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Cosmic ray contribution to environmental dose rates with varying overburden thickness

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Abstract: *The dynamic character of most natural depositional systems is such that the cosmic ray dose rate experienced by a buried luminescence dating sample is not static but changes with the fluctuations in the thickness of the overburden. The use of in situ (present day) cosmic ray contribution rates assumes instantaneous deposition of the sedimentary column overlying the sample followed by a period of non-deposition. Where the cosmic ray dose constitutes a major component of the total dose (which may be up to 60 %), as is the case with many quartz aeolian dune sand systems, the assumption of instantaneous deposition may introduce notable errors. By reconstructing the burial history of a sample from the top downwards, methodology can be formulated for estimating the true cosmic ray dose received. Two different scenarios are discussed: i) gradual burial in a single depositional episode and ii) burial by episodic (multiple) increase of overburden.*

Introduction

The dose rate contribution of cosmic rays to palaeodoses for luminescence dating of geological materials varies with changes in the thickness of the overburden. The majority of geological systems are dynamic such that cosmic ray dose rates for buried samples are seldom fixed, unless the overburden thickness remains static. Although this is well known, there has been little published work which attempts to evaluate the cosmic ray dose received by a sample over its burial history allowing for changes in cosmic ray dose rate that arise from variations in overburden thickness. Cosmic ray contribution rates quoted in many publications are obtained using the method of Prescott and Hutton (1988, 1994) and estimate contribution rates at specified depths. In some cases estimation is carried out using gamma ray spectrometry (Stokes et al., 1997). In most of the cases where the cosmic ray dose rates are evaluated using these two methods, the cosmic ray contribution rates correspond to in situ (present-day) contribution rates. This would effectively be accordant with the assumption that deposition of the sedimentary column overlying the sample was in an instantaneous episode. Alternatively, some workers find it convenient to use 'token' values for cosmic ray dose rates, typically in the range 0.14 - 0.15 mGy/yr. In this paper, methodology for estimating cosmic ray contribution is applied in two scenarios where cosmic ray contribution rates are not fixed: a single step gradual accumulation of overburden and a multi-step episodic accumulation of sediment.

Nature of cosmic Rays

Cosmic rays reaching the earth dominantly comprise protons, helium nuclei and heavier particles. Electrons and gamma rays account for a minor proportion. The origin of the cosmic rays is not known with certainty but a major component is widely believed to be produced by supernovas (Friedlander, 1989). When the nuclear cosmic rays collide in the atmosphere pi-mesons are produced and these decay rapidly into muons and neutrinos. The muons decay into electrons and additional neutrinos. For purposes of buried samples, it is the flux of muons that determines the cosmic ray dose rate because of their greater penetration depth. For a comprehensive discussion of the dependence of cosmic ray dose rate with depth and expressions for evaluating contribution rates at specified depths, see Prescott and Hutton (1988, 1994).

Variation of cosmic ray contribution with changes in sedimentary cover in systems with low internal dose rates

The proportion of cosmic ray contribution to dose rates for luminescence dating is generally low and frequently constitutes less than 10 % of the total dose. Thus, when calculating the total dose rate, disregarding the gradual changes in the cosmic ray dose rate that arise from variations in thickness of the overburden, i.e. essentially assuming that the in situ (present-day) dose rates have been effective from the beginning, may not necessarily introduce large errors. However, in aeolian dune sand systems whose

***Table 1**: Examples of dosimetry for samples collected from quartz dune sands with low internal dose rates (K, U & Th) and high cosmic ray contribution ratios.*

Source	Locality	Depth (m)	Lab No.	K %	K_2O %	U ppm	Th ppm	TSAC (Bq/kg)	Cosmic ray dose rate Gy/ka	Total annual dose rate Gy/ka	**Cosmic ray contribution as % of total dose rate**	Method used for determining cosmic ray dose rate
Thom et al., 1994	Eastern Australia	1-2	W1007	0.05				14.0 ±4	0.15	0.495	**30 %**	fixed approx[1]
Thom et al., 1994	Eastern Australia	1-2	W1008	0.05				11.7 ±4	0.15	0.452	**33 %**	fixed approx
Thom et al., 1994	Eastern Australia	1-2	W1015	0.07				10.3± 4	0.15	0.443	**34%**	fixed approx
Nanson et al, 1993	Simpson Desert Australia	2.0	W1310	0.57				19.1	0.15	1.163	**13%**	fixed approx
Chen, 1995	W. New South Wales, Australia	2.5	W1381	0.245 ±0.005				16.0± 0.5	not specified	0.701 ± 0.05	**-**	not specified
Rendell et al., 1993	Negev Desert, Israel	1.0	SH1.1	0.32 ± 0.05		0.61 ± 0.07	1.14 ± 0.21		not specified	0.919 ± 0.101	**-**	not specified
Stokes et al., 1997	N.E. Kalahari, southern Africa	0.5	1004/A		0.17 ± 0.01	0.5 ± 0.10	1.0 ± 0.15		0.21	0.54 ± 0.06	**39%**	in situ γ-ray[2] spectroscopy
Stokes et al., 1997	N.E. Kalahari, southern Africa	0.5	1005/A		0.08 ± 0.003	0.5 ± 0.07	1.2 ±0.11		0.20	0.46 ± 0.03	**43%**	in situ γ-ray spectroscopy
Stokes et al., 1997	N.E. Kalahari, southern Africa	2.0	1005/D		0.08 ± 0.003	0.7 ±0.13	1.3 ± 0.19		0.14	0.46 ± 0.05	**30%**	in situ γ-ray spectroscopy
Stokes et al., 1997	N.E. Kalahari, southern Africa	1.8	952/3		0.03 ± 0.001	0.5 ± 0.13	1.5 ± 0.17		0.18	0.43 ± 0.05	**42%**	in situ γ-ray spectroscopy
Stokes et al., 1997	N.E. Kalahari, southern Africa	5.0	1004/J		0.16 ± 0.001	0.6 ± 0.09	1.9 ± 0.22		0.10	0.51 ± 0.06	**20%**	in situ γ-ray spectroscopy
Stokes et al., 1997	SW Kalahari, southern Africa	3.5	942/1		0.08 ± 0.02	0.4 ± 0.12	1.7 ± 0.18		0.13	0.79 ±0.15	**16%**	in situ γ-ray spectroscopy
O'Connor & Thomas, 1999	E. central Kalahari, southern Afiica	0.63	Zam 95 20/2		0.02 ± 0.00	0.3 ± 0.03	1.10 ± 0.11		0.21± 0.01	0.37 ± 0.02	**57%**	Prescott and[3] Hutton, 1994
O'Connor & Thomas, 1999	E. central Kalahari, southern Afiica	1.8	Zam 95 32/1		0.01 ± 0.00	0.23 ± 0.03	0.45 ±0.05		0.18 ± 0.01	0.27 ± 0.01	**67%**	Prescott and Hutton, 1994
O'Connor & Thomas, 1999	E. central Kalahari, southern Africa	1.7	Zam 95 31/1		0.01 ± 0.00	0.22 ± 0.04	0.67 ± 0.03		0.18 ± 0.01	0.29 ±0.02	**62%**	Prescott and Hutton, 1994
O'Connor & Thomas, 1999	E. central Kalahari, southern Africa	1.85	Zam 95 24/1		0.03 ± 0.00	0.29 ± 0.03	1.32 ± 0.03		0.17 ± 0.01	0.37 ±0.02	**46%**	Prescott and Hutton, 1994

[1]Fixed approximation- standard fixed cosmic ray dose estimated to be contributed to each sample regardless of depth, altitude or geomagnetic latitude.

[2]In situ γ-ray spectroscopy - estimation of present-day cosmic ray contribution rate at ambient sample depth carried out in the field.

[3]Prescott and Hutton, 1994 - estimation of present-day cosmic ray contribution rate taking into account sample depth, altitude and geomagnetic latitude.

mineralogy predominantly comprises quartz and low feldspar content, as is the case over many of the world's deserts, internal dose rates tend to be low since quartz itself does not contain significant K, U or Th concentrations. Internal dose rates (from K, U & Th) ranging between 0.16 Gy/ka and 1 Gy/ka have been reported from aeolian dune sands from the southern African Kalahari, (O' Connor & Thomas, 1999; Stokes et al, 1997; 1998; Munyikwa, et al, 2000) and the Australian Simpson Desert (Nanson et al, 1993). Such low internal does rates imply that the proportion of the total dose rate that arises from cosmic rays is significantly higher, constituting up to 50-60 % of the total dose rate at times (Stokes et al, 1998; O'Connor and Thomas, 1999) (see Table 1). In such cases inaccuracies in the estimation of the cosmic ray dose rate may introduce significant uncertainties when a sample's age is evaluated.

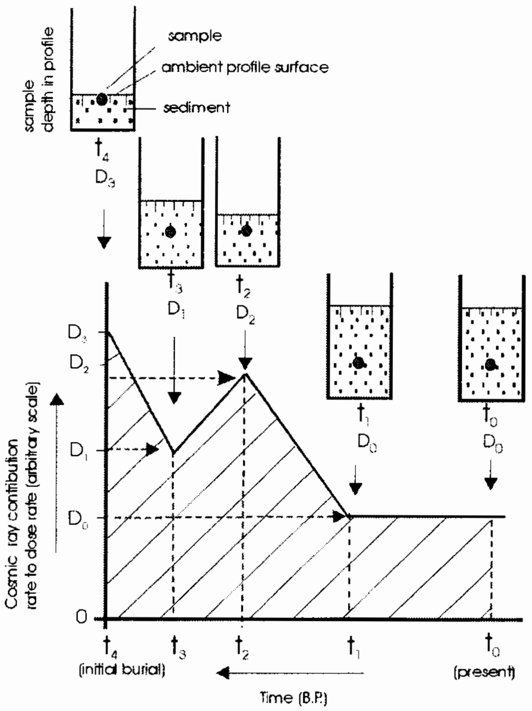

Figure 1: Variation of cosmic ray dose rate with fluctuating depth experienced by a hypothetical buried sample. The rates of change in dose rate are not necessarily straight lines and linearity has been adopted for simplicity in this case. The various stages in the burial history of a sample at times $t_4 - t_0$ B.P. as well as the corresponding cosmic ray dose rates are also indicated. Area under curve represents total energy received.

Storage of energy for luminescence dating purposes begins the moment a sedimentary particle is shielded from light (burial). Since penetration of cosmic rays depends on thickness of overlying sediments, the cosmic ray dose rate will vary with the rate of increase or decrease of the sedimentary cover (Figure 1). In aeolian depositional systems this rate is not necessarily linear and it may vary with geomorphic factors such as sediment supply, wind energy, topographic and climatic conditions.

Estimation of cosmic ray contribution

Cosmic ray dose received by a sample buried in a single episode at a constant depositional rate

A sample situated at the base of a stratigraphic column where the overlying sediments were deposited in a single episode at an approximately constant rate will have experienced a steady reduction in cosmic ray dose rate at a pace corresponding to the depositional rate. Depending on the sedimentation rate, such a column can either be deposited rapidly or gradually. In the case of a rapidly deposited column (Figure 2a(i)), estimating the total cosmic ray contribution by multiplying the in situ (fixed depth) cosmic ray dose rate (D_{B0}) (e.g. dose rate obtained using the method of Prescott & Hutton (1994)) by the burial age of the sample (t_2) would not significantly underestimate the true cosmic ray contribution.

Alternatively, if sediment overlying the sample is deposited gradually (at a relatively constant rate), the cosmic ray dose rate for a sample buried at the base of the column will reduce at a similarly gradual rate (Figure 2a(ii)). When the sedimentation ceases (at t_1) a period of stability may ensue during which the sample depth remains unchanged and the cosmic ray dose rate for the buried the sample stays effectively constant. Under such circumstances, the total cosmic ray dose received by Sample B (D_{CosB}^{tot}) retrieved from the base of the sediment column can be approximated by summation of the area under the curve in Figure 2a(ii) using the expression:

$$D_{CosB}^{tot} = D_{B0}t_2 + \tfrac{1}{2}(D_{B1} - D_{B0})(t_2 - t_1) \qquad (1)$$

where t_2 is the time Before Present (B.P.) since burial, t_1 is time since termination of the deposition and t_0 is the present (or 0 yr. B.P.). D_{B0} is the in situ (or current at time of sampling) dose rate and D_{B1} is the cosmic ray dose rate at time t_2 (just after burial began). Attempting to evaluate the total cosmic ray dose received by the sample by simply multiplying the in situ (fixed depth) cosmic ray dose rate by the burial age of the sample, t_2, will give a value of $D_{B0}t_2$. This effectively underestimates the true cosmic ray contribution rate by $\tfrac{1}{2}(D_{B1}-D_{B0})(t_2 - t_1)$. The magnitude of this underestimation relative to the total

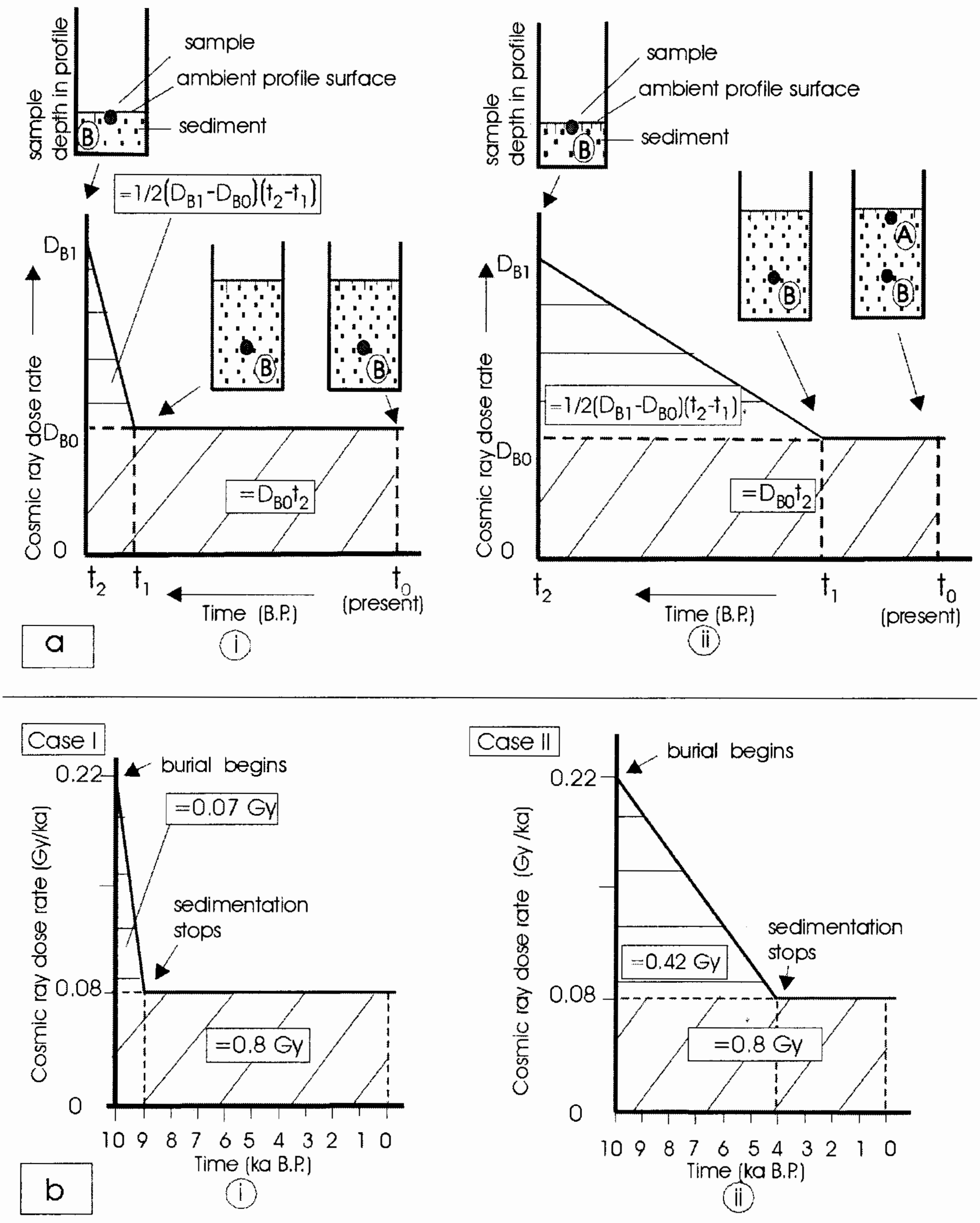

***Figure 2:** (a) Sediment deposited overlying Sample B in a single depositional episode under two possible scenarios: i) rapidly ii) gradually. Cosmic ray dose accumulated depends on sedimentation rate.*

(b) Numerical illustration of variations in cosmic ray dose received by a sample at a particular site that may occur as a consequence of differences in sedimentation rate. Case (I) is characterised by rapid deposition followed by a stable phase whilst in Case (II) the deposition is more protracted.

cosmic ray dose will depend on the sedimentation rate and duration over which the sedimentation occurs (thickness of the sedimentary column).

Accordingly, if the palaeodose for Sample B is determined from the luminescence signal to be P_B, then:

$$P_B = D'_B t_2 + D_{B0} t_2 + \frac{1}{2}(D_{B1} - D_{B0})(t_2 - t_1) \quad (2)$$

where D'_B is the annual dose rate from environmental radioactivity (α, β & γ) for Sample B. Expression (2) would still be difficult to solve for the burial age of Sample B (t_2) because both t_1 and t_2 are unknowns. The best manner to circumvent this problem is to reconstruct the burial history in reverse order. Thus, the first step would be to calculate the approximate date when sedimentation ceased at the top of the profile (t_1). To determine t_1, a sample is collected from just below the surface (Sample A, Figure 2a(ii)), sufficiently deep to avoid disturbances and material inhomogeneities but shallow enough to be representative of the period when sedimentation stopped. The depth of Sample A has remained fixed since it was buried, thus, the cosmic ray dose rate has been constant throughout most of the sample's burial history. If P_A is the measured palaeodose of Sample A, then:

$$P_A = (D'_A + D_{AC})\, t_1 \quad (3)$$

$$t_1 = P_A / (D'_A + D_{AC}) \quad (4)$$

where D'_A is the annual dose rate from environmental radioactivity for Sample A. D_{AC} is the mean annual cosmic ray dose rate evaluated using the method of Prescott and Hutton (1994).

Expression (4) can be solved for t_1 and subsequently this value (t_1) can be substituted into expression (2) to solve for t_2 (the burial age of Sample B) as below:

$$t_2 = \frac{P_B + \frac{1}{2}(D_{B1} - D_{B0})t_1}{D'_B + \frac{1}{2}D_{B1} + \frac{1}{2}D_{B0}} \quad (5)$$

Thus, expression (5) yields a luminescence age (t_2) that allows for the variations in cosmic ray contribution rate to the palaeodose of a sample collected from a profile where the overlying sediments have been deposited in a single episode at a gradual rate. To numerically illustrate how imperative such a correction can be, consider the two hypothetical cases (I and II) of samples collected from a site located at 20° S latitude at an altitude of 1100 m a.s.l. In case I, sedimentation commences at 10 ka B.P. (Figure 2b(i)) and a column of 10 m of aeolian sands are deposited rapidly between 10 ka and 9 ka B.P. From 9 ka to 0 ka B.P. there is a phase of stability during which no deposition occurs. If the sediments are essentially quartz sands with a porosity of 30 % and a corrected density of 1.8 g/cm^3, then the calculated cosmic ray dose rate for Sample B collected from the base of this column (using the method of Presscott and Hutton (1994)), changes from 0.22 Gy/ka just after burial of the sample (ca. 10 ka) to 0.08 ka at 9 ka BP when the deposition stops. From 9 ka to 0 ka the cosmic ray dose rate is fixed at 0.08 Gy/ka. The total cosmic ray dose received by the sample can be calculated to be about 0.87 Gy. If, however, the change in cosmic ray dose rate between 10 and 9 ka that arises from the increase in overburden, is ignored and the cosmic ray contribution is calculated using the in situ (fixed) dose rate of 0.08 Gy/ka by simply multiplying this dose rate by 10 ka, a cosmic ray dose of 0.8 Gy is obtained. Ignoring the change in dose rate between 10-9 ka, thus, effectively underestimates the true cosmic ray contribution by only about 9 %. Even in cases where cosmic ray contribution constitutes about 50 % of the total dose, such an underestimation would introduce an error of less that 5 % to the age calculation.

In hypothetical case II, however, sedimentation commences at ca. 10 ka B.P. and between 10 ka and 4 ka, 10 m of dune sands are deposited at a relatively constant rate, after which a period of geomorphic stability ensues, spanning 4 ka to 0 ka B.P. Calculation using the method of Prescott and Hutton (1994) shows that just after the beginning of sedimentation (10 ka) the Sample B located at the base on the column experiences a dose rate of 0.22 Gy/ka. This dose rate will decline gradually until 4 ka, when the calculated dose rate is 0.08 Gy/ka and sedimentation ceases. From 4 ka to 0 ka BP, the dose rate for Sample B remains static at 0.08 Gy/ka. The true total cosmic ray dose received by the sample between 10 – 0 ka is 1.22 Gy. If the column is viewed as having been deposited instantaneously and the cosmic ray dose between 10-0 ka is calculated by simply multiplying the in situ dose rate by the time of burial (10 ka), a value of 0.8 Gy for the cosmic ray contribution is obtained. This underestimates the true cosmic ray contribution by 0.42 Gy. If the cosmic ray constitutes 50 % of the total dose, this underestimation would translate into a luminescence age of at least 20 % older than the true age. The magnitude of this type of error increases with

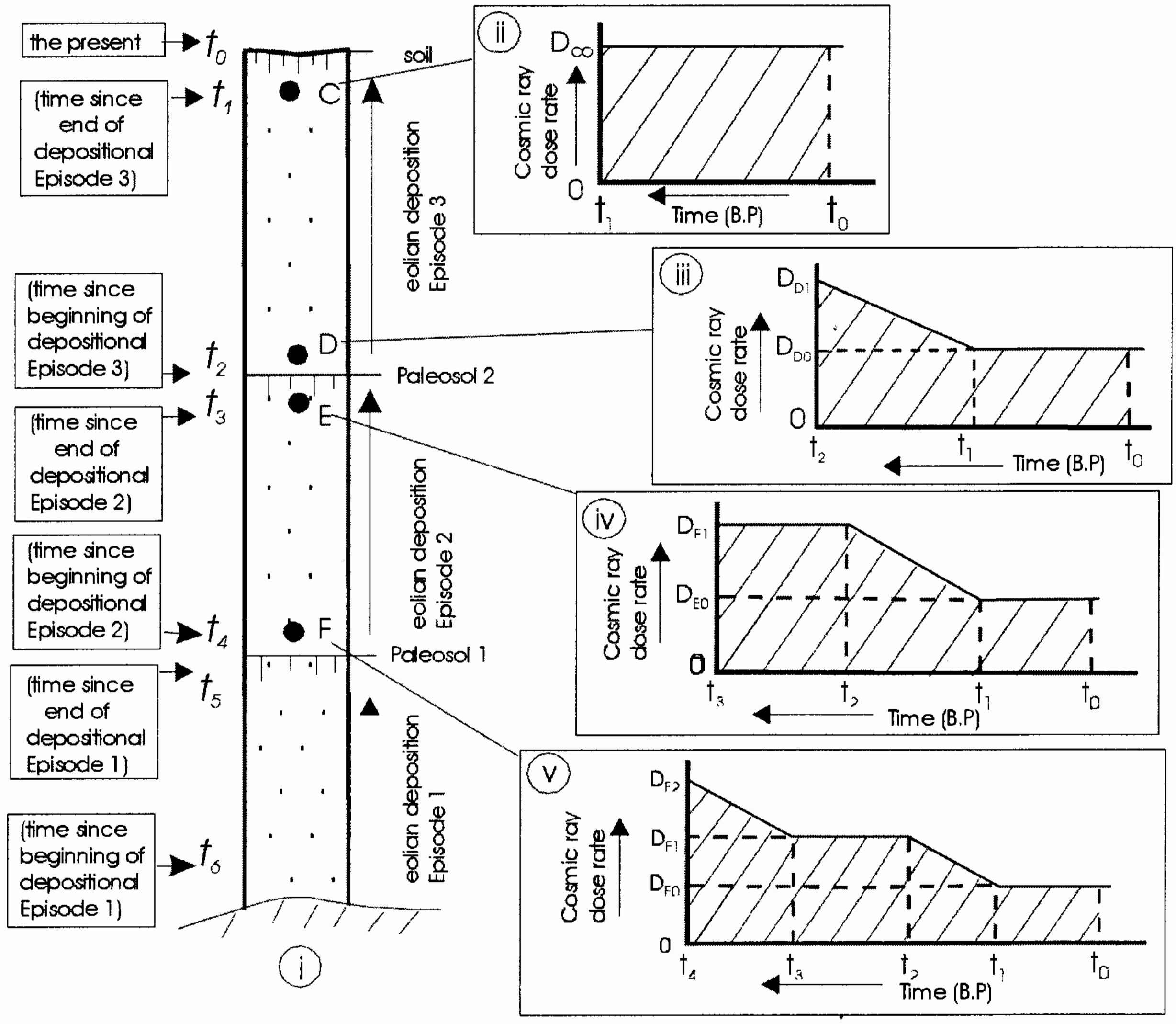

***Figure 3:** Stratigraphic column resulting from multiple episodes of deposition with intervening periods of stability. Also illustrated is the evolution of cosmic ray dose contribution for samples C, D, E and F recovered from specified positions down the profile.*

proportion of the total dose rate constituted by the cosmic ray contribution.

Cosmic ray dose received by a sample buried by sediment deposited in multiple episodes

As opposed to a single gradual depositional episode discussed above, accumulation of sediments can occur as multiple events with intervening phases of stability. Figure 3(i) demonstrates a profile in dune sands that accumulate from three depositional episodes (Episodes 1, 2 &3) separated by two stable periods (Paleosols 1 & 2). As in the case of gradual burial, the total cosmic ray dose received by a sample retrieved from any part of the stratigraphic column can be approximated by a systematic reconstruction of the burial history. Accordingly, the initial step would be to determine when sedimentation ceased at the top of the profile (end of Episode 3). Sample C is retrieved from just below the surface of the sedimentary column and its depth has not changed since burial. Thus, the cosmic ray dose rate it has experienced (D_{C0}) has remained fixed between the times t_1 and t_0 (Figure 3(ii)) and is approximately equal to the in situ cosmic ray dose rate (this can be approximated using the method of Prescott and Hutton (1994)). Once the palaeodose and environmental dose rate have been determined the burial age of the sample, t_1, can be calculated and this age approximates the end of Episode 3.

Sample D is recovered from just above Paleosol 2 and its cosmic ray dose rate history is more complex than that of Sample C (Figure 3(iii)). An increase in the overburden above the sample during aeolian Episode 3 (t_2 to t_1) resulted in a corresponding reduction in cosmic ray dose rate from D_{D1} to D_{D0}. No sedimentation occurred during the period t_1 to t_0 and the cosmic ray contribution to the dose rate was static at D_{D0}. An evaluation of the total cosmic ray dose rate received by Sample D should be a summation of the area under the curve in Figure 3(iii) and both t_1 and t_2 should be known to achieve this. The value of t_1 can be approximated by the burial age of Sample C and t_2 is the burial age of Sample D. Determination of the palaeodose and environmental dose rate enables t_2 to be calculated since D_{D1} and D_{D0} can be evaluated using the method of Prescott and Hutton (1994).

Sample E retrieved from just below Paleosol 2 would yield an age that approximates the end of the depositional Episode 2 (Figure 3(iv)). Reconstruction of the cosmic ray dose rate history shows that just after burial, (t_3), the dose rate experienced by the sample remained fixed at D_{E1} until t_2. Sediments were deposited in Episode 3 from t_2 to t_1 and the cosmic ray dose rate reduced to D_{E0} after which it remained unchanged between t_1 and t_0. The total cosmic ray dose received by the sample can be approximated by summation of area under the curve in Figure 3(iv) but the times t_1, t_2 and t_3 are required to achieve this. The values t_1 and t_2 are equivalent to the ages of samples C and D respectively and the dose rates D_{E0} and D_{E1} can be evaluated using the method of Prescott and Hutton (1994). Thus, t_3 (the age of Sample E) can be calculated once the palaeodose and environmental dose rate are determined.

The burial age for Sample F, deposited at the beginning of Episode 2 (overlying Paleosol 1), can also be evaluated by similar downward reconstruction. The cosmic ray dose rate for the sample changed from D_{F2} at t_4 to D_{F1} at t_3 then remained unchanged until t_2 when it went down to D_{F0} (Figure 3(v)). The times t_1, t_2, and t_3 are equivalent to the ages of samples C, D and E respectively and the cosmic ray dose rates D_{F0}, D_{F1} and D_{F2} can be approximated using the method of Prescott and Hutton (1994). If the palaeodose and environmental dose rate are known, the age of Sample F (t_4) can be calculated.

In summary, samples collected from profiles that are deposited in multiple episodes experience a stepwise reduction in cosmic ray dose rate. The total cosmic ray dose received by a given sample can be evaluated by summing up the area under the sample's cosmic ray dose rate history curve. In principle, it should be possible to carry out similar reconstructions for cosmic ray dose received by samples recovered from stratigraphic columns where deposition has occurred in any number of episodes. As has been demonstrated, it is always imperative that the time limits of the overlying depositional episodes and hiatuses are determined before an attempt can be made to evaluate the true cosmic ray dose received by the sample. This, therefore, necessitates cautious field procedures and the recognition of stratigraphical discontinuities where they exist.

Conclusions

The use of in situ (present day) cosmic ray contribution rates as the mean cosmic ray dose rates, operational throughout the burial history of a sample, may erroneously estimate the true cosmic ray contribution in cases where the sedimentary column was not deposited instantaneously. The magnitude of this inaccuracy depends on:

(i) the fraction of the total dose constituted by the cosmic ray dose,
(ii) depositional regime (whether it is single episode, rapid, gradual or multiple episode and
(iii) the duration of the depositional phase as opposed to the stable phase.

Methodology has been presented above that demonstrates that it is feasible to evaluate the cosmic ray dose received by a sample that is overlain by a sedimentary column deposited in a single, gradual depositional episode or episodically with intervening periods of stability. It is imperative to note that the evaluation is achieved by reconstructing the deposition of the column from the top downwards. This implies that sampling has to be done systematically, with samples collected above and below any evident discontinuities in deposition (e.g. paleosols).

This discussion has only considered cases where the sedimentary environment is purely depositional. Environments that involve intermittent erosional and depositional phases would imply a rising and falling cosmic ray dose rate and the accurate evaluation of such a cosmic ray contribution would be a more complex procedure. However even is such cases, there would be little justification for the use of in situ cosmic ray dose rates as the mean dose rates throughout the burial histories of the samples unless the deposition of the sedimentary column above the sample was relatively rapid.

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Reviewer
J.R. Prescott