Polar Meteorol. Glaciol., **18**, 1–18, 2004

Average time scale for Dome Fuji ice core, East Antarctica

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(Received February 5, 2004; Accepted June 8, 2004)

Abstract: Three different approaches to ice-core age dating are employed to develop a depth-age relationship at Dome F: (1) correlation of the ice-core isotope record to the geophysical metronome (Milankovich surface temperature cycle) inferred from the deep borehole temperature profile at Vostok, (2) importing a known chronology from another (Devils Hole) paleoclimatic signal, and (3) direct ice sheet flow modeling. Inverse Monte Carlo sampling is used to constrain the accumulation rate reconstruction and ice flow simulations in order to find the best-fit glaciological time scale matched with the two other chronologies. General uncertainty of the different age estimates varies from 2 to 6 kyr on average and reaches 6–14 kyr at maximum. Whatever the causes of this discrepancy might be, they are thought to be of different origins, and the age errors are assumed to be independent. Thus, the average time scale for the Dome F ice core down to a depth of 2500 m (ice age of 335 kyr) is deduced consistently with all three age-depth relationships within the standard deviation limits of ±3.3 kyr, and its accuracy is estimated as 1.4 kyr on average. The constrained ice-sheet flow model allows extrapolation of the ice age-depth curve further to the glacier bottom and predicts the ages at depths of 2800, 3000, and 3050 m to be 615±70, 1560±531, and 2985±1568 kyr, respectively.

key words: ice core, time scale, Dome Fuji, paleoclimate

1. Introduction

Ice-age dating is one of the principal steps in ice-core data interpretations and paleoclimatic reconstructions. There is no universal and/or standard procedure to determine depth-age relationships in polar ice sheets at deep drilling sites. This question is equally important for the 2500-meter deep ice core retrieved from the Antarctic ice sheet at Dome Fuji (Dome F) Station (Watanabe *et al*., 1999).

Application of sophisticated 2-D and 3-D thermomechanical ice flow models (Ritz, 1992; Ritz *et al*., 2001) for solving this problem suffers significantly from uncertainties in initial and input data: mainly in glacier bottom conditions, past ice flow patterns and accumulation rates. Nevertheless, the detailed analysis by Parrenin *et al*. (2001) and further studies by Hondoh *et al*. (2002) and Watanabe *et al*. (2003) show that the modeling of ice sheet dynamics becomes a useful tool for ice-age prediction if *a priori* chronological information is used to fit the model parameters. Although different sources of age markers and dated time series have their own specific errors they may be considered as reliable constraints if, in combination, they deliver statistically valid and independent estimates of ice age at various depth levels. The inverse Monte Carlo sampling method (*e.g*. Mosegaard and Tarantola, 1995; Mosegaard, 1998) may be especially helpful in this case (Parrenin *et al*., 2001; Watanabe *et al*., 2003). However, being somewhat in disagreement with statistical conceptions of this method, only a limited number of control points were used in the latter two cited papers for model constraining. Here we follow Salamatin *et al*. (2004) and employ a statistically representative set of age markers to fit the ice-sheet model on average, uniformly *versus* depth, although without putting excess weight on local fluctuations of the simulated depth-age curve caused by uncertainties in environmental conditions, reconstructed ice accumulation and other paleoclimatic characteristics. From this point of view, even simplified ice flow models (*e.g*. Salamatin and Ritz, 1996; Hondoh *et al*., 2002) may be quite appropriate to incorporate the principal laws of ice-sheet dynamics into the ice core dating procedure.

Among different depth-age relationships developed for Dome F, the geophysical metronome time scale (GMTS) (Hondoh *et al*., 2002; Salamatin *et al*., 1998a) represents the so-called orbitally tuned chronologies. It is based on correlation of the isotopic temperature signal with the geophysical metronome—Milankovich components of the surface temperature variations in the past inferred from the borehole temperature profile at Vostok (Salamatin *et al*., 1998b; Salamatin, 2000). Possible errors and uncertainties of GMTS are discussed elsewhere (Salamatin *et al*., 1998a; Salamatin, 2000), and its overall average accuracy was estimated as ± 3.5–4.5 kyr.

Another paleotemperature-proxy signal spanning over more than 500000 years is available from the calcite core (DH-11) in Devils Hole, Nevada (Winograd *et al*., 1992, 1997). The principal advantage of this $\delta^{18}O$ record is that the dense vein calcite provides a material for direct uranium-series dating (Ludwig *et al*., 1992) with the standard errors increasing from 1 to 7 kyr with time up to 400 kyr B.P. In addition, the signal may be influenced by different hydrological factors. In particular, systematic underestimation of the determined ages on the order of several thousands of years may take place due to the ground-water travel time through the aquifer (Winograd *et al*., 1992; Landwehr and Winograd, 2001). Nevertheless, the correlation of the Dome F ice core $\delta^{18}O$-depth signal with the Devils-Hole record (see U.S. Geological Survey Open-File Report 97-792 at http: //pubs.water.usgs.gov/ofr97-792) can also be considered as an independent approach to dating (Landwehr and Winograd, 2001).

Thus, in continuation of previous studies (Watanabe *et al*., 1999; Hondoh *et al*., 2002; Salamatin *et al*., 2004), the principal goals of this paper are (1) to combine the above sources of chronological information in order to constrain ice flow model parameters, reducing minimum systematic errors in the glaciological time scale based on simulations of the ice sheet dynamics in the vicinity of Dome F Station, (2) to deduce the average age-depth relationship consistent with different approaches to ice-core dating within the upper 2500 m, and (3) to extend the model predictions at Dome F to the deeper bottom part of the glacier.

2. Model description and parameterization

Here we use a simplified two-dimensional approach to ice flow modeling developed for ice-age predictions by Hondoh *et al*. (2002). For the ice-dome flow pattern we introduce the local ice-equivalent thickness $\Delta(t)$ depending on time t and the vertical coordinate ζ defined as the relative distance from the glacier bottom expressed in equivalent thickness of pure ice and normalized by Δ. The paleoclimate is characterized by the surface ice-mass balance $b(t)$.

The ζ-coordinate is expressed in terms of depth h (after Salamatin, 2000) as:

$$\zeta = 1 - \frac{h}{\Delta} + \frac{c_s}{\gamma_s \Delta}(1 - e^{-\gamma_s h}), \tag{1}$$

where c_s is the surface snow porosity and γ_s-the exponential densification factor.

Temporal variations of b and Δ are described in the following parametric form:

$$b = b_0 \exp\left(\eta_b \frac{\delta^{18}\mathrm{O} - \delta^{18}\mathrm{O}_{sw}}{C'_T}\right), \tag{2}$$

$$\Delta = \Delta_0 + \delta\Delta(t).$$

Here b_0 is the present-day ice mass balance at the site under consideration, and Δ_0 is the present-day glacier thickness (in ice equivalent). The last exponential term in the first of eqs. (2) describes the past changes in precipitation traditionally correlated to the inversion (isotopic) temperature in accordance with Robin (1977) and Ritz (1989, 1992). The accumulation-rate variations in central Antarctica are linked by means of the exponential factor η_b and the isotope/inversion-temperature slope C'_T to the ice-core isotopic content ratios δ^{18}O corrected for past changes in the oxygen-isotope composition of ocean water $\delta^{18}\mathrm{O}_{sw}$ (Sowers *et al*., 1993; Bassinot *et al*., 1994). Deviations δ^{18}O and $\delta^{18}\mathrm{O}_{sw}$ in eqs. (2) are referenced to their present-day values.

Ice-sheet thickness fluctuations $\delta\Delta(t)$ in the second of eqs. (2) are reconstructed after Salamatin and Ritz (1996). The latter model for $\delta\Delta$ was verified and its tuning parameters γ_b and γ_l were constrained on the basis of the 2-D thermomechanically coupled model of Antarctic ice sheet dynamics (Ritz, 1992). These results have also been recently supported by 3-D simulations (Ritz *et al*., 2001).

The ice-particle motion in the vertical direction is predicted (Hondoh *et al*., 2002) from an ordinary differential equation with respect to $\zeta = \zeta(t)$

$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = -\frac{b}{\Delta}\left[\zeta - \frac{\sigma}{\beta+1}(1-\zeta)(1-(1-\zeta)^{\beta+1})\right], \tag{3}$$

with b and Δ related to t by eqs. (2). By definition, β is the modified Glen flow-law exponent, which takes account of the vertical temperature gradient (Lliboutry, 1979), and σ is the proportion of the total ice-flow rate due to plastic (shear) deformation of the glacier body; $\sigma \approx 1$ for the ice-dome conditions without bottom melting (Hondoh *et al*.,

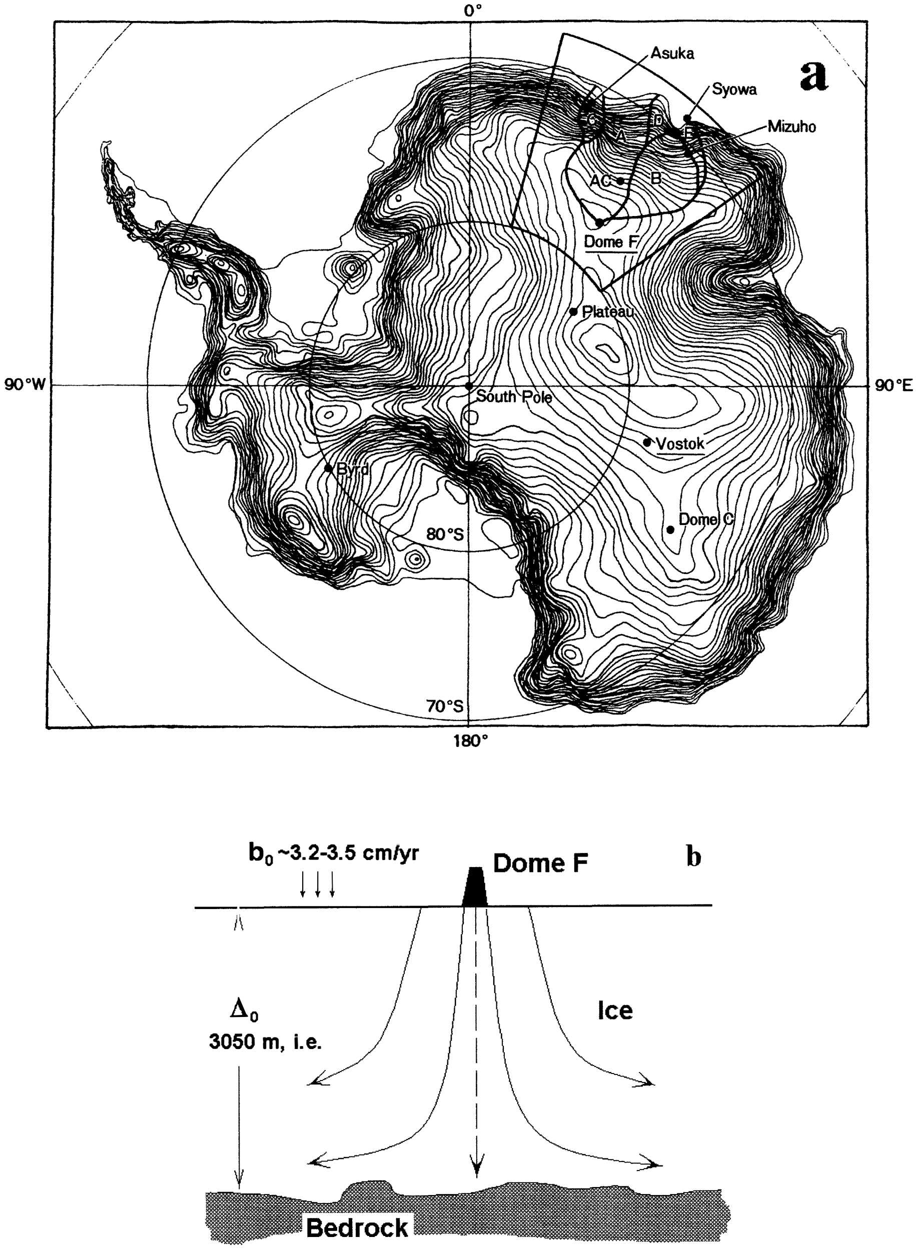


Fig. 1. Geographic conditions around Dome Fuji Station. (a) A map of Antarctica with underlined sites considered in this study and the Dome F sector with drainage basins adapted after Antarctica (1997). (b) The schematic of the ice flow pattern in the vicinities of Dome F.

2002).

Finally, the ice age t_0 of the ζ_0 level (at the corresponding depth given by eq. (1)) is determined by the equality $\zeta(t_0)=\zeta_0$, where $\zeta(t)$ is the solution of eq. (3) at the initial condition $\zeta_{|t=0}=1$. A depth-age relationship used initially for the ice-core isotopic record in eqs. (2) is corrected through iterative modeling. Although the computation of the depth-age relation is finally reduced to solving a "one-dimensional" eq. (3), the dating procedure itself is originally based on a 2-D ice flow model and, thus, inherits the principal laws of ice-sheet dynamics, taking into account the geographic conditions and climate changes.

A map of Antarctica with the Dome F sector adapted after Antarctica (1997) is presented in Fig. 1a. The schematic of the ice flow pattern in the vicinities of Dome F is shown in Fig. 1b.

The values and *a priori* ranges of the basic model parameters considered in computations are given in Table 1. The present-day ice accumulation rates at Dome F were assumed to be between 3.2 cm yr^{-1} (Watanabe *et al*., 1997; Dome-F Ice Core Research Group, 1998; Hondoh *et al*., 2002) and 3.5 cm yr^{-1} (Dome-F Deep Coring Group, 1998). The exponential approximation of the snow-firn density profile (the values of c_s and γ_s in eq. (1)) was obtained in (Hondoh *et al*., 2002) on the basis of (Hondoh *et al*., 1999).

3. Ice-core ages imported from paleoclimatic signals

Dome F ice age dating procedures, considered in this study, are substantially based on the $\delta^{18}O$ ice-core record (Watanabe *et al*., 1999) plotted in Fig. 2a together with its parabolic spline approximation (Hondoh *et al*., 2002). The GMTS results directly from correlation of the smoothed isotopic signal with the geophysical metronome (Milankovich cycles of the local surface temperature variations) inferred from the deep borehole temperature profile at Vostok (Salamatin *et al*., 1998a, b; Salamatin, 2000). The metronome and the correlated isotopic record are plotted in Fig. 2b by thick and thin solid lines, respectively. The GMTS correlation pairs, ages and depths of the respective climatic events (peaks and troughs) identified in the metronomic and isotopic signals (Hondoh *et al*., 2002), are depicted in Fig. 3a by solid circles.

Next, we apply the parabolic spline approximation (Salamatin *et al*., 2004) to the Devils Hole (DH) paleoclimatic record (Winograd *et al*., 1992) as plotted versus time in Fig. 2c. The extrema in the Dome F $\delta^{18}O$-depth curve are now identified with the corresponding maxima and minima discerned in the smoothed DH signal. Thus, another independent series of age markers are transferred to the Dome F ice core (see empty circles in Fig. 3a).

The mean-square (standard) deviation (SD) between GMTS and DHVTS is rather high ~7.6 kyr, and maximum mismatches reach 10–16 kyr (see Figs. 3a, b). Cuffey and Vimeux (2001) give a good illustration of how sensitive the details of isotope paleorecords are to changes in their water vapor sources and, hence, to their origins. The geophysical metronome, as a sum of Milankovich cycles, originally assumes quasi-linear response of the Earth's climate to orbital forcing with fixed constant frequencies and phase shifts, disregarding "climatic noise" and possible non-linearities

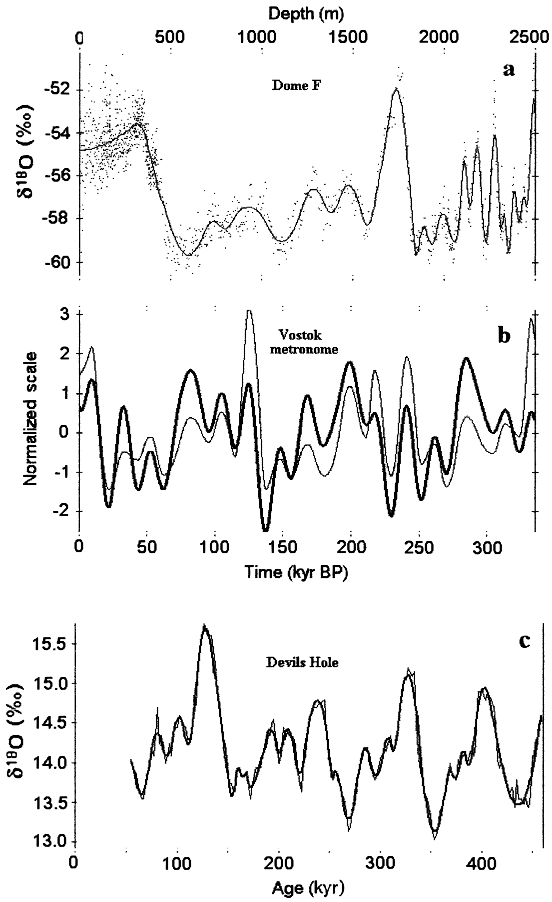


Fig. 2. Paleoclimatic signals used to constrain the ice flow model and the simulated (glaciological) ice age-depth relationship at Dome F. (a) Dome F ice core δ^{18}O-record (dots) and its parabolic spline approximation (solid line). (b) Correlation of the Dome F isotopic signal (thin solid line) to geophysical metronome inferred from the borehole temperature profile at Vostok (bold line). (c) Devils Hole δ^{18}O-record (thin line) and its parabolic spline approximation (bold line).

(Salamatin *et al*., 1998a; Salamatin, 2000). Thus, the above estimates may be understood if the ages from two different series with statistically independent perturbations (errors) of 4–6 kyr are intercompared. These conclusions are important and allow us to use the GMTS and DHVTS age-depth correlation points to constrain the ice flow model at Dome F on average, with minimum systematic errors in ice age predictions to a depth level of 2500 m.

4. Ice flow model constraints and glaciological time scale

The model (1)–(3) does not capture all the details of spatial and temporal changes in accumulation rate and ice flow pattern which will be a source of noise in the simulated

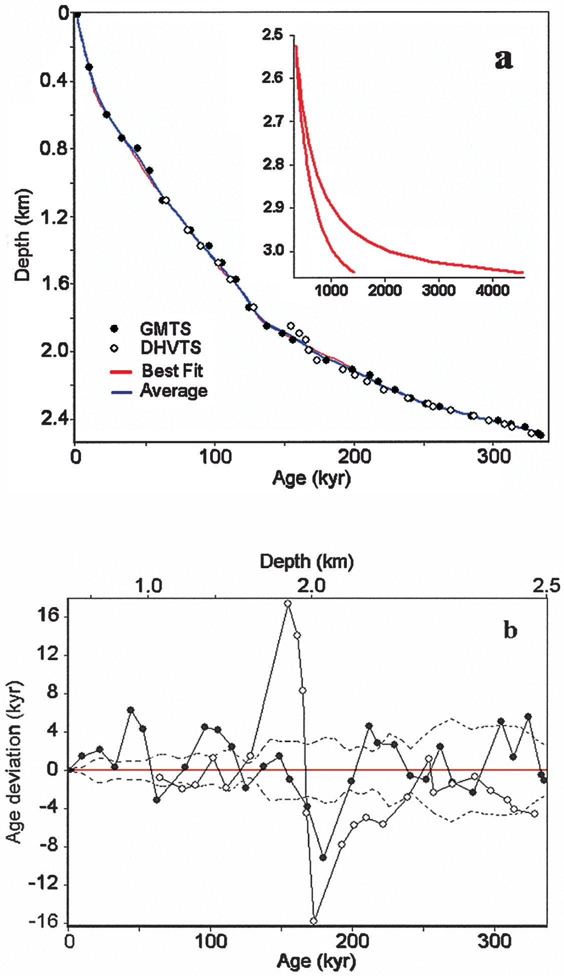


Fig. 3. Different ice age datings at Dome F. (a) Best-fit glaciological time scale (thin red line) and average ice age-depth relationship (bold blue line) compared with GMTS (solid circles) and DHVTS (empty circles) age-depth correlation points used for constraining the ice flow model. The inset shows the upper and lower age bounds of glaciological time scale extension to the 3050 m depth level, 40 m above the ice sheet bed. (b) The deviation of the linearly interpolated GMTS and DHVTS ages (solid and empty circles, respectively) from a reference time scale (zero red line) chosen as the mathematical expectation (best fit) of the sampled chronologies at Dome F. The dashed lines are the SD bounds of the age-depth curves selected through the Monte Carlo sampling procedure.

age-depth relation. These perturbations are thought to be uncorrelated with the ice-age dating errors introduced by use of the geophysical metronome or the DH paleoclimatic signal. Consequently, we expect that the modeled (glaciological) time scale at Dome F fitted to the two depth-age relationships of different origins (GMTS and DHVTS) might be considered as another source of ice age estimates with minimum systematic error, though containing independent short-term distortions.

Here we follow Salamatin *et al*. (2004) and employ the inverse Monte Carlo sampling procedure (*e.g*. Mosegaard and Tarantola, 1995; Mosegaard, 1998) to study the sensitivity of the target function, the standard deviation of the glaciological time scale from GMTS and DHVTS, to three tuning parameters: the present-day accumulation rate at Dome F b_0, the $\delta^{18}O$/inversion-temperature temporal slope C'_T (or equally η_b/C'_T), and the modified Glen creep index β. The plausible *a priori* ranges for these values are given in Table 1. Several series of computational experiments were conducted to perform the resolution analyses at different constraints. The best-fit estimates, obtained through the Monte Carlo method and discussed below, are summarized in Table 2.

Table 1. Ice flow model parameters for Dome F area.

Definition of parameters	Denotation	Values
Snow-firn densification and mass balance		
Surface–snow porosity	c_s	0.67
Exponential densification factor, m^{-1}	γ_s	0.017
† Present-day ice accumulation rate at Dome F, cm yr^{-1}	b_0	3.2–3.5
Paleoclimatic exponential factor, ℃$^{-1}$	η_b	0.11
† $\delta^{18}O$/inversion-temperature slope, ‰℃$^{-1}$	C'_T	0.87±0.038
Ice flow conditions		
Present-day ice-sheet thickness in ice equivalent, m	Δ_0	3050
Glen flow law exponent	α	3.0
† Modified Glen flow-law exponent	β	1–5
Shear-flow-rate factor	σ	1
Model of ice-sheet thickness variations (Salamatin and Ritz, 1996)		
Spatial mass balance amplification factor	γ_b	0.56
Ice-sheet growth feed-back factor	γ_l	2.5–3.0

†Parameters estimated through model constraining by Monte Carlo sampling method.

Table 2. Estimates of the model tuning parameters deduced through the Monte Carlo sampling method.

Parameter	Best fit	Mean	SD
$\delta^{18}O$/inversion-temperature slope: C'_T, ‰℃$^{-1}$	0.74	0.65	0.06
Present-day ice accumulation rate: b_0, cm yr^{-1}	3.2	3.3	0.1
Modified Glen flow-law exponent: β	3.2	3.3	0.9

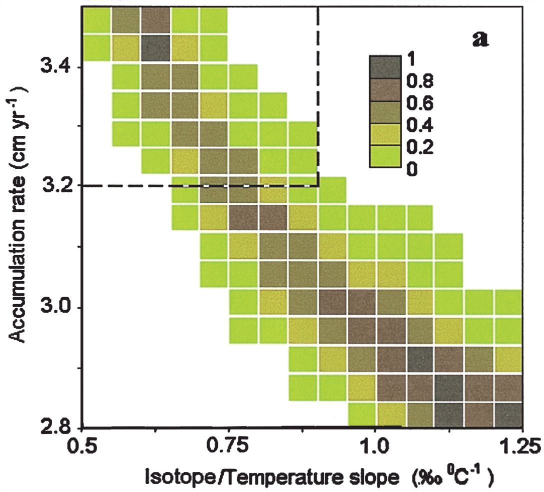
Preliminary tests showed unequal uncertainty levels of GMTS and DHVTS with the latter age fluctuations around the fitted model predictions 1.5–1.8 times higher than those of GMTS. The respective absolute values of the "Gaussian noise" SD assumed in the likelihood function of the Metropolis algorithm were estimated as 3.3 and 5.2 kyr. Although these uncertainties include modeling errors, they are close to the claimed accuracies of GMTS and DH age dating. In each computational experiment, depending on the frequency of selection and assumed ranges of the tuning parameters, about 1500–5000 uncorrelated chronologies were selected at a 40%-level of acceptance by the

Monte Carlo scheme, and the total number of tested time scales was $4 \cdot 10^4$–$1.5 \cdot 10^5$.

In general, the resolution analysis performed by random walk sampling shows that, as for Vostok (Salamatin *et al.*, 2004), the resulting posterior probability density in the space of the ice-flow model parameters is not unimodal and has an extended domain of global maximum. This means that feasible variations of some parameters can be counterbalanced by *a priori* accepted changes in others. Only additional constraints on the model parameters can lead to a more definite estimation. Nevertheless, all best-fit chronologies found in different computational series are practically undistinguishable and fell within 5.0 ± 0.4 kyr limits of the standard deviation from the GMTS and DHVTS age markers. This implies that the model (1)–(3) is sufficiently flexible and the simulated depth-age relationship can be uniquely constrained by the available chronological information at plausible values of the tuning parameters. The thin solid (red) line in Fig. 3a depicts the best-fit glaciological time scale. It converges to the mathematical expectation of the sampled (selected) age-depth curves. Deviations of the GMTS and DHVTS ages from the statistical mean, best-fit, ages (zero red line) are plotted in Fig. 3b. The dashed lines are the SD bounds of the tested chronologies. Since GMTS and DHVTS are used as model constraints, a certain apparent similarity of their fluctuations around the glaciological time scale in Fig. 3b should be assigned mainly to the short-term details missed in the modeled age-depth curve and not to the systematic statistically correlated errors between the time scales themselves.

With this result, let us discuss *a posteriori* information on the model parameters deduced through the Monte Carlo procedure. The isotope/inversion-temperature slope C'_T enters eqs. (2) as a ratio to η_b, and its estimates automatically include all errors of the latter factor (Ritz, 1992) as well as the general uncertainties of the assumed Robin's geographic relationship (1977).

First, the reconnaissance resolution analysis was performed in the space of the three model parameters b_0, C'_T, and β within the *a priori* bounds set in Table 1. The best-fit value of the ice-flow law exponent β was found to be around 3.2 with broad variations of b_0 and C'_T. Hence, further computations were constrained to narrower β-bounds: $2.7 < \beta < 3.7$. Next, a much wider range for b_0 from 2.8 to 3.5 cm yr^{-1} was chosen. A two-dimensional map of the normalized probability density sampled by the Monte Carlo method on the b_0-C'_T phase plane in this case for the basic value of the ice-thickness model parameter $\gamma_l = 2.5$ (see Table 1) is plotted in Fig. 4a. It clearly shows that only the values of $C'_T \sim 0.56$–$0.88‰°C^{-1}$ are consistent with the *a priori* estimates of $b_0 \sim 3.2$–3.5 cm yr^{-1} (see the bold-dashed outlined rectangle domain in Fig. 4a). In these computational experiments the inverse procedure revealed a nearly uniform distribution of the sampling probability density *versus* b_0, a "sharp" unimodal histogram for C'_T, and, as mentioned above, a clearly resolved maximum in the histogram for β. All three distribution functions are presented in Fig. 4b. Finally, the localized area of the feasible b_0- and C'_T-variations was additionally explored by random walk sampling. The obtained estimates of the model parameters are summarized in Table 2. The best fit was found at a standard deviation of the glaciological time scale from GMTS and DHVTS (the target function value) of about 4.8 kyr. The inferred values of $C'_T \approx 0.65 \pm 0.06‰°C^{-1}$ and its best-fit value $0.74‰°C^{-1}$ can be compared to the deuterium/inversion-temperature slope $C_T \approx 8C'_T$ and agree with $C_T \approx 5.6 \pm 0.6‰°C^{-1}$ and the



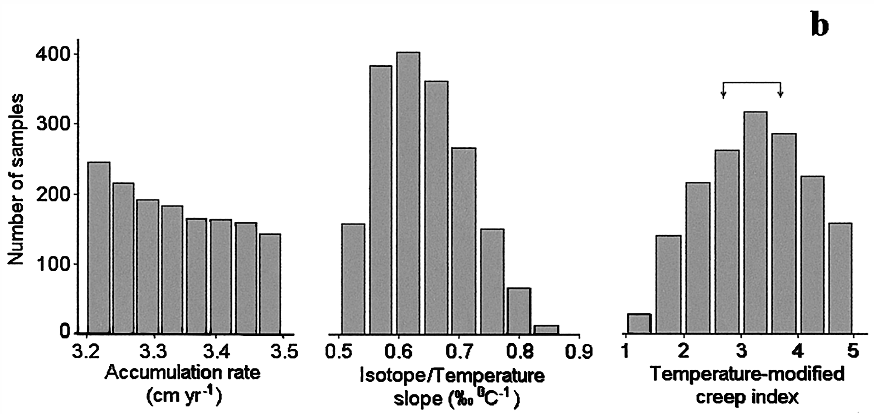


Fig. 4. The a posteriori information on the ice-flow model parameters deduced through the Monte Carlo sampling procedure. (a) A map of the normalized sampling probability density on the b_0*-*C'_T *phase plane for* $2.7<\beta<3.7$*. (b) The histograms of the three principal model parameters: present-day accumulation rate* b_0 *at Dome F,* $\delta^{18}O$*/inversion temperature slope* C'_T*, and modified Glen flow-law exponent* β *(the arrows show the* β*-interval for sampled* b_0*- and* C'_T*-values).*

best-fit value $C_T \approx 6.3‰°C^{-1}$ found in (Salamatin *et al.*, 2004) as well as with simulations of ice-sheet dynamics (Hondoh *et al.*, 2002) and previous results based on borehole temperature analysis (Salamatin *et al.*, 1998a). The above estimates slightly increase to $C'_T \approx 0.68 \pm 0.06‰°C^{-1}$ and $0.76‰°C^{-1}$, respectively, at the upper limit of $\gamma_l = 3.0$ given in Table 1. The deduced C'_T-slope corresponds to the deuterium ratio—inversion temperature relationship, which falls exactly in the middle between the bounds reconstructed by the inverse procedure in Parrenin *et al.* (2001). The best-fit present-day ice accumulation rate at Dome F is found at its lower bound 3.2 cm yr^{-1}.

Although somewhat higher rates ~3.5 cm yr^{-1} were determined for recent decades by the Dome-F Deep Coring Group (1998), the above estimate agrees with a longer-term (Holocene) mean value found by the Dome-F Ice Core Research Group (1998).

5. Average time scale: discussion

The three depth-age relationships introduced and compared in the previous sections are uniformly consistent with each other to the maximum (borehole) depth 2500 m of the Dome F ice core. The errors of these primary, basic time scales differ in magnitude and by origin. In accordance with Salamatin *et al.* (2004), we assume that each of the three basic depth-age relationships has its own uncertainty level and iteratively calculate the weighted mean time scale, using the running averaging procedure over a 4-kyr interval comparable with the average error level. The weights are taken inversely proportional to standard deviations of the basic chronologies from the resulting smoothed average curve. This condition yields the converged normalized weighting coefficients of 0.54, 0.32, and 0.14 for the best-fit glaciological time scale, GMTS, and DHVTS, respectively with the corresponding standard deviations from the mean ages equal to 1.4, 2.3, and 5.4 kyr. The latter estimates characterize the quality of different sources of chronological information and reveal the higher statistical validity (the lower error level) of the properly constrained glaciological time scale. The bold (blue) line in Fig. 3a shows the average time scale. The deviations of the three basic time scales from the average age-depth curve (zero blue line) are plotted in Fig. 5a. The dot-dashed lines in the figure are the total standard error bounds of $\pm$3.3 kyr which correspond to the upper estimate of age uncertainty. Actually, the deduced error level of the best-fit glaciological time scale $\pm$1.4 kyr, *i.e.* the weighted mean SD of all three chronologies, is thought to be a more reliable measure of the accuracy of the newly developed time scale. The average age-depth relationship is presented in Table 3 together with the running weighted mean SD (errors) also shown in Fig. 5b by dashed lines. It predicts the ice age of 335$\pm$1 kyr at the limiting depth 2500 m of the borehole bottom. The average time scale has also been substituted into eps. (2) to calculate the isotopic content of precipitation versus time and, thus, is additionally fitted through iterations.

Both Fig. 5 and Table 3 show non-uniform distribution of errors *versus* depth and age. The age uncertainties range from 0.2 kyr to 3 kyr at maximum. Obviously, the highest errors (2–3 kyr) are located within the age interval 130–160 kyr (depth interval 1800–1940 m) where the maximum mismatch between the Dome F and DH isotopic records and/or their chronostratigraphies is observed (see Figs. 3b and 5a). In all these cases the best-fit glaciological depth-age relationship and GMTS agree with the average time scale within the standard uncertainty bounds, and only the ages imported from the DH paleosignal display abrupt fluctuations with 2–3 times higher amplitudes.

In Fig. 5b the average time scale (zero blue line) is compared to the official working time scale (green line) previously used for the Dome F ice core. As emphasized by Hondoh *et al.* (2002), the difference between the two time scales gradually grows with depth and reaches 10–16 kyr at the borehole bottom (2500 m). Two other recently modeled age-depth relationships (Hondoh *et al.*, 2002) and (Watanabe *et al.*, 2003) are also shown in Fig. 5b by red and black lines with squares. As mentioned before, the former work assumed higher values of $C'_T \approx 0.84‰°C^{-1}$ than the best fit found here, while the latter one used only a limited number of control points and overtuned the ice-flow simulations. Nevertheless, both age-depth curves predict close ages and display similar fluctuations around the average time scale with SD of about 1.5–2 kyr and maximum deviations not higher than ±4.5 kyr. Being uniformly constrained by numerous ice-age control points of different origins, the best-fit glaciological time scale deduced in our study is the most statistically valid one. The weighted averaging procedure additionally reduces the error level of the resulting mean ages and makes the

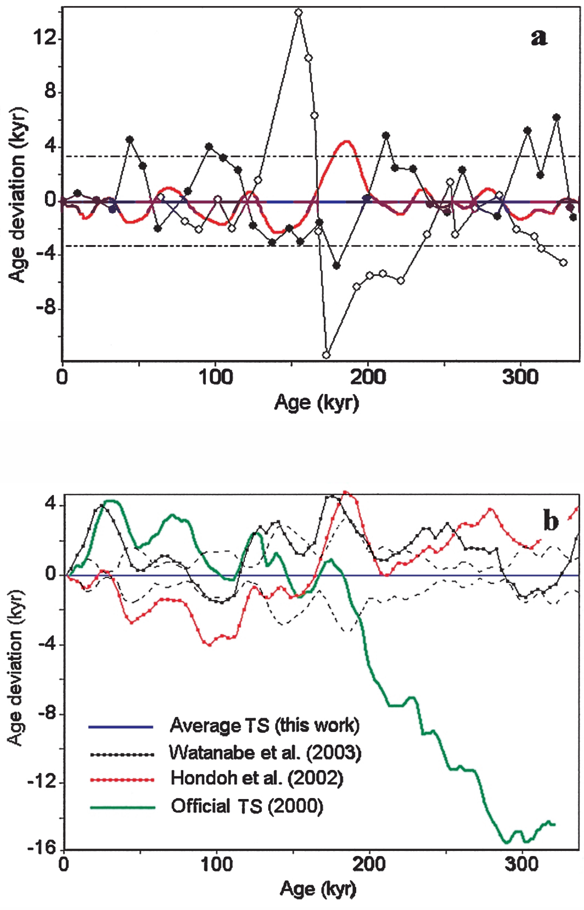


Fig. 5. Comparison of the average time scale developed for the Dome F ice core with other time scales. (a) The deviation of the three basic Dome F age-depth relationships, i.e. GMTS (linearly interpolated solid circles), DHVTS (linearly interpolated empty circles) and the best-fit glaciological time scale (bold red line) from the averaged time scale (zero blue line). The dot-dashed lines show the standard error bounds of the mean ages. (b) Deviation of the previously used official working time scale for Dome F ice core (bold green line) and recently modeled time scales (red and black lines with squares) from the average time scale (zero blue line). Dotted lines are the running weighted mean SD bounds of the average ice ages from Table 3.

Table 3. Average age-depth relationship for Dome F ice core and its theoretical extension to the glacier bottom.

Depth, m	Age, kyr	SD, kyr	Depth, m	Age, kyr	SD, kyr
0	0	0.0	2083.3	192	2.4
150.5	4	0.3	2099.7	196	1.7
284.1	8	0.4	2117.1	200	1.3
402.0	12	0.7	2133.2	204	1.5
494.3	16	0.9	2148.7	208	1.5
564.1	20	0.6	2166.4	212	1.4
619.9	24	0.3	2186.7	216	1.3
668.8	28	0.2	2205.1	220	1.3
717.0	32	0.3	2219.4	224	1.3
762.0	36	0.8	2231.8	228	1.2
802.8	40	1.5	2244.3	232	1.1
846.3	44	1.6	2258.3	236	0.9
897.1	48	1.4	2273.8	240	0.6
951.9	52	1.2	2288.9	244	0.3
1007.3	56	0.7	2302.0	248	0.3
1060.0	60	0.5	2312.7	252	0.3
1104.6	64	0.7	2321.9	256	0.5
1143.3	68	0.7	2330.7	260	0.7
1182.7	72	0.6	2339.4	264	0.6
1224.6	76	0.5	2348.2	268	0.3
1268.0	80	0.4	2356.2	272	0.3
1309.3	84	0.6	2364.1	276	0.5
1346.7	88	1.0	2372.3	280	0.5
1381.7	92	1.3	2381.1	284	0.4
1417.6	96	1.3	2389.9	288	0.4
1456.6	100	1.3	2398.2	292	0.9
1496.9	104	1.3	2405.9	296	1.4
1535.4	108	1.2	2413.2	300	1.6
1571.1	112	1.0	2420.9	304	1.4
1608.9	116	0.6	2429.7	308	1.1
1653.9	120	0.4	2439.2	312	1.2
1705.2	124	0.5	2447.8	316	1.6
1754.9	128	1.0	2455.6	320	1.6
1795.7	132	1.7	2464.6	324	1.2
1826.1	136	2.4	2475.2	328	1.0
1847.5	140	2.8	2487.6	332	0.9
1864.1	144	2.8	2500.0	335	1.0
1880.9	148	2.5	Extrapolated time scale		
1898.9	152	2.3	2525	342	9
1917.6	156	2.0	2550	356	12
1936.6	160	1.6	2575	372	14
1958.3	164	1.1	2600	391	18
1983.6	168	1.2	2625	410	21
2007.7	172	1.9	2650	431	25
2027.0	176	2.6	2675	454	29
2042.6	180	3.1	2700	479	35
2056.1	184	3.3	2725	507	41
2069.1	188	3.0	2750	538	49

Table 3 (continued).

Depth, m	Age, kyr	SD, kyr	Depth, m	Age, kyr	SD, kyr
2775	575	59	2925	969	205
2800	615	70	2950	1104	270
2825	663	85	2975	1287	368
2850	719	104	3000	1560	531
2875	785	128	3025	2017	838
2900	868	161	3050	2985	1568

average time scale most consistent with all three datings. Comparison of the glaciological time scale (see Fig. 5a) with the average time scale reveals noticeably better agreement than all previously simulated age-depth relationships plotted in Fig. 5b.

To qualitatively evaluate the average time scales developed here and in (Salamatin *et al*., 2004) for the Dome-F and Vostok ice cores, it is interesting to compare their age predictions for corresponding climatic events (peaks and troughs) depicted in the isotopic records from these two sites (see Fig. 1a). Figure 6 shows the smoothed spline approximations of δ^{18}O- and deuterium-content variations at Dome F (see Fig. 2a, Hondoh *et al*., 2002) and Vostok (Salamatin, 2000) plotted against the respective average time scales. The overall correlation between the two climatic signals is 96%. The two age datings of their corresponding climatic events are compared with each other and with GMTS control points in Table 4. The SD between the climatic event ages given by the Dome F and Vostok chronologies is 1.8 kyr on average, being in full agreement with the estimated error levels of these time scales 1.4 and 2.2 kyr, respectively. The deviations do not exceed ±2.7–3.2 kyr in the interval (110–180 kyr) of their maximum uncertainty. However, a single mismatch of 5.3 kyr is found between the age datings for the isotopic content minimum around 39–45 kyr BP (see Fig. 6 and Table 4). In the latter case the two average time scales oppositely deviate from the GMTS control points, and the above difference in ages represents the doubled mean error. This analysis confirms the predicted accuracy of both average age-depth relationships established for Dome F and Vostok ice cores.

We can now attempt to estimate the ice age at Dome F below 2500 m. Let us note that the recent climate periodicity revealed in the geophysical metronome cannot be continued too far back in time and the reliability of an extended time scale based on the simplified model (1)–(3) should not be exaggerated. Our goal here is to deduce feasible upper and lower age bounds. To do this, we first calculated the long-term mean accumulation rate, 2.23 cm yr^{-1}, at Dome F, which delivered a best fit to the newly developed average time scale over three climatic cycles with the standard deviation of about 5 kyr. Another somewhat lower estimate of the mean accumulation rate, 2.0 cm yr^{-1}, can be derived from the similar value found at Vostok for four climatic cycles by Salamatin *et al*. (2004) if the ratio 1.45 between the present-day accumulation rates (3.5 and 2.4 cm yr^{-1}) at the two sites is used. The best-fit glaciological time scale has then been continued in our simulations at $\sigma = 1$ to a depth of 3050 m with the minimum mean accumulation rate of 2.0 cm yr^{-1}. Thus, the upper bound of ice ages in the bottom part of the glacier has been obtained. Next, to deduce a lower age estimate, we note that an accurate temperature profile is not available at Dome F and in case of the basal ice

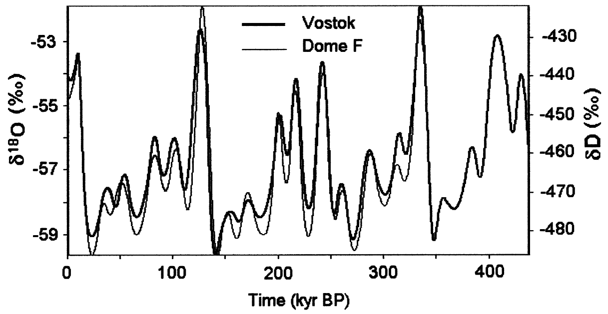


Fig. 6. Comparison of the smoothed $\delta^{18}O$ and deuterium ice core records from Dome F and Vostok, respectively, plotted against their average time scales.

Table 4. GMTS ages of climatic events (peaks and troughs on isotopic records) compared to average time scales for Vostok and Dome-F ice cores.

GMTS	Vostok		Dome F	
Age, kyr	Depth, m	Age, kyr	Depth, m	Age, kyr
9.6	233	9.4	317	9.1
22.2	448	22.7	598	22.4
33.0	623	36.9	737	33.8
43.9	704	44.7	797	39.4
52.8	811	53.3	929	50.3
62.3	967	64.9	1108	64.3
82.4	1171	81.9	1286	81.7
95.8	1272	90.5	1379	91.7
105.2	1389	100.2	1476	101.9
115.2	1521	110.0	1578	112.7
124.8	1789	124.9	1739	126.7
137.5	2006	140.2	1852	141.1
148.2	2121	153.9	1893	150.7
155.9	2185	160.9	1933	159.2
168.1	2278	170.6	1994	169.7
179.8	2358	181.4	2057	184.3
199.0	2490	200.6	2111	198.6
211.4	2538	207.9	2142	206.3
217.1	2596	215.4	2180	214.7
229.6	2678	227.6	2229	227.1
240.9	2751	240.3	2278	241.1
251.7	2810	251.7	2314	252.6
261.7	2836	258.7	2329	259.2
270.0	2876	269.7	2353	270.4
284.7	2932	285.6	2385	285.8
304.2	2975	299.0	2411	298.8
313.2	3029	313.1	2437	311.1
323.6	3050	319.2	2450	317.1
332.4	3110	333.1	2490	332.7

melting parameter σ can be less than unity. Special computational experiments show that the consistency of ice age predictions with the developed average time scale within the upper part of the ice sheet down to a depth of 2500 m can be maintained only for $\sigma > 0.75$ with the best-fit value $\beta = 1.5$ corresponding to the limiting case $\sigma = 0.75$. This delivers the lower bound of ice ages below 2500 m at the maximum mean accumulation rate of 2.23 cm yr^{-1} assumed for the paleoclimatic history before 335 kyr B.P. These bounds are plotted in the inset in Fig. 3a and their arithmetic mean continues the average time scale at the end of Table 3. The error estimates are the mean age deviations from the simulated bounds plus additional standard errors ~5 kyr caused by averaging the past accumulation rates before 335 kyr B.P. The ice age calculated at the limiting depth of 3050 m is found to be 29852 $\pm$ 1568 kyr.

6. Conclusions

Three different approaches to ice-core age dating are employed to develop an average age-depth relationship at Dome F to the maximum (borehole) depth of 2500 m. First, the geophysical metronome time scale (GMTS) established in Hondoh *et al*. (2002) is used as a so-called orbitally tuned chronology. It is based on correlation of the Dome F isotopic temperature signal with the geophysical metronome-Milankovich components of the surface temperature variations in the past inferred from the borehole temperature profile at Vostok (Salamatin *et al*., 1998b; Salamatin, 2000). Another paleotemperature-proxy signal is available from the calcite core (DH-11) in Devils Hole, Nevada (Winograd *et al*., 1992, 1997). The principal advantage of this $\delta^{18}O$ record is that the dense vein calcite provides a material for direct uranium-series dating (Ludwig *et al*., 1992). The correlation of the Dome F ice core $\delta^{18}O$-depth signal with the Devils Hole record yields a second, independent, time scale (DHVTS). Ice flow modeling also becomes a useful tool for ice-age prediction if *a priori* statistically valid chronological information is used to constrain the model parameters. Here we base our study on a simplified 2-D approach to ice flow simulations as described in Salamatin and Ritz (1996) and Hondoh *et al*. (2002). Consequently, the modeled (glaciological) time scale at Dome F fitted to the GMTS and DHVTS represents a third source of ice age estimates and incorporates the principal laws of ice-sheet dynamics into the ice core dating procedure. The inverse Monte Carlo sampling method proves to be especially helpful for constraining the accumulation rate reconstruction and ice flow modeling to find the best-fit glaciological time scale matched with the two other chronologies (see Table 2). General uncertainties of the above age estimates vary from 2 to 6 kyr on average and reach 6–14 kyr at maximum. Whatever the causes of these discrepancies might be, they are thought to be of different origins with statistically independent errors. Thus, the average time scale for the Dome F ice core down to a depth of 2500 m is deduced consistent with all three dating procedures within the standard deviation limits of $\pm$3.3 kyr. The estimate of the actual accuracy of the developed average age-depth relationship should take into account the different error levels of the primary basic time scales and is determined as $\pm$1.4 kyr on average. This prediction is additionally confirmed by intercomparison of the isotopic ice core records from Dome F and Vostok. The ice age at the limiting depth 2500 m of the borehole bottom is 335 $\pm$ 1 kyr. The constrained ice-sheet flow model allows extrapolation of the average ice age-depth curve to the glacier bottom where the ice age at a depth of 3050 m may reach ~3000±1600 kyr.

Acknowledgments

The authors are grateful to J.M. Landwehr and I.J. Winograd for Devils Hole data. This work was presented and discussed at the 26th Symposium on Polar Meteorology and Glaciology (19–20 November, 2003, NIPR, Tokyo, Japan), and partly supported by a Grant-in-Aid for Creative Scientific Research, Japan.

References

Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackleton, N.J. and Lancelot, Y. (1994): The astronomic theory of climate and age of the Brunhes-Matuyama magnetic reversal. Earth Planet. Sci. Lett., **126** (1-3), 91–108.

Cuffey, K.M. and Vimeux, F. (2001): Covariation of carbon dioxide and temperature from Vostok ice core after deuterium-excess correction. Nature, **412**, 523–527.

Dome-F Deep Coring Group (1998): Deep ice-core drilling at Dome Fuji and glaciological studies in east Dronning Maud Land, Antarctica. Ann. Claciol., **27**, 333–337.

Dome-F Ice Core Research Group (1998): Preliminary investigation of paleoclimate signals recorded in the ice core from Dome Fuji station, east Dronning Maud Land, Antarctica. Ann. Glaciol., **27**, 338–342.

Hondoh, T. and 15 others (1999): Basic analyses of Dome Fuji deep ice core. Part 2: Physical properties. Proc. NIPR Symp. Polar Meteorol. Glaciol., **13**, 90–98.

Hondoh, T., Shoji, H., Watanabe, O., Salamatin, A.N. and Lipenkov, V.Ya. (2002): Depth-age and temperature prediction at Dome Fuji station, East Antarctica. Ann. Glaciol., **35**, 384–390.

Landwehr, J.M. and Winograd, I.J. (2001): Dating the Vostok ice core record by importing the Devils Hole chronology. J. Geophys. Res., **106** (D23), 31837–31851.

Lliboutry, L. (1979): A critical review of analytical approximate solutions for steady state velocities and temperatures in cold ice sheets. Z. Gletscherkd. Glazealgeol., **15** (2), 135–148.

Ludwig, K.R. and 6 others (1992): Mass-spectrometric ^{230}Th-^{234}U-^{238}U dating of the Devils Hole calcite vein. Science, **258**, 284–287.

Mosegaard, K. (1998): Resolution analysis of general inverse problems through inverse Monte Carlo sampling. Inverse Problems, **14** (1), 405–426.

Mosegaard, K. and Tarantola, A. (1995): Monte Carlo sampling of solutions to inverse problems. J. Geophys. Res., **100** (B7), 12431–12447.

National Institute of Polar Research (1997): Antarctica: East Queen Maud Land—Enderby Land. Glaciological Folio. Tokyo, National Institute of Polar Research, 38 p.

Parrenin, F., Jouzel, J., Waelbroeck, C., Ritz, C. and Barnola, J.-M. (2001): Dating the Vostok ice core by inverse method. J. Geophys. Res., **106** (D23), 31853–31861.

Ritz, C. (1989): Interpretation of the temperature profile measured at Vostok. East Antarctica. Ann. Glaciol., **12**, 138–144.

Ritz, C. (1992): Un modèle thermo-mecanique d'évolution pour le bassin glaciaire Antarcique Vostok—glacier Byrd: sensibilité aux valeurs des paramèters mal connus. Thése de Doctorat d'Etat. Université Joseph Fourier—Grenoble I.

Ritz, C., Rommelaere, V. and Dumas, C. (2001): Modeling the evolution of Antarctic ice sheet over the last 420,000 years: Implications for the altitude changes in the Vostok region. J. Geophys. Res., **106** (D23), 31943–31964.

Robin, G de Q. (1977): Ice cores and climatic changes. Philos. Trans. R. Soc. London, Ser. B, **280**, 143–168.

Salamatin, A.N. (2000): Paleoclimatic reconstructions based on borehole temperature measurements in ice sheets. Possibilities and limitations. Physics of Ice Core Records, ed. by T. Hondoh. Sapporo, Hokkaido University Press, 243–282.

Salamatin, A.N. and Ritz, C. (1996): A simplified multi-scale model for predicting climatic variations of the ice sheet surface elevation in Central Antarctica. Ann. Glaciol., **23**, 28–35.

Salamatin, A.N., Lipenkov, V.Ya., Barkov, N.I., Jouzel, J., Petit, J.R. and Raynaud, D. (1998a): Ice core age dating and paleothermometer calibration based on isotope and temperature profiles from deep boreholes at Vostok Station (East Antarctica). J. Geophys. Res., **103** (D8), 8963–8977.

Salamatin, A.N., Vostretsov, R.N., Petit, J.R., Lipenkov, V.Ya. and Barkov, N.I. (1998b): Geophysical and paleoclimatic implications of the stacked temperature profile from the deep borehole at Vostok Station (Antarctica). Mater. Glyatsiol. Issled. [Data Glaciol. Stud.], **85**, 233–240.

Salamatin, A.N., Tsyganova, E.A., Lipenkov, V.Ya. and Petit, J.R. (2004): Vostok (Antarctica) ice-core time scale from datings of different origins. Ann. Glaciol., **39** (in press).

Sowers, T. and 7 others (1993): A 135,000-year Vostok-SPECMAP common temporal framework. Paleoceanography, **8**, 737–766.

Watanabe, O. and 15 others (1997): A preliminary study of ice core chronology at Dome Fuji Station, Antarctica. Proc. NIPR Symp. Polar Meteorol. Glaciol., **11**, 9–13.

Watanabe, O. and 16 others (1999): Basic analyses of Dome Fuji deep ice core. Part 1: Stable oxygen and hydrogen isotope ratios, major chemical compositions and dust concentration. Proc. NIPR Symp. Polar Meteorol. Glaciol., **13**, 83–89.

Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H. and Yoshida, N. (2003): Homogeneous climate variability across East Antarctica over the past three glacial cycles. Nature, **422**, 509–512.

Winograd, I.J. and 7 others (1992): Continuous 500,000-year climate record from vein calcite in Devils Hole, Nevada. Science, **258**, 255–260.

Winograd, I.J., Landwehr, J.M., Ludwig, K.R., Coplen, T.B. and Riggs, A.C. (1997): Duration and structure of the past four interglaciations. Quat. Res., **48**, 141–154.