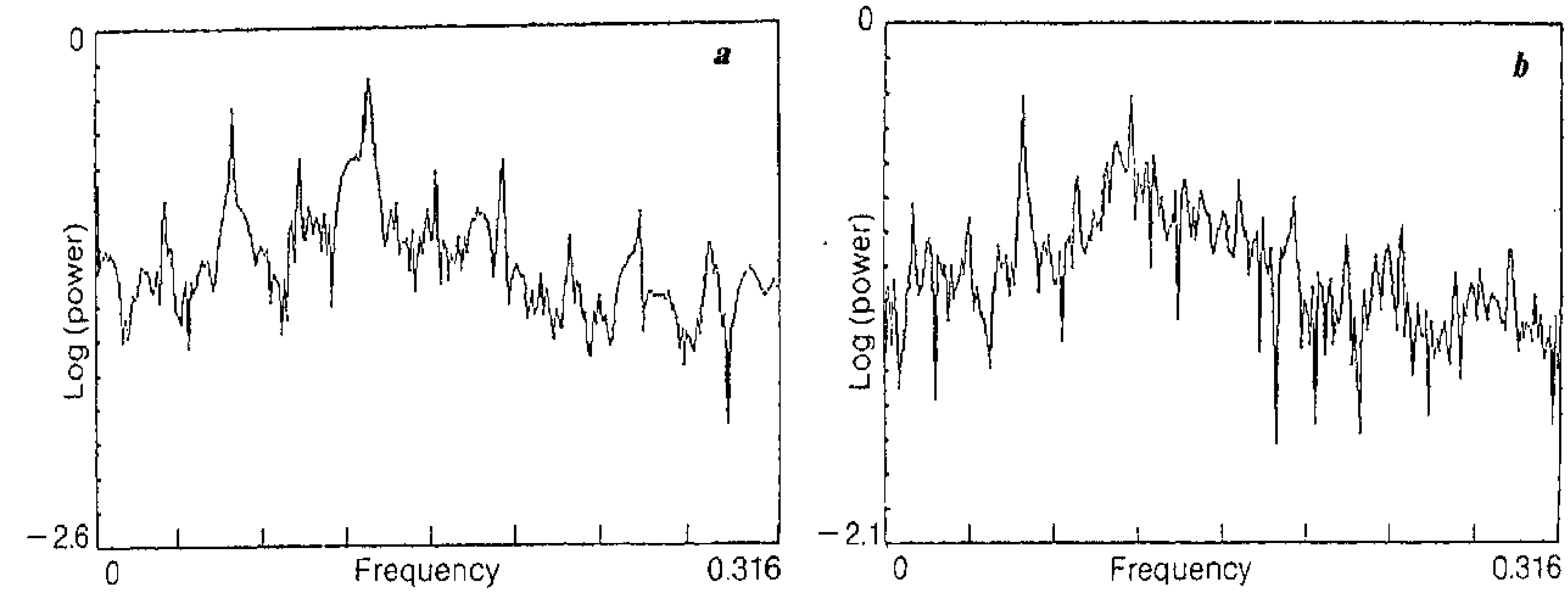

Figure 3. Power spectra showing that as A is increased additional frequencies appear in the system. In **b** ($A = 0.26$), the system shows chaotic behaviour.

We feel that the frustration makes the system extremely sensitive to changes in the external parameters, so that a small change in the control parameter can drive the system to the chaotic state. More detailed investigations are necessary before one can make definite predictions regarding the nature of the transition to chaos. We are currently investigating this and the results will be presented elsewhere.

Table 1. The maximum Lyapunov exponent λ_{max} for the system when $\omega = 0.4$, $g = 0.2$, and A is varied.

A	λ_{max}
0.15	-2.338065×10^{-3}
0.2	-6.341918×10^{-4}
0.21	5.757624×10^{-4}
0.22	1.253144×10^{-3}
0.24	1.979667×10^{-3}
0.26	3.467343×10^{-3}
0.28	3.55532×10^{-3}
0.3	4.432041×10^{-3}

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Decline of ^{210}Pb fallout on Greenland in the last century

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We have carried out systematic measurements of ^{210}Pb fallout over a period of about 100 years at Dye-3 station in Greenland using a precisely dated 77-m deep ice core. The core was dated using data on annual cyclic variations in δ^{18}O, artificial radioactivity and elevated levels of acidity due to major volcanic eruptions. The results indicate that the fallout of ^{210}Pb has not remained constant over the last century and was higher by a factor of about two during 1885–1920 than in 1920–1975. Possible causes for the changes in fallout due to volcanic eruptions and nuclear explosions are discussed. If the observed trend is valid on a global scale, it raises serious doubts about the basic assumption of ^{210}Pb geochronology.

PAST records of climatic changes, atmospheric and nuclear fallouts, volcanic debris and a wealth of other information are preserved systematically in polar glaciers and ice sheets. Favourable areas for studying such deposition events are the high-latitude regions of large ice sheets, such as Greenland in the northern hemisphere, which is fed by relatively frequent and heavy snowfalls[1]. Greenland ice cores are most suitable for dating the annual layers of snow deposition using very sensitive δ^{18}O and past-acidity records[2]. The natural ^{210}Pb background in Greenland being low compared to that in other locations in the northern hemisphere because of its remoteness from natural sources, it is easy to observe even small changes in the deposition flux of ^{210}Pb caused by natural or artificial events, such as volcanic eruptions or thermonuclear explosions. Analytical study of a well-dated core from

Greenland therefore provides systematic undisturbed records of atmospheric and nuclear fallouts, volcanic debris and wind-borne materials.

Over the past two decades, ^{210}Pb, by virtue of a convenient half-life (22.3 yr), has found several applications as a chronometer in diverse fields like glaciology[3-7], limnology[8], oceanography[9] and atmospheric sciences[10]. One of the basic assumptions in ^{210}Pb geochronology is that deposition flux has remained constant over the dating interval. The present work seeks to verify this assumption made in dating glaciers by ^{210}Pb. Short-term and long-term variations in natural levels of ^{210}Pb fallout in the northern hemisphere over the last 100 years have been investigated and contributions from natural and artificial sources are assessed.

A 77-m deep ice core of 8 cm diameter at Dye-3 station, South Greenland (65° 11′ N, 43° 29′ W; 2930 m.a.s.l), was raised in 1976 during the American–Swiss–Danish Greenland ice sheet programme (GISP) using a light-weight core drill[6]. Dye-3 station receives an average of 60 cm of ice equivalent as annual precipitation. The complete ice core, which spans over 100 years, was stored at −25°C at the Geophysical Institute in Copenhagen, Denmark.

The ice core has been dated by analysing $\delta^{18}O$ (‰) and total beta activity (dph per kg ice) using standard techniques[5,6]. Systematic measurements of oxygen-isotope ratios in the core demonstrated the typical annual variation of $\delta^{18}O$ (i.e. the consecutive maxima and minima corresponding to summer and winter precipitations in a year), indicating strong dependence of the ratio on atmospheric temperature. The annual cyclic variation of $\delta^{18}O$, combined with fixed points from past records of total beta activity, volcanic eruptions and acidity records[2], provided precise ages with depth in the ice core. The error in dating on the timescale of ~100 years is less than 1 year.

The core section used in this study represents the period 1886–1975. ^{210}Pb activity was measured by standard procedures[5] in several samples taken from the core. Measurements of ^{210}Bi activity (daughter of ^{210}Pb) were carried out on yearly samples (0.8–2.2 kg of ice) for 1936–1975, whereas for the older samples dating back to 1886, successive 5-year accumulations (2.1–4.8 kg of ice) were combined to yield better signals. The five-year weighted means of observed ^{210}Bi activity signals ranged from 10 to 52 cph, which are much higher than the background (~3 cph). The ^{210}Pb activities with analytical errors less than 10% (similar to those observed by Goldberg in Greenland ice[11]) enabled us to obtain better accuracy in dating the old ice at the cost of time resolution. The ^{210}Pb activity was calculated using the net ^{210}Bi activity after subtracting background and contributions from blanks.

The results of our measurements are shown in Figure 1. The data do not show any significant enhancement in ^{210}Pb fallout during three decades (1950–80) of atmospheric nuclear weapons test series (Figure 1 *b*,*c*). The artificial production of ^{210}Pb in the atmosphere due to nuclear weapons tests has been suggested to be comparable to that produced from the decay of ^{222}Rn emanating from the earth's crust[12]. If this is true, one would expect a sharp increase in ^{210}Pb fallout, to

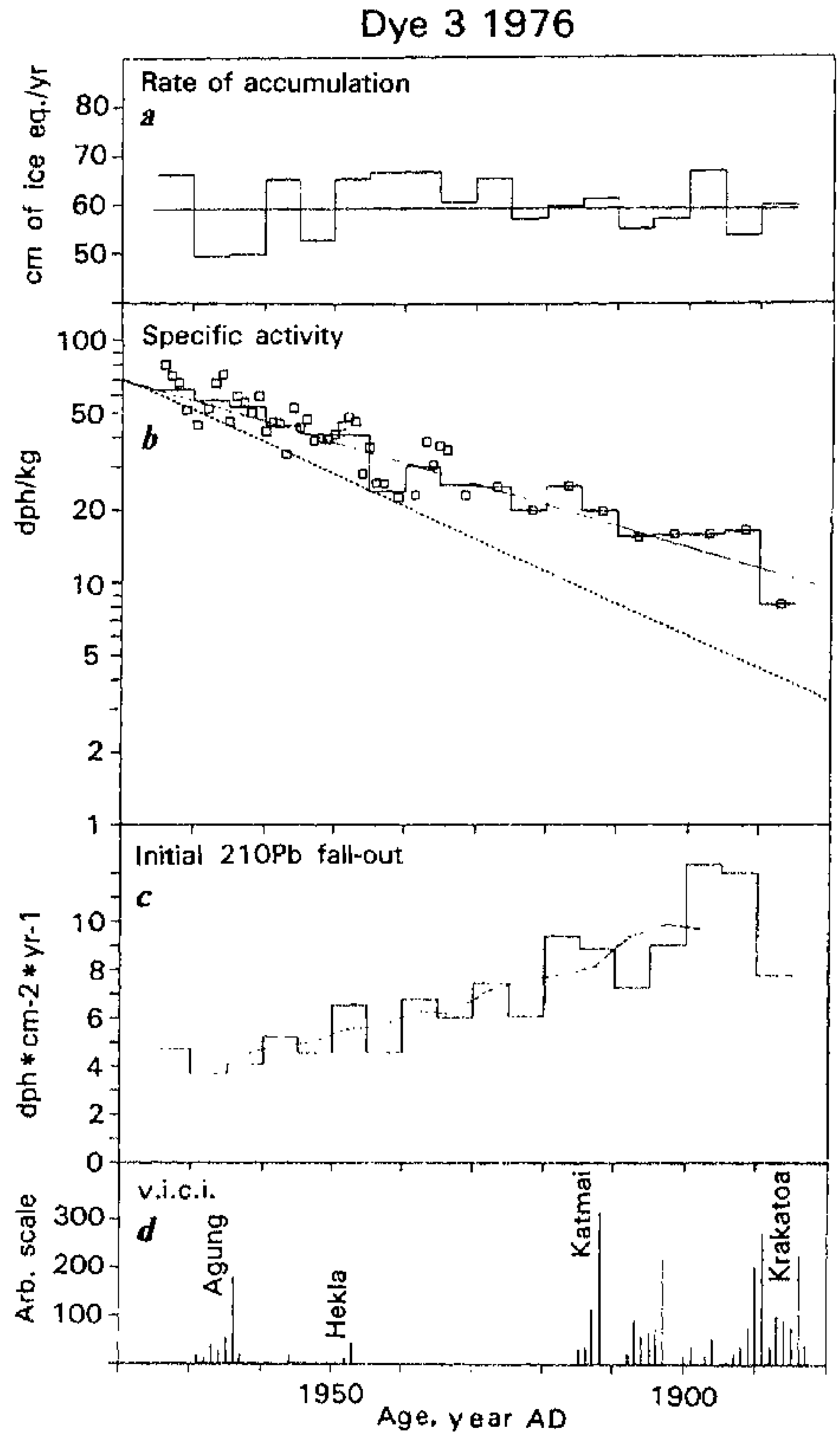

Figure 1. *a*, Five-year means of the annual rate of accumulation at Dye-3 (cm of ice equivalent per year) for the period 1886–1975. *b*, Specific ^{210}Pb activity (dph per kg of ice) in the Dye-3 ice core for the period 1886–1975. The horizontal step curve shows 5-year mean values. The regression line (solid line) is based on the 5-year means. The slope of this line, based on $\delta^{18}O$ chronology, deviates from the expected ^{210}Pb decay (dotted line); see text. The statistical errors are less than the size of the boxes (generally 5%). *c*, Initial ^{210}Pb fallout for the period 1886–1975. The step curve represents 5-year means of the annual initial ^{210}Pb fallout (dph cm^{-2} yr^{-1}). The smooth curve represents 25-year running means. *d*, The volcanic impurity concentration index (v.i.c.i) plotted on an arbitrary scale for the period 1886–1975. The names of volcanic eruptions, like Katmai, Hekla, etc., are shown over the corresponding v.i.c.i. signals.

~10 dph cm^{-2} yr^{-1} during 1963–64 from a constant natural fallout of ~5 dph cm^{-2} yr^{-1} observed during the late '50s, '60s and early '70s. But such a large contribution from nuclear tests is definitely not observed, indicating the absence of bomb-produced ^{210}Pb in Greenland precipitation.

It is also evident from Figure 1*b* that the slope of the theoretical decay curve is different from that of the regression line drawn on the basis of 5-year means of observed specific activities (dph per kg ice) of ^{210}Pb during the span of ~100 years. Based on these observations, an apparent half life of 35 years is deduced for the observed ^{210}Pb decay. The longer decay period is a result of variation in the fallout of ^{210}Pb over the past century.

The step and smooth curves shown in Figure 1*c* represent the 5-year means and 25-year running means respectively of initial ^{210}Pb fallout. They indicate a decreasing trend of initial ^{210}Pb fallout during the past 100 years and that the observed ^{210}Pb fallout for the period 1920–75 is lower by at least a factor of two than that for the period 1885–1920. This decreasing trend cannot be explained as being due to a changing rate of annual accumulation of the Greenland ice sheet as the latter has remained fairly constant (Figure 1*a*). Sanak *et al.*[4] suggested that drastic changes occurred at the South Pole either in the accumulation rate of ice or in ^{210}Pb content of freshly fallen snow in 1920 and 1954. The present data for Greenland also show considerable changes around the same time. This can be explained only by higher deposition of ^{210}Pb in view of the fairly constant accumulation rate of ice (Figure 1*a*).

The signatures of the violent volcanic eruptions of Katmai (1912), Krakatoa (1883), etc. have been identified by increase of acidity in Greenland ice cores[1,2]. These volcanoes ejected large amounts of volcanic gases, dust and other impurities into the atmosphere, which in turn got deposited on Greenland ice within a year or two after the eruption[2]. It is therefore interesting to compare the ^{210}Pb fallout with the volcanic impurity concentration index[13] on the same timescale. Such a comparison shows a good correlation between ^{210}Pb deposition (1880–1920) and volcanic activity (Figure 1*d*). This cannot, however, explain the observed ^{210}Pb fallout trend, which is monotonously decreasing. If volcanic eruptions were the cause of higher fallout during 1880–1920, then the fallout pattern should have shown sharp changes in response to the residence time of one year for ^{210}Pb aerosols in the stratosphere.

^{222}Rn emanation depends primarily on the nature of the soil (porosity, grain size, soil moisture, etc.) and environmental conditions (temperature, wind pattern, etc.). The observed excess of ^{210}Pb fallout can be partially explained as being due to enhanced ^{222}Rn exhalation from land from breaking of virgin soils in north-west America. With the presently available data, we are unable to offer any definite cause for the observed decreasing trend of ^{210}Pb fallout over Greenland.

The assumption usually made in geochronological studies that ^{210}Pb fallout has remained constant over the last 100 years does not hold for Greenland. If this trend is valid on a global scale, geochronological studies based on ^{210}Pb would have to be reassessed.

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Raoellid astragali from the Kalakot zone (Subathu Group): evidence for assignment to the Artiodactyla

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Size correspondence as well as *in situ* association of morphologically distinct artiodactyl astragali and at least two genera of the family Raoellidae conclusively prove their ordinal assignment. This contention, in the light of recent work, has important bearing on studies dealing with the evolution and radiation of several mammalian orders in the area of the Himalayan Tethys.

THE Raoellidae[1] represents a family of primitive ungulates that are morphologically distinct from any