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by

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One-sentence summary: **In this report, submitted directly from the EPICA (European Project for Ice Coring in Antarctica) drilling camp in Dronning Maud Land (DML), Antarctica, we describe the microstructure of deep layers of soft ice in the EPICA–DML ice core.**

Abstract: **A peculiarity of the EPICA–DML drilling camp in Antarctica has been the establishment of a subterranean laboratory for ice microscopy on site. There we performed the first microscopic observations of soft ice strata in the EPICA–DML deep ice core. Contrary to common expectations, the softening is not produced by preferred orientations of the ice lattice (fabric), but rather by dynamic grain boundary structures formed by microshear under conditions of high temperature, moderate stress, small grain size and high impurity content. Evidently, the existence of layers of soft ice has serious implications for ice core dating and related paleoclimatic studies.**

Thanks to the modern globalization of culture (and sad as it may be), the contemporary idealization of a birthday cake is roughly the same throughout the world: a pile of sweet bread pieces separated by layers of soft (usually creamy) filling. The prospect that the stratigraphy of the Antarctic ice sheet could resemble the structure of such a birthday cake —namely, strata of soft ice sandwiched between layers of normal (harder) ice— has been the fear of many glaciologists and climate scientists. The reasons for such a worry are indeed justified: the overburden pressure of the ice sheet may squeeze soft ice faster than normal ice, invalidating standard models of ice dating based on the premise of monotonic layer thinning. Evidently, errors in ice core dating imply uncertainties in climatic records. Furthermore, soft ice strata may produce layers of enhanced deformation, which are particularly susceptible to flow instabilities that disrupt the temporal stratification of the ice core and consequently destroy its climatic records.

Despite several evidences for soft ice layers derived from tunnel and borehole closure/tilting rates in polar regions (*1–4*), the causes of such enhanced flows have been poorly investigated, remaining a matter of speculation. Certain is only the fact that all soft ice strata reported so far coincide with layers of high impurity content and small grain sizes. Presently, the most accepted explanation for the formation of soft strata in ice sheets is related to the preferred lattice orientations of the ice grains, often called fabric. According to this conjecture (*4*), a soft ice stratum should be characterized by an exceptionally strong fabric, produced by some unspecified effect of high impurity concentration and small grain sizes. The strong fabric so generated should be compatible with the stress acting on that layer, in the sense that ice with such a fabric would be softer (for that particular stress state) than isotropic ice.

Accidentally, we have had in the current season (Antarctic summer 2005/06) the opportunity to discover our own evidences for soft ice layers at the EPICA–DML drilling camp in Antarctica (*5*). An insufficient amount of densifier in the borehole fluid, used to counterbalance the closing pressure on the hole walls, gave rise to a noticeable closure (diameter reduction by about five millimeters) in a deeper part of the hole, namely from 2385 m down to the final depth reached in the former drilling season (2565 m depth, Antarctic summer 2003/04). Unfortunately, no correlation between closure and tilt of the hole was possible, due to problems with the inclinometer. Most interesting is that the closure occurs quite abruptly with depth. This fact has attracted our attention to the existence of a remarkable softening effect in the deep ice.

In contrast to former investigations of soft ice layers, we did not have solely the fabric and stratigraphic (linescanner) data, but also a detailed microscopic mapping of the whole ice core, mostly prepared in our on-site laboratory (*6*). We started, however, with a standard fabric analysis. To our surprise, we found no noticeable difference between the fabrics in the soft stratum and in the surrounding ice (Fig. 1). However, as in other accounts of soft ice layers, we observed from stratigraphic and chemical data a precise correlation between borehole closure, high impurity content and small grain sizes (*5, 7*). The unchanged fabric lead us to conclude that the softening should not be associated to an enhancement of dislocation glide by impurities, since an increase in glide activity would certainly affect the fabric. In order to corroborate this hypothesis, we decided to analyze ice core photomicrographs made on site, with the hope of finding in subgrain boundaries and slip bands some hint about changes in the dislocation activity of ice. Nevertheless, no noticeable change in the structure of slip bands and subgrain boundaries was visible: dislocation glide seemed not strongly affected by impurities. Additionally, we found also no indication of intense deformation by diffusion (Nabarro–Herring/Cobble creep), which should be revealed by zones of clean ice near grain boundaries.

Notwithstanding, the micrographs revealed something unexpected. The upper image in Fig. 1 illustrates the usual grain boundary structure of polar ice from the EPICA–DML site (2185 m depth). Similar structures have been also observed in ice from Dome C (Antarctica), GRIP and NorthGRIP (Greenland) (*6, 8, 9*). There is no identifiable pattern in that sample, just an irregular network of grain boundaries. In contrast, the lower images in Fig. 1 show the typical grain boundary structure within the EPICA–DML soft ice layer (2385 m and 2395 m depth): there is a conspicuous pattern of aligned grains, with most grain boundaries oriented in two preferred directions and having a strong tendency to produce long, unbroken chains nearly parallel to the local stratigraphy (see also Fig. 2). Such a *“slanted brick wall pattern”* is particularly evident in the depth range 2385–2405 m, although its presence can be continually identified in all ice core samples down to 2575 m depth.

As the current data on impurity content and borehole closure end at the depth reached in the former drilling season (2565 m depth, Antarctic summer 2003/04), we have no direct indication of the precise depth where the soft ice layer ceases. Nevertheless, from the grain size data and the persistence of the slanted brick wall pattern —both extracted from on-site microstructure mapping— we estimate that the soft ice layer at the EPICA–DML site should lie between 2385 m and 2575 $\pm$5 m depth. If this depth range corresponds to a single soft ice layer, 190 m thick, or if it is composed of a series of thinner strata, is still not certain.

Now, what is the relation between the observed “slanted brick wall pattern” of the microstructure and the softening of ice evidenced by the closure of the EPICA–DML borehole? The answer can be found in a careful analysis of the high-resolution micrographs, which reveal a frequent arrangement of subgrain boundaries, as illustrated in Fig. 2: most subgrain boundaries tend to act as “bridges” connecting the detached parts of long chains of grain boundaries. Grains containing such subgrain boundaries appear to be “sheared off” by the grain boundary chains crossing them. This kind of microscopic deformation mechanism is known as *microstructural shear*, or simply *microshear* (*10,11*). It has often been studied in laboratory experiments (where a corresponding pattern, called “tabular-grain structure”, is frequently generated), but its observation in naturally deformed rocks has been so far inhibited by extensive grain boundary migration and recrystallization. The reason why we are able to identify microshear in the polar ice samples shown in Figs. 1 and 2 is an exceptional combination of high temperature (approx. $> -15°$C, i.e. $> 94\%$ of melting temperature) and moderate stresses —both occasionally found in the lower depths of ice sheets— with a high impurity content that hinders recrystallization and reduces the migration rate of grain boundaries (indeed, this is one reason why small grain sizes correlate so well with high impurity content in all polar ice core records).

The manner in which microshear produces and maintains the slanted brick wall pattern is explained in Fig. 2. It is clear that a certain amount of sliding along grain boundary chains is necessary to produce the microshear zones shown in Fig. 2. However, in contrast to those deformation mechanisms usually subsumed under the names “grain boundary sliding” and “superplasticity”, in which each grain slides past its neighbors, the sliding by microshear is chiefly restricted to zones containing long grain boundary chains (several grains in size) and such zones can make their way also through grains, when suitable. As the grain boundary network evolves by deformation and grain boundary migration, new microshear zones may come into existence, while older ones are deactivated. As a result, at any instant the dislocation creep by basal glide is enhanced by transient, localized zones of microshear.

Even though the eventual displacement within a single microshear zone usually corresponds only to a fraction of the average grain size (i.e. up to several hundreds of microns in the EPICA–DML soft ice layer), extensive strain can be accumulated in a relatively short period of time if a large number of active microshear zones is sustained. It should be emphasized, however, that microshear does not replace the standard deformation mechanism in polar ice by dislocation glide. Rather, both processes must be complementary. More precisely, the natural deformation of normal (“clean”) polar ice should indeed be entirely caused by dislocation glide, whereas certain deep layers of ”warm” polar ice with high impurity content (like the one reported here) may deform in situ by a *combination* of dislocation glide *and* microshear. This combination renders the material softer than clean ice with the same fabric and deformed under the same conditions.

How and which impurities may affect the viscosity of the grain boundaries of polar ice (as well as the diffusive mass transfer needed to accommodate sliding along trijunctions and small grain boundary irregularities) remains a matter of future study, as the chemical properties of the EPICA–DML ice core are still under investigation (*5, 7*). Certain is that temperature should play a decisive role in the activation of microshear in ice, seeing that its competing mechanisms of promotion (grain boundary sliding, self-diffusion, subgrain formation) and inhibition (recrystallization, recovery, grain growth) are all thermally activated.

The discovery of cloudy ice layers softened by microshear in deep Antarctic ice has serious consequences not only to ice core dating and paleoclimate records, as already discussed, but also for rock mechanics and geology. Indeed, to the knowledge of the present authors this is the first observation of microshear in naturally deformed rocks, a deformation mechanism proposed since many years to be active in tectonites, but never observed in situ because of its concealing by recrystallization effects. Therefore, the current results prove that polar ice can serve very well as a geophysical model material.

A fundamental question which remains open is if the flow enhancement by microshear could be intense enough to generate *extrusion* of the soft ice stratum (somewhat like the extrusion of the soft filling of a birthday cake, when you warm it up) or even the mixing of distinct age layers. In principle, the microstructure of the soft ice layer is indeed compatible with extrusion flow, even though no pronounced change in the fabrics is visible. Nevertheless, a tangible corroboration of the extrusion conjecture would require the knowledge of the relation between shearing orientation and ice flow direction with depth. The problem is that such an information seems impossible to be obtained for the time being, as the relative orientation of the ice core —achieved by fitting its pieces, since the fabrics in that depth range have rotational symmetry with respect to the core axis (cf. Fig. 1)— has repeatedly been lost. This last issue obviates the need for drilling devices that can track the orientation of the ice core. As long as such an equipment is not available, we may be loosing essential information about the ice sheet dynamics of Antarctica and Greenland.

References and Notes

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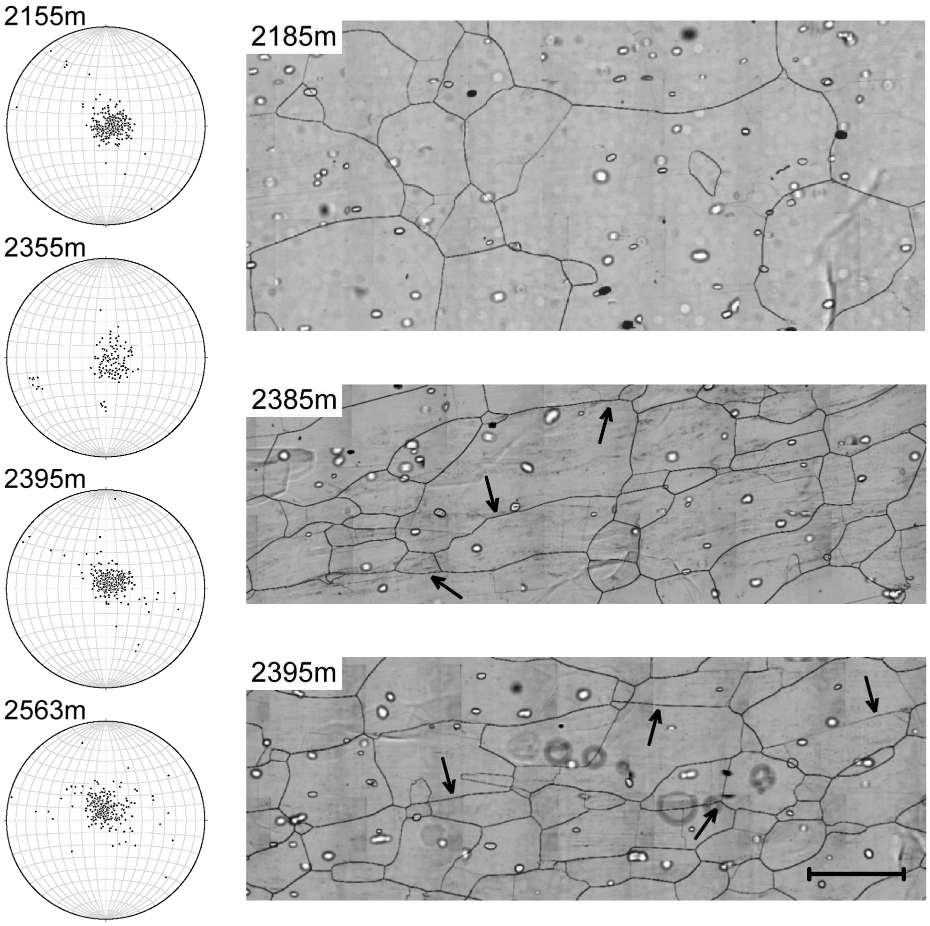
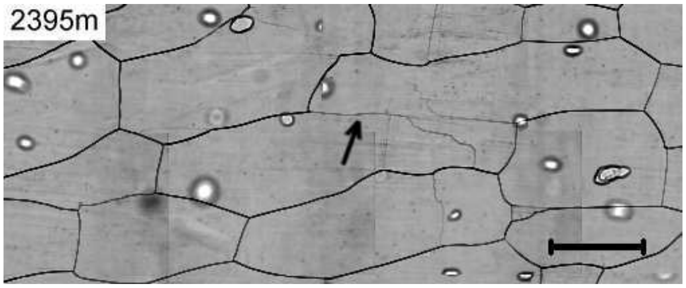


Figure 1: Microstructure of the EPICA–DML soft ice layer and its surroundings. (**Left**): Equal area fabric diagrams of four distinct borehole depths. There is no noticeable difference between the distributions of lattice orientations outside (2155 m and 2355 m depth) and inside (2395 m and 2563 m depth) the soft ice layer. (**Right**): Microstructure mapping micrographs of normal ("clean") polar ice (2185 m depth) and of ice from the soft layer (2385 m and 2395 m depth). Thick and thin lines denote grain and subgrain boundaries, respectively, bright and dark spots correspond to air hydrates, while the grey circles in the lowest picture are just bubbles in the silicone oil film that protects the ice surface. No peculiar pattern can be found in the grain boundary structure of normal polar ice (2185 m depth), whereas the lowest two pictures (2385 m and 2395 m depth) clearly show the slanted brick wall pattern and the long chains of grain boundaries (marked by arrows) characteristic of the soft ice stratum. All micrographs have the same magnification, the scale bar in the lowest picture has 2 mm.



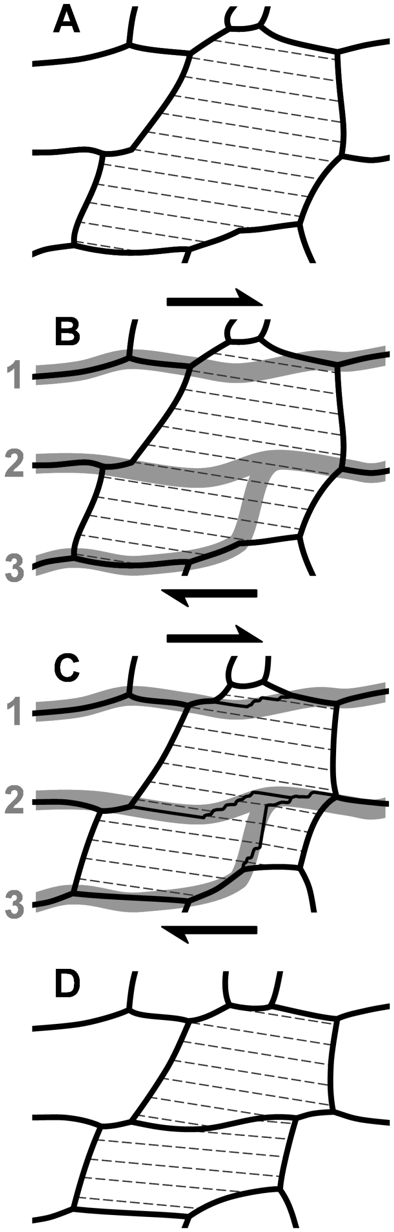


Figure 2: Relation between microshear and the "slanted brick wall pattern". (**Left**): Typical layered structure of grains in the soft ice stratum of the EPICA–DML ice core. The basic features of the micrograph follow the description given in Fig. 1; the scale bar stands here for 1 mm. Many grains are 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" (as indicated by the arrow). (**Right**): Pattern formation via microshear. Suppose that a certain grain (A) is corrupting the layered structure of the slanted brick wall pattern. Natural deformation of the ice sheet produces microshear zones along grain boundary chains (B), following the local stratigraphy. Such microshear zones can cross an obstructing grain in several ways, e.g. by cutting off its edges and protrusions (1), or by dividing it in two parcels (2), else by branching towards more active grain boundary chains (3). In any case, subgrain boundaries are formed (C). It should be remarked that dislocation activity within the grain is essential for subgrain formation. Finally, cut fragments are slowly consumed by grain boundary migration and the slanted brick wall pattern of the grain boundary network is improved (D). Evidently, such a layered structure promotes a positive feedback for further microshear.