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Cosmic ray dose rate determination using a portable gamma-ray spectrometer

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Introduction

Cosmic rays usually contribute only a few percent of the total dose of a TL sample. At very high altitudes the cosmic dose becomes much more important (e.g. Prescott & Hutton, 1988).

An interdisciplinary study from Bern University is trying to reconstruct the environmental history and the climatic change of the Altiplano in the Andes of northern Chile (Messerli et al., in press). In this study TL dating plays an important role besides other dating techniques.

Some approximate calculations on samples from this project showed that cosmic rays contribute up to 40 % of the total dose. It was therefore desirable to measure the cosmic dose rate at the sample locality itself. The aims of this study were as follows:

(i) to draw up a calibration curve for our 4-channel γ-spectrometer when the probe was unshielded;
(ii) to establish the shielding effect of a rock column of various depths at various altitudes;
(iii) to quantify the influence of high cosmic dose rates to channels 1 (K), 2 (U) and 3 (Th).

A comprehensive introduction to the complex subject of cosmic radiation and its implications concerning TL dating is given by Prescott & Stephan (1982). See also Prescott & Hutton (1988) and Aitken (1985, Appendix I) for further information.

If one searches for dose rate values in the free atmosphere things become difficult very rapidly. Basic research has been done by Rossi (1948; see also references therein). More recent papers have been published by Lowder & Beck (1966), Kyker & Liboff (1978) and Sztanyik & Nikl (1982). The dose rate values given in these papers show certain differences which may have many reasons (see Kyker & Liboff, 1978 and Sztanyik & Nikl, 1982 for further information). We have put together the data from these three more recent papers (see fig. 1) and calculated an exponential curve fit. With an assumed error of 12 %, all points fall within the curve. This seems reasonable, since the estimated calibration error for the CIT ionization chambers is about 17% (Carmichael, 1971).

The Harwell 4-channel γ-spectrometer type 95/0928

All measurements were carried out using this instrument, which contains a NaI(Tl) crystal scintillator of 44.5 mm dia x 50.8 mm. The instrument was calibrated in the Research Laboratory for Archaeology in Oxford according to the procedure described by Murray (1981). An alternative calibration method has been proposed by Sanzelle et al. (1988). (For instrumental properties and settings see Tables A1 and A2.) The setting of the discriminator channel allows no response to terrestrial γ-rays (Aitken, 1985). According to data published by Allkofer & Grieder (1984), the discriminator channel is sensitive to both hard and soft components. The low background values obtained in the Bern C-14 Laboratory (Table A3) correspond to 40 ppm K_2O, 18 ppb U and 80 ppb Th. This is equivalent to a total γ-dose rate, calculated using the conversion factors of Nambi & Aitken (1986), of 7 μGy/a. These figures are considered to be negligible and therefore no background correction has been made to calculate concentrations.

Measurements

The measurements made in Chile were carried out at altitudes of between 130 m and 5150 m and at geomagnetic latitudes of between 22.5° S and 24.3° S. All field readings are adjusted to a latitude of 47° (Bern). The mean latitude correction factor for the data from Chile is 1.049 (taken from fig. 2, Prescott & Stephan, 1982). Measurements in Switzerland were made at altitudes of between 420 m and 4554 m. The measurements in the glacier ice of the Monte Rosa Massif (Switzerland/Italy) were made in a borehole of ~15 cm diameter. The measurements on the glacier surface were made in two different ways: with the probe standing upright and with the probe lying flat. This was done because of the shape of the NaI crystal.

All measurements were made on well exposed sites, which is important because surface irregularities influence registration geometry, as was demonstrated in a short experiment in Switzerland. The count rate in the discriminator channel increases by about 20 % when the horizontal distance from a 60 m high wall of rock increases from 5 to 200 m.

The measurements made using the unshielded probe are plotted in fig. 2. An exponential curve computed through all points has a correlation coefficient of $r^2 = 0.995$. On 12 different sites, measurements at depths ranging from 50 to 7350 g/cm^2 of rock were made to find out whether a given count rate corresponds to the same dose rate using both the shielded and unshielded probe (fig. 3). For the unshielded probe the dose rates were taken from fig. 1. For the shielded probe the dose rates were estimated using fig. 1 as well as data published by Prescott & Stephan (1988) - see also discussion. The results for the shielded probe differ clearly from those for the unshielded one, although the data are few and have a considerable uncertainty.

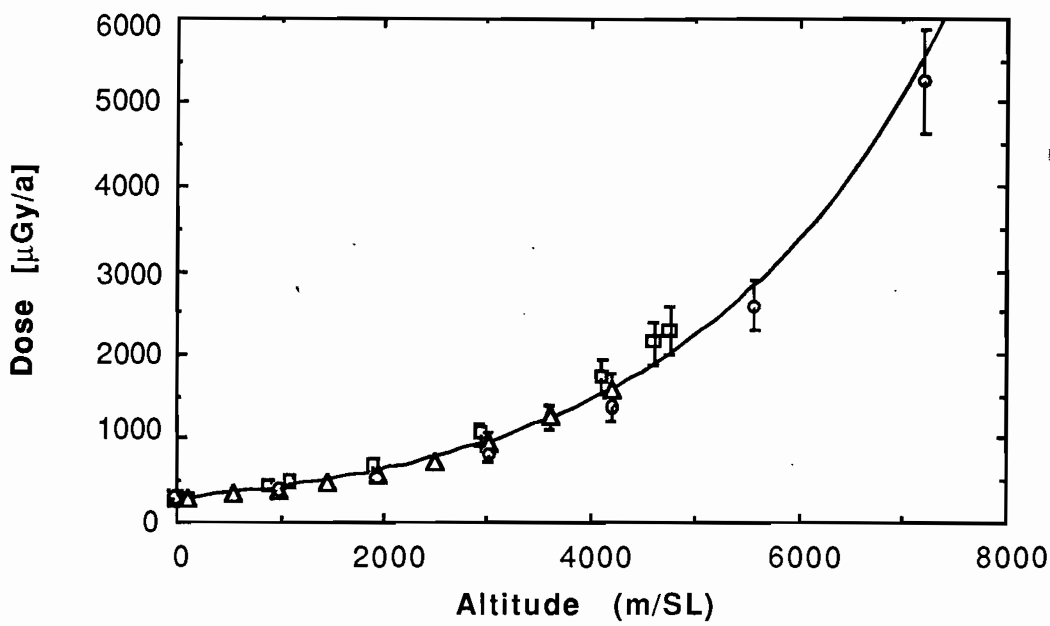

Figure 1.

Key: o - *Kyker and Liboff (1978);* □ - *Sztanyik and Nikl (1982);* Δ - *Lowder and Beck (1966).*

Dose rate of cosmic radiation (hard and soft components) as a function of altitude. The curve is calculated using all three data sets where: $y = 273.2 \log_{10}(1.81E\text{-}04x)$; r^2 *(corr. coeff.)* = 0.987.

The data set is based on the ICAO standard atmosphere (1013.2 hPa at sea level, 15 °C).

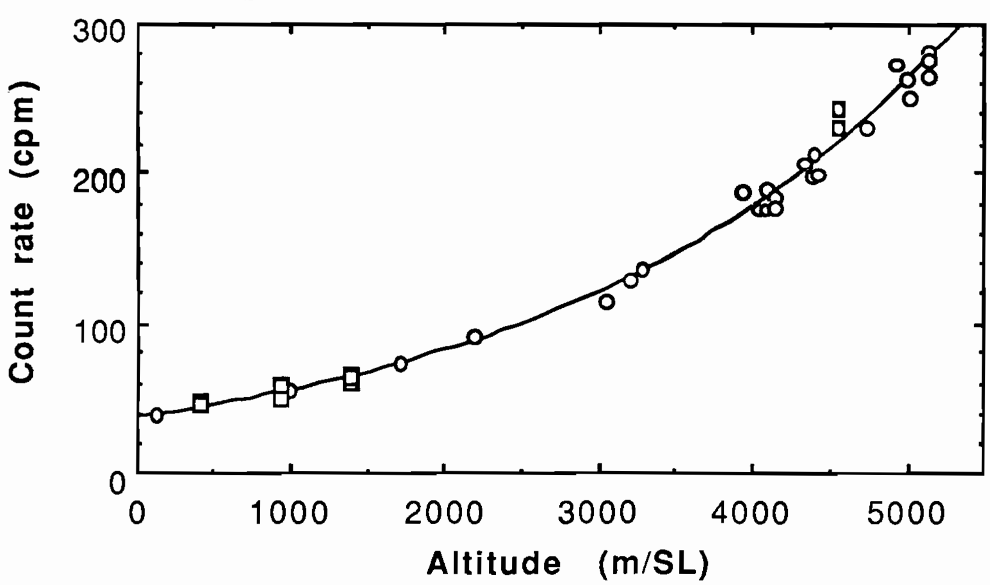

Figure 2.

Key: o - *data from Chile,* □ - *Data from Switzerland*

Count rate in the discriminator channel as a function of altitude. All count rates are adjusted to a latitude of 47 °N (Berne). Curve fitted to data: $y = 37.7 \log_{10}(1.68E\text{-}04x)$; $r^2 = 0.995$.

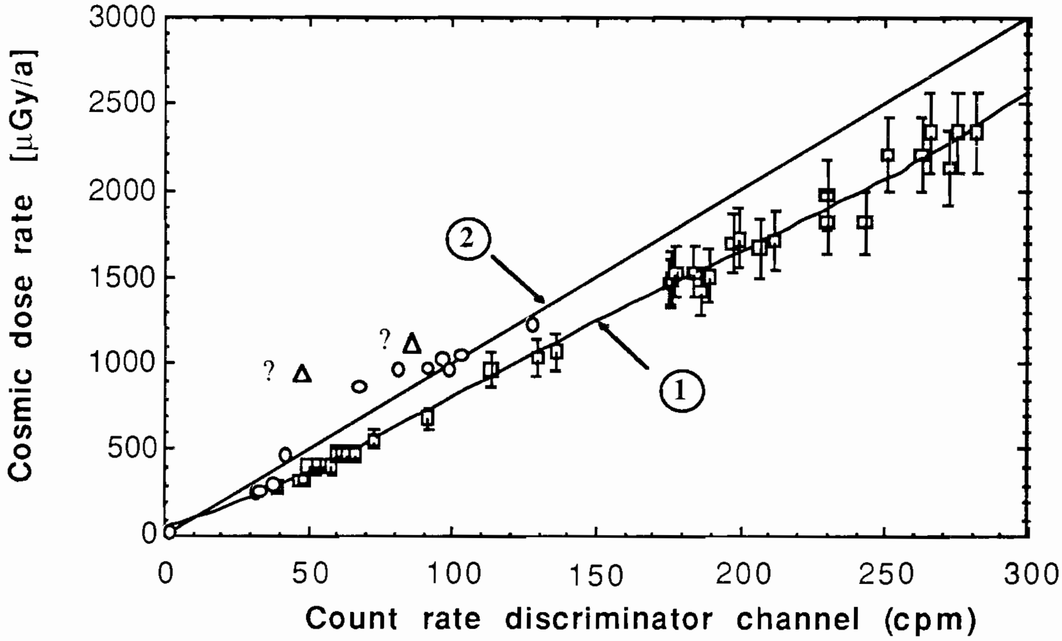

Figure 3.
Key: o *- underground measurements (shielded probe);* □ *- surface measurements (unshielded probe);* Δ *measurements in glacier ice.*
Curve fit calculated for the unshielded (polynomial fit 4th order) and the shielded (= buried) probe (regression line), respectively, where:

Curve 1) $y = 51.6 + 4.22x + 5.5E\text{-}02x^2 - 2.7E\text{-}04x^3 + 4.5E\text{-}07x^4$ $(r^2 = 0.991)$

Curve 2) $y = 10.5x - 14.1$ $(r^2 = 0.957)$

The results from the measurements in the glacier ice have not been used to calculate the regression line, because the dose rate cannot be determined with sufficient accuracy (see text).

Discussion

Since cosmic radiation is influenced by numerous factors which could not be taken into account, some simplifications are necessary in order to interpret the results in a general way:

(i) All measurements were made close to solar maximum (Solar Geophys. Data, 1990), and we have to assume that the results obtained are valid for the whole solar cycle.

(ii) The measurements were carried out at any time of the day and in any weather conditions. Any possible uncertainty caused by varying atmospheric pressure or clouding are not taken into consideration.

(iii) The data published by Lowder & Beck (1966), Kyker & Liboff (1978) and Sztanyik & Nikl (1982) refer to the dose rate in air. The figures given in Aitken (1985) and Prescott & Hutton (1988) refer to material of rock like composition. According to Sztanyik & Nikl (1982) and Prescott & Hutton (1988) the difference between the dose rate in air and that in rock is barely significant and certainly within the experimental error. These restrictions must be borne in mind when interpreting the results.

A straight line calculated through the points representing the data obtained using the unshielded probe has a negative intercept on the y-axis. This may be due to the changing ratio of the hard to soft component in the vertical direction of the atmosphere (Rossi, 1948; Prescott & Stephan, 1982) as well as to the different sensitivity of the NaI crystal towards the hard and soft component. The plot of the data obtained using the unshielded probe (fig. 3) is therefore a superposition of several non-linear functions. The lack of data at low dose rates also contributes to the negative intercept on the y-axis. One would expect an approach of the curve to the x-axis towards the origin. Since the expected count rate at sea-level is about 38 cpm (see fig. 2), it is impossible to obtain results for low count rates. We have therefore calculated a polynomial fit (expression (1) in fig. 3) for the data obtained using the unshielded probe (fig. 3). The intercept of 51.6 seems rather high, which may also be due to the lack of data at low count rates. For count rates in the discriminator channel between 50 and 300 cpm the cosmic dose rate can be approximated by:

$$\dot{D}\ [\mu Gy/a] = 8.5 \times (cpm_{discr.-ch.}) - 54.3,$$

where cr = count rate in cpm

The data obtained using the shielded probe (fig. 3) have a significantly lesser correlation than the data obtained using the unshielded one. One important reason for this is that the density and the water content of the overlying sediments could not be determined precisely. Furthermore, the measurements were made at varying depths below the surface and at varying altitudes. As a result each measurement corresponds to conditions where the intensity and the ratio of hard to soft component are different. The dose rates can only be estimated using the values from fig. 1 together with the relative variation of the soft component with depth (fig. 1 of Prescott & Hutton, 1988). Although the uncertainty is quite large, the results obtained using the shielded probe show one important fact: The measurements diverge significantly from those obtained with the unshielded probe. This can only be explained by the higher sensitivity of the NaI crystal to the hard component compared to the soft component. The dose rate obtained using the shielded probe can be calculated approximately using formula (2) in fig. 3.
At low altitudes (i.e. below 800 m) the present data do not allow a distinction to be made between the dose rate at a depth of < 100 g/cm^2 and that at the surface, although the difference is significant (see fig. 1 of Prescott & Hutton, 1988). At an altitude of 4080 m, for example, the difference is measurable for a smaller mass thickness. Here the measured dose rate at the surface is 18 % higher than that at a depth of around 70 g/cm^2 .
The measurements made in the glacier ice were not used to calculate the regression for the shielded probe, because the exact attenuation factor in ice is not known. The points plotted in fig. 3 were calculated using an attenuation factor of 10% per 100 g/cm^2 (Prescott & Hutton, 1982). Unfortunately the saddle-shaped geometry of the glacier also introduces some uncertainty as far as concerns the precise estimation of the dose rate for these two measurements; the horizontal flux of the cosmic radiation might be somewhat increased.
In order to get precise values for a good calibration of the γ-spectrometer, however, one should bury TL dosemeters at all depths and altitudes, but the results presented here are sufficiently accurate for our dating purposes.

The measurements made in the Monte Rosa Massif clearly show that there is a weak but significant dependence of the count rates in channels 1 to 3 on the count rate in the discriminator channel. It was noticed that the direction of the probe axis in relation to the vertical has an important influence on the count rate: all channels give a clearly lower count rate when the probe is vertical. This is to be expected for the discriminator channel because of the shape of the NaI crystal. Since channels 1 to 3 show the same feature, we have to assume that they are also influenced by cosmic radiation. If this were not the case, i.e. if the count rates in channels 1 to 3 were only due to terrestrial gammas, the count rates should be roughly the same in both cases, whether the probe was standing or lying. In the absence of precise values for dust and other impurities embedded in the glacier ice we estimate that about one-third of the count rate in channels 1 to 3 originates from these impurities and from nearby rocks. About two-thirds of the count rate therefore represents cosmic radiation.
Although channels 1 to 3 are influenced to roughly the same extent, the Th is much more affected than U and K (see Table A1, equations to calculate the concentrations of K_2O, U and Th). A count rate of 100 cpm in the discriminator channel leads to an over-estimation of a few ppm for K_2O and 0.15 ppm for U. A count rate of 50 cpm in the discriminator channel results in an over-estimation of the Th concentration of 0.375 ppm. We propose therefore a correction for the K and U channel if the count rate in the discriminator channel exceeds 100 cpm and a correction for the Th channel if the count rate (cr) in the discriminator channel exceeds 50 cpm using the following formulae:

$$cr\ (eff.)_{ch.\ 1} = cr\ (meas.)_{ch.\ 1} - 0.017\ cr_{discr\text{-}ch.}$$
(for $cr_{discr\text{-}ch.} > 100$ cpm)

$$cr\ (eff.)_{ch.\ 2} = cr\ (meas.)_{ch.\ 2} - 0.020\ cr_{discr\text{-}ch.}$$
(for $cr_{discr\text{-}ch.} > 100$ cpm)

$$cr\ (eff.)_{ch.\ 3} = cr\ (meas.)_{ch.\ 3} - 0.019\ cr_{discr\text{-}ch.}$$
(for $cr_{discr\text{-}ch.} > 50$ cpm)

Conclusions

The data presented here show that it is possible to determine the cosmic dose rate with sufficient accuracy using an unshielded probe. With the shielded probe it is still possible to make a first approximation of the cosmic dose rate.
The influence of high cosmic radiation on channels 1 to 3 can be corrected to prevent over-estimation of K_2O, U and Th.

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Table A1. Window settings

Channel No.	Isotope	Peak Energy (MeV)	Energy Window (MeV)
1 (K)	^{40}K	1.461	1.385 - 1.535
2 (U)	^{214}Bi	1.764	1.685 - 1.835
3 (Th)	^{208}Tl	2.615	2.464 - 2.764
Discriminator	cosmic rays (muons/electrons)		> 3.4

Table A2. Stripping factors and sensitivity coefficients (using terminology by Sanzelle et al., 1988). Owing to two minor misprints, the equations for α_1 and β_2 given in this paper have been corrected to:

$$\alpha_1 = -\frac{u_1}{u_2} - \frac{u_3}{u_2}\left\{\frac{\frac{t_2}{t_3}\cdot\frac{u_1}{u_2} - \frac{t_1}{t_3}}{1 - \frac{t_2}{t_3}\cdot\frac{u_3}{u_2}}\right\}; \quad \beta_2 = -\frac{\frac{t_2}{t_3}}{1 - \frac{t_2}{t_3}\cdot\frac{u_3}{u_2}}$$

Stripping factors:

$t_1/t_3 = 0.533$; $t_2/t_3 = 0.597$;

$u_1/u_2 = 0.960$; $u_3/u_2 = 0.012$

Sensitivity coefficients: $k_1 = 45.25$ cpm / [% K_2O]

$u_2 = 4.88$ cpm / [ppm U]

$t_3 = 2.145$ cpm / [ppm Th]

Equations to calculate the concentrations of K_2O, U and Th:

K_2O [wt-%] $= (2.21\ n_1 - 2.12\ n_2 + 0.051\ n_3)\ 10^{-2}$

U [ppm] $= (20.64\ n_2 - 11.95\ n_3)\ 10^{-2}$

Th [ppm] $= (-\ 0.564\ n_2 + 46.95\ n_3)\ 10^{-2}$

where n_1, n_2 and n_3 are count rates (cpm) in the K-, U- and Th- channels respectively.

Table A3. Instrumental background (cpm)

Locality	Discr. chnl (cpm)	K chnl (cpm)	U chnl (cpm)	Th chnl (cpm)
Low level counting lab, Phys. Dept., Bern	1.918 ± 0.039	0.370 ± 0.017	0.188 ± 0.012	0.173 ± 0.012
C-14 Lab, Harwell, U.K.	24.3 ± 0.3	0.809 ± 0.06	0.448 ± 0.04	1.009 ± 0.07

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