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Age of Himalayan bottom ice cores

Dating of tropical and Equatorial ice cores drilled in high mountain glaciers is difficult because seasonal variations can be traced only in the upper part. Modelling of the ice flow is difficult at depth due to the rapid thinning of the ice layers. Fortunately, atmospheric trace gases whose lifetime exceeds the inter-hemispheric mixing time (~1 year) are tracers on a global scale. By combining several gases, it is possible to attribute the age of an unknown ice layer by comparison with other well-dated ice-core records (Chappellaz and others, 1997a; Landais and others, 2003). Methane and the isotopic composition of atmospheric O_2 ($\delta^{18}O_{atm}$) are preferentially used for such purposes because of their suitable atmospheric turnover time (~10 years for CH_4 and ~ 1500 years for atmospheric O_2).

We recovered one ice core to bedrock (117.06 m long) in 2001, and two more, also to bedrock, (108.83 and 95.80 m) in 2002 on the col of East Rongbuk Glacier (28°01′ N, 86°58′ E; 6518 m a.s.l.) on the north slope of Qomolangma (Mount Everest) (Fig. 1). Hereafter we refer to the 117.06 m core as "core 2001", and the 108.83 m core as "core 2002". East Rongbuk Glacier covers an area of 48 km^2 with a length of 14 km. Borehole temperatures at the 108.83 m core site range from –8.9°C at 10 m to a minimum of –9.6°C at 20 m, then increase slightly to –8.9°C at the bottom. Measurements of $\delta^{18}O_{atm}$ and methane were performed at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) and the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) respectively. Details of the measurements are available elsewhere (Chappellaz and others, 1997b; Landais and others, 2003).

The narrow range of our $\delta^{18}O_{atm}$ results (–0.09‰ to 0.26‰) with respect to the Greenland Ice Sheet Project 2 (GISP2) ice core (Fig. 2; note the different vertical scales) suggests no glacial origin of the bottom ice. But we cannot decipher whether the bottom ice originated from the early or late Holocene, because the narrow $\delta^{18}O_{atm}$ band of our cores runs across the GISP2 $\delta^{18}O_{atm}$ profile during these two periods. If early-Holocene, the age of core 2001 at 102.5 m depth or of core 2002 at 87.5 m depth should be > 8000 years if adopting the GISP2 $\delta^{18}O_{atm}$ time-scale. However, an 80.4 m annually dated ice core recovered from the same East Rongbuk Glacier has a maximum age of 154 years (Kang and others, 2002; Qin and others, 2002). This excludes any possibility of early-Holocene origin for the bottom ice of our cores.

Both methane profiles show a rapid increase during the industrial period and low methane concentrations (a little below 700 ppbv pre-industrial methane level) in the very bottom sections, but these values are still much higher than the methane concentrations during the middle Holocene (~570 ppbv) as depicted by the Greenland Ice Core Project (GRIP) ice core (Fig. 2), even after taking into account the interpolar methane gradient (35 ppbv for the period 250–1000 years BP: Chappellaz and others, 1997b; Houweling and others, 2000). This further indicates the age of the bottom ice to be late Holocene.

To estimate precisely the age of the bottom ice, we prepared a $CH_4/\delta^{18}O_{atm}$ phase plane by using the GRIP CH_4 and GISP2 $\delta^{18}O_{atm}$ records, then superimposed our CH_4 and $\delta^{18}O_{atm}$ pairs (Fig. 3). All the CH_4 and $\delta^{18}O_{atm}$ pairs from the bottom 2 m of our cores are situated within BOX 1 (in Fig. 3). The ages of the CH_4 and $\delta^{18}O_{atm}$ pairs of the GRIP and GISP2 ice cores within BOX 1 are in the range 1498–2055 years BP, confirming the late-Holocene origin of the bottom ice. Furthermore, we exclude any possibility of connecting the $CH_4/\delta^{18}O_{atm}$ pairs within BOX 1 to the early Holocene. Otherwise, some of the $CH_4/\delta^{18}O_{atm}$ pairs within BOX 2 (in Fig. 3; from shallower sections, thus younger than those in BOX 1) would be dated at middle Holocene (Fig. 3), a period that is beyond any possible connection to BOX 2, even after considering the cumulative

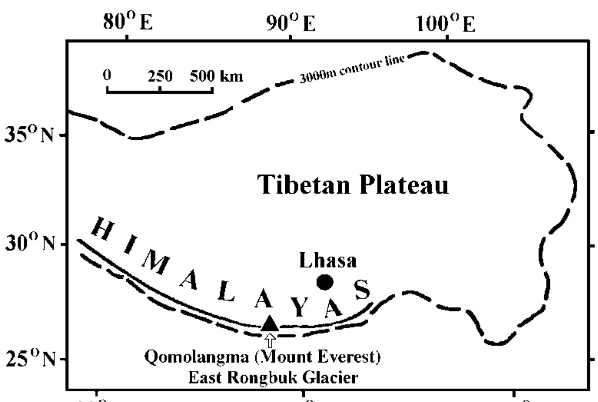

Fig. 1. Location map of ice-core drilling site.

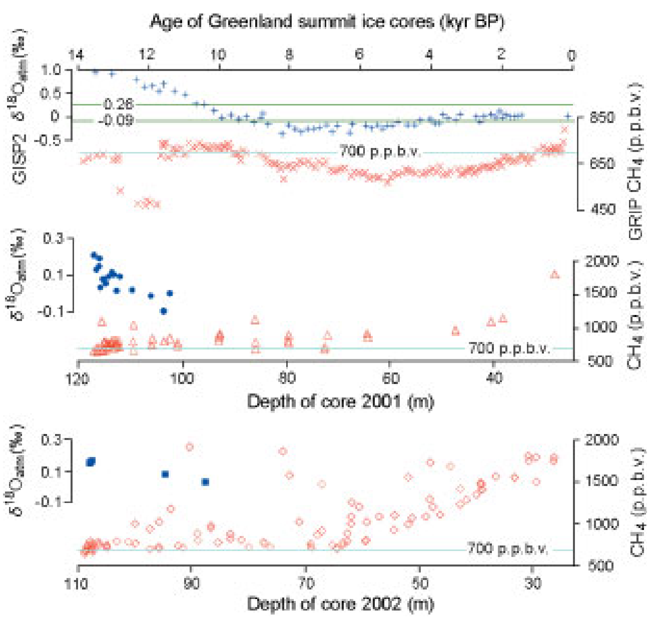

Fig. 2. Ice-core methane and $\delta^{18}O_{atm}$ profiles of the GRIP, GISP2, Himalayan core 2001 and core 2002. All the methane results are on the LGGE–University of Bern internal scale (Chappellaz and others, 1997b), which excludes the experimental bias for comparison. The 700 ppbv pre-industrial CH_4 level depicted by polar ice cores is added for clarity. The –0.09‰ and 0.26‰ $\delta^{18}O_{atm}$ horizons of the summit core panel are the minimum and maximum of the Himalayan ice cores, respectively.

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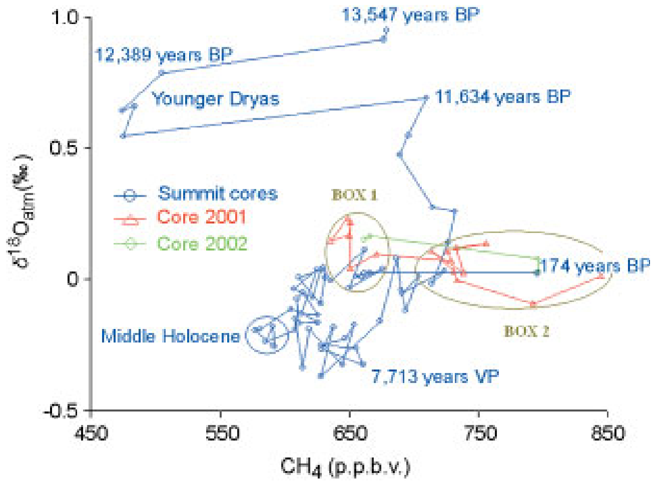

Fig. 3. The $CH_4/\delta^{18}O_{atm}$ pairs of the Himalayan ice cores superposed on the GRIP–GISP2 $CH_4/\delta^{18}O_{atm}$ phase plane. The ages are GISP2 time-scale (Meese and others, 1994) after correction of gas–ice time difference, and the GISP2–GRIP chronologies are in good agreement back to 3300 years BP (Southon, 2002), avoiding bias for our dating due to its younger age.

effects of the experimental uncertainty (Chappellaz and others, 1997a; Landais and others, 2003) and the methane interpolar gradient (Chappellaz and others, 1997b; Houweling and others, 2000). The ice-core base is dated at $\sim$ 1650 years BP when applying a simple flow model. Thus our ice cores will provide extremely high-resolution paleoclimate records for the Himalayan region.

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