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Highly deformed basal ice in the Vostok core, Antarctica

R. Souchez,[1] J.-R. Petit,[2] J. Jouzel,[3] J. Simões,[2] M. de Angelis,[2] N. Barkov,[4]
M. Stiévenard,[3] F. Vimeux,[3] S. Sleewaegen,[1] and R. Lorrain[1]

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[1] Our paper documents the build-up of a highly deformed basal ice layer in the basal part of the Vostok ice core. This is done mainly on the basis of an isotopic composition investigation of the ice. Complex deformation in the lower 228 m of the ice sheet has resulted in folding and intermixing of ice at a submetric scale and, for the upper part of this basal sequence, in interbedding of ice layers from distinct origins at a larger scale. This complex deformation occurred at a temperature largely below the pressure-melting point. The basal ice layer has built upwards and size-selective incorporation of bed material into the ice has taken place. The documentation of this complex basal deformation has implications for the maximum age of ice that will be useful in paleoclimate studies and for ice sheet dynamics. *INDEX TERMS:* 1040 Geochemistry: Isotopic composition/chemistry; 1827 Hydrology: Glaciology (1863); 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 9310 Information Related to Geographic Region: Antarctica

1. Introduction

[2] From the surface to a depth of 3310 m the Vostok ice core has given one of the most interesting paleoenvironmental record at interglacial-glacial time scales [*Petit et al.*, 1999]. Below 3538 m, *Jouzel et al.* [1999] showed that the ice core consists of lake ice developed above subglacial lake Vostok. The mechanism of lake ice formation was further investigated by *Souchez et al.* [2000a]. In between, the ice core shows either evidence for the presence of dust particles coming from the ice-bed interface [*Simões et al.*, in press] or ice properties indicating that the past-environmental record in the ice is lost [*Petit et al.*, 1999]. A detailed investigation of this part of the core between 3311 and 3538 m depth constitutes the subject of this paper.

[3] The deepest 89 m of this 228 m thick part of the core shows evidence of glacial flour coming from the bed. This is indicated by a higher mean mode of dust particles if compared with the ice above (3.4 μ instead of 2.1 μ) and by the presence of particles as large as 30 μ. Also the curve with depth of the weight ratio of particles larger than 2.5 μ in diameter to the total dust weight shows a step-like increase at 3449 m depth. The higher value of this weight ratio is maintained throughout the lowest 89 m of the record. Furthermore, the close correlation between lower δ-values and higher non-sea salt calcium content which is present above 3449 m disappears in the lowest 89 m of ice above the lake ice [*Simões et al.*, in press].

2. Ice Composition Characteristics

[4] The hydrogen and oxygen isotopic composition were determined in Saclay on 5 ml samples with an accuracy of 0.5‰ in δD and 0.05‰ in δ^{18}O. These accuracy's give a one σ error on deuterium excess ($d = \delta D - 8\,\delta^{18}O$) of ±0.7‰. Such a value makes possible an investigation of this parameter which exhibits much less variability than δD or δ^{18}O. The sampling interval is 1 m.

[5] Figure 1 gives the δD − δ^{18}O relationship for the basal part of the Vostok ice core between 3311 m depth and the lake ice at 3538 m depth. The regression line obtained has the equation $\delta D = 8.06\,\delta^{18}O + 17.8$ with $R^2 = 0.99$. This is not very different from the relationship obtained for the whole core down to 3310 m [*Vimeux et al.*, in press] on ice age interval 0–420,000 years ($\delta D = 7.94\,\delta^{18}O + 11.33$). Such similarity precludes any major change in isotopic composition for the basal ice due to phase changes between liquid water and ice.

[6] Figure 2 gives the δD profile of the Vostok core between 3311 m and 3538 m. This profile shows a striking difference in amplitude of δ-variations from the top to the bottom. Down to 3346 m the δD values oscillate between −433‰, typical interglacial value, to −480‰, typical glacial value. This does not mean that older climatic cycles are displayed undisturbed since there is no lag between gas parameters and δ-values, a situation not present for the four climatic cycles identified higher up in the core [*Petit et al.*, 1999]. This can be interpreted as interbedding of ice layers with different characteristics (either glacial ice or interglacial ice). The interbedding is most probably the result of large scale folding as indicated by inclined ash layers (up to 25° to the horizontal) in opposite directions (at 3310.6 and 3310.8 m depth). Such interbedding in top of the basal sequence was also found to be present at GRIP in Central Greenland [*Souchez et al.*, 2000b].

[7] After a decrease in the amplitude of δD values down to 3405 m, the isotopic signal oscillates quite regularly within a narrower range between about −450‰ and about −465‰. The deuterium excess provides insight that helps explain the situation. *Vimeux et al.* [1999] showed that, if deuterium excess is plotted against δD for the glacial-interglacial climatic cycles displayed in the Vostok core, a complex behaviour appears. During transitions from glacial to interglacial values, d remains quite stable. During glacial inceptions, there is an inverse relationship between d and δD. Finally during glacial stages, no definite trend is displayed.

[8] In Figure 3, the two oldest glacial-interglacial climatic cycles from the Vostok ice core are displayed on a d-δD diagram. They represent ice between 2755 and 3108 m depth (black circles) and between 3109 and 3309 m depth (open circles) respectively. Ice from these two cycles or from older ones is more likely to be affected by complex deformation (more complex than simple shear) than ice from the two last glacial-interglacial climatic cycles which is closer to the surface of the ice sheet. Now, samples of ice below 3405 m depth (crosses) are also indicated in Figure 3. The crosses representing such ice samples are mostly filling the central hole of the closed figure representing the distribution of sample points from the two oldest climatic cycles. Moreover, if a vertical

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[1] Département des Sciences de la Terre, Université de Bruxelles, Brussels, Belgium.

[2] Laboratoire de Glaciologie et de Géophysique de l'Environnement, Saint-Martin-d'Hères, France.

[3] Laboratoire des Sciences du Climat et de l'Environnement- CEA Saclay, France.

[4] Arctic and Antarctic Research Institute, St Petersburg, Russia.

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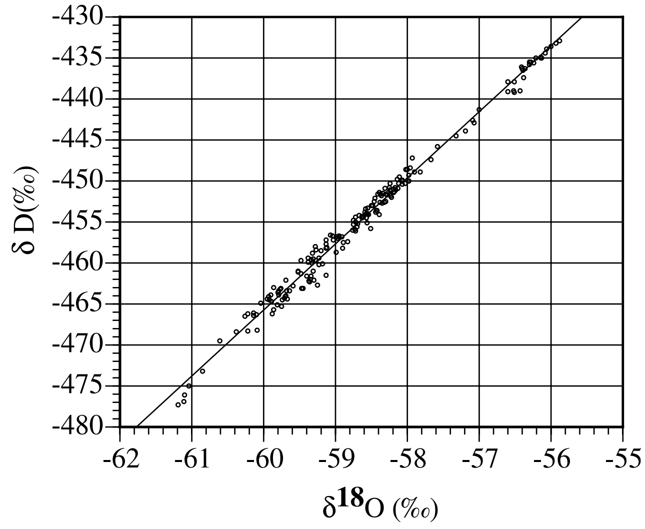

Figure 1. $\delta D - \delta^{18}O$ relationship in basal ice from the Vostok ice core (between 3311 and 3538 m depth).

line corresponding to the δD value of the middle of the maximum range for the climatic cycles is drawn in the figure (dotted line), most of the sample points from the two oldest climatic cycles are within the part containing the more negative values. Since one sample was measured per meter of core, this indicates that the colder periods are more developed in terms of ice thickness than the warmer ones. Now, the crosses representing ice samples below 3405 m depth are all included within this part containing the more negative values.

[9] Such characteristics point to the occurrence of a folding/mixing process for the basal ice of the Vostok core. Folding/mixing will produce ice having an isotopic composition intermediate between those of ice layers before such a complex deformation, hence the distribution of the ice samples in a d-δD diagram in the hole described above. There is a higher probability that the intermediate isotopic compositions produced result from folding/mixing of ice more frequently present at depth. The distribution within the part containing the more negative δD values can so be understood. Within this context, the reduction in amplitude in the δD variations with depth can be viewed as implying more complex ice deformation at depth, a very likely situation if one considers the uneven bedrock topography (Siegert and Ridley, 1998) where the ice is grounded upstream from Vostok station. Deformation more complex than simple shear is most pronounced close to the bed where ice viscosity is reduced by higher temperatures.

[10] Since ice from the two climatic cycles considered here is most probably not deformed by such a process upstream from Vostok, it must be assumed that older climatic cycles which are presumably involved in basal ice deformation have the same general isotopic characteristics with a similar d-δD pattern. This is in our mind reasonable since all the four climatic cycles present in the Vostok ice core display such characteristics.

[11] The damping of δD variations due to folding/mixing is also present in the trace impurities distribution. Marine (Na^+_m , Cl^-) and terrestrial (non sea salt Mg^{++} and Ca^{++}) trace impurities have been studied in the basal ice below 3311 m depth by *Simões et al.* [in press]. The concentrations found are intermediate between those found in interglacial and glacial ice. The amplitude of the variations are between 30 and 50% lower than the ones observed between the Last Glacial Maximum and the Holocene and is further reduced below 3449 m depth. Total dust concentrations exhibit a similar pattern although below 3449 m depth the ice is loaded with particles coming from the bed which changes the picture. The above-cited properties reinforce the concept of folding/mixing at a submetric scale as indicated by the isotopic properties. Independently, below 3449 m depth, the presence of particles coming from the bed is associated with a layered ice structure characterised by interbedding of fine-grained and coarse-

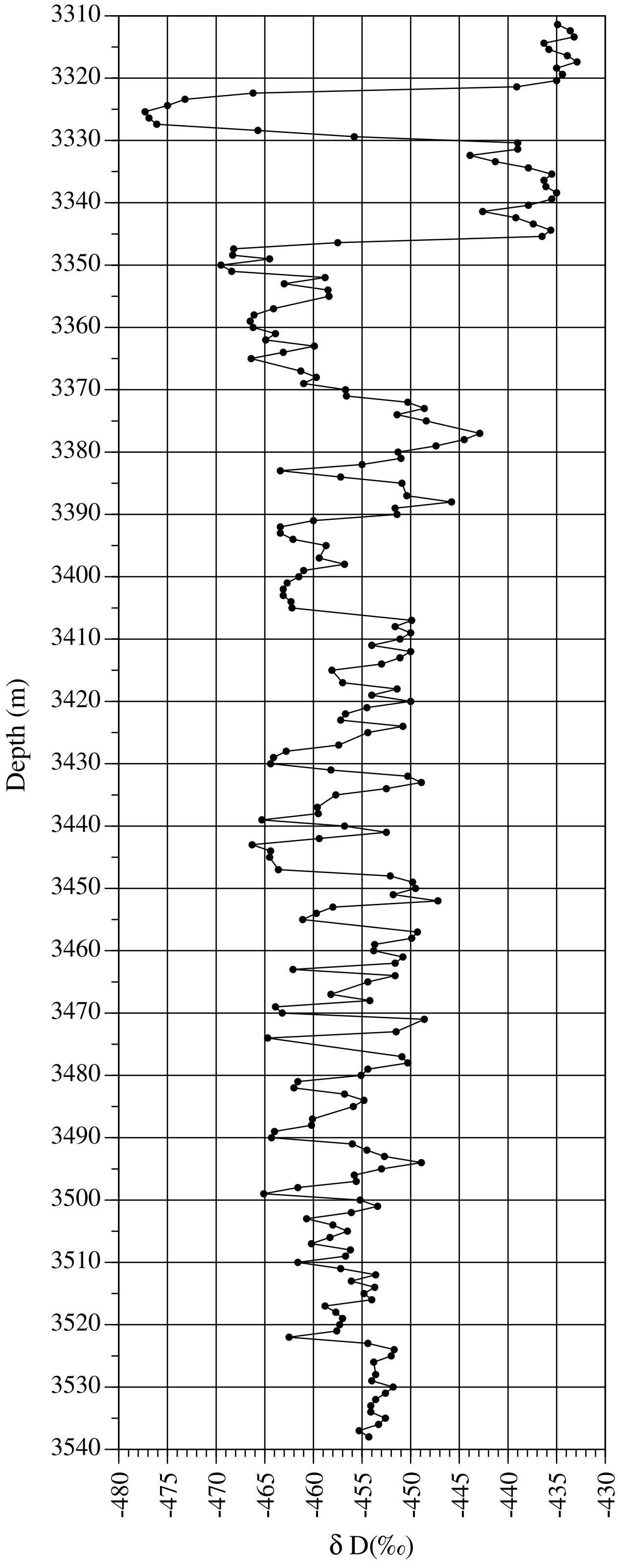

Figure 2. The δD profile of the Vostok ice core between 3311 and 3538 m depth.

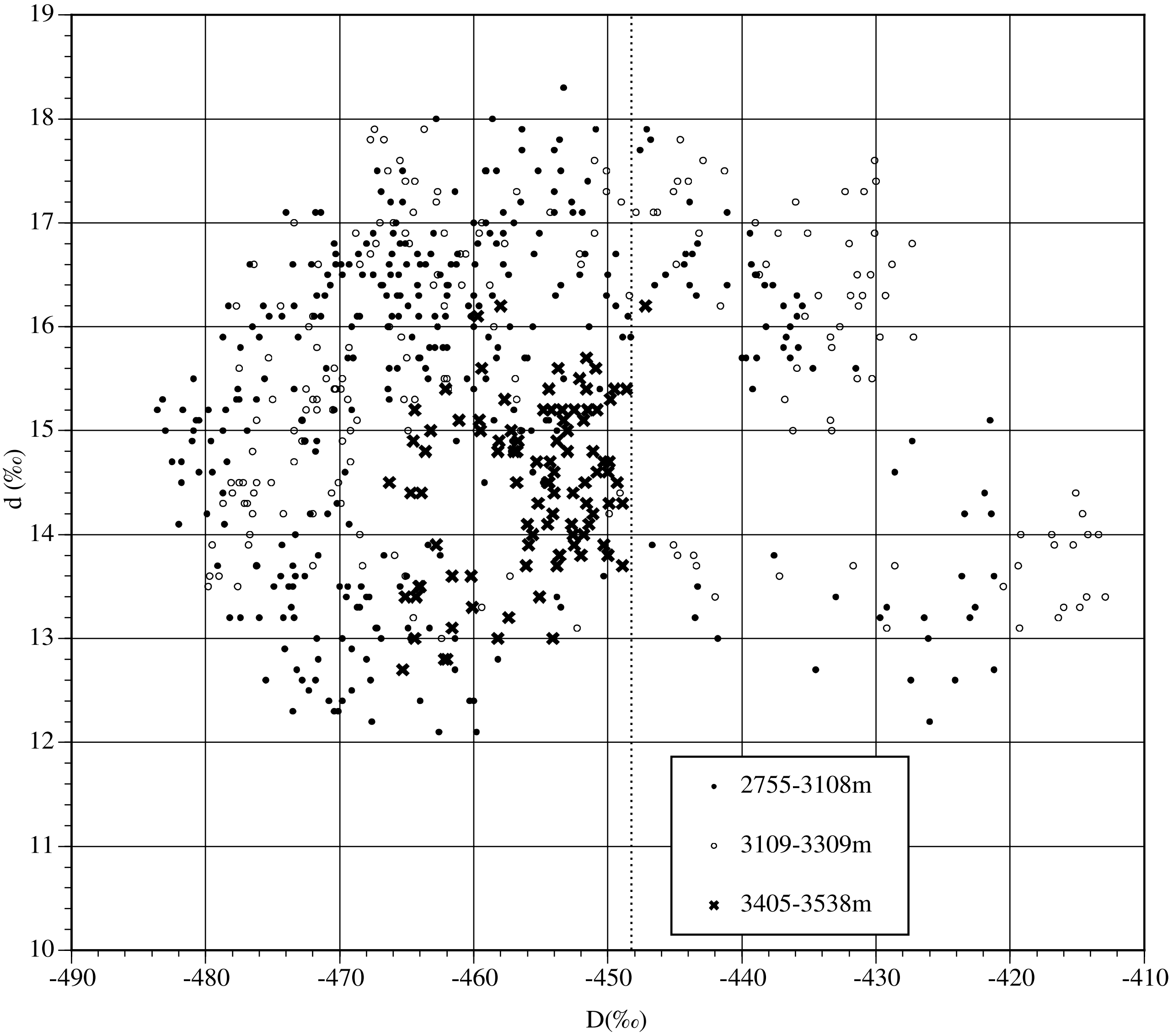

Figure 3. Deuterium excess-δD diagram for ice of the Vostok ice core between 2755 and 3538 m depth. The black dots represent ice from the second oldest climatic cycle present in the Vostok core (2755–3108 m depth), the open circles the oldest climatic cycle (3109–3309 m depth) and the crosses basal ice between 3405 and 3538 m depth.

grained ice layers. Higher impurity content and single maximum fabric is associated with fine-grained ice while low particle concentration and girdle fabric is associated with coarse-grained ice. One section (3491–3492 m) was studied in detail in *Simões et al.* [in press]. It indicates most probably the presence of a major shear zone and will be considered below.

3. Mechanism of Ice Deformation

[12] Underneath the basal sequence considered here, lake ice is present. This is the consequence of the fact that grounded ice upstream became floating on subglacial lake Vostok on its eastward journey. Arguments developed in *Souchez et al.* [2000a] indicate that freezing of lake water occurred along this flow line as soon as the ice overtakes the grounding line. It is therefore reasonable to assume that the basal sequence is complete with no ice loss from below by melting in contact with the lake waters. Melting is considered to only occur at the ice ceiling in the northern part of the lake.

[13] Individual particles coming from the bed and present in the basal ice have a mode of 3.4 μm in diameter with a maximum size of about 9 μm. Larger particles up to 30 μm in diameter are aggregates. This raises the question of size-selective incorporation into the basal ice since it is quite improbable that only such fine particles are present at the ice-substratum interface. Amber ice consisting of silt-sized particles embedded in the ice, although in higher proportion, is shown to rest above a substratum with various and larger grain sizes at some glaciers in South Victoria Land. In such cases, the ice-substratum interface temperature is also well below the pressure melting point.

[14] *Cuffey et al.* [1999, 2000] developed the role of interfacial water films at the surface of rock particles embedded in the ice for glacier sliding at −17°C. Interfacial films exist due to a reduction of the chemical potential of water very close to the surface of an embedded particle [*Wettlaufer et al.*, 1996].

[15] Pressure inequality between overlying ice and interfacial films at the ice-substratum interface may allow ice to penetrate a small distance into the inter-particle voids in patches of fine-grained sediment at subfreezing temperature. Such a process makes

possible incorporation and entrainment of fine particles and adhesion to the glacier sole can promote the formation of aggregates. *Fisher and Koerner* [1986] found strain rates in an Agassiz Ice Cap core to be directly related to debris concentration and inversely related to ice crystal size. The non-homogeneity in ice properties induces differences in rheological behaviour and a small fold can be created. Simple shear close to the bed tends to rotate transverse structures such that folds become progressively recumbent and they ultimately approach parallelism with the flow lines. Shear zones can eventually occur in such conditions. Deformation is more pronounced in zones of strong longitudinal compression. This longitudinal compression is responsible for tectonic thickening of the deformed ice. There is a progressive build-up of the basal sequence upwards with more advanced deformation stages close to the bed. This explains the presence of the shear zone studied by *Simões et al.* [in press] in the basal part of the sequence, followed higher up by recumbent folding at the submetric scale propagating first in the ice layers containing rock fragments from the bed and then through ice devoid of such particles. A change in ice properties indeed often results in a change in ice viscosity.

[16] Interbedding of ice layers at a larger scale which is present in top of the basal sequence is most probably related to large scale rock protuberances at the bed.

4. Conclusion

[17] Complex ice deformation has occurred at the base of the Vostok core above lake ice. This is indicated by a detailed investigation of ice properties, mainly the isotopic composition. This complex deformation developed in the lower 228 m of the ice sheet has resulted in folding and intermixing of ice, at two distinct scales. A size-selective entrainment of bed material into basal ice has most probably occurred. The basal layer has built upwards through longitudinal compression and complex deformation associated with inhomogeneities in the ice and with bedrock protuberances.

[18] This conclusion is relevant to ice core paleoclimatology and to ice sheet modelling. It suggests that it is unlikely to find very old ice with a proper chronology.

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R. Lorrain, S. Sleewaegen, and R. Souchez, Département des Sciences de la Terre et de l'Environnement, Faculté des Sciences, CP 160/03, Université Libre de Bruxelles, 50, av. F.D. Roosevelt, B-1050, Brussels, Belgium. (glaciol@ulb.ac.be)

M. de Angelis, J.-R. Petit, and J. Simões, Laboratoire de Glaciologie et de Géophysique de l'Environnement, F-38402, Saint-Martin-d'Hères, France.

J. Jouzel, M. Stievenard, and F. Vimeux, Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS 1572, CEA Saclay, F-91191, Gif sur Yvette, France.

N. Barkov, Arctic and Antarctic Research Institute, 199397, St Petersburg, Russia.