Available online at www.sciencedirect.com

C. R. Physique 5 (2004) 683–685

COMPTES RENDUS PHYSIQUE

http://france.elsevier.com/direct/COMREN/

Ice: from dislocations to icy satellites / La glace : des dislocations aux satellites de glace

Foreword

From snow crystals to large ice-sheets and from terrestrial ice to icy satellites of the solar system, ice and icy objects have forever fascinated and sometimes frightened mankind. This is justified by the role that ice has played – and continues to play – in shaping the Earth's surface, in affecting climate, in dictating lines of communication in polar and in mountainous regions, in supplying water to populations, etc.

This fascination and fear turned into scientific curiosity near the end of the XVIIIth century when H.B. de Saussure climbed Mont Blanc to discover and study the world of glaciers and altitude (de Saussure, 1780 [1]). Since then, this interest has never declined. Indeed, the interest in ice has been renewed during these past few decades when it was realized: (i) that ice-sheets have recorded the Earth's climate over thousands of years (Petit et al. [2]); (ii) that the sea ice cover and the polar ice-sheets play a fundamental role in the Earth's climate through complex interactions with the oceans and the atmosphere, a role which becomes even more critical in the recent context of global warming; and (iii) that ice and possibly liquid water constitute a significant part of many satellites of the giant planets of the outer solar system, qualifying them as candidates for extraterrestrial life.

The phase diagram of solid water is complex: there are 12 allotropic phases with different crystallographic structures plus at least two amorphous phases. However, the only phase stable under the conditions of pressure and temperature encountered on Earth or within the upper layers of the icy satellites is hexagonal ice Ih. Details about the other allotropic phases as well as the physical properties of ice Ih have been reviewed by Petrenko and Whitworth [3]. Reviews on ice mechanics and fracture, as well as applications to civil engineering, can be found in a recent special issue of Engineering Fracture Mechanics [4].

This special issue of Les Comptes Rendus – Physique presents a compilation of papers that focus on some particularly 'hot' topics in the physics of deformation and fracture of ice Ih and its consequence in terms of mechanical modelling. One of the links between these contributions is the change of scale: ice mechanics and glaciology explore a huge range of time and spatial scales, from millennia to microseconds and from atoms to planets. The aim is to link these different scales.

Hexagonal ice Ih is characterized by very strong plastic anisotropy (Duval et al. [5]). This results from the structure and behaviour of dislocations which move preferentially over the basal planes. The subject of dislocations is treated by Louchet [6] who presents new insights from a comparison of ice Ih with semiconductors. Louchet discusses first the core structure of dislocations and its relation to dislocation mobility. Proton disorder, an atomic-scale mechanism specific to ice, influences bond reconstruction, thereby affecting kink formation rates and kink velocities, which in turn control the velocity of individual dislocations. From velocity equations, coupled with evolution equations for the density of dislocations deduced from multiplication and annihilation kinetics, Louchet derives the constitutive equation for the flow of ice single crystals and then compares this result with macroscopic experimental data.

Montagnat and Duval [7] discuss also the viscoplastic behavior of ice. They consider a larger range of spatial scale, from polycrystals to the ice sheets, and stress the importance of the viscoplastic anisotropy. Indeed, basal slip of dislocations generates strain incompatibilities between neighbouring grains with different crystallographic orientations. This determines the rate-controlling processes in the creep of polar ice; that is, the processes which relax these incompatibilities. Under the low-stress conditions relevant for ice sheets, Montagnat and Duval argue that grain boundary migration associated with grain growth and recrystallisation are the best candidates. Polycrystalline ice can become mechanically anisotropic when fabrics form as the result of deformation (see e.g. Gow and Williamson [8]; Thorsteinsson et al. [9]). Consequently, the observed changes of size and orientation of grains with depth result in large variations of viscosity within ice sheets. This complicates ice flow modelling and consequently the dating of ice layers along ice cores (Durand et al. [10]). Montagnat and Duval present the different 'micro–macro' approaches which can be used to account for the development of fabrics and the anisotropic behavior of polar ice.

Despite its importance in terms of mechanical deformation, anisotropy is generally ignored when modelling the flow of ice sheets, except in some recent works (Gagliardini and Meyssonnier [11]). Another simplification is made when modelling ice sheet flow, regarding the aspect ratio thickness/horizontal extension of the glacier. This ratio is sufficiently small for the

doi:10.1016/j.crhy.2004.08.003

mechanical problem to be expressed within the so-called 'shallow ice approximation' (SIA). As it greatly reduces the complexity of modelling, it is tempting to extend the SIA for the modelling of mountain glacier flow. However, Lemeur et al. [12] shows that the validity of the SIA is at least questionable in this case, and he proposes new tracks to get a compromise between reasonable approximations and reasonable complexity of the modelling.

If the viscosity of ice within ice sheets changes with depth, deformation is also strongly heterogeneous on the horizontal plane. The discharge of the flux from ice sheets does not occur homogeneously. Instead, it occurs along narrow (relative to the ice sheet size) regions of rapidly moving ice called ice streams (Bamber et al. [13]). Alley et al. [14] address this complicated topic which involves ice flow as well as friction over bedrock or subglacial till. They review the mechanisms that can explain why ice is flowing faster within ice streams than elsewhere, and then discuss the restraining forces on ice-stream flow. In the second part of their paper, Alley et al. open a question which is common to different contributions of this issue; that is, the interaction between the cryosphere and the Earth's climate. As ice streams discharge much of the flux of large ice sheets, their response to global warming is critical in predicting the ice sheet mass balance (Rignot and Thomas [15]). Alley et al. report increasing evidence for an acceleration of ice streams in response to warming, with consequences in terms of ice sheet mass imbalance and possibly sea level rise (Miller and Douglas [16]), although they stress the difficulty of predictions at our current level of knowledge.

It is now well established that the mass balance of mountain glaciers, especially when measured each year at the same (local) place, is an excellent measure of the energy budget and consequently a good proxy of climatic changes (Vincent et al. [17]). Unfortunately, such monitoring has been performed only on few glaciers and from 50 years at best. Observations of glacier front positions are much more widely spread, with sometimes time series as long as 200 years or more (Hoelzle et al. [18]). However, the interpretation of glacier retreats in terms of climatic warming is difficult, as the front position depends on climatic parameters as well as on glacier flow, with a century-scale inertia. This underlines the need for better modelling of glacier flow, as detailed by Lemeur et al. [12], in order to differentiate these different effects.

Another element of the cryosphere is also strongly interdependent with the Earth's climate: sea ice. Sea ice, whose average thickness is around 2 m for multiyear ice, insulates the ocean from the atmosphere. The fracturing and divergent deformation of the ice cover decreases the albedo and allows more shortwave absorption by the ocean, thereby shrinking the ice cover during summer, thus reducing its strength and possibly increasing the fracturing – a positive feedback loop (Moritz et al. [19]; Zhang et al. [20]). On the other hand, sea ice fracturing during winter enhances the production of new ice and thereby modifies the heat budget in polar regions. Within the context of global warming, these complex interactions could be critical (Morison et al. [21]). Observations reveal that the Arctic sea ice cover already has shrunk during the past few decades, either in terms of average thickness (Kerr [22]) or of geographical extent (Morison et al. [21]). These trends should increase during the 21st century with strong climatic, environmental and economical consequences (Kerr [23]). Therefore, better characterization and better modelling of sea ice deformation and fracture appear as important scientific challenges for the next decades.

Compared to ice sheet and glacier flow, sea ice deformation is characterized by much larger strain-rates and consequently by more brittle behavior. As observed from satellites, the deformation of the Arctic sea ice cover is characterized by an extremely strong spatial heterogeneity with zones of intense deformation and fracturing separating quasi-rigid plates (Moritz and Stern [24]). Weiss and Marsan [25] study this heterogeneity by means of multiscaling analyses. They show that the fracture patterns as well as the deformation fields of the cover have a scale-invariant, multifractal character similar to what is observed for velocity fields in turbulent flow. This raises the question of the origin of this heterogeneity: localization resulting from the fracture process and the associated long-range interactions between fractures, and/or the fingerprint of the main driving force for sea ice deformation which is the turbulent winds? Weiss and Marsan then discuss how this heterogeneity implies a strong spatial and temporal variability of ice thickness or of the fraction of open water which should be taken into account in climatic models.

Using the multiscaling properties of sea ice deformation Marsan et al. [26] extrapolated the large-scale observations down to the meter scale, where the mechanical behavior of ice is well documented (Schulson [27]), and show that most of this deformation is accommodated by brittle failure over short, transient and very localized fracturing episodes. In agreement with this view, Schulson and Hibler [28] propose an interpretation of sea ice deformation and faulting in terms of scale-independent fracture mechanics concepts. They interpret the elongated zones of intense deformation lacing through the cover as Coulombic shear faults, and establish strong analogies with compression failure mechanisms observed during laboratory testing (Schulson et al. [29]). On this basis, they propose a numerical modelling of faulting based on a scale-independent effective friction, which reproduces the localization of the deformation.

The last contribution of this special issue strikingly illustrates the problem of the link between (very) different scales. Ice is a major component of the outer solar system, especially of the satellites of the giant planets, such as the jovian satellites Europa, Ganymede and Callisto. Sotin and Tobie [30], discuss the internal structure and dynamics of these icy satellites, and particularly how this dynamics can be constrained by ice physics and ice rheology. This is a difficult task, owing to the spatial and time (billions of years) scales involved as well as the exotic conditions encountered, particularly the very low temperatures near the surface. This implies an extrapolation of the ice flow laws documented under 'classical' conditions from small scales physics (see Louchet [6] as well as Montagnat and Duval [7] in this issue) down to very low temperatures, very low stresses and strain rates, and very large time scales. Keeping in mind these difficulties, the analysis of Sotin and Tobie, which involves thermal convection as well as tidal dissipation within the ice, argues for the existence of an ocean under the icy crusts of Europa, Ganymede and Callisto, thereby opening fascinating questions.

To conclude, this special issue of les Comptes rendus – Physique presents up-to-date discussions on several aspects of the physics of deformation of one of Nature's most fascinating materials, which takes a fundamental place in our fragile environment. We hope this will stimulate further research, possibly from new perspectives.

Finally, I would like to thank the contributors to this issue, as well as Jean Dercourt, Editorial Director of les Comptes rendus, and Guy Laval for their invitation to edit this special issue on ice.

References

[1] H.B. de Saussure, Voyage dans les Alpes, Neuchâtel, Suisse, 1780.
[2] J.R. Petit, J. Jouzel, D. Raynaud, N.I. Barkov, J.M. Barnola, I. Basile, M. Bender, J. Chapellaz, M. Davis, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, M. Stievenard, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, Nature 399 (1999) 429–436.
[3] V.F. Petrenko, R.W. Whitworth, Physics of Ice, Oxford University Press, Oxford, 1999.
[4] E.M. Schulson (Ed.), Special issue on Fracture of Ice, Eng. Fract. Mech. 68 (17/18) (2001).
[5] P. Duval, M.F. Ashby, I. Andermann, Rate-controlling Processes in the creep of polycrystalline ice, J. Phys. Chem. 87 (1983) 4066–4074.
[6] F. Louchet, Dislocations and plasticity in ice, C. R. Physique 5 (2004), this issue.
[7] M. Montagnat, P. Duval, The viscoplastic behaviour of ice in polar ice sheets: experimental results and modelling, C. R. Physique 5 (2004), this issue.
[8] A.J. Gow, T. Williamson, Rheological Implications of the Internal Structure and Crystal Fabrics of the West Antarctic Ice Sheet as Revealed by Deep Core Drilling at Byrd Station, CRREL, Hanover, NH, USA, 1976.
[9] T. Thorsteinsson, J. Kipfstuhl, H. Miller, Texture and fabrics in the GRIP ice core, J. Geophys. Res. 102 (1997) 26583–26599.
[10] G. Durand, F. Graner, J. Weiss, Anisotropy of grain boundaries in crystals: a new measurement technique applied to polar ice, Europhys. Lett., in press.
[11] O. Gagliardini, J. Meyssonnier, Simulation of anisotropic ice flow and fabric evolution along the GRIP-GISP2 flow line (Central Greenland), Ann. Glaciol. 30 (2000) 217–223.
[12] E. Lemeur, O. Gagliardini, T. Zwinger, J. Ruokolainen, Glacier flow modelling: a comparison of the Shallow Ice Approximation and the full Stokes Solution, C. R. Physique 5 (2004), this issue.
[13] J.L. Bamber, D.G. Vaughan, I. Joughin, Widespread complex flow in the interior of the Antarctic ice sheet, Science 287 (2000) 1248–1250.
[14] R.B. Alley, S. Anandakrishnan, T.K. Dupont, B.R. Parizek, Ice streams – fast and faster?, C. R. Physique 5 (2004), this issue.
[15] E. Rignot, R.H. Thomas, Mass balance of polar ice sheets, Science 297 (2002) 1502–1506.
[16] L. Miller, B.C. Douglas, Mass and volume contributions to twentieth-century global sea level rise, Nature 428 (2004) 406–409.
[17] C. Vincent, G. Kappenberger, F. Valla, A. Bauder, M. Funk, E. Le Meur, Ice ablation as evidence of climate change in the Alps over the 20th century, J. Geophys. Res. 109 (D10104) (2004).
[18] M. Hoelzle, W. Haeberli, M. Dischl, W. Peschke, Secular glacier mass balances derived from cumulative glacier length changes, Global Planet. Change 36 (2003) 295–306.
[19] R.E. Moritz, C.M. Bitz, E.J. Steig, Dynamics of recent climate change in the Arctic, Science 297 (2002) 1497–1502.
[20] J. Zhang, D. Rothrock, M. Steele, Recent changes in arctic sea ice: the interplay between ice dynamics and thermodynamics, J. Climate 13 (17) (2000) 3099–3114.
[21] J. Morison, K. Aagaard, M. Steele, Recent environmental changes in the Arctic: A review, Arctic 53 (4) (2000) 359–371.
[22] R.A. Kerr, Will the Arctic Ocean lose all its ice?, Science 286 (1999) 1828.
[23] R.A. Kerr, A warmer Arctic means change for all, Science 297 (2002) 1490–1492.
[24] R.E. Moritz, H.L. Stern, Relationships between geostrophic winds, ice strain rates and the piecewise rigid motions of pack ice, in: J.P. Dempsey, H.H. Shen (Eds.), Scaling Laws in Ice Mechanics and Ice Dynamics, Kluwer Academic Publishers, Dordrecht, 2001, pp. 335–348.
[25] J. Weiss, D. Marsan, Scale properties of sea ice deformation and fracturing, C. R. Physique 5 (2004), this issue.
[26] D. Marsan, H. Stern, R. Lindsay, J. Weiss, Scale dependence and localization of the deformation of arctic sea ice, submitted, 2004.
[27] E.M. Schulson, Brittle failure of ice, Eng. Fract. Mech. 68 (17/18) (2001) 1839–1887.
[28] E.M. Schulson, W.D. Hibler III, Fracture of the winter sea ice cover on the Arctic Ocean, C. R. Physique 5 (2004), this issue.
[29] E.M. Schulson, D. Iliescu, C. Renshaw, On the initiation of shear faults during brittle compressive failure: a new mechanism, J. Geophys. Res. 104 (1999) 695–705.
[30] C. Sotin, G. Tobie, Internal structure and dynamics of the large icy satellites, C. R. Physique 5 (2004), this issue.

Jérôme Weiss
Laboratoire de glaciologie et géophysique de l'environnement,
CNRS, 54, rue Molière, 38402 St Martin d'Hères cedex, France
E-mail address: weiss@lgge.obs.ujf-grenoble.fr (J. Weiss)