattice misorientation across a subgrain boundary is limited to a few degrees (usu. ca. $< 5^\circ$; although this limit is somewhat arbitrary [158]).

Texture: see *crystallographic texture*.

Tilt boundary: Special type of subgrain boundary in which the misorientation axis is tangential to the boundary interface.

[5] Calculations show [23, 84] that classical nucleation recrystallization is extremely unlikely to occur in single-phase materials, owing to the high energies required for the creation and growth of classical nuclei, except if strong chemical driving forces are present, which is clearly not the case for polar ice.

[6] the prefix "pseudo-" is used here to emphasize that this nucleus is usually much greater than the nucleus formed by classical nucleation but still small enough to be strain-free. It should be noticed that the distinction between pseudo-nucleation and a combination of SIBM-O with rotation recrystallization is basically a matter of scale: in the latter case the new crystallite is large enough to inherit a considerable amount of internal structures from the parent grain.

[7] Plate-like inclusions should not be confused with Tyndall figures: the latter are negative crystals produced in ice by internal melting and filled with liquid water and vapor [104].

[8] In contrast to the definition adopted here, some authors reserve the term "recrystallization" solely for those processes driven by the stored strain energy, therefore excluding e.g. normal grain growth (NGG, cf. id.) from its definition. Other authors (especially in the older literature) loosely use "recrystallization" as a synonym for SIBM-N (cf. migration recrystallization).

Twist boundary: Special type of subgrain boundary in which the misorientation axis is orthogonal to the boundary interface.

Wind crust: Hard, thin layer of snow with high mass density, produced on the ice-sheet surface by strong, persistent winds combined with appropriate conditions of humidity, temperature, insolation, etc.

2 Ice sheets and the environment

The first day or so, we all pointed to our countries. The third or fourth day, we were pointing to our continents. By the fifth day, we were aware of only one Earth.

Prince Sultan bin Salmon al-Saud, Saudi Arabian astronaut. Quoted by Carl Sagan [125], p. 139

Today it is common knowledge that Antarctica and Greenland are covered by immense ice sheets, both huge ice masses of continental size. There is also indisputable evidence that other equally large ice sheets have existed in the past, overlaying extensive parts of North America, Europe and Asia about 20–100 thousand years ago [4, 132]. By the time of maximal volume, these frozen giants might have contained more than two times the actual amount of ice found on Earth (ca. $29 \times 10^6\,\mathrm{km}^3$). The withdrawal of such a colossal amount of ice cannot be explained simply by melting: the ice had to have flowed away over the millennia, creeping slowly like a very viscous fluid towards the ocean, until disintegrating itself into countless icebergs (see Part II [94]). At present, polar ice continues this saga, flowing from the remaining ice sheets in Antarctica and Greenland at a pace from several to many meters per year [9, 79].

The waxing and waning of polar ice sheets render them an essential part of Earth's environmental system, owing to their ability to interact with the atmosphere and the hydrosphere on a global scale. This interaction is conspicuous in contemporary environmental issues, like sea-level rise and global warming, and remains recorded in deep ice, viz. in layers of dust, aerosols and isotopes once deposited on the snow surface and later buried and compacted by the burden of subsequent snowfalls. The resulting stratification makes ice sheets also unique archives of Earth's climate in the past hundreds of thousands of years [46, 47, 117, 157].

The basic coupling between the *active* interaction of ice sheets with the environment and their *passive* recording of the past climate is highlighted by their *dynamic multiscale structure*, composed of structural features ranging from kilometer-long megadunes and subglacial lakes [64, 133] to sub-microscopic dislocation walls and micro-inclusions [92, 111]. In other words, the strata in an ice sheet vary with depth not only in thickness and impurity content, but also in crystallographic texture,[9] grain stereology, and other structural features that depend upon the deposition and deformation history.

A severe complication to the interpretation of such structures is the fact that most of them evolve with time. This means that whereas the diversity of structures in an ice sheet may provide a wealth of information about its flow and interaction with the environment, a proper understanding of this information requires knowledge of the mechanisms of genesis and evolution of each of these structures. To the despair of the traditional ice-sheet modeler, such mechanisms are often coupled in a so intricate manner as to require special models to describe their reciprocal interactions.

Owing to the complications mentioned above, the study of the *multiscale structure* of polar ice sheets has only recently received proper attention [25, 38, 43, 49, 51, 60, 64, 65, 99, 101, 126, 134, 137, 142, 144]. This work discusses the importance of multiscale modeling for modern polar research and highlights some past and current issues on this topic. *It is intended to be neither a general review nor a focused report on a specific investigation*. Rather, it presents a selection of glaciologically relevant results from recent studies carried out *by the authors themselves* with collaborators inside and outside the glaciological scene. Our main objective with such a summary of our own work is to examine the rise of multiscale modeling as an autonomous branch of research, based on our own recent experiences in this field. In this context, the literature cited here is neither complete nor representative, but rather illustrative only. It may be biased by the personal opinions and interests of the authors.

3 Modeling

Don't get involved in partial problems, but always take flight to where there is a free view over the whole single *great problem, even if this view is still not a clear one.*

Ludwig Wittgenstein [161], p. 23

As it happened in most fields of science, also the early research in the dynamics of glaciers and ice sheets was performed by individual, multifaceted scientists that could conduct field measurements and laboratory experiments with the same ability as to develop theories and models, and still apply these models to practical problems [1, 61, 151]. This primordial approach, simplistic and romantic in its essence, was soon replaced by the more efficient dichotomy "experiment (field work) & theory (modeling)", each part performed by distinct individuals, which is still today the paradigm of the academia and policy makers. The greatest advantage of this dissociation is that it opened the doors of glaciology to the talented theoretician, who was interested in ice modeling but was not fond of the perils and discomforts of the field work on ice (Fig. 1a).

As a natural consequence of the rise of scientific computing, during the last four decades numerical modeling of ice sheets has established itself as an indispensable branch of polar research, as a complement to theoretical modeling. Initially, computer simulations were simple and restricted to highly idealized situations [108, 120].

[9] See the definition of "crystallographic texture" in the Glossary in Sect. 1.

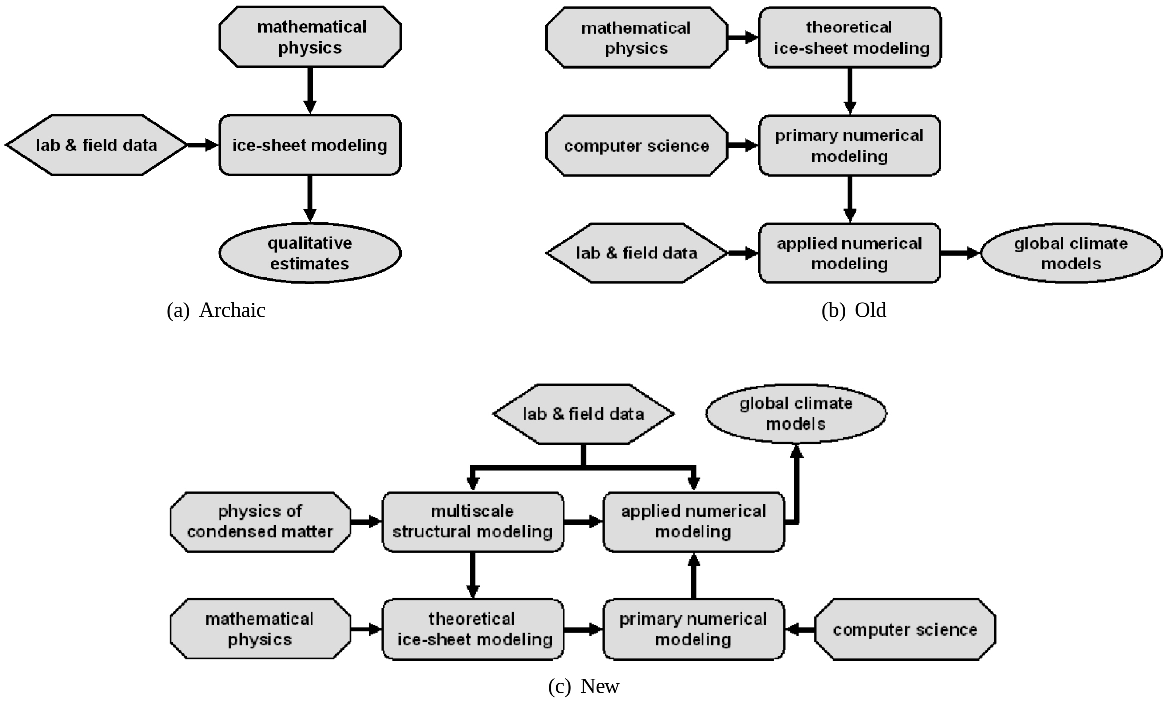


Figure 1: *Schematic illustration of modeling strategies. Although feedbacks do exist in each organigram between the several branches of modeling, these are not included here for simplicity.* (a): *Archaic strategy, used in the early times of ice-sheet modeling, prior to scientific computing. In the absence of numerical simulations, only highly idealized problems could be tackled. In this primordial stage all tasks were performed by only one modeler.* (b): *Strategy adopted after the emergence of scientific computing. Initially, numerical models were relatively simple and idealized, but they soon developed into realistic simulations that split numerical modeling into "primary" and "applied". In principle there are three types of modeling tasks, but often they are performed by just two modelers.* (c): *The newest strategy for ice-sheet modeling. Notice that multiscale structural modeling provides support not only to theoretical ice-sheet modeling, but also to applied numerics. In principle there are four types of modeling tasks, but often they are performed by just three modelers.*

More recently, however, the increasing complexity of programs and applications has induced a splitting of numerical modeling into so-called "primary" and "applied": the former is supposed to denote the development of new simulation programs and algorithms, while the latter describes the application of established simulation programs and algorithms to realistic boundary-value problems (Fig. 1b). On many occasions applied numerical modelers employ programs developed by themselves in an earlier period of their careers, when they were engaged in primary numerical modeling. Modelers that manage to act alone in both fields simultaneously and with a certain degree of success are becoming scarce, owing to the strenuous effort to conform to the increasing standards of sophistication and realism required for modern numerical simulations.

Curiously, the sophistication of the newest ice-sheet simulations produced an interesting effect upon theoretical modeling, which culminated with a complete rearrangement of the modeling hierarchy: ever more realistic applications set off a quest for not only more elaborate theoretical models, but also more refined field data… and soon it turned out that this quest was revealing a growing number of relevant structures in ice sheets. Distinct structures could be found on diverse scales and many of them could evolve according to their own laws, often forming a coupled system.

All these results doomed the traditional theoretical modeler, who could not cope with the complexity of evolving structures in multiple scales. It transpired that a fundamental reorganization of the modeling strategy was needed, with the emergence of a particular kind of modeling, not for the entire ice sheet itself, but for its intrinsic structures. The main task of this particular branch of ice-sheet modeling, from now on named *multiscale structural modeling*, should be to solve completely the problem of evolution and multiscale interaction of distinct structures in ice sheets, by using theoretical and, when necessary, also numerical ingredients. Consequently, it should provide support not only to theoretical ice-sheet modeling, but also directly to applied ice-sheet simulations (Fig. 1c). A simple example of the first kind of support is the modeling of crystallographic texture, which gives rise to *anisotropic ice-sheet models*. The second type of support is illustrated e.g. by the modeling of subglacial till deformation, which after being combined with an appropriate model of ice-sheet dynamics leads to an example of the class of *coupled ice-sheet models*.

Today, multiscale structural modeling is a prolific field in glaciology. Models of fabric evolution [7, 55, 67, 68, 102, 141], snow and firn metamorphism [2, 6, 28, 32], dislocation dynamics [30, 82], recrystallization [51, 101, 137, 153] and subglacial hydrology [18, 25, 49] are just some of many examples (see also Part II [94]). Studies of the multiscale interactions between these structures themselves and/or the environment are, nevertheless, not very frequent. In the sequel we examine some potentially significant types of multiscale structural interaction and present some recent research results that are directly or indirectly related to them.

Before we embark on practical examples, however, it should be remarked that the emergence of multiscale structural modeling should not be misinterpreted as another triumph of specialization, but rather the opposite. It is indeed a specific research field, but its main role is that of intermediator, which tailors concepts from theoretical modeling and condensed matter physics to suit the needs of applied ice-sheet modeling and the findings from field observations. Thus, it promotes multidisciplinarity and union against specialization and isolation, for it links fields that would otherwise remain poorly connected.

4 Polar ice formation and climate records

I closed my eyes.

There was a sound like that of the gentle closing of a portal as big as the sky, the great door of heaven being closed softly. It was a grand AH-WHOOM.

I opened my eyes—and all the sea was ice-nine.

The moist green earth was a blue-white pearl.

The sky darkened. Borasisi*, the sun, became a sickly yellow ball, tiny and cruel.*

The sky was filled with worms. The worms were tornadoes.

Kurt Vonnegut, Jr. [154], p. 174

Climate conditions initially determine the size and shape of snow crystals —the first structures of interest— as well as the concentration of dust, aerosols and other trace compounds deposited on/within the snow crystals that accumulate on the ice sheet surface [34, 58]. Isotopes ratios of precipitation ($HD^{16}O$ and $H_2^{18}O$ relative to $H_2^{16}O$) are commonly used as proxies for the temperature at the time of snow formation, even though seasonal variations are usually lost by diffusive mixing [31]. Some types of snow crystals may drift long distances under the action of strong winds, and accumulate selectively in a variety of surface patterns on multiple size scales, ranging from flimsy wind crusts up to vast megadunes [64]. These multiscale surface structures are then further modified by the rapid metamorphism of snow, triggered by direct exposition to insolation, wind, moisture and temperature gradients [28, 32, 63].

Figure 2: *Patchy snow surface at Dronning Maud Land, Antarctica. The layered structure in the center is the remnant of an old barchan-like dune disfigured by weathering. The steps produced by wind erosion reveal the stratified structure of the dune, characterized by alternate layers of dense, fine-grained snow (wind crusts) and less compact, coarse-grained material. The width of the central part of the image corresponds to ca. 30 m.*

The surface of the Antarctic ice sheet consists basically of such a patchwork of different types of compacted snow, discontinuously accumulated during snowfall and drifting events over numerous years (Fig. 2). The origins of the various granular compositions found in these multiscale surface structures, marked by contrasts in grain size and shape, texture, porosity, impurity and moisture content, are still not fully understood, owing to the intricate chemical and metamorphic processes taking place in the snowpack. Indeed, air–snow exchanges of trace compounds affect considerably the chemistry of the snow cover and the lower atmosphere, and consequently interfere with the snow metamorphism [34, 75]. In addition to the evident consequences for the climate records, such changes in the chemistry and metamorphism can alter the surface albedo and the permeability of snow, with significant implications for the validation of radar backscatter signals (ERS SAR, Radarsat, CryoSat) detected from the ice sheet surface during altimetry/interferometry surveys [159].

Subsequent snow compaction caused by the increasing overburden of new snow layers leads to the formation of a porous material called *firn* (Fig. 3). In dry polar regions, the firn zone extends from the near surface down to 50–100 m depth, with a gradual mass density increase from about $0.2\,g/cm^3$ to $0.8\,g/cm^3$. In the top 10–20 m, air is exchanged with the atmosphere mainly through forced convection in response to pressure gradients at the surface [13, 29]. Below this depth, gas transport occurs predominantly via diffusion driven by water vapor density gradients [28]. At the critical depth for pore close-off (named *firn–ice transition* depth), the connected pore space separates into isolated bubbles occupying approximately 10% of the bubbly ice volume [139]. These bubbles represent a unique archive for the reconstruction of past changes of the atmospheric composition, provided their ages can be correctly determined.

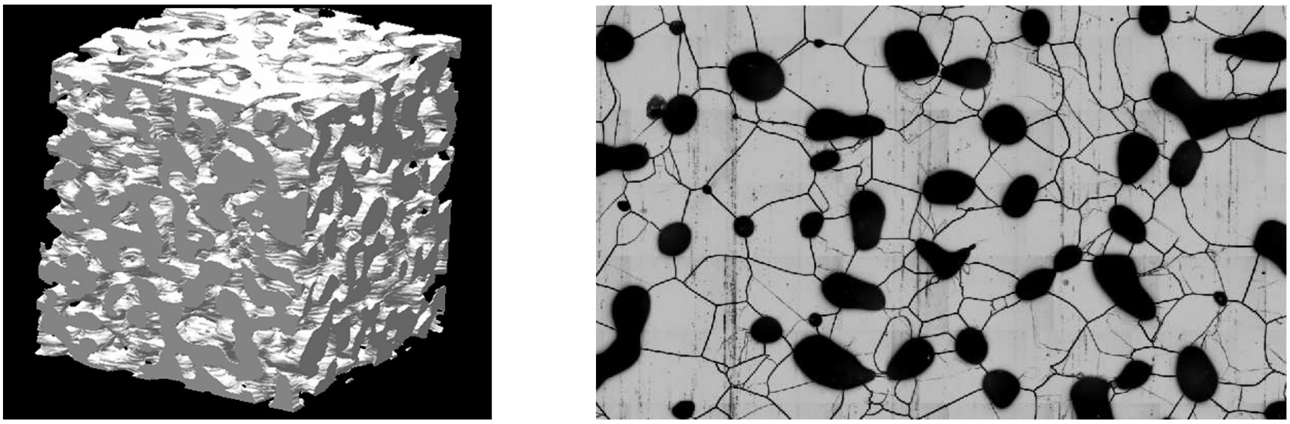


Figure 3: *Different aspects of the firn structure.* Left: *3D-reconstruction via computer tomography of a cubic firn sample (side length 5 mm) from 10 m depth, EDML firn core B33. Computer tomography is a powerful tool for studying the topological and geometrical properties of the pore network and ice skeleton, like e.g. porosity, tortuosity, neck size distribution, etc. It is also very useful in studies of pore-space anisotropy and in providing realistic boundary conditions for gas percolation studies.* Right: *Microstructure mapping photomicrograph of a firn sample from 80 m depth, EDML firn core B37 (image width ca. 5 mm; from [93]). In contrast to computer tomography, the microstructure mapping method is especially convenient for studying the microstructure of the ice skeleton (viz. grain boundaries, deformation-induced structures, etc.).*

Due to a lack of absolute dating tools, the age of an ice layer is usually estimated by a mixture of several methods [96, 113], including theoretical models combined with layer counting and records of chemical components with seasonal cycles (e.g. sodium, calcium or sulphate). Some ice horizons containing volcanic events can be also cross-correlated with other well-dated archives to give absolute markers for the age scale [80]. It should be noticed, however, that gas inclusions are always younger than the surrounding ice matrix: air in a firn column down to 50–100 m depth is still in exchange with the atmosphere by connected pathways in the pore network. Hence, ice underneath the firn–ice transition depth can be a few thousands of years older than the air entrapped in it [10, 12, 122]. A correct interpretation of climatic records in the upper part of ice cores depends therefore on the knowledge of the link between atmospheric composition and the climatic signal stored in ice, together with a reliable dating of ice and gas inclusions [96]. Both issues are strongly connected to the structural properties of snow and firn, as well as their accumulation rate and metamorphism.

Below the firn–ice transition, bubbles decrease in size and the enclosed gas pressure increases with depth [97, 127, 129]. When the pressure in the bubbles becomes high enough (depending on ice temperature), they start to convert into crystalline compounds called *clathrate hydrates* [91, 100, 128]. Clathrate hydrates in polar ice are essentially composed of oxygen and nitrogen molecules confined in water-molecule cages. Interestingly, not all bubbles transform into clathrates simultaneously: there exists a *bubble–clathrate transition zone*, which generally spans several hundreds of meters in depth. Within this zone, there occurs a depth-dependent gas fractionation, with N_2-enriched bubbles co-existing with O_2-enriched clathrates [86, 87]. This fractiona-

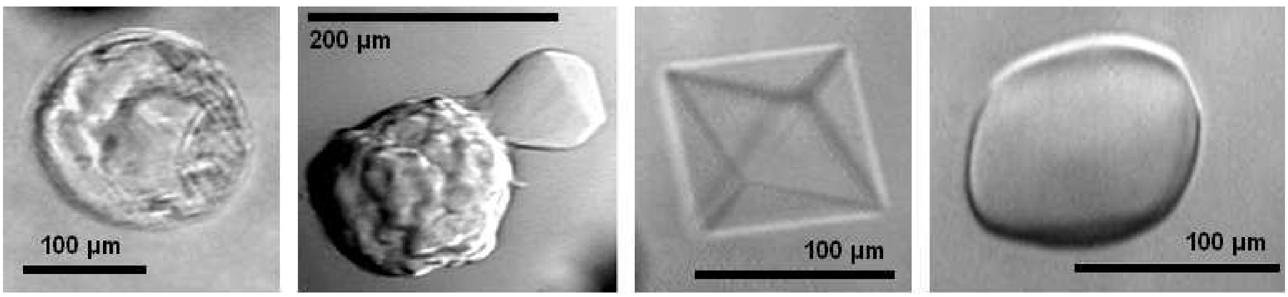


Figure 4: *Clathrate-hydrate structures observed at different depths in the NGRIP deep ice core.* From left to right: *primary hydrate (polycrystalline spheroid), rough spheroid metamorphosing into a multifaceted protrusion; polyhedral shape; smooth globule (from [114]).*

tion process is still not perfectly understood, even though it is crucial for a correct interpretation of paleoclimatic records [12, 122, 138]. Trace gases such as CH_4 and CO_2 are also expected in clathrate hydrates, often combined with N_2 and O_2 [95].

Below the bubble–clathrate transition zone, the lasting clathrate hydrates continue to evolve along the millennia in a strange fashion (Fig. 4): from rough polycrystalline spheroids over faceted and/or slender shapes towards usually isometric single-crystals [91, 115, 130, 152]. The activation energies and driving forces causing such ceaseless metamorphoses going from air bubbles into various forms of air hydrates are still not completely understood and their determination may shed new light on the interactions between deep polar ice and air inclusions.

Studies of climate records in the lowest tens of meters of deep ice cores are usually impaired by dynamic recovery and recrystallization, flow disturbances (folding, etc.) and interactions with subglacial features. Additionally, regardless of careful low-temperature storage, relaxation structures quickly emerge throughout deep ice cores. They consist mostly of polygonal cavities called *plate-like inclusions* (PLIs; Fig. 5) [72]. In spite of the paucity of studies about these objects, recent spectroscopic observations [105] revealed that plate-like inclusions are negative crystals frequently filled with O_2-enriched air. A better understanding of PLI formation is urging in order to clarify its relation to diffusion processes in polar ice. Unfortunately, many glaciologists insist on ignoring these relaxation features, by regarding them as futile artifacts.

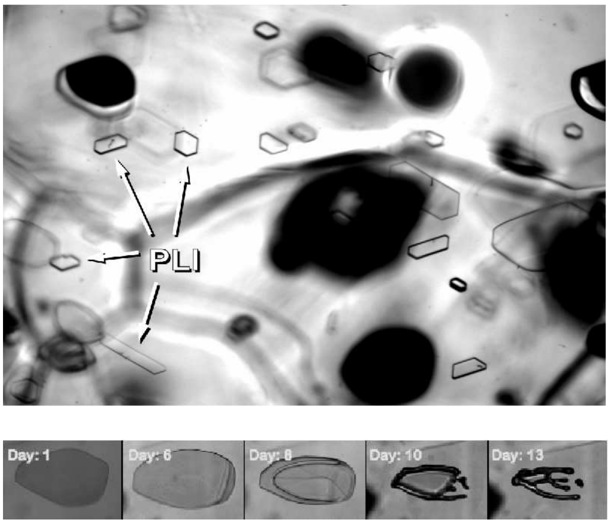


Figure 5: *Plate-like inclusions in the EPICA Dome C (EDC) core.* Top: *Numerous plate-like inclusions (PLIs) in an EDC sample from 511 m depth. The width of the image is 2.5 mm.* Bottom: *Time series of micrographs showing the gradual decompositions of a PLI. During the first days the PLI becomes thicker and loses the polygonal shape. Finally, it collapses into microscopic cavities/bubbles. The width of each image is 300 μm.*

5 Microstructure

> [...] *the very term structure implies interrelation between parts with reference to a whole.*
>
> Cyril Stanley Smith [136], p. 3

> [...] *the whole is not merely the sum of its parts. It is this, and much more than this. For it is not a bundle of parts but an organization of parts, of parts in their mutual arrangement, fitting one with another, in what Aristotle calls "a single and indivisible principle of unity"* [...]
>
> D'arcy Wentworth Thompson [147], p. 714

At temperatures and pressures prevailing on Earth's surface, ice possesses a hexagonal crystalline structure called *ice Ih*, which is characterized by a wurtzite-like lattice of oxygen atoms stabilized by statistically distributed protons that form covalent and hydrogen bonds [59, 81]. For our purposes, the major features of this lattice structure are: its hexagonal symmetry —which defines the well-known *basal*, *prismatic* and *pyramidal planes* (Fig. 6)— and the existence of two categories of basal planes, called *glide set* and *shuffle set* [118]. Interestingly, the planes of the glide set have the ability to fit over one another in a very peculiar way, which resembles well the close packing of metals and allows so the dissociation of dislocations on such planes into *Shockley partial dislocations* separated by a stacking fault [66, 82]. This dissociation is only possible because the energy of a stacking fault lying on a basal plane of the glide set is very low. Thus, basal dislocations are expected to stabilize into ribbon-like structures that severely restrict the dislocation-glide motion to the basal plane, since cross slip to other planes would require a constriction of the extended dislocation. From this succinct description we conclude that the peculiar properties of dislocations in ice, and in particular the *low stacking-fault energy* of its basal planes, endow ice crystals with a strong plastic anisotropy [82, 118]. In simpler words, ice crystals deform easily by *dislocation creep via basal slip*.

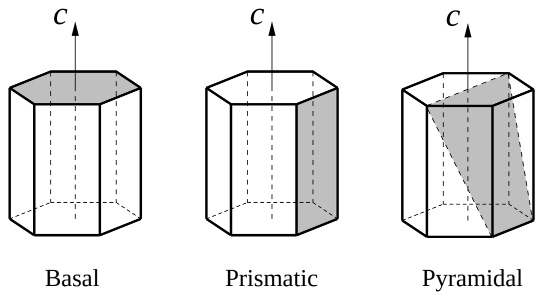


Figure 6: *Sketch of a monocrystalline, hexagonal prism of ice. Three families of crystallographic planes are indicated. Basal planes* (0001) *lie orthogonal to the* c *axis, which is the main axis of optical and crystallographic symmetry of the crystal. The prismatic faces* $\{10\bar{1}0\}$ *are parallel to the* c *axis, while pyramidal planes, e.g.* $\{10\bar{1}1\}$*, cross the bulk of the prism (from [50]).*

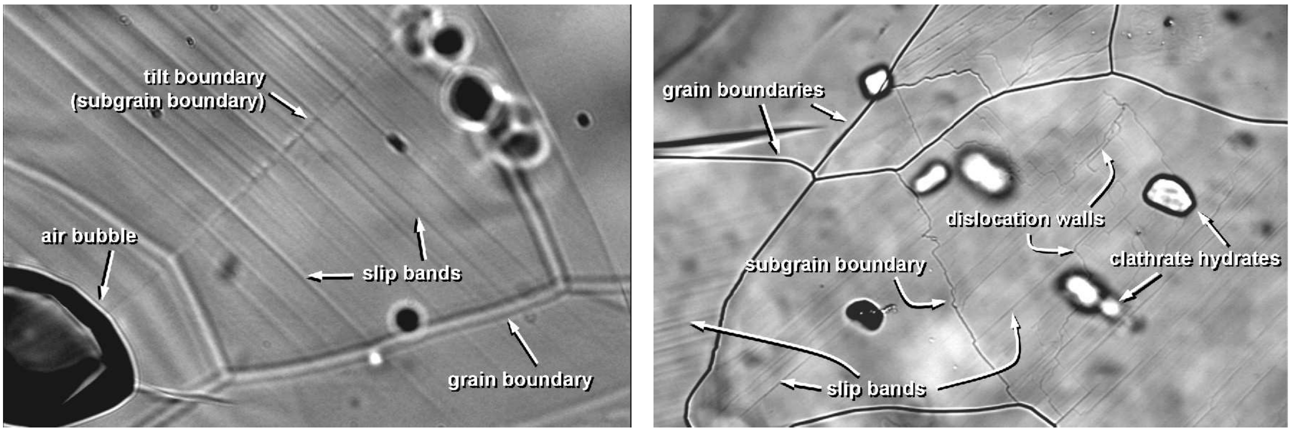


Figure 7: *Microstructural features of Antarctic ice revealed by the method of microstructure mapping.* Left: *Slip bands, air bubbles and a subgrain boundary in a sample from 610 m depth, EPICA-Dome C deep ice core (from [156], with modifications).* Right: *Diverse microstructural features in a sample from 1320 m depth, EPICA-DML deep ice core (from [92], with modifications). The width of each image is 700 μm.*

The conjecture that the creep of polycrystalline ice sheets should also be dominated by intracrystalline basal slip has been supported by the extrapolation of results from *laboratory tests* [8, 21, 88] and by reasonable arguments concerning the *crystallographic texture evolution* in polar ice [39]. Additionally, it has received recent support from measurements of *dislocation density* via X-ray diffraction [78] and most particularly from the direct visualization of *slip bands* in ice core samples from Greenland and Antarctica [53, 92, 149, 156]. As explained in Sect. 1, slip bands are series of parallel layers of intense slip activity and relatively high amount of intracrystalline lattice deffects (dislocations, etc.). In naturally deformed polar ice they consist exclusively of basal planes and are so faint, owing to the low strain rate, that their direct visualization requires the use of special microscopy techniques, like e.g. microstructure mapping [92] (Fig. 7).

Because of the strong plastic anisotropy of the ice lattice and the need of topological compatibility between neighboring grains, the slow deformation of polar ice is very *inhomogeneous* (Fig. 7). Not only does the stress vary immensely from grain to grain in the polycrystal, but also the deformation inside each grain is inhomogeneous, with the marginal region (the "*mantle*") experiencing more deformation than the central part (the "*core*") of the grain (Fig. 7b). Thus, the deformation of polar ice is characterized by the continual rearranging of dislocations into *dislocation walls*, forming *subgrain boundaries* which provide evidence for *grain subdivision* by shearing, twisting and bending (sometimes called "polygonization") under the action of local stress concentrations [53, 77, 158]. According to recent observations of the EDML deep ice core [92, 93], such subgrain boundaries seem to occur throughout the ice sheet and interact markedly not only with grain boundaries but also with pores, bubbles, clathrates, dust and other climate-related features. Together with slip bands they constitute the most relevant examples of what is sometimes called the *deformation-related microstructures* of polar ice.

As in other geological materials, the *microstructure* of polar ice evolves over centuries and millennia under the action of continual deformation and thermally activated processes like dynamic recovery and recrystallization. During several decades glaciologists have devised a simple model for the evolution of the microstructure in polar ice sheets. It is based on the assumption that a single, universal hierarchy of three thermally activated processes should control the microstructural evolution of polar ice throughout the ice sheet [3, 39, 40, 55, 74, 113, 116, 148]. Succinctly, according to this *three-stage model* the microstructure of polar ice in the upper layers of an ice sheet should evolve under the regime of "normal grain growth" (NGG), being counterbalanced after some hundreds of meters depth by grain splitting via "polygonization", while in the deepest hundreds of meters of the ice sheet, where the ice temperature raises above ca. $-10°$C, the microstructure evolution should be dominated by dynamic recrystallization with nucleation of new grains (SIBM-N).[10]

One of the great virtues of the three-stage model is undoubtedly its simplicity. It provides a satisfactory fit of the average grain size data of most polar ice cores and promises to modelers an ice sheet consisting in great part (excluding the messy bottom layers where SIBM-N is supposed to be active) of harmonious grains growing like bubbles of froth, without being considerably afflicted by stress concentrations or deformation inhomogeneities, except for the sporadic punishment of "polygonization", applied to those eager grains that happened to grow too much. Nevertheless, an increasing number of scientists is coming to the conclusion that the three-stage model may be more than just simple, namely an *over-*

[10] See Glossary in Sect. 1.

simplification. The basic argument is that a more careful consideration of the ice microstructure reveals that (cf. [23, 71, 84, 140]; see also the detailed definitions in the Glossary in Sect. 1):

1. NGG cannot strictly take place in a material undergoing deformation, since the necessary "foam-like structure" is usually not preserved in this case. Thus, the usual fitting of the average grain size versus age in polar ice cores with a parabolic NGG-type law (e.g. the Burke–Turnbull–Hillert law) may have no physical significance.

2. Polygonization is just one of a number of grain-subdivision processes that may occur in an inhomogeneously deforming polycrystal. More complex subdivision processes cannot be explained by grain size arguments only (as done in the simplest versions of the three-stage model), but rather by stress inhomogeneities on the grain scale. Whether one can trace a direct relation between mean grain size and stress inhomogeneities on the grain scale remains an open question.

3. Dynamic recrystallization need not necessarily involve the energetically expensive nucleation of new grains, as already demonstrated by Beck & Sperry [11] more than a half-century ago. Consequently, the assertion that dynamic recrystallization becomes significant only above a critical temperature of ca. $-10°$C should be reconsidered.

Recent microscopic investigations have also cast doubt on the validity of the three-stage model. For instance, Kipfstuhl and others [54, 92, 93, 158] studied the microstructure of the whole EDML deep ice core in microscopic resolution and concluded that grain subdivision and migration recrystallization (SIBM-O) are significantly active in diverse depths at the EDML site, including the firn layers. Additionally, Faria and others [56, 57] investigated the microstructures of certain deep strata of "soft ice" found in the EDML deep ice core and discovered a curious grain stereology that was attributed to the existence of well-developed microshear boundaries [15]. Now, if we consider the fact that there is no reason to regard the EDML core as extraordinary —actually, it has been extracted from a much less exotic site than most deep ice cores, since it was not extracted from a dome— then we are led to the conclusion that the structures observed in the EDML core may well be representative of many sites in Antarctica.

From the arguments above we can infer that although most microstructural features of polar ice are related to deformation, their evolution is strongly influenced by chemical impurities and thermally activated processes. Thus, with respect to the deformation history, the polar ice microstructure may be regarded at best as a qualitative "fading record" only [54]. The "memory persistence" of this fading record depends on a series of factors, ranging from stress and impurity content to the rates of recovery, recrystallization and related thermally activated processes. Unfortunately, in situ rates of recovery and other thermally activated processes are very difficult to evaluate for polar ice, not only because of the inhomogeneity of the deformation on the microscale, but also because of potential relaxation effects taking place in the ice core. It is believed that such undesirable relaxation effects can be minimized by appropriate core storage conditions (temperatures below $-50°$C are currently pursued as standard) and early preparation of thin sections (supposed to hinder relaxation via surface pinning effects). There is, however, no ultimate conclusion about the efficiency of these measures, especially for the lowest parts of deep ice cores.

6 Stratification

> *Undoubtedly we have no questions to ask which are unanswerable. We must trust the perfection of the creation so far, as to believe that whatever curiosity the order of things has awakened in our minds, the order of things can satisfy.* [...] *nature is already, in its forms and tendencies, describing its own design.*
>
> Ralph Waldo Emerson [45], p. 7

As discussed in the previous sections, the formation of polar ice from snow is a lengthy and intricate process that takes many centuries and entails a series of multiscale interactions between various snow structures, the lower atmosphere, and the firn layer. In view of the diversity of structures and chemical reactions involved in the densification process, as well as the strong inhomogeneity of the upper snow layers, it is not without little surprise that we realize how ordered and regular the ice layers underneath the firn–ice transition are. More fascinating is the fact that this stratified structure, characterized by chemical and microstructural variations with depth, persists throughout the ice sheet (with the exception of the mixed strata near the bedrock).

Methods for visualizing the stratigraphy of polar ice sheets are numerous and well known by any glaciologist. In fact, almost all properties measured in polar ice reveal some kind of stratification: (di-)electric contrasts measured via ECM or DEP,[11] variations in the concentration of isotopes or impurities (e.g. dust or soluble traces), variations in grain size… all reveal some particular type of stratified structure [46, 47, 146, 162].

Another useful method to visualize isochronous strata is radio-echo sounding, in which the detected internal reflections are related to horizons of dielectric contrast [106, 134]. The origins of such internal reflections are still matter of debate, with variations in density, acidity and texture being the most common causes [43, 65, 131]. The main advantage of radio-echo sounding is that it provides a three-dimensional representation of a large portion of the ice sheet, which is useful for ice-sheet flow studies. On the other hand, its shortcomings are the low

[11] See Glossary in Sect. 1.

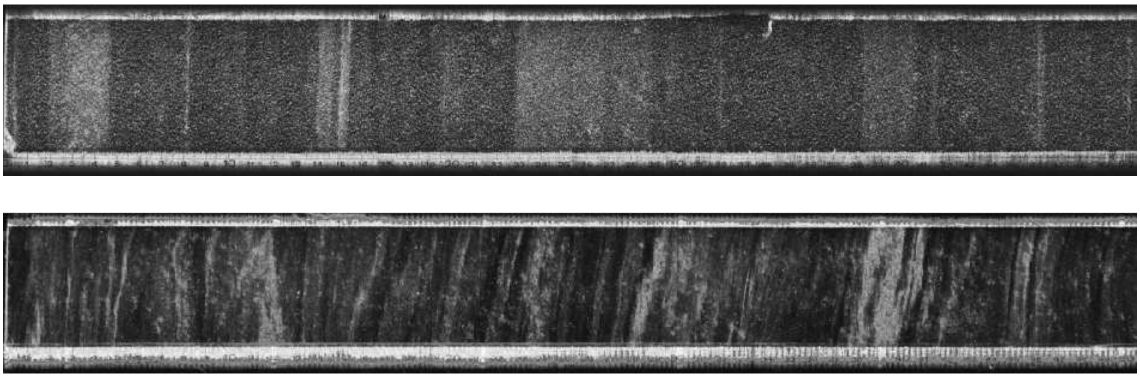


Figure 8: *Linescanner images of two EDML deep ice core pieces from distinct depths. Recall that the images are produced by light scattering from above, against a dark background; consequently they appear as negative pictures of the core. Brighter regions indicate stronger light scattering due to a higher concentration of impurities. The top of the cores is to the left.* Top: *upper 50 cm of an ice core piece from 855 m depth. The "granulated" appearance of the core is due to the light scattering by air bubbles.* Bottom: *upper 50 cm of an ice core piece from 2434 m depth. Note the inclined wavy strata and the sudden change in layer inclination after the first 10 cm, with some indication of intermixing.*

resolution of the data and the complete lack of internal layering signal from deeper ice, within what is called the *echo-free zone* of the ice sheet.

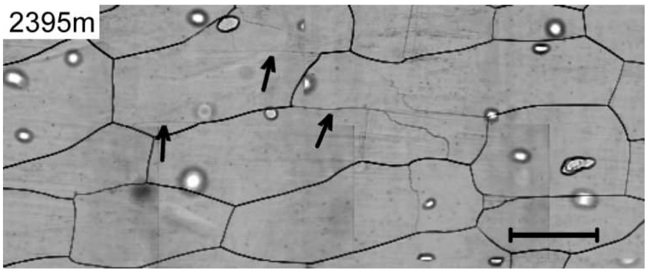
In the last years, a modern version of the old method of visual stratigraphy has brought new impulse for stratigraphic studies. The essential idea of modern ice-core linescanners is simply to scan the whole ice core using a high-resolution CCD-camera with enhanced contrast option [142, 144]. The resulting image reveals internal layering of polar ice due to variations in the light scattering properties of the core (Fig. 8). The information obtained from linescan studies is two-dimensional, in contrast to radio-echo sounding, but it is much more localized (limited to the diameter of the core) and has incomparably higher resolution. As a consequence, it reveals details of the ice sheet flow that could not be achieved by other methods, including waving, mixing and folding of strata, even in the deepest parts of the ice core.

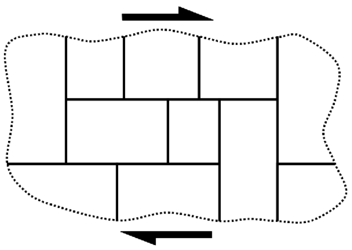
In spite of the long tradition of stratigraphic studies and the vast literature on the subject, often have polar ice strata been regarded as mere *passive* structures recording past climate changes and ice flow tendencies. The recognition that stratification may also have an *active* effect upon the rheological properties of polar ice, and consequently that it does not only record but also interact with the ice flow, can nevertheless be traced back at least to many decades ago [83, 112, 113, 143]. For instance, deep ice layers from the cold, dry, windy ice ages are particularly rich in *cloudy bands*, viz. layers with an unusually high concentration of micro-inclusions and other chemical impurities [73, 142]. The grains in such bands are generally much smaller than those in the surrounding ice and the crystallographic texture ("fabric") is often stronger. Observations of tunnel and borehole closure/tilting rates suggest that the microstructure of such layers tends to evolve towards a pronounced enhancement of the ice flow, especially at warmer layers, culminating with the formation of shear zones and extruded strata [48, 56, 76, 83, 112, 143]. The possible causes of this flow enhancement are apparently not unique, although all enhancement mechanisms seem to be ultimately related to interactions between microstructure and impurities under special conditions of stress, impurity content and temperature.

During the last years, the interest in the interaction between ice-sheet stratigraphy and flow has increased significantly. Several models have been applied to simulations of Antarctic sites [38, 126, 155], with the intention of reproducing at least some of the typical effects of stratification. These simulations often take for granted that the high fluidity ("softness") of an ice layer is mainly caused by a relatively strong single maximum texture ("fabric").

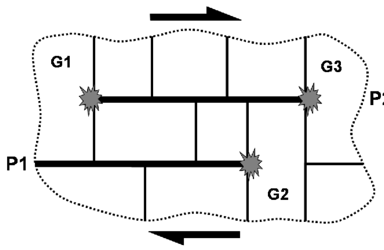
However, not all soft ice layers can be explained in terms of suitable crystallographic textures. One interesting example is given by the EDML soft ice layer described in [56, 57]. A noticeable closure of the EDML borehole starting abruptly at 2385 m depth indicated a sudden change in ice rheology, i.e. a soft layer. Fabric analysis showed no conspicuous difference between the crystallographic textures above and inside the layer, whereas the microstructure mapping images revealed a striking change in the grain stereology. It was concluded that the high impurity content and temperature, combined with the typically low deviatoric stress of ice sheets, activated within that layer a microstrain mechanism known as *microshear* [15, 36, 85]. This means that the usual deformation regime of dislocation creep has been enhanced within that particular layer by a special accommodation mechanism, which involves the formation of microshear boundaries (Fig. 9) and small amounts of grain boundary sliding [140].

This accommodation mechanism via microshear has the ability to release stress concentrations and strain incompatibilities, without severe impact on the crystallo-

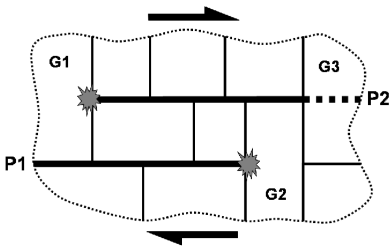




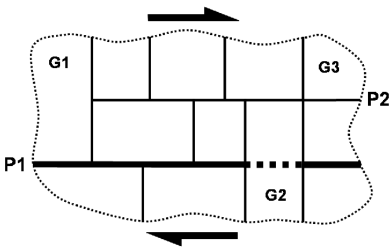
(a) Original structure



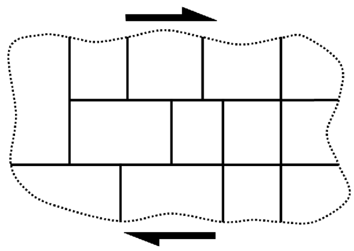
(b) Stress concentration



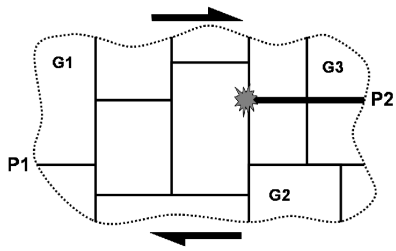
(c) Subgrain formation



(d) First path inactivation



(e) Complete inactivation



(f) Microshear reactivation

Figure 9: *Formation of subgrain-boundary "bridges" and maintainance of the "brick-wall pattern" via microshear.* Top (image): *Typical layered structure of grains ("brick-wall pattern") in the soft ice stratum of the EPICA-DML ice core. Many grains are block- or S-shaped, with most boundaries oriented nearly parallel or orthogonal to the local stratigraphy. Long chains of grain boundaries following the local stratigraphy are also quite common, being frequently connected by* subgrain boundary "bridges". *In this image we see three of such subgrain boundary "bridges" in early stage of formation (indicated by the arrows). Notice also the faint, but visible, slip bands in the large S-shaped grain in the center. The scale bar stands for 1 mm.*

Bottom (illustration sequence): *Simplified cartoon of the "micro-slide avalanches" associated with microshear. For simplicity, grains are schematically represented by rectangles and the grain shifts related to micro-slide have been neglected (otherwise more complex geometries would be needed to avoid incompatibility between the grains). Therefore, this cartoon is* not *intended to explain the mechanism of microshear itself (which involves rather more complicate geometries, subgrain rotation, etc.; cf. [56]), but rather simply the concept of "micro-slide avalanches", which has not been addressed in detail in [56].* (a): *We consider a polycrystalline region of the soft ice layer, subjected to locallized shear stress.* (b): *Due to a particular combination of high impurity content, low stress and high temperature, certain grain boundaries seem to have potential to slide. We identify two grain boundary paths (thick lines marked by P1 and P2) that are active for sliding. The ends of these paths (at the blocking grains G1, G2 and G3) become points of stress concentration.* (c): *Suppose that microshear occurs first in G3. Thus, a subgrain (microshear) boundary is formed, which slowly evolves into a grain boundary as the micro-slide continues. The stress concentration is now transferred to G1 and G2.* (d): *Assuming that G2 is the first grain to undergo microshear along the path P1, then the whole stress concentration at G1 and G2 is released through a microscopic stress discharge along P1. The path P2 becomes now inactive.* (e): *Further micro-slide avalanches transfer the stress concentrations to other regions of the polycrystal, making the path P1 also inactive. By comparing (a) and (e) we can notice how the "brick-wall" pattern has been enhanced.* (f): *the lack of activity of the paths allows grain boundaries to migrate, weakening the "brick-wall" pattern. However, further stress discharges elsewhere may soon or later activate one of the paths again, in this case, P2, so that a new cycle of slidings starts.*

graphic texture evolution via dislocation creep, by means of intermittent microscopic stress discharges (or "micro-slide avalanches") in different points of the soft ice layer (Fig. 9). Additionally, the formation of microshear bands generates a feedback to the microstructure, seeing that they contribute to the formation of long grain boundary paths that facilitate further grain boundary sliding.[12] These paths (or chains) of grain boundaries endow the microstructure with a "brick-wall" appearance that is considerably stable and typical of the microshear mechanism (cf. [15, 36]).

From the discussion above we realize that stratification is involved in a number of multiscale interactions with the microstructure and the ice-sheet flow. Many of these interactions are still not well understood, and many others probably remain to be discovered. A typical example is the *conjecture of mesoscale strain*, proposed few years ago by Faria & Kipfstuhl [53]. According to this conjecture, the stratification of the ice sheet could possibly induce a sort of deformation inhomogeneity on the mesoscale, viz. on the scale of several centimeters, which is spatially larger than the microstructural inhomogeneities on the grain scale, but still sufficiently small to become homogenized on the large scale relevant for ice-sheet flow. Be that as it may, further research on this and other types of multiscale interactions is needed in order to elucidate the real importance of stratification for the dynamics of polar ice sheets.

7 Subglacial structures

False hopes are more dangerous than fears.

J. R. R. Tolkien [150]
(character: Sador "Labadal"), p. 41

Much has been said here about the *intrinsic structures* of ice sheets. There are, however, many *extrinsic structures* that are crucial for the behavior of large polar ice masses. Most of them lie beneath the ice and are therefore called *subglacial structures*. These comprise sediment and till layers, topographic features (hills, valleys, etc.), meltwater channels and lakes. From the point of view of modeling, intrinsic structures affect the constitutive laws of ice, while extrinsic, subglacial structures have a decisive effect upon interface/boundary conditions.

During long time modelers tried to avoid the complications caused by the subglacial environment. They used to subsume all effects of subglacial interactions into a prescribed field of sliding velocity of ice over hard bedrock, which should vanish whenever the temperature at the base of the ice sheet is below the pressure-melting point. Among other shortcomings, such treatments were incompatible with many real examples of warm-based ice that experiences alternating cycles of slow and fast flow, such as glacier/ice-sheet surges and ice streams. As neatly stated by Fowler [62]: "It is not so long since theoreticians awoke from their clean studies of ice sliding over hard bedrock, and realized that life at the subglacial bed was less pristine than they had thought; that metres-thick layers of subglacial till sometimes exist [...], and that this material deforms." Not only the rheology of till, but also the effect of the subglacial hydrology has been neglected in this manner.

Hydrological models describing the dynamics of subglacial channels and lakes existed already in the early 1970s [107, 124]; theories of till rheology appeared some years later [16, 17, 24]. Attempts to incorporate the deformation of subglacial till into glacier and ice-sheet models followed shortly after [5, 33, 89], but the debate about the appropriate till rheology (plastic versus viscous: the old dilemma of realism versus simplicity) persists today. On the other hand, only in the last few years have hydrological models been successfully coupled with models of ice-sheet dynamics, undoubtedly one of the greatest achievements of multiscale modeling [60].

Latest findings of a number of subglacial lakes and channels underneath Antarctica have caught the interest of the scientific community and the lay public [19, 123, 133]. Actually, this is not as surprising as it may seem at first sight, for it is well known that thick ice masses (>1 km thick), like those covering Antarctica and Greenland, insulate well the bed from the polar atmosphere and enhance internal strain heating. Warm-based conditions can therefore be achieved, where basal ice is at pressure-melting point and liquid water can accumulate under the ice. The main concern about the unexpectedly large (and still increasing) number of lakes and channels discovered in Antarctica comes from the fact that high subglacial water pressures over significant portions of the ice-sheet bed can decouple the ice from the underlying bedrock substrate, reducing or even eliminating basal friction, and permitting high rates of ice flow (up to several kilometers per year). Indeed, there are strong evidences that similar flow phenomena have occurred in the past, sometimes with dramatic consequences for the environment [14, 27]. The consequences of the recently discovered subglacial structures underlying the Antarctic ice sheet are still difficult to work out, although it is evident from the above discussion that processes operating underneath a large ice mass can sometimes have a greater influence on ice flow than those operating within it [18, 25].

Additionally, it should be remarked that besides the interplay between subglacial structures and ice dynamics mentioned above, there exists also a reciprocal interplay between subglacial dynamics and ice structures. The latter has been recently observed in subglacial lake discharges promoted by the overburden pressure of the overlying ice [26, 160], which indicate that the dynamics of subglacial hydraulic systems can be quite sensitive to the mechanical properties of the ice cover.

Exciting news in the context of Antarctic subglacial hydrology has been the recent discovery of meltwater

[12] It should be remarked that no evidence of superplastic flow could be found, which would require much larger amounts of grain boundary sliding and grain switching (cf. [41, 69, 70, 119, 140]).

at the bottom of the EDML deep borehole at Dronning Maud Land, Antarctica [35, 109]. Large amounts of subglacial water invaded the lowest 170 m of the 2774.15 m depth borehole and obstructed the hole by freezing at ca. 2600 m depth. The source of all this water is still unclear: no indication of water could be recognized in the radar-echo sounding data (F. Wilhelms and D. Steinhage, personal communication), whereas the lowest two meters of the EDML deep ice core consist of a rather unusual ice that shows very low electrical conductivity and is essentially free of air hydrates or other impurities [90]. No trace of geological sediments could be detected either (F. Wilhelms, personal communication).

A sample of the EDML subglacial water (SGW) was collected from the bottom of the hole in January 2006. It froze almost immediately during its way up to the surface, due to the pressure–temperature shock (pressure and temperature changes of ca. 25 MPa and $-40°$C, respectively, in less than one hour). X-ray and Raman investigations of the SGW sample [103] revealed that at least a substantial part of it consists of *clathrate hydrates with structure type II* (*sII hydrates*). After several investigations, the drilling fluid densifier used in the EDML drilling program, viz. hydrochlorofluorcarbon 141b (HCFC-141b, also abbreviated as R-141b), has been identified as the main sII-hydrate former. It is conjectured that the HCFC-141b has reacted with the SGW in the borehole during drilling [103].

It should be remarked that HCFC-141b is known by chemical engineers as an effective sII-hydrate former at any temperature below 8.6°C and pressure higher than 42 kPa [20, 110]. Consequently, the use of HCFC-141b as densifier for deep drilling raises several concerns. Former investigations by Talalay & Gundestrup [145] indicate that HCFC-141b has the ability to “bond”, to a limited extent, to ice chips within the borehole, thereby increasing their mass density. Over a long period of time such chips may sink to the bottom of the borehole to form slush, which may contribute to the sticking of the drill when the driller ignores the possibility of a slushy bottom, e.g. after a long period of pause such as a long winter of inactivity. In addition, the observed formation of HCFC-141b clathrate hydrate explains the abrupt termination of a major fraction of drill runs in the warm ice, where the drill suddenly blocks completely and a bright white material is found between ice core and core barrel or in the chip transport system of the drill.

From the arguments above we conclude that the use of HCFC-141b as drilling fluid densifier should be avoided and prospective new drilling liquids should be screened for their ability to form clathrate hydrates when in contact with ice or meltwater.

The case of the EDML borehole reminds us that field surveys using radar-echo sounding and similar methods are still not fully adequate for the identification of small subglacial structures, like narrow channels or layers of water-saturated sediment. This fact added to the recent findings of numerous lakes and complex hydrological systems beneath the Antarctic ice sheet show that the risk of inadvertently meeting pristine subglacial water at the bottom of future boreholes is still not quite predictable. It is now widely recognized that the Antarctic subglacial environment is very vulnerable to contamination, especially by harmful chemicals as HCFC-141b. We have at the moment no means to estimate the damage that could be caused by a potential contamination of the Antarctic hydrological system… and to rely on the hope that this may not happen, or if it happens, that the contamination will be restricted to a small, isolated sector, is so far totally unfounded. Indeed, false hopes are more dangerous than fears.

8 Conclusion

> *Es ist ein herrliches Gefühl, die Einheitlichkeit eines Komplexes von Erscheinungen zu erkennen, die der direkten sinnlichen Wahrnehmung als ganz getrennte Dinge erscheinen.*[13]
>
> Albert Einstein [42], in a letter to Marcel Grossmann, 14 April 1901.

The importance of polar ice sheets for the dynamics of Earth’s climate is evidenced not only by their active interplay with the atmosphere and the hydrosphere (e.g. sea-level rise, global warming), but also by their passive recording of the global past climate. The basic coupling between these two processes, viz. active environmental interplay and passive paleoclimate recording, is revealed by the multiscale structure of the ice sheet, which comprises a series of dynamic structural features ranging from megadunes and subglacial lakes (up to several kilometers in size) to sub-microscopic features like dislocation clusters and micro-inclusions.

The significance of these structures is four-fold:

1. They enhance/inhibit the ice flow.
2. They determine the integrity of the climatic record.
3. They serve as qualitative indicators of the ice-flow history.
4. They serve sometimes as complementary records of past climate.

Clearly, items 3 and 4 show that the genesis and evolution of such structures are caused by the ice-sheet deformation and the action of the environment, whereas items 1 and 2 tell us that the multiscale structure of an ice sheet provides feedbacks to the ice deformation and its interactions with the environment. Thus, an intricate *Structure–Form–Environment Interplay* (SFEI) takes place in polar ice sheets, which is further complicated by the reciprocal interaction of structures on different scales

[13] Transl.: *It is a wonderful feeling to recognize the unity of a complex of appearances which, to direct sense experiences, appear to be quite separate things.*

(consider for instance the interplay between flow, temperature, impurity content, grain stereology and crystallographic texture, as described in Sect. 6 for soft ice layers in grounded ice, as well as in Part II [94] for ice shelves).

Glaciologists and climatologists are not unaware of the SFEI issue, as particular aspects of the problem are well documented in the literature, e.g. the relationship between ice-sheet flow and crystallographic texture, or the role of the pore space geometry of firn (porosity, tortuosity, etc.) on the transport of climatic tracers into deep ice. Actually, it can be said that, in a certain sense, any study of polar ice structures invariably represents an attempt to understand some aspect of the SFEI. Notwithstanding, many features of the SFEI remain unclear and a comprehensive perspective of the problem is lacking.

In this work we discussed many examples of multiscale structures and interactions that support the view of the Antarctic ice sheet as a heterogeneous mixture of structured media that interact in a hierarchical fashion via the SFEI. This view is based on the concept that the usual interpretation of structures on diverse scales as "quite separate things" is in fact misleading. Most of these structures are so intimately coupled that their dynamics can only be understood when they are collectively regarded as a "unity of a complex of appearances", that is, as a *multiscale structure*. This does not mean that we should discard the specialized studies of ideally isolated structures, but rather that the time has come to complement them with a unifying, more comprehensive perspective.

The quest for a comprehensive perspective of the SFEI problem should not be considered an exercise of self-indulgence, innocence, arrogance or vagueness. Rather, it is a necessary requisite to make a sensible advance in a subject that is becoming increasingly multidisciplinary. As discussed in [52], geoscientists see in the flow of ice sheets a unique oportunity to study the natural deformation of polycrystals on size- and timescales far beyond those achieved experimentally, physicists and materials scientists regard ice as a useful ideal material for the research of diverse physical processes, crystallograpers wonder at the complex structures of air hydrates enclosed in polar ice, and there are many other examples. To exploit all these possibilities in a systematic manner, we have to have multiscale scientists able to coordinate and harmonize all specific lines of research with a wide view of the whole problem.

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