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Thermoluminescence Dating of Soil Carbonate

by

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ABSTRACT

Pedogenic calcium carbonate from calcic soils 10,000 years to at least 500,000 years old shows increasing levels of natural thermoluminescence (TL) with age. As such, carbonate TL may provide a relative age-dating technique for calcic soils and other carbonate-rich deposits. Within this age span, TL N/AEx ratios (natural to artificially induced TL normalized for trap density and mean annual radiation dose) increase monotonically when plotted against mean age of the soil. Analytical errors in measured TL peak heights and radiation dose rates are less than ± 10 percent at the level of one standard deviation. However, the resultant TL ratios commonly have statistical errors of as much as 25 percent owning to the cumulative nature of calculations.

N/AEx ratios from buried and surface calcic soils reflect the time carbonate accumulated as well as the last time of accumulation. For example, a buried soil that formed from 300,000 years ago to 200,000 years ago has a TL ratio that corresponds to a mean soil age of 250,000 years. This buried soil also has the same TL ratio as a relict surface soil that had been forming continuously for the past 500,000 years (average age of 250,000 years for the soil carbonate).

TL ratios were measured from samples of calcic soils in two areas in the Rio Grande Valley of New Mexico that have arid to semiarid climates. These ratios suggest that little or no solution and reprecipitation of carbonate occurs once the carbonate has moved into the C horizon, probably because their soil waters are relatively saturated with Ca^{++} ions. In regions having substantially higher rainfall, or lower rates of influx of Ca^{++} ions to the soil surface, one might expect periodic resetting of TL rather than progressive accumulation of TL.

INTRODUCTION

Pedogenic calcium carbonate is an important constituent of soils that form under arid to semiarid climates. These soils are known collectively as calcic soils (Bachman and Machette, 1977) and where strongly indurated are termed pedogenic calcretes. Calcic soils are common over much of the southwestern United States, as well as in similar climatic regions of the world's middle latitudes. In the Southwest, most soil carbonate accumulates slowly through time, principally by the mechanisms of dissolution of relatively soluble calcium carbonate at or near the soil surface and downward transportation into the subsurface by meteoric water (Bachman and Machette, 1977; Gile and others, 1981; Machette and others, in press). Ca^{++} ions subsequently precipitate as calcium carbonate through supersaturation of soil water.

In the Southwest relict calcic soils in alluvial sequences show systemmatic changes in development with increasing age (Gile and others, 1981; Machette and others, in press). If the age and rate of accumulation of carbonate could be established for a relict soil, then ages of other soils from the same sequence could be estimated from their total content of pedogenic $CaCO_3$ (Machette and others, in press). Previous attempts to determine the age of calcic soils (Arkley, 1963) have been severely limited by poor age calibration. However, the development of dating methods such as potassium argon, fission track, and uranium trend (Rosholt, 1980) has provided better age control for many Quaternary sequences. Machette (1978) devised a quantitative method for estimating soil ages based on the weight of pedogenic $CaCO_3$ in relict calcic soils and the rate of accumulation of carbonate. Thus, with the advent of these new methods we have the opportunity to study the TL characteristics of some moderately well dated calcic soils.

Quantitative studies of calcic soils in the Southwest show that the rate of pedogenic $CaCO_3$ accumulation is largely a function of two factors: 1) the supply of Ca^{++} ions to the soil surface as either solid wind-blown calcareous sand and dust or in rainfall, and 2) the amount and distribution of rainfall to the soil (Gile and others, 1981; Machette and others, in press). Other factors that affect the amount of $CaCO_3$ that accumulates or is preserved in soils (such as erosion, deposition, and topographic relief) are controlled by using the chronosequence concept of sampling (Harden and Marchand, 1977; Birkeland, 1984). Under the controlled conditions of a chronosequence study, the content of secondary $CaCO_3$ will provide a quantitative measure of the age of a calcic soil, especially when augmented by isotopic age determinations.

THERMOLUMINESCENCE AS A POTENTIAL SOIL-DATING TECHNIQUE

This paper reports our development of a thermoluminescence (TL) dating technique for pedogenic calcium carbonate. Thermoluminescence is the property of light emission from a crystalline or glassy material when it is heated after having been exposed to ionizing radiation from either a natural or an artificial source (Wintle and Huntley, 1982, p. 32). Our TL investigation is founded on the basic premise of thermoluminescence—that crystallization of a mineral sets its TL clock in motion. However, because soils accumulate carbonate with time, new TL clocks are being set in motion continually, rather than at one specific point in time. In this respect, the processes that lead to accumulation of TL in carbonate are much different than those in igneous rocks or in sediments. Yet soil carbonate has several unique TL properties, notably a high sensitivity to ionizing radiation (Zeller, 1954) and no initial (or inherited) TL because it has precipitated from a solution. Thus, when exposed to radiation from the soil parent material, carbonate should acquire TL at a rate proportional to the natural-dose rate of the soil environment and the density of electron traps in the crystallizing carbonate. (See Wintle and Huntley, 1982, for a rigorous discussion of TL dating of Quaternary sediment.)

One problem that must be addressed in using soil carbonate for TL is the physical processes of $CaCO_3$ accumulation. For example, if calcic soils are strictly a mixture of carbonate grains of old to young age, then the TL of the mixture should yield some sort of average age, much as organic matter in A horizons of soils often yield mean-residence ages when dated by the ^{14}C method. However, if solution and redeposition of existing carbonate occurs in the soil, the TL could be partially or totally reset, rendering ages that are too young for the soil and its parent material (host deposit). Because ^{14}C determinations from soil carbonate often yield ages substantially younger than other dating techniques (Gile and others; 1981), we anticipated that soil horizons would show "TL stratification" in response to upward-accumulation of carbonate or resolution of carbonate as suggested often by seemingly young carbonate in old B horizons. Although this process was not prevalent in the soils we sampled, some select soils might have TL ratios that will show evidence of the process, rate, and timing of carbonate accumulation.

Dating in this study is strictly empirical. Ages determined from independent geologic, pedologic, and isotopic studies were used to construct plots of TL intensity versus mean soil age. TL intensity was measured as either the ratio of peak heights from the emission of natural to artificial TL (N/A ratio) or as this same ratio which has been normalized for the amount of annual radiation in the sample (N/AEx ratio). The resulting "relative-dating curves" should be useful in estimating the age of other soil carbonates in similar environments. However, before such dating is attempted we need to study the processes of TL acquistion in carbonate, make in situ determinations of dose rates, and document changes in dose rate through time.

GEOLOGIC SETTING AND AGE CONTROL

We sampled calcic soils from two areas in the Rio Grande Valley of New Mexico. The first area is near Albuquerque, in north-central New Mexico (fig. 1). Here, both buried and surface soils occur in natural exposures adjacent to the Bernalillo County Dump, about 15 km west of Albuquerque. Machette (1978) made a quanitative study of these soils to assess the potential of calcic soils in dating the recurrent movement of faults. His study provided a detailed base from which we tested the feasibility of TL techniques on surface and buried calcic soils.

The second area we sampled is near Las Cruces, in south-central New Mexico (fig. 1). We chose this area because it was the focus of a long-term study of calcic soils, geomorphology, and Quaternary geology by the Soil Conservation Service (Gile and others, 1981). As a result of the SCS research, we feel that the calcic soils in the Las Cruces area are perhaps the best studied in the world.

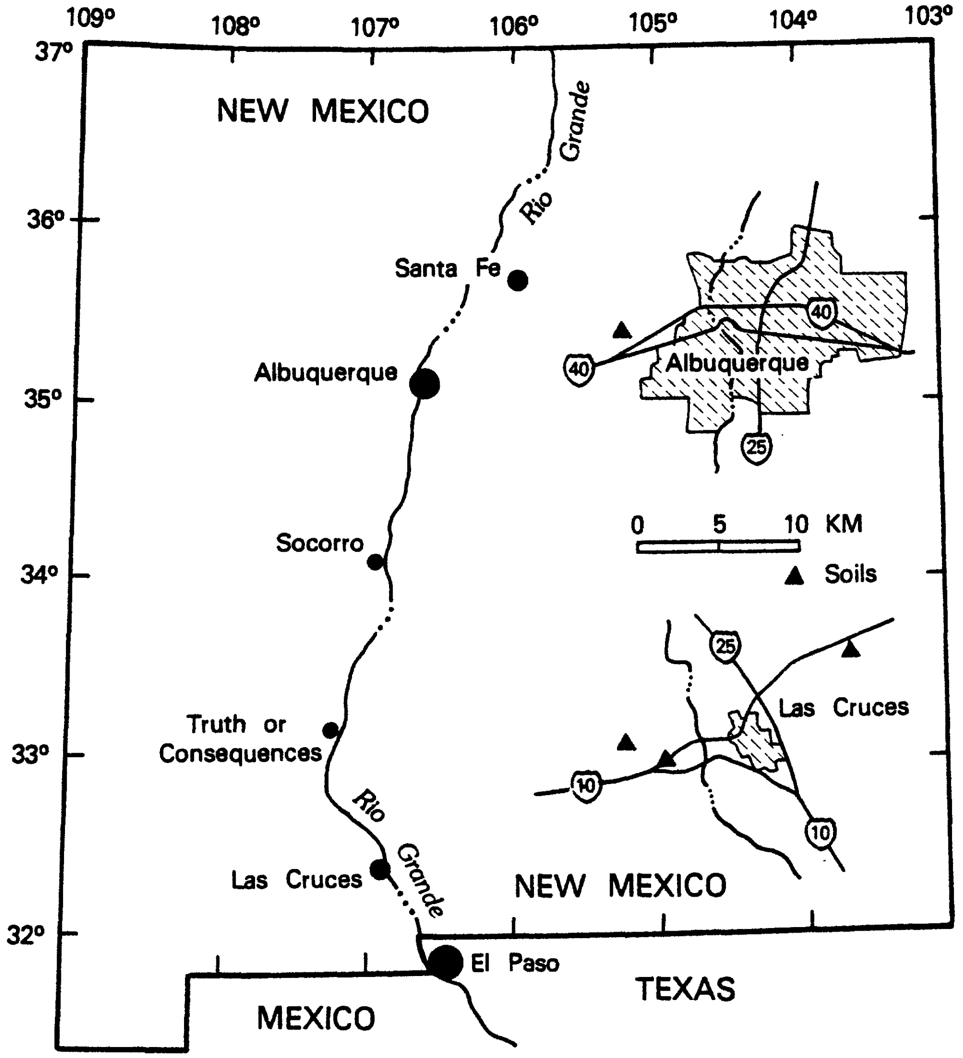

Figure 1. Index map showing sampling areas in the Las Cruces and Albuquerque areas of New Mexico.

We sampled weakly to moderately developed upper Pleistocene soils and strongly developed middle to early Pleistocene soils. The upper Pleistocene soils are in loose, poorly consolidated sands to silty sands, that were initially noncalcareous to very slightly calcareous (less than 2 percent $CaCO_3$ by weight). In fine-grained alluvium, these soils have less than 10 percent $CaCO_3$ disseminated in the matrix or concentrated in discrete nodules (stage II of Gile and others, 1966). The older middle Pleistocene soils are massive, indurated calcic soils and pedogenic calcretes having stage IV and V morphology (Bachman and Machette, 1977; Machette and others, in press) that is characterized by more than 75 percent carbonate in the upper part of their 1- to 2-m-thick K horizons.

Albuquerque Area

The site near Albuquerque contains a 20-m-thick sequence of four stratigraphically distinct calcic soils that have been successively buried by recurrent movement on a steeply dipping normal fault (fig. 2). The fault is overlain by a fifth soil (soil U of Machette, 1978) that is formed in eolian sand of uppermost Pleistocene to perhaps Holocene age. The block east of the fault has been downdropped and flexed such that the buried soils converge into a massive 1.5-m-thick relict surface soil (soil U-Z of Machette, 1978) about 600 m east of the fault (fig. 3). This relict soil is exposed along the eastern escarpments of the Llano de Albuquerque surface for a distance of about 100 km in north-central New Mexico.

The relict soil U-Z (fig. 3, column E,) is typical of those found on the Llano de Albuquerque and many other middle Pleistocene geomorphic surfaces of New Mexico (Machette and others, in press). Soil U-Z is here considered to be about 500,000 years old based on 1) our correlation of the Llano de Albuquerue with other geomorphically equivalent surfaces in the Rio Grande Valley of New Mexico, 2) the presence of vertebrate fossils and dated volcanic ashes in the deposits that form these surfaces, and 3) dated under lying and overlying basalt flows (Hawley and others, 1976; Hawley, 1978; Machette, 1978; Machette and others, in press).

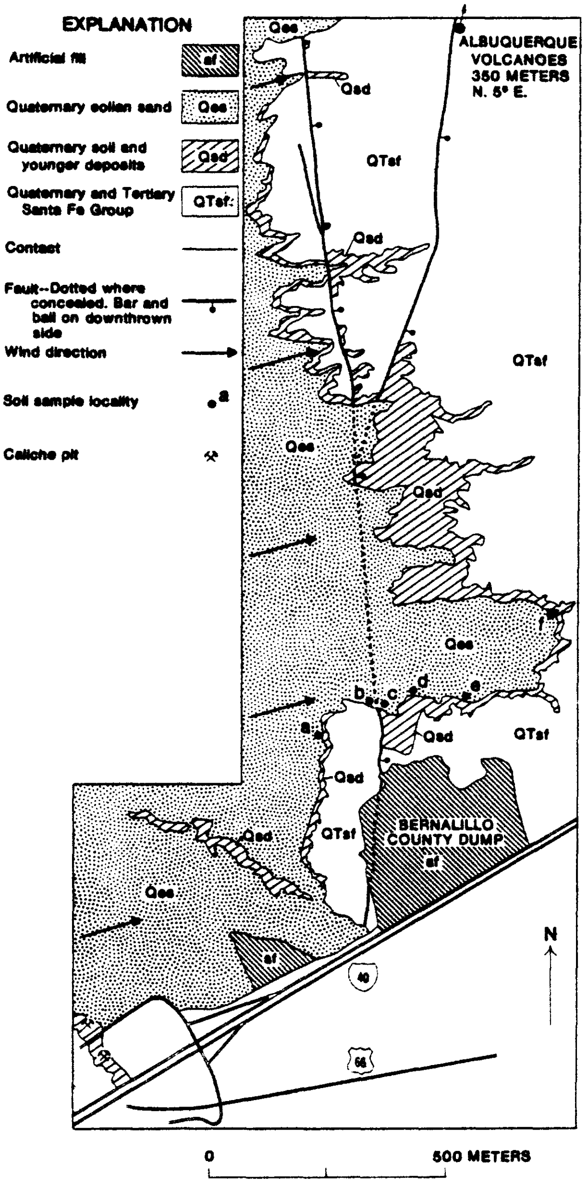

Figure 2.—Geologic sketch map of the Albuquerque site.

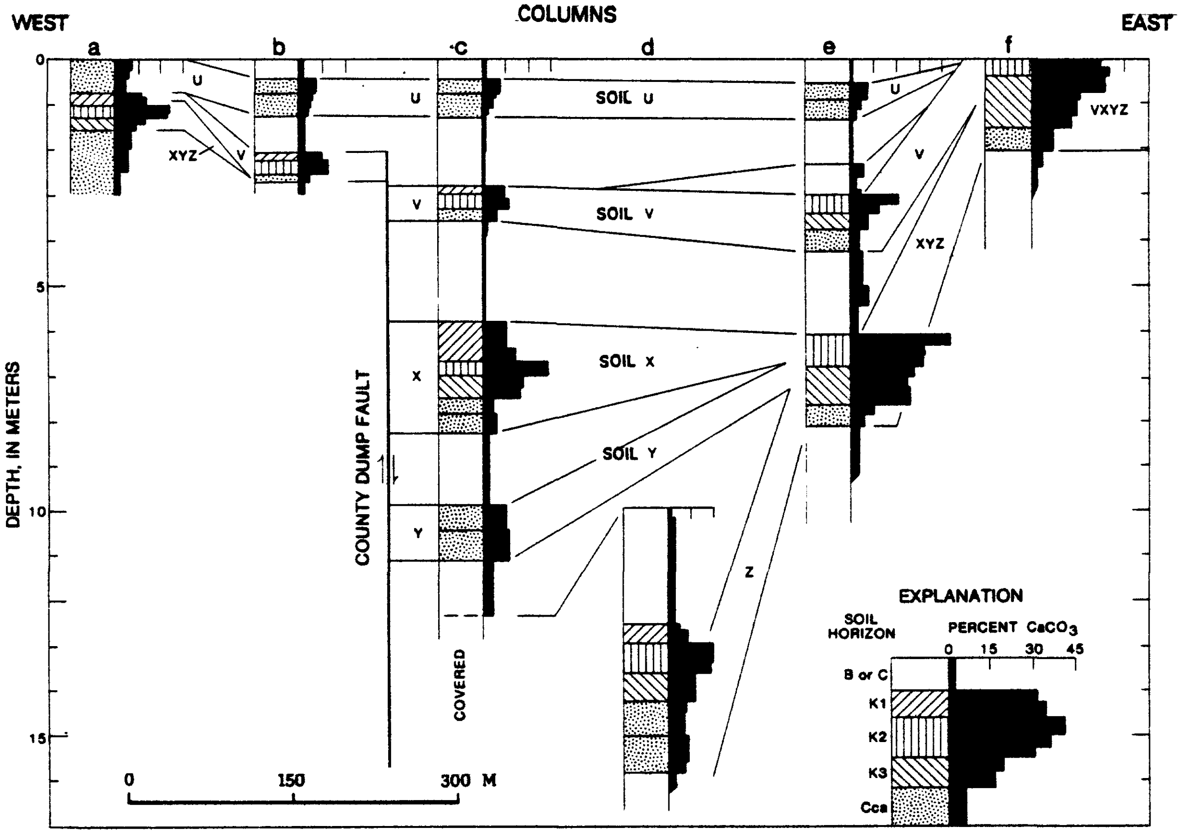

Figure 3.—Cross section showing relation between soils, deposits, and the County Dump fault at the Albuquerque site.

Table 1. Ages of soils at the Albuquerque and Las Cruces sites

ALBUQUERQUE AREA	Soil carbonate		
Soil name	Time of formation, in yrs	Duration of formation, in yrs	Mean age, in yrs
Soil U-Z	Present-500,000	500,000	250,000[a]
Soil U	Present- 20,000	20,000	10,000
Soil V	20,000-120,000	100,000	70,000
Soil X	120,000-310,000	190,000	215,000
Soil Y	310,000-400,000	90,000	355,000
Soil Z	400,000-500,000	100,000	450,000

LAS CRUCES AREA	Soil carbonate		Parent material
Soil name (informal)	Time of soil formation, in yrs	Mean soil age, in yrs	Uranium-trend age[b]
Isaack's Ranch	Present- 12,000	6,000	9,000 ± 2,000
Jornada II	Present-120,000	60,000	98,000 ± 15,000
Lower La Mesa	Present-500,000	250,000	Not determined
Upper La Mesa	Present-750,000?	375,000?	$390{,}000\ ^{+140{,}000}_{-50{,}000}$

a 240,000 years is predicted from ages and TL ratios of soils X and Y.

b Unpublished age determinations of J. N. Rosholt (USGS).

The buried soils (soils V, X, Y, and Z; fig. 3) formed during tectonic stablility along the fault. After movement of the fault, the previous surface soil was isolated from further development by burial under a wedge of colluvium derived from the adjacent fault scarp and eolian sand deposited from the west. Thus, because the relict soil U-Z and the composite of the four buried soils (V, X, Y, and Z) and surface soil (U) must represent a total of 500,000 years of carbonate accumulation, each soil's individual content of secondary carbonate (expressed in weight of $CaCO_3$ per 1-cm^2 column through the soil) represents an increment of that time. Machette (1978) estimated the ages of soils at the Albuquerque site (table 1) from their secondary carbonate content and an assumed linear carbonate accumulation rate that was calculated from the 500,000-year-old relict soil.

Las Cruces area

The second suite of calcic soils are formed in four widespread alluvial units of the Las Cruces area (fig 4). These soils are differentiated from one another by their thickness, by the presence of diagnostic soil horizons, and by the relative degree of their horizon's development (Gile and others, 1981). The alluvial deposits are differentiated on the basis of their soils, their relative stratigraphic and topographic position, and geomorphic criteria such as surface morphology and degree of dissection.

The two young soils are in gravelly to sandy alluvium that was derived mainly from rhyolite, quartz monzonite, and granite in the Organ Mountains, east of Las Cruces (Seager, 1981). Along the piedmont-slope west of the Organ Mountains, the alluvium of Isaack's Ranch (uppermost Pleistocene) and the alluvium of Jornada II (upper Pleistocene) form prograding alluvial fans that grade westward in successively inset alluvial terraces and arroyo channels (see Gile and others, 1981, for a detail description of the Quaternary geology of this area.) We collected only one sample (101) from the soil in alluvium of Issack's Ranch because it contains but a thin horizon of sparse carbonate nodules (stage II morphology of Gile and others, 1966). However, we collected four samples (102a-d) from the soil in the alluvium of Jornada II to see if differences in TL occur between soil subhorizons.

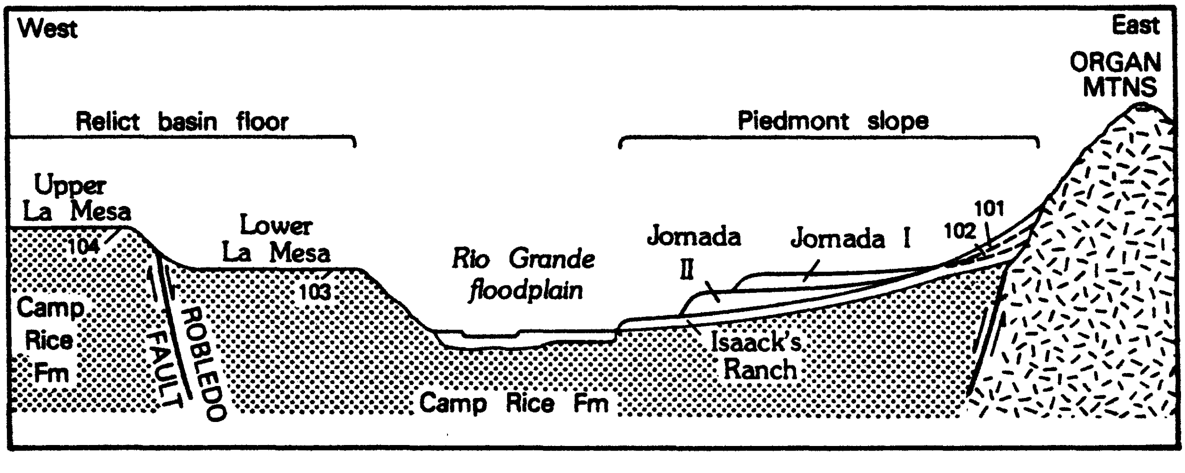

Figure 4.—Schematic cross-section of the alluvial deposits and soils at the Las Cruces site.

The two other soils we sampled from the Las Cruces area are below flat-lying geomorphic surfaces related to deposition of mixed-lithology sand and gravel of the Rio Grande. These surfaces are informally named lower La Mesa and upper La Mesa. The younger of the two, the lower La Mesa, is an extensive depositional surface throughout southern New Mexico; it represents the last major phase of basin-fill deposition before the Rio Grande began its present downcutting cycle, about 500,000 years ago (Hawley and others, 1976). The upper La Mesa is an ancient basin floor that was uplifted along the west side of the Robledo fault during early? to middle Quaternary time. West of Las Cruces the upper La Mesa is uplifted 60-75 m above the final depositional level of lower La Mesa (fig. 4). One sample was collected from near the top and the base of the calcareous parts of the relict soils associated with the lower and upper La Mesa surfaces (samples 103a,b and 104a,b; respectively).

Two types of age control are available for the Las Cruces soils. Ages estimated from carbonate content (in the manner described previously; Machette and others, in press) are available for all four soils, and recently determined uranium-trend ages (J. N. Rosholt, written commun., 1981) are available for three of the four soils (table 1). The two types of ages for two younger soils agree well, but we consider the uranium-trend age of the upper La Mesa to be a minimum age estimate (see Machette and others, in press). Indirect age control comes from correlations with dated alluvial deposits in the region and from their relation to pluvial and interpluvial episodes (Hawley and others, 1976; Machette and others, in press).

SAMPLING AND SAMPLE PREPARATION

Samples of calcic soils were collected from exposures in arroyo channels and along the eroded edges of elevated surfaces, and from artifical exposures. A 15- to 30-cm-thick layer of soil was removed before sampling to avoid material exposed to sunlight. Exposure to sunlight could cause bleaching (the draining of accumulated TL) and yield ages that are too young for the carbonate. About one kg of material was collected from each horizon of the soil. The carbonate content of the two youngest soils was enriched to about 25 percent by hand-picking discrete $CaCO_3$-rich nodules in the laboratory. Samples were stored in the dark to minimize possible drainage of TL by sunlight or artificial light.

The samples were prepared in the laboratory by crushing soil peds gently by hand with a mortar and pestle, thus minimizing mechanically induced drainage of natural TL. The gravel-size material (>2 mm diameter) was removed by dry sieving the crushed soil. The resulting soil matrix (<2 mm; 2000 microns) was then sized to 45-75 microns using a sonic sifter. Concentrations of the radioactive elements uranium, thorium, and potassium were determined from 15 g splits of the soil matrix that were crushed to pass a 125-micron screen.

TL EQUIPMENT AND EXPERIMENTAL TECHNIQUE

Equipment and Measurements

Measurements of TL were made using equipment and techniques described in detail by May (1979). Only the photomultiplier tube (PMT) and absorption filter have been changed in these experiments. We use a EMI model 9635-QB photomultiplier tube fitted with a Corning number 1-75 infrared-absorbing filter. We deposit 4-7 mg of 45-75 micron-size material evenly over the 1.2-cm-diameter central depression of a carbon-backed, fine-silver planchet (sample carrier).

After the sample is in place, the planchet is put in the heating chamber which has upper and lower windows made of silica. Dry nitrogen containing less than 5-ppm oxygen is passed through the chamber for seven minutes prior to and during heating of the planchet. The planchet is heated from below by reflecting infrared radiation generated by three symmetrically arranged 650-watt incandescent bulbs. The rate of heating is controlled at 20° ± 0.5°C sec^{-1} by a motor-driven Variac. Sample temperature is measured using a chromel-alumel thermocouple welded to the planchet near the depression in which the sample rests.

Light emitted by the sample is detected with the PMT, which is directly over the sample in a position such that the active area of the cathode intercepts the TL emission. The output from the PMT is measured by an SSR 1105/1120 photon-counting system that records on the ordinate trace of an two-axis recorder while temperature is being recorded on the abscissa trace. The resulting curve of light intensity versus temperature, hereafter refered to as a "glow curve", is the basis from which TL peak height is measured. Examples of typical natural-TL glow curves are shown in figure 5A. Peak height is adjusted for sample weight; thus, TL peak height is reported in units of cm/mg of sample (table 3). However, the illustrated glow curves have peak heights which are shown in arbitrary units.

A minimum of seven measurements is made from each sample and the TL peak heights reported here are the average of those measurements. The natural emission of light (natural TL) is measured during the initial heating of each sample. Because the sample is drained of TL after heating, it is then exposed to 700 ± 25 air-equivalent rads of x-radiation, which induces an "artifical" TL signature. After a delay of seven minutes that allows the release of spureous TL, the sample is reheated and emits artificial TL.

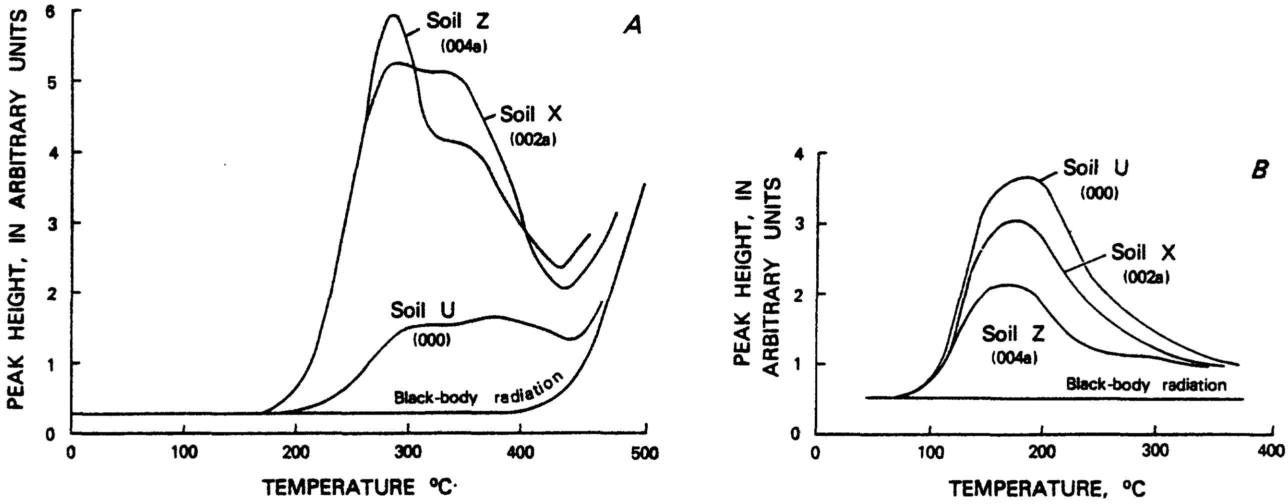

Figure 5.--TL glow curves for three buried soils at the Albuquerque site: A) natural TL, B) artificial TL.

Because all the samples are irradiated the same amount, the amplitude of the resultant artificial-TL peaks is an indicator of the number of electron traps that occur in the sample. Thus, by comparing the amplitude of natural and artificial TL peaks on a ratio basis (hereafter referred to as N/A ratios), we compensate for potential differences in trap density that may exist between samples and between soils.

The natural-TL curves are characterized by two prominent, closely spaced peaks at 300°C and 350°C (fig. 5A). After dissolving the carbonate from splits of the same samples and reheating the residual material, the 350°C peak remained prominent; it must be produced by detritial mineral grains in the soil, such as quartz and feldspar, whereas the 300°C peak is produced by carbonate. The peak intensity of natural and artificial TL from soil carbonate does not occur at the same temperature: the artificial-TL has a single asymmetric peak at 125°-150°C that is a composite of nearly coincident quartz-feldspar and carbonate peaks, respectively (fig. 5B). Thus, we only used the 300°C natural TL peak and the 150°C artificial TL peak emitted by carbonate in our calculations.

Determining Radiation Dose Rates

Annual dose rates (En) calculated from contents of uranium, thorium, and potassium are used as approximations of the radiation level in the natural soil environment. The samples content of uranium and thorium were determined by delayed-neutron-activation analysis and their potassium content was determined by flame photometry. For the purposes of calculating dose rates (table 2), the decay chains of these elements are considered to be in secular equilibrium. The dose rates are obtained by summing the energies emitted by each primary and daughter nuclide in each decay chain. The energy from alpha particles is weighted at one-tenth their nominal energy to reflect their short travel distance in a soil matrix and thus, a diminished efficiency in generating TL. Because most of our samples come from 0.5 m or more below the surface, or are buried by younger sediment, we did not compensate for cosmic radiation as a source of TL-producing radiation nor did we model radiation absorption by soil water (see discussion by Wintle and Huntley, 1982, p. 36). Implacing dosimeters, such as LiF, in the soil would allow one to better document the natural radiation in soils. The constants used for the conversion from concentration of radioactive elements to emitted energy (in rads/yr) are those tabulated by Bell (1979). May (1979) gives a description of the energy-conversion calcuation.

Calculating Mean Dose Rates

To complicate matters even more, the dose rates calculated from our laboratory data (En, table 2) do not reflect the effective (or mean) annual radiation dose rates (Ex) for calcic soils. We found an inverse correlation between the dose rate for a sample and its carbonate content. Samples with high carbonate contents have inherently low dose rates. We now realize that the older soil's measured dose rates (En) represent residual values, and that their initial dose rates (Ei) must have been substantially higher.

The accumulation of carbonate during formation of calcic soils causes a volumetric dilution of the soil's framework grains. Bachman and Machette (1977) have shown that expansion of the soil matrix occurs when 20-30 percent $CaCO_3$ has accumulated in the soil. From this point on, the framework grains in the soil matrix become diluted by carbonate, such that calcic horizons having 90 percent or more $CaCO_3$ have expanded 400-700 percent in volume. Because framework grains supply most of the radiation in the soil, the dose rate decreases with increasing carbonate accumulation (fig. 6).

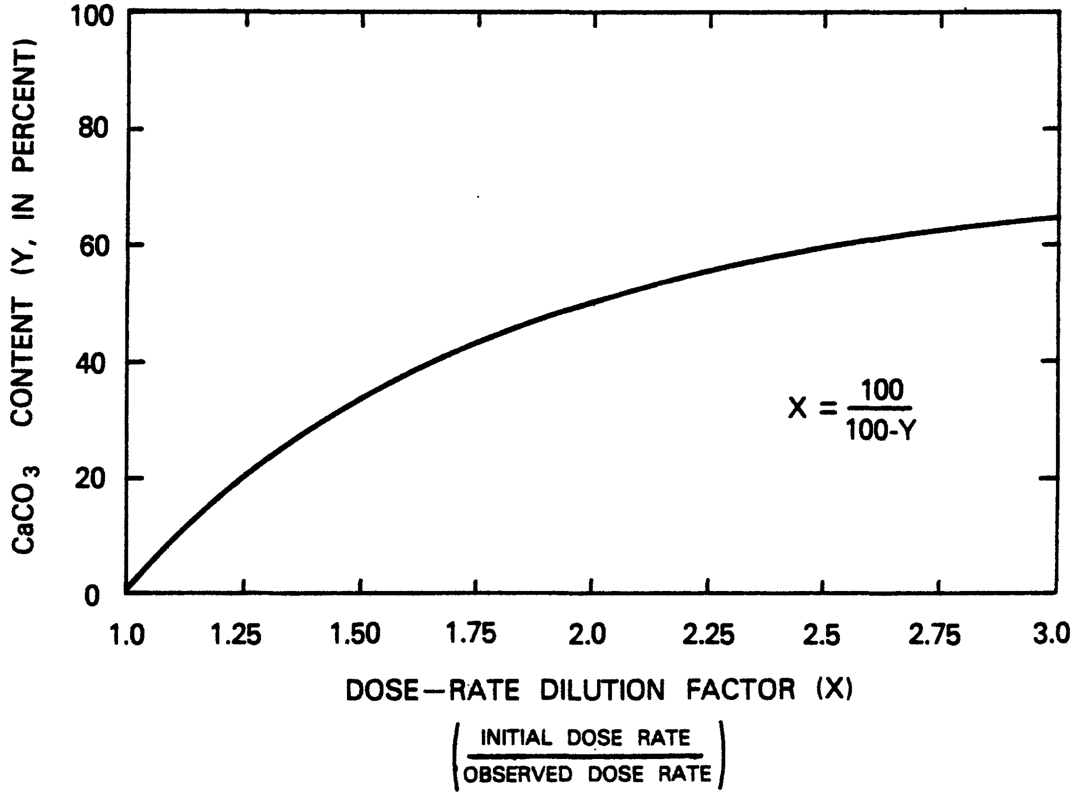

Figure 6.—Dilution of dose rates caused by the volumetric expansion accompaning accumulation of $CaCO_3$ in calcic soils (based on model of Bachman and Machette, 1977).

In order to compensate for pedogenically induced changes in dose rate, we use a simple model of decreasing dose rates for these soils. We choose intitial dose rates that are slightly more than the measured rates found in the youngest soils in each lithology of parent material. For example, soil U (sample 000) at Albuquerque has an measured dose rate of 0.48 rads/yr, which closely approximates its initial dose rate. Likewise, the measured dose rate of the soil in the alluvium of Isaack's Ranch (sample 101) is 0.78 rads/yr, a higher value that reflects its rhyolitic lithology (tables 2 and 3). We choose initial (Ei) values of 0.50 rads/yr for the Albuquerque and Las Cruces soils that are in the mixed lithology alluvium deposited by the Rio Grande. For the two youngest soils at Las Cruces, we chose Ei values of 0.80 rad/yr. If one assumes that the accumulation of carbonate and reduction of in-place radiation is a linear process, you can approximate the soil's "mean dose rate" (Ex) by using the initial (Ei) and measured (En) dose rate values weighted for the length of time the soil was forming at those rates.

The calculation of mean dose rate (Ex) for surface soils is a simple matter. They have an initial dose rate (Ei) that decreases to the measured dose rate (En) during soil formation. Therefore, Ex is an average of the Ei and En values. For example, soil U (sample 000, table 3) has an En of 0.46 rads/yr; thus, using an Ei of 0.50 rads/yr yields a mean-annual dose rate of 0.48 rads/yr.

Table 2.--Content of radioactive elements and calculated annual dose rates and standard deviations (sd) for soils at the Albuquerque and Las Cruces sites, New Mexico

Laboratory sample number	Field sample number	K_2O (weight percent)	Dose rate and sd (rads/yr)	U[b] (ppm)	Dose rate and sd (rads/yr)	Th[b] (ppm)	Dose rate and sd (rads/yr)	Total dose rate[d] (En) and sd (rads/yr)
ALBUQUERQUE SOILS								
000	78Mnm0	1.956	0.174 ± 0.002	2.57	0.139 ± 0.004	9.30	0.143 ± 0.016	0.456 ± 0.017
001a	78Mnm1a	1.922	0.171 ± 0.002	1.60	0.086 ± 0.003	4.80	0.074 ± 0.013	0.331 ± 0.013
001b	78Mnm1b	2.005	0.178 ± 0.002	1.98	0.107 ± 0.003	5.94	0.091 ± 0.013	0.376 ± 0.013
001c	78Mnm1c	1.892	0.168 ± 0.002	1.74	0.094 ± 0.004	5.10	0.079 ± 0.014	0.341 ± 0.015
001d	78Mnm1d	0.368	0.033 ± 0.0003	1.10	0.059 ± 0.004	2.50	0.039 ± >40%[c]	0.131 ± 0.021
002a	78Mnm2a	1.961	0.174 ± 0.002	1.83	0.099 ± 0.004	5.60	0.086 ± 0.013	0.349 ± 0.014
002b	78Mnm2b	1.577	0.138 ± 0.001	1.69	0.091 ± 0.004	4.20	0.065 ± 0.012	0.294 ± 0.013
002c	78Mnm2c	1.463	0.130 ± 0.001	1.65	0.089 ± 0.004	3.60	0.055 ± 0.014	0.274 ± 0.015
002d	78Mnm2d	1.186	0.105 ± 0.001	1.27	0.068 ± 0.003	2.60	0.040 ± >30%[c]	0.213 ± 0.020
003a	78Mnm3a	1.333	0.118 ± 0.001	1.34	0.072 ± 0.004	3.80	0.059 ± 0.013	0.249 ± 0.014
003b	78Mnm3b	1.617	0.144 ± 0.001	1.37	0.074 ± 0.003	2.90	0.045 ± 0.012	0.263 ± 0.012
003c	78Mnm3c	1.442	0.128 ± 0.001	1.28	0.069 ± 0.003	3.60	0.055 ± 0.012	0.252 ± 0.012
003d	78Mnm3d	1.979	0.176 ± 0.002	1.46	0.079 ± 0.003	4.10	0.063 ± 0.013	0.318 ± 0.013
004a	78Mnm4a	1.772	0.157 ± 0.002	1.60	0.086 ± 0.003	2.30	0.035 ± >30%[c]	0.278 ± 0.018
004b	78Mnm4b	0.512	0.046 ± 0.001	0.87	0.047 ± 0.003	2.00	0.031 ± >30%[c]	0.124 ± 0.017
004c	78Mnm4c	1.043	0.093 ± 0.001	1.39	0.075 ± 0.004	3.60	0.055 ± 0.013	0.223 ± 0.014
006a	78Mnm6a	1.18	0.105 ± 0.001	1.67	0.090 ± 0.004	4.1	0.063 ± 0.011	0.258 ± 0.012
006b	78Mnm6b	1.07	0.095 ± 0.001	1.24	0.067 ± 0.003	3.0	0.046 ± 0.010	0.208 ± 0.010
006c	78Mnm6c	0.16	0.054 ± 0.001	0.97	0.052 ± 0.003	2.2	0.033 ± 0.010	0.139 ± 0.010
006d	78Mnm6d	0.79	0.070 ± 0.001	1.51	0.081 ± 0.003	2.1	0.032 ± 0.016[c]	0.183 ± 0.016
006e	78Mnm6e	0.94	0.084 ± 0.001	1.52	0.084 ± 0.003	5.1	0.078 ± 0.011	0.244 ± 0.011
006f	78Mnm6f	1.92	0.170 ± 0.002	1.70	0.092 ± 0.003	5.6	0.086 ± 0.010	0.348 ± 0.011
LAS CRUCES SOILS								
101	DPTL-1	4.39	0.390 ± 0.004	2.41	0.130 ± 0.009	15.12	0.223 ± 0.021	0.753 ± 0.023
102a	DPTL-2a	3.20	0.284 ± 0.003	2.26	0.122 ± 0.006	8.59	0.132 ± 0.016	0.538 ± 0.017
102b	DPTL-2b	3.36	0.298 ± 0.003	2.09	0.113 ± 0.007	7.10	0.109 ± 0.016	0.520 ± 0.018
102c	DPTL-2c	3.62	0.321 ± 0.003	2.24	0.121 ± 0.006	9.93	0.153 ± 0.015	0.595 ± 0.016
102d	DPTL-2d	2.99	0.266 ± 0.003	2.17	0.117 ± 0.006	8.22	0.127 ± 0.015	0.510 ± 0.016
103a	DPTL-3a	1.03	0.091 ± 0.001	1.53	0.082 ± 0.003	4.0	0.062 ± 0.012	0.235 ± 0.012
103b	DPTL-3b	1.12	0.100 ± 0.001	2.41	0.129 ± 0.004	6.9	0.106 ± 0.014	0.335 ± 0.015
104a	DPTL-4a	0.50	0.044 ± 0.001	1.17	0.063 ± 0.004	3.4	0.052 ± 0.012	0.159 ± 0.012
104b	DPTL-4b	0.74	0.066 ± 0.001	1.80	0.097 ± 0.004	4.3	0.066 ± 0.013	0.229 ± 0.014

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[a] Potassium contents determined by photometry by the U.S.G.S., Branch of Analytical Laboratories, Menlo Park, CA. Analyst: P. Klock. Error in the analyses are uniformly 1 percent; the energy conversion coefficient from weight percent ^{40}K to rads/yr is 0.107.

[b] Uranium and thorium contents determined by delayed neutron activation by the U.S.G.S., Branch of Analytical Laboratories, Denver, CO. Analyst: H. Millard. Energy coeffiecents for converting from ppm of U and Th to energy in rad/yr are 0.0539 and 0.0154 respectively. Alpha particles were weighted at 0.1 of their nominal decay energy in the dose rate calculations.

[c] Thorium values for which the reported coefficient of variation values are greater than 30 percent are not reliable. The thorium contents of these samples were near or below the threshold value for accurate detection.

[d] Total dose rates are sums of the energies from the three prinicipal isotopes. Errors are cumulative errors calculated by standard error-propagation techniques.

Consider a slightly more complicated example of the calculation of mean dose rate. Soil Z, which had a En of 0.50 rads/yr, formed during the interval of 500,000 to 400,000 yrs ago (table 1). It was then buried (as a result of fault offset) and resided in a non-soil forming position for the next 400,000 yrs. The present En in its uppermost horizon (sample 004a, table 2) is 0.28 rads/yr, and it is at this rate that sample 004a has been acquiring TL for the last 400,000 yrs (80 percent of the soil age). However, during soil formation (100,00 yrs; 20 percent of the soil age) the sample must have had a dose rate that gradually decreased from an Ei of 0.50 to an En of 0.28 rads/yr, or an effective rate of 0.39 rads/yr. Thus, we calculate a mean-annual dose rate of 0.30 rads/yr for sample 004a (table 3); the sum of 0.2 x 0.39 rads/yr and 0.8 x 0.28 rads/yr.

Normalizing the TL Data

TL peak heights are used to calculate the ratio of natural TL (N) to artificial TL (A), the latter of which are generated under a standardized artificial radiation exposure of 700 ± 25 rads. This basic TL ratio, referred to as the N/A ratio, represents natural TL intensity normalized for the trap density. The N/A ratio can be used to evaluate certain soil properties from a qualitative standpoint. However, for dating applications the N/A ratio is further adjusted for the annual (En) and mean-annual (Ex) dose rates. The latter ratios, which have the form N/AEn and N/AEx respectively, represent natural TL ratios that are normalized for all factors except age. The constant K (units year^{-1}) is included in calculations to render the ratios dimensionless numbers (May, 1979).

Experimental Techniques

We tried two different experimental techniques in this feasibility study. Initially, we thought we should determine which TL contributions came from the carbonate and non-carbonate fractions of the soil. Thus, we made TL measurements on the non-gravel soil fraction (matrix) and on the same soil fraction from which carbonate had been removed in 6N hydrochloric acid. The soil's noncalcareous matrix is composed primarily of quartz, feldspar, and clay minerals, with quartz probably the dominant nonsoluble TL dosimeter. This procedure doubled the number of measurements over that needed in TL-dating of volcanic rocks (May, 1979) or sediments, but was considered necessary to resolve the potential overlap of quartz-feldspar and carbonate TL peaks (fig. 5). The height of theoretically unobstructed TL peaks was calculated from the glow curves and the carbonate content of the sample. Carbonate content was determined by Chittick gasometric analysis (Driemanis, 1962; Bachman and Machette, 1977, appendix).

We found that the first approach yielded less satisfactory results than a second, simpler approach that uses unleached soil matrix, with no elaborate corrections for peak interference or carbonate content. Intuitively, the first method should be more reliable, yet it may have been less satisfactory because of the possible compounding effects of small errors in the several corrections. The second approach yielded better results for reasons that are not wholly obvious to us. Perhaps this is because of the simplicity of the calculations, or because of a fortuitous cancelling of the interference (overlap) of quartz-feldspar and carbonate peaks by using the data in ratio form. For these reasons, in this paper we used results generated by the simplier second approach.

ANALYTICAL RESULTS

Two basic measures of TL were evaluated in this study: 1) the N/A ratio, which is natural TL normalized only for the sample trap density as measured by the artificial TL; and 2) the N/AEn and N/AEx ratios that represent natural TL normalized for all pertinent variables except age. The TL peak heights, radiation dose rates, and resulting TL ratios for calcic soils are shown in table 3. At the present stage of our study the N/A ratios can be used to establish stratigraphic order in calcic soil chronosequences and to suggest correlations of soils over discontinuous lateral exposures. On a more powerful level, the empirical age curves derived soils studied in this investigation can be used to assign tentative TL ages to other calcic soils from the same regions. However, further refinement and a broader data base are needed before such ages are more than preliminary age estimates. As a consequence of their pedogenic histories, the TL characteristics of the buried soils at Albuquerque and surface soils at Las Cruces are sufficiently different that soil from these sites will be described separately, then compared in the discussion section.

Albuquerque Soils

We analyzed samples from buried soils V, X, Y, and Z and surface soils U and U-Z at the Albuquerque site. Soils U, V, X, Y and Z form a downward stratigraphic sucession that spans the last 500,000 years, whereas relict soil U-Z represents that same time span compressed into a single, but massive soil (fig. 3). This site allows us to see now buried and surface soils interrelate and to analyze how TL ratios reflect individual pedogenic histories.

The basic shape of TL glow curves gives some indication of the age of a sample. From our investigations it is apparent that the intensity of the 300°C carbonate and the 350°C quartz-feldspar peaks of natural TL glow curves change relative to one another in a predictable manner with time. In soils of 5,000-20,000 years age (soil U, fig. 5A) these peaks are small and have nearly the same amplitude. With increasing age, the carbonate peak increases in amplitude relative to the quartz-feldspar peak, owing both to the greater innate TL sensitivity of calcium carbonate from ionizing radiation and to the increasing concentration of carbonate in the soil. In soils of about 200,000 years age (soil X, fig. 5A) both peaks have increased substantially in amplitude, but the carbonate peak is now dominant over the quartz-feldspar peak. By 400,000 years, the carbonate peak is half again larger than the quartz-feldspar peak (soil Z, fig. 5A). These relations provide the basis for relative ages based on N/A ratios. However, these relations are not now sufficiently documented to be used as a rigorous test of sample age.

The next level of comparison of TL data is in the form of N/A ratios. The buried soils have N/A ratios that increase monotonically with soil age, although there is not a dramatic spread in the ratios (table 3, figure 7). Samples from subhorizons of a soil usually have similar N/A ratios; in most cases the ratios differ by less than the experimental error in the individual measurements. The similarity of these ratios for soil subhorizons suggests that a sample from near the middle of a soil may yield a N/A ratio that is characteristic of the soil as a whole. On a reconnaissance level then, TL N/A ratios could be useful in establishing the relative ages of calcic soils from other chronosequences.

Table 3.--TL data for calcic soils

[Natural (N) and artificial (A) TL peak heights, measured annual (En) and mean annual (Ex) dose rates, and ratios of natural to artificial TL peak heights (N/A) that include annual dose rate (N/AEn) and mean-annual dose rate (N/AEx). All analyses are from the 45-75 micron size fraction of the soil matrix (less than 2 mm size fraction). Symbol n.d. means not determined.]

Lab. sample number	Natural (N) peak height (cm/mg ± s[a])	Artificial (A) peak height (cm/mg ± s[a])	N/A ratio ± s[b]	Dose rate, En (rads/yr ± s[a])	N/AEn ratio ± s[b]	N/AEn ratio, weighted mean ± s[b]	Mean dose rate, Ex (rads/yr[c])	N/AEx ratio ± s[d]	N/AEx ratio, weighted mean ± s[b]
ALBUQUERQUE SOILS									
000	261.0 ± 14.6	595.0 ± n.d.	0.44 ± 0.03	0.46 ± 0.02	0.96 ± 0.08	0.96 ± 0.08	0.48 ± 0.04	0.92 ± 0.10	0.92 ± 0.10
001a	792.3 ± 84.8	496.5 ± 17.3	1.60 ± 0.18	0.33 ± 0.01	4.83 ± 0.56	4.28 ± 0.97	0.40 ± 0.02	4.00 ± 0.49	3.67 ± 0.89
001b	887.6 ± 47.2	583.6 ± 25.1	1.52 ± 0.12	0.38 ± 0.01	4.00 ± 0.34		0.43 ± 0.02	3.53 ± 0.33	
001c	825.4 ± 114.4	554.7 ± 38.1	1.49 ± 0.23	0.34 ± 0.02	4.38 ± 0.72		0.41 ± 0.04	3.63 ± 0.66	
001d	n.d.	n.d.	n.d.	0.13 ± 0.02[d]	n.d.		0.29 ± 0.04	n.d.	
002a	1,337.0 ± 33.5	576.8 ± 45.7	2.32 ± 0.34	0.36 ± 0.01	6.50 ± 0.57	7.81 ± 2.25	0.39 ± 0.02	5.97 ± 0.58	6.45 ± 2.16
002b	1,218.0 ± 91.8	560.4 ± 38.8	2.17 ± 0.24	0.29 ± 0.01	7.48 ± 0.86		0.33 ± 0.02	6.58 ± 0.82	
002c	1,294.0 ± 164.0	587.1 ± 33.2	2.20 ± 0.31	0.27 ± 0.02	8.15 ± 1.28		0.31 ± 0.04	7.10 ± 1.35	
002d	1,170.0 ± 53.1	501.5 ± 43.8	2.33 ± 0.23	0.21 ± 0.02[d]	11.10 ± 1.52		0.29 ± 0.04	8.03 ± 1.36	
003a	980.0 ± 66.4	375.8 ± 30.8	2.61 ± 0.28	0.25 ± 0.01	10.49 ± 0.77	10.54 ± 0.85	0.29 ± 0.02	8.99 ± 1.14	9.23 ± 1.77
003b	1,040.5 ± 45.7	394.4 ± 17.9	2.64 ± 0.20	0.26 ± 0.01	10.03 ± 0.49		0.29 ± 0.02	9.10 ± 0.85	
003c	1,195.0 ± 84.9	427.7 ± 16.6	2.79 ± 0.24	0.25 ± 0.01	11.11 ± 1.15		0.29 ± 0.02	9.63 ± 1.05	
004a	1,390.0 ± 48.9	406.7 ± 26.4	3.42 ± 0.25	0.28 ± 0.02[d]	12.21 ± 1.25	12.97 ± 2.34	0.30 ± 0.04	11.40 ± 1.74	12.11 ± 2.43
004b	1,574.0 ± 123.2	457.5 ± 39.0	3.44 ± 0.40	0.12 ± 0.02[d]	28.67 ± 5.82[e]		0.16 ± 0.04[d]	22.50 ± 6.20[e]	
004c	1,800.0 ± 123.2	562.4 ± 45.7	3.20 ± 0.34	0.22 ± 0.01	14.55 ± 1.94		0.25 ± 0.02	12.80 ± 1.70	
006a	1,061.0 ± 112.3	491.0 ± 58.7	2.16 ± 0.35	0.26 ± 0.01	8.31 ± 1.37	8.87 ± 4.99	0.38 ± 0.02	5.68 ± 0.96	6.97 ± 2.97
006b	1,115.0 ± 85.6	495.7 ± 25.9	2.25 ± 0.21	0.21 ± 0.01	10.71 ± 1.12		0.36 ± 0.02	6.25 ± 0.68	
006c	799.0 ± 54.8	339.6 ± 36.1	2.35 ± 0.30	0.14 ± 0.01	16.78 ± 2.44		0.32 ± 0.02	7.34 ± 1.04	
006d	1,337.0 ± 180.0	498.7 ± 52.9	2.68 ± 0.46	0.18 ± 0.02[d]	14.89 ± 3.04		0.34 ± 0.04[d]	7.89 ± 1.64	
006e	1,604.0 ± 158.5	527.9 ± 87.0	3.04 ± 0.59	0.24 ± 0.01	12.66 ± 2.49		0.34 ± 0.02	8.94 ± 1.80	
006f	1,535.0 ± 54.6	583.2 ± 38.0	2.63 ± 0.20	0.35 ± 0.01	7.52 ± 0.60		0.37 ± 0.02	7.11 ± 0.65	
LAS CRUCES SOILS									
101	70.3 ± 8.9	382.0 ± 18.8	0.18 ± 0.02	0.75 ± 0.02	0.24 ± 0.03	0.24 ± 0.03	0.78 ± 0.04	0.23 ± 0.03	0.23 ± 0.03
102a	225.5 ± 10.6	138.8 ± 7.0	1.63 ± 0.11	0.54 ± 0.02	3.02 ± 0.24	3.11 ± 0.58	0.67 ± 0.04	2.43 ± 0.22	2.53 ± 0.52
102b	365.4 ± 12.9	214.0 ± 15.0	1.71 ± 0.13	0.52 ± 0.02	3.29 ± 0.29		0.66 ± 0.04	2.59 ± 0.26	
102c	512.9 ± 18.0	291.7 ± 22.0	1.76 ± 0.15	0.60 ± 0.02	2.93 ± 0.26		0.70 ± 0.04	2.51 ± 0.25	
102d	492.4 ± 30.6	282.0 ± 22.5	1.75 ± 0.18	0.51 ± 0.02	3.43 ± 0.37		0.66 ± 0.04	2.65 ± 0.31	
103a	451.3 ± 39.0	223.6 ± 23.9	2.02 ± 0.28	0.24 ± 0.01	8.42 ± 1.21	8.21 ± 1.64	0.37 ± 0.02	5.46 ± 0.81[e]	
103b	629.0 ± 55.3	230.7 ± 20.7	2.73 ± 0.34	0.34 ± 0.02	8.03 ± 1.11		0.42 ± 0.04	6.50 ± 1.03	6.50 ± 1.03
104a	386.6 ± 33.7	237.6 ± 26.4	1.69 ± 0.15	0.16 ± 0.01	10.19 ± 1.57	11.66 ± 2.14	0.33 ± 0.02	4.94 ± 0.75[e]	
104b	1,005.2 ± 80.8	338.3 ± 22.2	2.98 ± 0.20	0.23 ± 0.01	12.91 ± 1.45		0.37 ± 0.02	8.03 ± 0.94	8.03 ± 0.94

[a] Errors are one standard deviation (s).

[b] Fractional errors are cumulative, at the level of one standard deviation, and calculated by standard error-propagation techniques (Young, 1962).

[c] Mean dose rates are calculated from reported En values, initial dose rates (0.50 rad/yr for the Albuquerque samples and Las Cruces samples 103a-b and 104a-b; 0.80 rads/yr for Las Cruces samples 101 and 102a-d), and duration of soil formation (in yrs). Mean dose rates are assigned arbitary error limits twice as large as corresponding En values.

[d] These dose rates had unreliable thorium concentrations. We used the reported Th values, but assigned them arbitrary errors of 50 percent

[e] These values are considered anomalous and are disregarded in calculations of the weighted mean values of N/AEn and (or) N/AEx

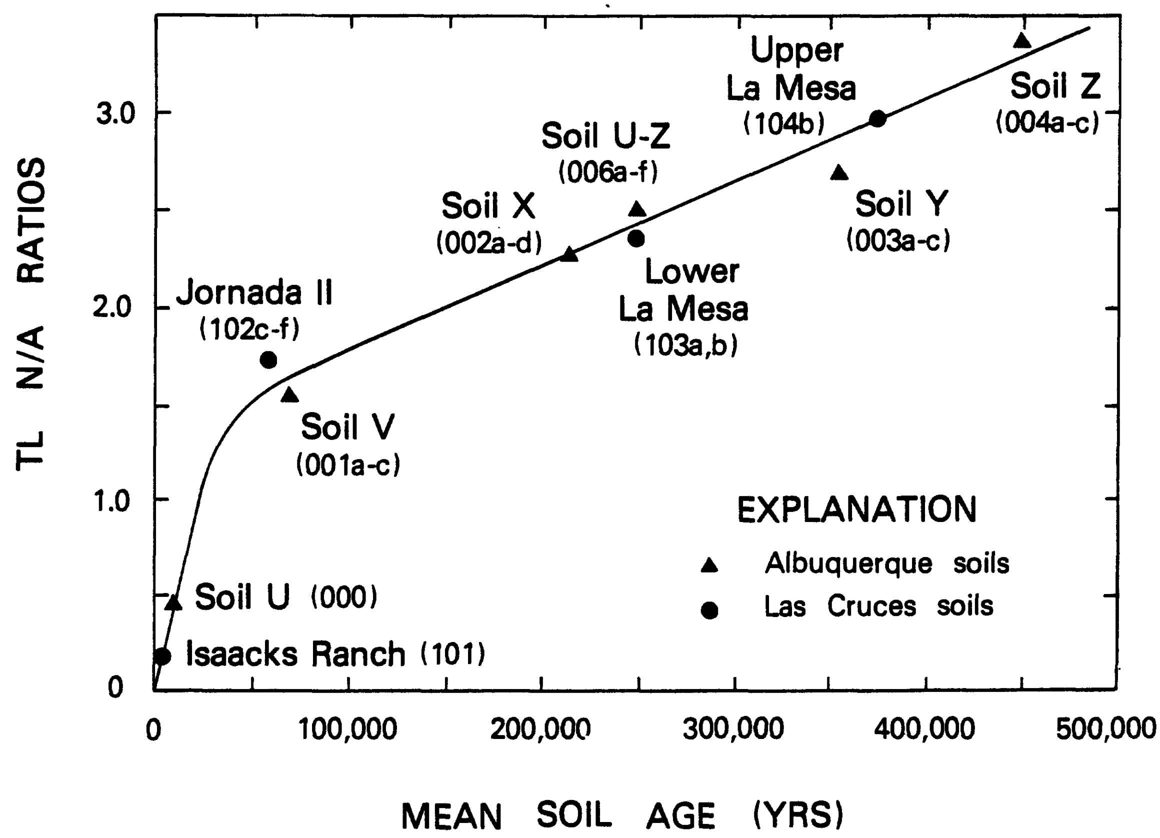

Figure 7.--TL N/A ratios for buried and surface soils at the Albuquerque and Las Cruces sites. TL ratios are the weighted means from several subhorizons of each soil (sample numbers shown in parentheses).

The N/A ratios of the buried and surface soils do not reflect accurately soil age because the ratios do not compensate for the annual radiation dose rate. Nonetheless, the similarity of ratios from different suhorizons of a soil and the fact that the values from each soil increases monotonically with age (and depth in the section) suggest that the basic N/A ratios may be used for establishing relative sample age on a reconnaissance basis or for correlating discontinuous soils.

There is an inverse relation between dose rate and N/A ratios for all the soils at the Albuquerque and Las Cruces sites. The dose rates typically are highest in young soils which have a small volume of carbonate and a large volume of framework grains (fig. 8); this relation leads to rapid storage of electrons that produce natural TL. With time, the carbonate content of calcic soils increases and the dose-rate decreases though a process of dilution. Rapid changes in dose rate associated with dilution are most prominent in soils that have formed over periods of 100,000 to 300,000 years. For soils of even greater length of formation, the rate of change in both the dose rates and TL ratios slows to a fairly uniform rate, and may become stable in old calcic soils (middle Pleistocene or older).

Although we have calculated N/AEn ratios (table 3), we will discuss only N/AEx ratios because the latter reflect the soil's history of changing radiation environment. The N/AEx ratios from buried soils at Albuquerque are plotted against mean soil age in figure 9 (note that the relict surface soil U-Z also is included for comparison). We used weighted mean values computed from averages of soil subhorizons. The method of computing mean values gives more weight to ratios with small errors and less weight to ratios with large errors.

The errors in TL ratios are cummulative; that is, they are the sum of uncertainties in the basic TL peak heights and various dose rates. These errors are assessed using a standard error-propagation technique (Young, 1962) and, although this technique is statistically appropriate, it results in net standard deviations that are fairly large (table 3). Using this technique, the standard deviation of the TL ratios must be larger than the largest single error associated with the computation of the ratios. More importantly, this technique does not consider that the errors may be random and cancel one another. Therefore, our error limits might be considered as potential error limits. Although the individual errors in peak heights and dose rates are generally less than 10 percent, the resultant TL N/AEn and N/AEx ratios commonly have cumulative errors of 20-30 percent.

The N/AEx ratios of the buried soils increase systematically with age and desending stratigraphic position, as do the N/A and N/AEn ratios. However, by incorporating the mean dose rate in the ratios, much of the intra-soil variations are reduced or eliminated. The buried soils have mean N/AEx ratios that lie on a nearly linear trend (fig. 9), with a major change in trend occurring at about 100,000 years. When plotted in the manner used here, the TL ratios from the Albuquerque soils (fig. 9) show no evidence of approaching an upper limit of TL acquistition that would be denoted by a levelling off of the curve. This suggests that some calcic paleosols as old as 0.5 m.y. may be dated by TL, especially where initial natural-radiation levels are equal to or less than 0.5 rads/yr.

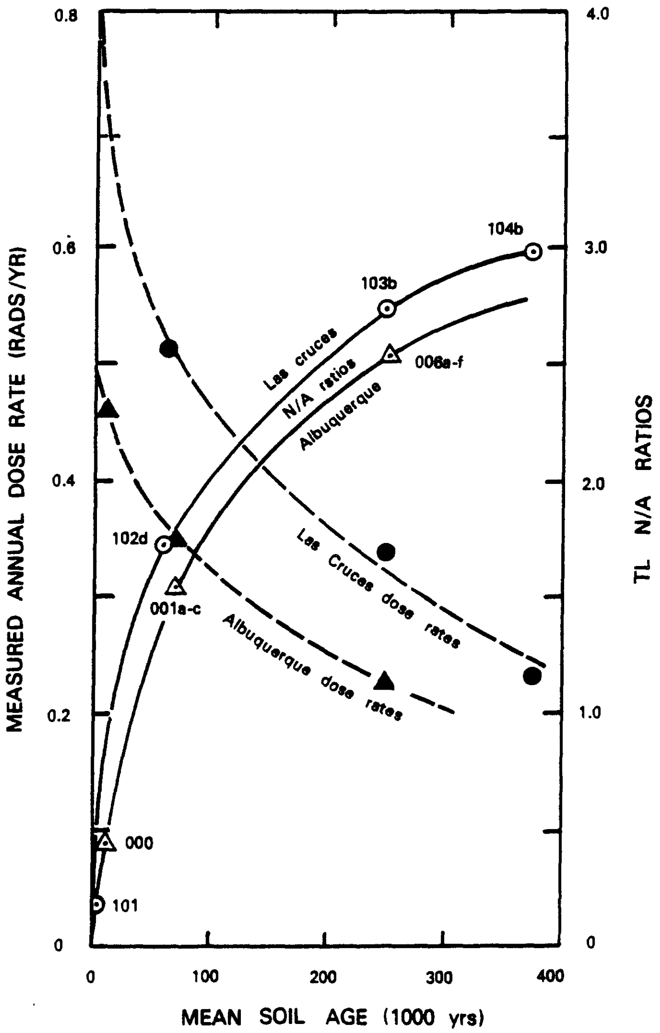

Figure 8.--Annual dose rate (En) and TL N/A curves for some samples (data from table 3).

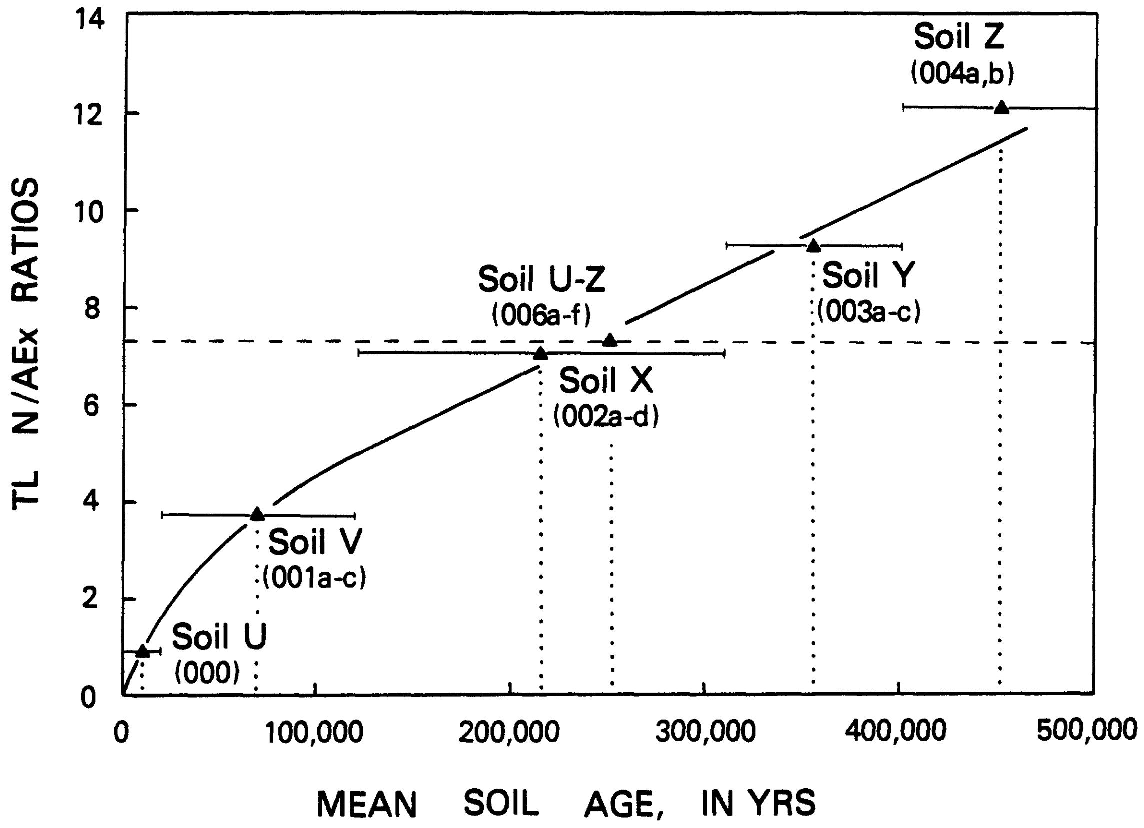

Figure 9.--TL N/AEx ratios for buried and surface soils at the Albuquerque site plotted against mean soil age (table 1). TL values are weighted mean of averages values from soil subhorizons (table 3).

Some of the deviations in the TL ratios within soils (table 3) may reflects differences in soil age, whereas other variations may result from inaccurate determinations of dose rate. For example, the TL ratios of samples 001d, 002d, 004a, 004b, and 006d are considered unreliable because the analytical uncertainity of their Th contents, which were barely detectable, exceeds 30 percent (see footnote c, table 2). Lacking more precise data, we used the reported concentrations of Th for the dose-rate calculations, but assigned an arbitrary analytical error of ± 50 percent. Such errors cause large uncertainties in the resulting TL ratios.

Some of the soils at the Albuquerque site have N/AEx ratios that may reflect internal soil age differences. This is best demonstrated by the relict soil U-Z (table 3, samples 006a-f), which shows a increase in N/AEx ratios from 5.68 at the top of the soil to a maximum of 8.97 below the middle of the soil, and decreasing to 7.11 at the base of the soil (a decrease that is inexplicable). In this soil, all samples except the uppermost (006a) have ratios that lie within concordant error limits; however, these errors are cumulative and rather large. We feel that the internal TL differences in the relict soil, and some of the buried soils too, might be ascribed to periodic accumulation of carbonate in certain parts of the soil, especially young carbonate in the upper part of the soil.

The lack of consistent intrasoil variations in TL ratios (table 3) should not be interpreted strictly to mean the TL procedure is incapable of resolving differences in age. First of all, samples from a single soil were not so closely spaced that subtle differences would be expected to show up. Secondly, many of the buried soils are fairly old (such as Y and Z, table 3) and have been buried much longer than the time it took them to form. In such cases, internal differences in TL that might have formed during early pedogenesis were later obscured by the large increment of TL added since burial. Internal differences might be preserved and detected most easily in young soils. Nonetheless, the overall similarity of intrasoil TL ratios suggests accumulation of carbonate throughout the soil during pedogenesis.

The Albuquerque soils document the relation between TL ratios of a relict soil (U-Z) and its buried counterparts. The relict soil has formed since 500,000 years ago, therefore it has a mean age of 250,000 years. It has an N/AEx ratio of 6.97 (samples 006, table 3), a value that fits nicely between the ratio of 6.45 for soil X (samples 002) and the ratio of 9.23 for soil Y (samples 003). These two latter soils have mean ages of 215,000 and 355,000 years, respectively (table 1). Using the ages and ratios of soils X and Y, one would predict a mean age of 240,000 years for soil U-Z. We feel that this relation both confirms the use of mean soil age for TL studies of pedogenic carbonate, and provides an analytical tie between buried and relict calcic soils.

Las Cruces Soils

We sampled four prominent and well studied calcic soils in the Las Cruces area. Most of these soils are relict, that is they have been continuously exposed and presumably accumulating carbonate since deposition of the parent material. This means that the carbonate present in each soil spans the time between inception of carbonate accumulation and the present.

As with the buried soils from Albuquerque, the N/A ratios for the Las Cruces soils increase monotonically with age (fig. 7). Subhorizons from each soil had similar N/A ratios, with the exception of the old soil below the upper La Mesa surface (samples 104a and 104b; table 4). Sample 104a was collected from near the top of the La Mesa soil's K horizon and thus may contain substantial amounts of young carbonate, as suggested by C^{14} ages of 28,000-32,000 years B.P. (Gile and others, 1981) on middle Pleistocene soils. The N/A ratio for sample 104b, which is from the middle part of the K horizon, is more consistent with TL ratios for middle Pleistocene soils such as soil U-Z at Albuquerque. Thus, we prefer the TL value from sample 104b for the upper La Mesa soil. The N/A ratios are almost the same for similar-age soils from the Las Cruces and Albuquerque areas. However, the N/AEx ratios clearly reflect age differences and display greater internal consistency than do the N/A ratios, and thus reflect the dependency of TL data on sample age and dose-rate history.

The soil ages shown on figure 10 utilize our best estimates based on all available geologic data. The weighted mean of TL ratios for several horizons in each soil are plotted against mean soil age, as was done for the buried soils. Also included on figure 10 are TL data for Albuquerque soils U, U-Z, and V (recently buried) as a comparison of the difference in rates of TL acquisition at each site.

The N/AEx ratios of the Las Cruces surface soils increase monotonically with age. Indeed, the data for both the Las Cruces and Albuquerque samples lie on parallel trends. These trends probably reflect the similarity in carbonate accumulation rates (Machette and others, in press) and in the systematics of carbonate crystallization at both sites. They also suggest a basic commonality in such factors as the spectral composition of carbonate TL emission. There are however, significant differences between the lithology of parent material in these two areas, as evidenced by the higher annual dose rates (En of about 0.75) in the young soils at Las Cruces versus those at Albuquerque (En of about 0.46; table 3). The higher dose rates in the Las Cruces soils results in faster generation of TL, and suggests that TL saturation may occur in 500,000-750,000 years (mean soil age of 250,000-375,000 years).

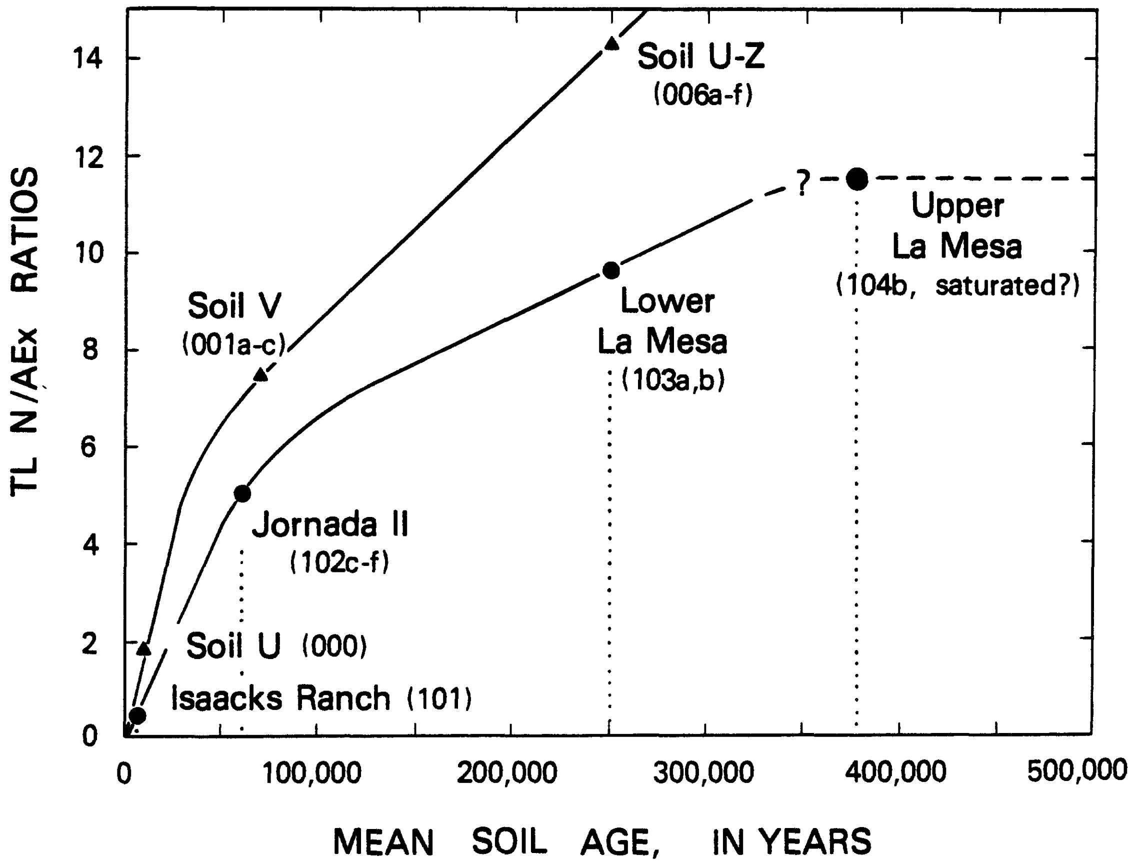

Figure 10.--TL N/AEx ratios for the surface soils at the Las Cruces and Albuquerque sites plotted against mean soil age (also includes recently buried soil V). TL values are weighted means of of average values from soil subhorizons (table 3).

DISCUSSION

The monotonic, nearly linear increase in TL N/AEx ratios from both buried and surface calcic soils (figs. 9 and 10) clearly demonstrates that soil carbonate acquires TL in a predictable manner and is suitable for soil-dating applications. However, the different slopes of TL ratios versus soil age reflect the dependence of TL acquistion of natural radiation in the geologic environment. For example, the dose rates for the young Las Cruces samples are considerably higher than those for the Albuquerque samples.

Convincing evidence of the applicability of TL to calcic soils is found in the Albuquerque samples. Here, N/AEx ratios from relict soil U-Z (mean age of 250,000 years) are slightly more than that of buried soil X (mean age of 215,000 years), but slightly less than that of buried soil Y (mean age of 355,000 years). This relation suggests that both surface and buried soils from similar soil environments may be dated using a single empirical TL curve. Further research should address whether the similarities in TL ratios from the Las Cruces and Albuquerque surface soils, for instance, are due to similar rates of carbonate accumulation, or are due to a basic uniformity in the factors controlling generation and storage of TL.

The systematic increase in N/AEx ratios provides substantiation from a practical point of view for two empirical techniques employed in this study. First, we use the weighted mean of average TL ratios determined from subhorizons of a soil, occasionally excluding anomalous ratios from the upper or lower parts of the soil if they differ significantly from the mean value. Secondly, we think N/AEx ratios reflect the mean age of the soil and thus, plot all values accordingly.

N/AEx ratios show several trends with age (figs. 9 and 10). For young soils, the ratios increase rapidly up to about 100,000 years mean soil age, then the slope of the curve decreases. This change in the rate of TL acquistion is probably caused by the decrease in the dose rate that accompanies increasing carbonate concentration levels and inherent dilution of the soil's framework grains. From 100,000 to 250,000 years mean soil age, the effect of dilution is less pronounced and both buried and surface soils acquire TL at a nearly linear rate. The TL level of surface soils in the Las Cruces area appear to become saturated sometime after 250,000 years mean age.

We did not calculate soil ages from the TL data because of the preliminary nature of this research. Cumulative standard-deviation errors of TL ratios range from about 10-30 percent, and average about ± 25 percent (table 3). Errors in soil ages estimated by Machette (1978) are more difficult to determine, however it is his opinion that they could as much as 25 percent of the reported age. Both types of errors are important because they determine the error in the slope of the empirical curves, and hence the probable accuracy of ages generated from them. If these errors are taken into account, the best ages derived from carbonate TL ratios might be accurate to within ± 25 percent.

TL was measured from samples of calcic soils in two areas in the Rio Grande Valley of New Mexico, that have arid to semiarid climates. The resulting N/AEx ratios suggest that an insignificant amount of solution and reprecipitation of carbonate occurs once the carbonate has moved into the C horizon, probably because their soil waters are relatively saturated with Ca^{++} ions. In regions having substantially higher rainfall, or less influx of Ca^{++} ions to the soil surface, one might expect periodic resetting of TL rather than progressive accumulation of TL.

The TL technique is applicable to a wide age range of calcic soils. The lower age limit is determined not so much by analytical considerations, but by the physical concentration of carbonate in a soil. By isolating discrete nodules of carbonate, the sample can be enriched to about 25 percent carbonate content. Using this technique, the lower age limit for TL-dating of carbonate may be about 5,000 years. Although the upper age limit for soil carbonates appears to be at least 500,000 years (250,000 years mean soil age), this limit is controlled by the rate of TL acquisition. This limit is defined as the age at which all available traps within the carbonate are filled (the saturation point); this condition is manifested by a gradual stablizing of N/AEx ratios (fig. 10). From this point on, ages predicted from TL ratios are too young; in a sense they become infinite ages.

SUMMARY

The results of our experiments show that pedogenic calcium carbonate has TL properties that make it a promising dating technique for calcic soils. Although the applicability of the data reported here is somewhat limited by our sampling of soils from two limited areas, we feel that TL-dating of pedogenic carbonate could be applied to most calcic soils that have formed in arid to semiarid climates. Further work is required to test the applicability of carbonate TL in soils from other regions. The age limits of the method appear to be from about 5,000 years to more than 500,000 years. Although the analytical precision in N/AEx ratios is typically ± 10 percent, our preliminary estimate is that TL ages could be accurate to ± 25 percent of the soil age.

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