Radiometric dating of hillslope calcrete in the Negev Desert, Israel

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The radiometric dating of calcrete is often problematical because impurities and open system conditions affect the apparent ages obtained. By applying both radiocarbon and uranium-series dating to calcrete in colluvium, it is shown that such conditions can be identified. In correlation with the stratigraphy, it is found that partial recrystallization severely decreases the radiocarbon ages of the upslope and shallower samples further down, whereas incorporation of limestone fragments from bedrock significantly increases the apparent ages of some of the uranium-series samples. It is concluded that the hillslope calcrete at the study site near Sede Beker in the Negev Desert, Israel, mainly developed shortly after 40 kyr ago, at a time when the Jordan Valley was being inundated to form the fossil Lake Lisan. Since their formation would have required higher rainfall than today, the results provide further evidence that the whole region was experiencing an increase in precipitation.

Introduction

Calcrete crusts are widespread in arid and semi-arid regions where the rainfall is less than 500 mm/yr. They usually occur in alluvial fans and in the alluvium of gently sloping streambeds. Less frequently, calcrete is also found in colluvium that accumulates on the lower slopes of hills or ridges. The conditions under which such hillslope calcrete forms differs from those of calcrete in low-lying valleys and floodplains: whereas the formation of calcrete in near-horizontal deposits is attributed to leaching processes within the profile, direct runoff from upslope supplies additional dissolved carbon to the colluvial variety.

Such sloping calcrete horizons occur on the Mediterranean side of the Negev Desert in southern Israel, where the average annual rainfall is less than 200 mm.[1] In an attempt to determine when these crusts formed, both radiocarbon and uranium-series dating were applied to a typical occurrence on the Negev Highlands. In this brief report a possible interpretation of the dating results will be presented.

The site

The study was conducted at an experimental site near Sede Boker. On the initiative of A. Issar, a trench was dug through the colluvium on the lower section of a small hill to expose the secondary calcrete formation. The area today receives about 95 mm rain per annum with a range of 30–183 mm. The rainy season extends from October to May. Up-slope the surface consists mainly of exposed limestone rock of Turonian age with sparse patches of a thin soil cover here and there. Mechanically and biologically weathered sediment is visible everywhere.

The total length of the trench is 42 m. Down-slope the colluvium thickens and eventually interfingers with alluvium in the adjacent drainage channel. Two distinct calcrete horizons are present over the first 22 m of the colluvium, one above the other. Beyond this an occasional calcrete nodule occurs (Fig. 1).

The rainfall and runoff at the site has been recorded in detail over several seasons.[2] Most rainfall events produce only little precipitation. Storms in excess of 20 mm/day may occur only once every two or three years. However, showers with an intensity exceeding 5 mm/h for a three-minute period will produce runoff from the bare up-slope surfaces. Such runoff is rapidly absorbed into the porous matrix once it reaches the colluvium mantle. This moisture tends to move down-slope on the semi-impermeable crusts of the two calcrete sub-units and along the

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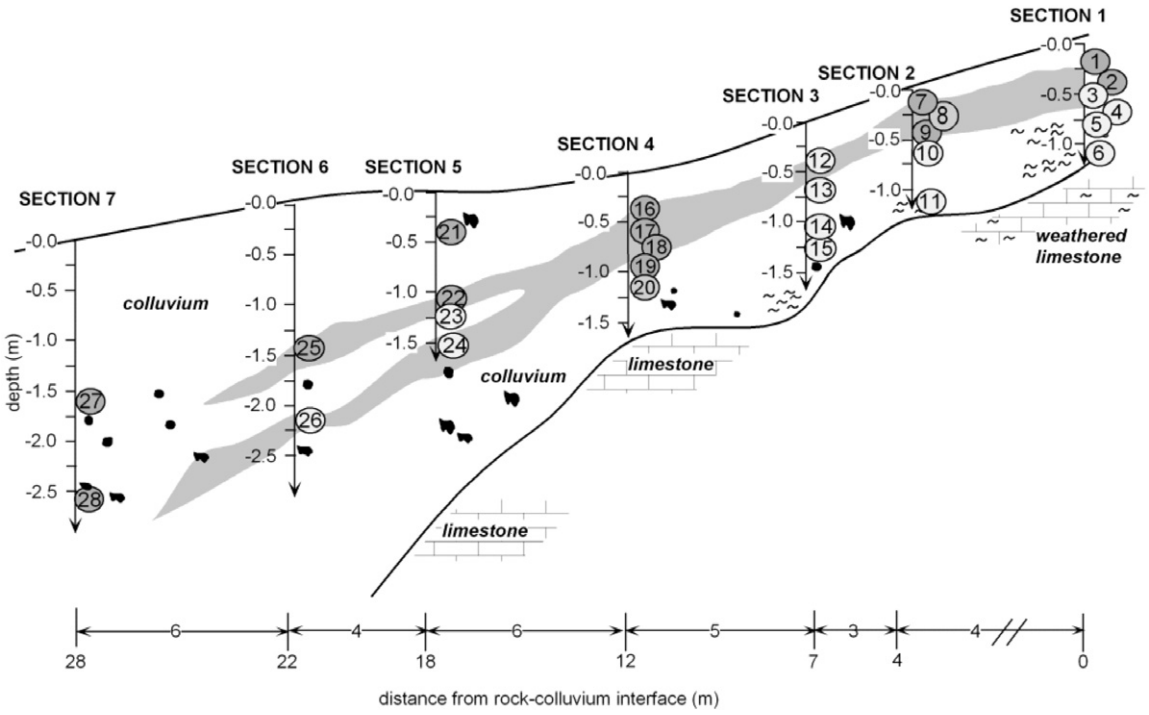

Fig. 1. Profile of the colluvial hillslope deposit, showing the positions where samples for dating were taken. The numbers refer to the sample numbers in Table 1. The shaded areas show the position of the calcrete layers, while the black dots represent calcrete nodules.

Table 1. Summary of the results of the radiocarbon and uranium-series dating.

Sa. no.	Depth (cm)	Description	^{14}C age (yr)		^{230}Th/^{234} U	^{230}Th/^{232} Th	Appar. Th/U age (kyr)	Corr. age* (kyr)
			CSIR Pretoria	GGA Hannover				
		Section 1. 0 m						
1a	29	1st calcrete top		10 365 ± 140	0.806	1.42	172.8 ± 15,8	42.1 ± 4.1
1b	32	1st calcrete centre	17 900 ± 80	18 280 ± 225				
1c	33	1st calcrete base		21 730 ± 300	3.58 (!)		(?)	
4a	60	2nd calcrete top		7 485 ± 80	0.757	2.256	150.5 ± 6.5	69.1 ± 2.8
4b	62	2nd calcrete centre	18 700 ± 140	18 720 ± 120	0.617	9.51	102.6 ± 8.1	88.2 ± 7.3
4c	65	2nd calcrete base		24 330 ± 825	0.674	2.03	119.9 ± 3.7	53.7 ± 1.8
5	70	Soft chalk	24 000 ± 460					
		Section 2. 4 m						
7a	20	1st calcrete top		17 720 ± 220				
7b	22	1st calcrete centre	22 700 ± 270					
8	27	1st calcrete base		33 330 ± 910				
9	40	2nd calcrete top	19 100 ± 210					
10	65	Soft chalk	37 400 ± 1100					
		Section 3. 7 m						
12a	40	1st calcrete top	23 400 ± 300	23 175 ± 365	0.795	4.223	164.8 ± 7.3	107.5 ± 4.2
12b	42	1st calcrete centre		33 980 ± 1400				
12c	45	1st calcrete base		38 620 ± 1550	0.724	9.114	135.8 ± 5.8	113.9 ± 4.6
13	65	2nd calcrete centre	34 900 ± 940		0.829	16.307	180.3 ± 7.8	169.6 ± 8.2
14	105	Carbonate nodules	34 600 ± 1000		0.802	1.353	173.5 ± 25.7	38.6 ± 8.3
15	125	Soft calcrete	39 900 ± 1900					
		Section 4. 12 m						
16	40	1st calcrete centre	18 000 ± 150					
17	60	2nd calcrete top		15 775 ± 180				
18	70	2nd calcrete centre	29 300 ± 480	33 140 ± 1010	0.409	3.32	56.4 ± 1.5	39.1 ± 1.3
19	90	2nd calcrete base		40 700 ± 2000				
20	115	Carbonate nodules	37 400 ± 1700					
		Section 5. 18 m						
21	40	Carbonate nodules	24 000 ± 330					
22	110	Calcrete			0.704	2.365	128.0 ± 3.7	64.6 ± 2.0
23	120	Soft calcrete	34 200 ± 950					
		Section 6. 22 m						
25	140	1st calcrete	32 100 ± 760		0.645	1.62	110.6 ± 5.1	39.7 ± 2.7
26	220	2nd calcrete	40 800 ± 1800		0.74	3.68	140.5 ± 6.7	89.5 ± 4.1
		Section 7. 28 m						
27	160	Carbonate nodules	35 400 ± 970		0.696	1.47	127.0 ± 8.9	37.7 ± 3.8
28	260	Carbonate nodules	36 200 ± 1200		0.701	1.47	129.2 ± 9.2	38.1 ± 3.9

Column 7 gives the thorium isotope activity ratios, which show that the detrital contamination is high.
*Uranium series dates corrected for an initial detrital thorium isotope ratio (^{230}Th/^{232} Th) of 0.855 (see Fig. 2).

basal contact with bedrock. Occasionally, the colluvium further down-slope becomes moist to a depth of *c.* 40 cm below the surface. This moisture is subsequently removed by evaporation.

Sampling and analysis

Initially, a set of bulk samples was collected from the trench for radiocarbon dating at the CSIR in Pretoria, South Africa. Subsequently, a more detailed set was collected for radiocarbon and uranium-series dating at the GGA (Geowissenschaftliche Gemeinschafts Aufgaben) laboratory in Hannover, Germany. A few days before sampling, the wall of the trench was cut back to expose a fresh surface in both cases.

In Pretoria, 20–30 g of material from the different sub-units was used and the analyses performed in CO_2 proportional counters.[3] In Hannover, from 200 mg to 5 g from the top rim, centre and base of the different sub-units was processed for radiocarbon dating and analysed as acetylene or CO_2 for samples that yielded 0.1–3 g and 25 mg carbon, respectively.[4] All the results were corrected for isotope fractionation using the ^{13}C content of the counting gas.

The uranium-series dates were determined by alpha-spectrometry using a few tens of grams of material. The samples were washed and visible contamination was removed mechanically before total dissolution[5] following the procedure described by Ivanovich and Harmon.[6]

Results and discussion

The results of the analyses are listed in Table 1. The apparent radiocarbon ages cover a wide range from 7.5 thousand to 40.8 thousand years ago (kyr), whereas the apparent ages of the uranium-series samples are all beyond 56.4 kyr.

There are two matters that need to be taken into account when interpreting these data, namely:

The effect of the matrix. The colluvium consists mainly of weathered limestone fragments and this material is incorporated into the calcrete deposit, with a very different effect on the ages obtained for the two dating techniques. If, for instance, half the carbonate in a sample derives from the ancient limestone, it would add one half-life, or 5700 years, to the radiocarbon age of the mixture. On the other hand, if half the uranium with its associated ^{230}Th derives from the limestone, it would increase the age by some 70 000 years. It is thus not surprising that the

uranium-series dates are so much older than the radiocarbon ages.

The effect of re-crystallization. Recent analysis of the runoff at the site has shown that the water is highly unsaturated in bicarbonate—0.3 mmol/l or *c.* 80% unsaturated.[7] When such moisture reaches the calcrete, it will dissolve carbonate. Later, when the moisture evaporates, the carbonate will be re-precipitated, without actually adding more mass to the calcrete. It will, however, have introduced new ^{14}C, which will reduce the apparent age of the sample. This process of rejuvenation is active still today.

With these two effects in mind, the results become understandable.

The radiocarbon dates

One half of the samples (15 of 29) give ages between 31 and 41 kyr. The rest all have younger apparent ages. These dates need some adjustment: first, the initial radiocarbon content of such terrestrial carbonate is normally lower than the atmospheric value.[8] This makes the sample appear up to a few thousand years older. On the other hand, radiocarbon dates in this time range are known to be several thousand years too young.[9,10] The combined result of these two effects is that there is an uncertainty of a few thousand years attached to the figures.

The samples that are younger than 30 kyr are those from Section 1 in the profile and those that are less than 40 cm below the surface lower down. It is concluded that these samples are ones that have been subjected to rejuvenation by the re-crystallization process described above. The dense upper crusts of the two calcrete horizons in Section 1 that give the youngest apparent ages are the levels that are most frequently affected by runoff. By the time moisture reaches Section 3 in the profile (Fig. 1), it would be saturated in bicarbonate so that no further solution of calcium carbonate can occur and the radiocarbon dates will not be affected.

The uranium-series dates.

The ages obtained need to be corrected for the presence of initial detrital thorium. Unfortunately, the $^{230}Th/^{232}Th$ activity ratios are very low (see Table 1), so that large adjustments to the apparent ages are required. In Fig. 2 the relevant activity ratios of the samples are plotted. Six of them lie on a straight, upward-sloping line indicating that these samples formed at the same time, but contained varying amounts of detrital thorium. The isochron line crosses the *y*-axis at 0.302, which corresponds to a common corrected age of 39 kyr. The slope of the line (0.855) represents the activity ratio, $^{230}Th/^{232}Th$, of the detrital thorium. All the other samples lie above and to the left of the isochron line in Fig. 2. This would be consistent with the assumption of admixture with primary limestone fragments (for which the activity ratio $^{230}Th/^{234}U$ would be equal to 1). Considering the position of the sample points in Fig. 2, leaching of uranium seems less likely because that would cause the points to lie further to the right. In the last column of Table 1, all the age results are corrected for an initial $^{230}Th/^{232}Th$ ratio of 0.855. This would account for the initial thorium contamination, but not for the inclusion of limestone fragments.

Conclusion

A rough average for the radiocarbon ages of the fifteen deeper down-slope samples is 34 kyr. Considering that radiocarbon ages at 41 kyr appear some 6000 years too young,[9] this figure is in acceptable agreement with the average age of 39 kyr for the six consistent uranium-series samples. The overall conclusion thus is that the hillslope calcrete at the site mainly developed shortly after 40 kyr ago; that the occurrences in the upper reaches were subsequently subjected to partial re-crystallization, causing rejuvenation of the ^{14}C contents; and that many of the carbonate crusts incorporate limestone fragments from bedrock, making the uranium-series dates appear much older.

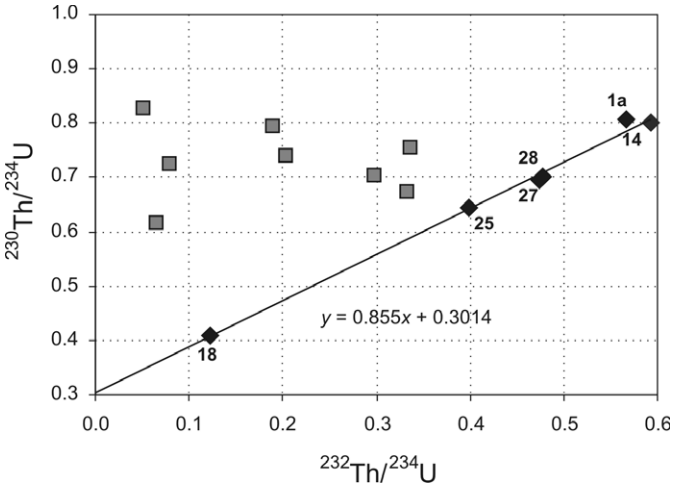

Fig. 2. Plot of the thorium/uranium activity ratios of the samples. The numbers refer to the sample numbers in Table 1. The intercept of the straight line with the *y*-axes gives an activity ratio of 0.302, which corresponds to an age of 39 kyr. The slope of the line (0.855) represents the activity ratio of the detrital thorium.

The formation of the calcrete would have required considerably more rainfall than today. Interestingly, the dating places the event at a time when the Jordan Valley was inundated to form the massive fossil Lake Lisan,[11] suggesting that precipitation was generally higher in the whole region.

Such impure calcrete deposits are less than ideal material for dating by either of the two radiometric techniques. However, by applying both techniques to a set of selected samples and evaluating the results in the context of the stratigraphy, reasonable conclusions about the age and subsequent development can be drawn.

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