Chapter 13

ELECTRON SPIN RESONANCE (ESR) AND MASS SPECTROMETRIC U-SERIES (MSUS) DATING OF TEETH IN CRIMEAN PALEOLITHIC SITES: STAROSELE, KABAZI II, AND KABAZI V

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INTRODUCTION

The dating program which included the sites of Starosele, Kabazi II, and Kabazi V was carried out during the summer field seasons of 1993 through 1995, with J. Rink doing on-site dosimetry, tooth collection, and making detailed field observations of the site lithologies in 1993 and 1994. Most of the ESR laboratory analyses are complete, but the MSUS dating is still underway. Although the dating of these sites using thermoluminescence of burned flint was also studied, the apparently burned flints from Starosele were not sufficiently heated for application of this method. No windblown sediment was found, which precluded the application of optical luminescence dating at these sites. The sites of Zaskalnaya V and GABO were also studied in this field program, but the results will be reported elsewhere.

EXPERIMENTAL METHODS

The general approach in this work to ESR dating is the same as that proposed by Grün et al. (1987), with the exception of the beta dose calculations and very slight refinement of the alpha dose calculations. Briefly, the method is based on the measurement of the intensity of a characteristic signal produced by trapped electronic charges in samples of tooth enamel which is detectable on an electron spin resonance spectrometer. The height of the signal increases with the radiation dose. We calibrate its sensitivity to dose by exposing it to additional doses of artificial gamma rays, permitting us to convert the peak height to an equivalent dose (D_e) in grays. The dose rate (that is, the annual dose) is determined from the natural radioactivity of the sample and its surrounding sediment, as well as the calculated cosmic dose (specific details about this dose rate determination are provided along with dating results for each site). The present-day gamma dose rate from the surroundings and the cosmic dose rate are best determined by in situ measurement using thermoluminescence dosimeters (TLD's). The cosmic + gamma and the beta ray dose rate from sediments is assumed to have remained constant through time or, at most, to have varied with water content as a function of climate. The internal dose rate of the enamel and the dose of beta-rays from adjacent dentine and cementum, is attributed to uranium absorbed by these materials. This dose rate is assumed to have increased through time from an initial zero value, as a result of: (a) uptake of U; and (b) growth of the daughter isotopes of ^{238}U. The increase in U content is assumed to be a regular continuous function of time, two possible limiting cases of which are early uptake (EU): acquisition of present-day U content soon after burial; and linear uptake (LU): where the present U content has been acquired at a constant rate through time.

Most ESR dates on tooth enamel published before 1997 have been based on a particular model for calculating the beta radiation doses in tooth enamel (Grün 1986). Early uptake (EU) and linear uptake (LU) ages have both been based on this approach. More recently (Rink et al. 1996a, 1996b; Brennan et al. 1997) have begun to report ESR ages using a new method for calculating the beta radiation doses which is based on One-Group Theory (O'Brien 1964; Prestwich et al. 1997). These ESR age calculations have been dubbed ROSY ESR ages after the name of a hippopotamus who died at the Toronto Zoo and who posthumously lost her teeth to the cause of ESR dating at McMaster University Geology Department. ROSY EU and ROSY LU ESR age calculations differ from those based on the previous approach only with significant respect to the beta dose calculations (Brennan et al. 1997). ROSY ESR ages are almost always older than those of the previous approach, unless the enamel contains very large amounts of uranium, making the internal alpha doses very large with respect to all other doses including beta doses. Most recently, experimental studies of beta attenuation in tooth enamel (Yang 1997; Rink and Yang in prep.) have strongly supported the new calculation method employed in ROSY ESR age calculations, and have shown good agreement with Monte Carlo calculations of beta doses in tooth enamel. These new results are expected to bring about a general revision in past published ESR ages, which will increase these ages from 0-30%. The age results presented in this paper are ROSY ESR ages and will not be subject to further revision except for refinement using mass-spectrometric U-series data which is not yet incorporated into the age calculation package for ROSY ages. These refined ages will appear in future publications.

The MSUS dating reported herein follows the approach of Li et al. (1989). The use of conventional U-series ages based on alpha spectrometry to refine ESR model ages, such as early uptake (EU), linear uptake (LU), and recent uptake (RU) ages, was pioneered by Grün et al. (1988). Over the past decade there has also been an order-of-magnitude increase in the precision of uranium-series (US) dating, through the advent of thermal ionization mass spectrometric (TIMS) analyses of U and Th isotope ratios (Edwards et al. 1986). McDermott et al. (1993) were the first to use this method for mass spectrometric U-series (MSUS) dating of teeth, and greater detail on these studies was provided by Grün and McDermott (1994). The basic approach is to do MSUS dates on the different tissues (enamel, cementum, and dentine) which have absorbed uranium (U) in the teeth. A direct comparison of MSUS ages and ESR early uptake ages provides direct information on the uptake history in the tooth. Coupled ESR/MSUS ages and uptake parameters (p-values) can be calculated (Grün and McDermott 1994) making various assumptions about which tissues should be used as the primary determinant in the uptake history for the coupled age calculation, which has in these earlier works apparently been considered to be the enamel. Although coupled ages are most desirable, this cannot yet be done for ROSY ESR ages as mentioned above. Nonetheless, the ROSY ESR ages reported here can be refined using Figure 13-1, as discussed below.

The U-series age of the dental tissues in a tooth whose enamel has been dated by ESR are a crucial source of information needed to better constrain the ESR results. It is essential to keep in mind that ESR EU and LU ages are simple model assumptions, and cannot be considered definitive age estimates (except in cases where no U has been absorbed into the teeth, where the EU and LU ages are essentially the same and thus they provide a true age estimate, e.g., Rink et al. 1996). The purpose of doing MSUS dating in this work was to refine the simple EU and LU models and obtain the best age estimates available. This was essential for the Crimean sites, where U-uptake into dentine and cementum was large. Figure 13-1 shows how to use U-series ages to refine ESR ages. Simple EU, LU, and in some cases RU, ages can be calculated without U-series data. They provide the reference frame for comparison with U-series data. The aim of the comparison is to decide whether the simple EU or LU model is appropriate, or whether the true age estimate is younger or older than those simple models. In general, the tissue (cementum, dentine, or enamel) which has absorbed the most uranium is the most important tissue to date with MSUS. The ESR enamel age may be refined by placing it into zones 1-6 on this basis. For example, if the MSUS age of the dentine (the dominant U-bearing tissue) in a particular tooth is 60% of the ESR EU enamel age, then the true burial age falls within zone 3, which means that it is between the EU and LU enamel ages (which are known to certain absolute numerical values). Whereas if the MSUS age was only 25% of the ESR EU enamel age, then it would fall into zone 5, and the true burial age would be older than the ESR LU enamel age. For some of the teeth in each of the three sites reported on here, at least three dates are provided for each tooth: ESR EU and LU enamel ages and at least one MSUS age on a dominant U-bearing tissue from that same tooth. The refined ages will be reported using the data of Figure 13-1.

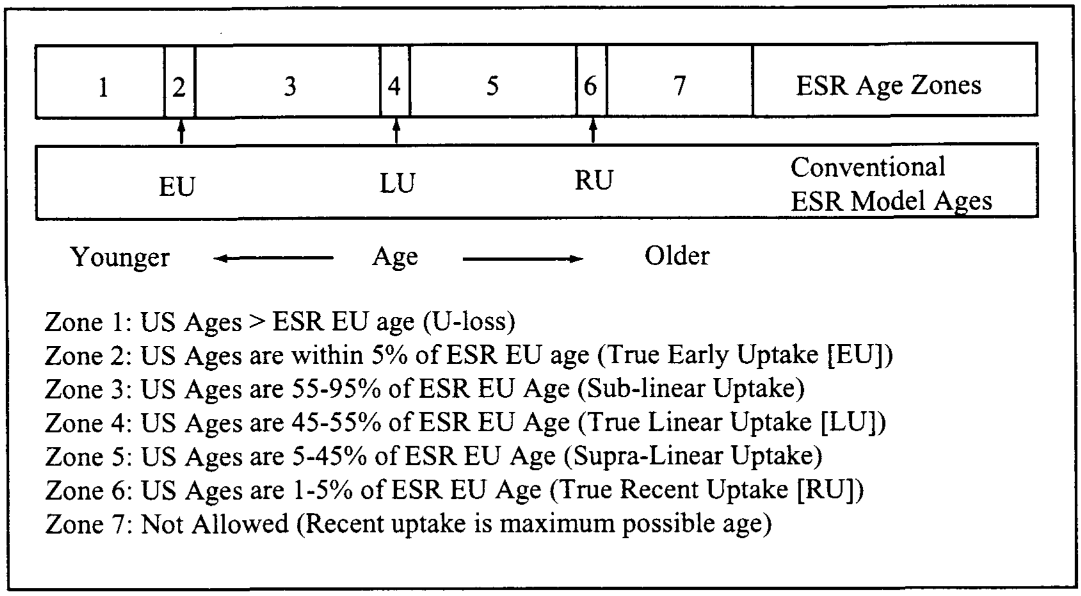

Fig. 13-1—Refined ESR enamel ages zones in relation to EU, LU, and RU ESR model ages for a given tooth using U-series ages (often referred to as MSUS ages in the text) as constraints. A tooth enamel sample dated by ESR can be placed into one of the zones based on a comparison of the ESR EU age with a U-series age on dentine, cementum, or enamel from the same tooth (note: U-series ages are not shown on the diagram). The refined ESR enamel age is a better estimate of the true burial age than either the EU or LU model on its own.

Although U-series dating of tooth enamel is considered by other workers to be a secure absolute dating method without comparison to ESR dating (e.g., McKinney 1991), it is our view that the assumption of the early uptake model for tooth enamel (as used to support this claim) will only be true under certain burial conditions, but not for all situations.

For all of the teeth in this study, the beta dose from sediment was relatively small because the cementum layers protected the enamel from direct exposure to the nearby sediment, and absorbed much of the beta doses coming from sediment. Nearly all of the beta dose received by most teeth was from U in cementum and dentine. The sediment that was collected from very close to the tooth was used whenever possible to calculate the small doses from sediment, but in some cases, this sediment had been packed into the same bag with the tooth, and became contaminated by the U-rich cementum and pulp of parts of the tooth which broke down. In general, this was less of a problem for the Starosele teeth where preservation was better than at Kabazi II and Kabazi V. Whenever high U was observed in the sediment that was collected with the tooth, the beta dose from sediment to the enamel was reconstructed using the sediment from that level which had been collected from one of the holes made for gamma dosimetry purposes, and we also did this for cases where sediment had inadvertently not been collected with the teeth.

Statistical Methods

The analytical uncertainty in reported MSUS ages are ± 2σ errors based on counting statistics on the ion beams in the mass spectrometer. The analytical uncertainty in reported ESR ages is not based on the root mean square standard deviation of all of the individual terms of analytical uncertainty combined (e.g., estimated error in the equivalent dose, U concentrations, Th concentration, K concentration, thicknesses, densities of tissues, moisture content). Instead, the ESR age is calculated first with the errors subtracted from each value and again after they are added to the value. The quoted uncertainty for a single enamel sample is the spread between these two calculated ages using the same uptake model. Mean ESR ages for a given level are reported with a +/- 1σ standard deviation of the mean age, with no weighting of the individual ages based on their specific reported analytical uncertainty. Reported analytical uncertainties in U, Th, and K values are based on neutron activation analysis counting statistics.

STAROSELE RESULTS

Dating results (Tables 13-1 and 13-2) were obtained using teeth from four different archeological levels of the site designated in descending stratigraphic order as 1, 3, 4, and "Below 4." The considerable degree of U-uptake in these teeth is represented by the large U-content of the dentine and cementum, whereas the enamel had only absorbed tiny amounts of U. This highly radioactive "sandwich" of cementum/enamel/dentine led to a strong divergence of the EU and LU model ages, based on simple assumptions about possible U-uptake. The U-series ages (Table 13-2) can be used to refine these EU and LU ESR enamel ages. All of the teeth were *Equus hydruntinus*, nearly all of which were molars.

Starosele: Ages in Level 1

In this level, U-series ages were obtained on dentine in four different teeth (Table 13-2). Although the cementum has higher U content (Table 13-1), the dentine was considered as a dominant source of U-based radiation because it was much thicker (about 2 mm) than the cementum layers, which ranged from 0.4 to 1.4 mm. The dentine ages range from 4.4 to 8.8 ka, which are only 19 to 44% of the ESR EU ages for the three teeth which have counterparts in Table 13-1. Based on the interpretive data of Figure 13-1, they fall into ESR age zone 5, which means their true burial age is older than the reported LU ages which range from 30-34 ka, and younger than the RU age (not reported). In fact, a mean coupled ESR/MSUS ages was reported for this level (Monigal et al. 1997), but they were based on the old style of beta dose modeling. The reported coupled age was 41.2 ± 3.6 ka, based on the assumption that the cementum U-series ages are similar to those of the dentine. These previously reported coupled ages must be considered minimum ages because they will increase when the new coupled age calculations are made using the ROSY approach, unless the cementum layers are found to have a very different U-series age from those in the dentine. The enamel U-series ages are not important for the refinement of the ESR ages because the enamel has absorbed so little uranium.

Starosele: Dosimetry in Level 1

For these teeth, the approximate ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is quite variable and ranges from 7/35/45/13 % to 5/59/28/8 % (EU model). The EU model is chosen only for the convenience of the calculation here (and elsewhere in this paper), and these ratios simply allow a quick method to see how the dose is generally distributed for a given model (for the LU model, the alpha and beta doses would be about half of what they are in the EU model). The true relative proportions can only be determined when coupled ages are calculated. The total annual doses ranged from 973 to 1589 μGy/a.

TABLE 13-1
Starosele, ROSY ESR Ages on Enamel and Analytical Data

Sample	*Level*	*Square*	*Elev. (cm below datum)*	*Cementum U (ppm)*	*Enamel U (ppm)*	*Dentine U (ppm)*	*Early Uptake ESR Age (ka)*	*Linear Uptake ESR Age (ka)*
94107A	1	H23	-283	51.1	0.6	40.8	20 ± 2	30 ± 3
94108A	1	H23	-292	46.3	0.4	33.1	20 ± 1	29 ± 2
94108B	1	H23	-292	43.5	0.3	32.9	21 ± 2	29 ± 2
94103A1	1	I23	-303	29	0.4	21.9	22 ± 1	30 ± 2
94103A2	1	I23	-303	28.4	0.4	10.3	27 ± 2	34 ± 3
94104B	1	H23	-308	27.7	0.4	29.4	23 ± 2	29 ± 2
	Mean Level 1			**37.6 ± 10.5**	**0.4 ± 0.1**	**28.1 ± 10.6**	**23 ± 3**	**31 ± 3**
95116A	3	F21	-430	41.6	0.4	4.3	29 ± 3	37 ± 3
95116B	3	F21	-430	42.7	0.2	3.5	30 ± 3	38 ± 4
95116C	3	F21	-430	37.3	0.3	6.7	34 ± 3	41 ± 3
95116D	3	F21	-430	44.3	0.4	8.6	35 ± 3	43 ± 4
94118A	3	F21	-431	59	< 0.1	27.7	22 ± 2	33 ± 3
94118B	3	F21	-431	60.7	0.4	11.9	21 ± 2	29 ± 2
95114A	3	F21	-440	9.3	< 0.1	2.8	38 ± 4	42 ± 4
	Mean Level 2			**42.1 ± 17.0**	**0.3 ± 0.1**	**9.4 ± 8.7**	**30 ± 6**	**38 ± 5**
95117A	4	H23	-524	10.6	< 0.1	3	48 ± 4	57 ± 5
95117B	4	H23	-524	10.6	< 0.1	4.7	46 ± 4	55 ± 4
95118A	4	K23	-529	59	< 0.1	27.7	24 ± 1	37 ± 2
95119B	4	J22	-537	27.4	< 0.1	11.6	32 ± 2	44 ± 4
95120AB	4	J22	-537	28.2	< 0.1	21.2	34 ± 2	47 ± 3
	Mean Level 4			**27.2 ± 19.8**	**< 0.1**	**13.7 ± 10.6**	**37 ± 10**	**48 ± 8**
95122AC	Below 4	J22	-559	25.2	< 0.1	13.7	37 ± 2	53 ± 3
95122B	Below 4	J22	-559	22.9	< 0.1	14.7	43 ± 3	58 ± 4
95122D	Below 4	J22	-559	25.8	< 0.1	15.8	42 ± 3	57 ± 4
95121A	Below 4	J22	-590	34.8	< 0.1	30.2	33 ± 2	52 ± 4
	Mean Level Below 4			**27.2 ± 5.2**	**< 0.1**	**18.6 ± 7.8**	**39 ± 5**	**55 ± 3**

The gamma plus cosmic dose (contributing from 36 to 58% of the total annual dose) was determined using a single in situ CaF_2 thermoluminescence dosimeter (TLD 103), which gave an annual dose rate of 539 μGy/a corrected for a burial depth that was assumed to be 1 meter greater than present day. (It is believed that some of the deposit has been stripped off in the recent past.) Neutron activation analysis (NAA) of sediment from the same hole (Gam Hole 10 in square H24, elev. -278 cm) yields a gamma plus cosmic dose rate of 691 μGy/a (micrograys/year), which is about 28% higher than the TLD value which was used in the age determinations. This is expected due to the absence of large lumps of lower radioactivity limestone not present in the NAA sample, but which were detected by the in situ measurement which detects the radioactivity over a sphere of about 30 cm radius (which contained limestone lumps). The in situ measurement value was used for the age calculations and makes up from 36 to 58% of the total dose received by these teeth.

Starosele: Ages in Level 3

Here, U-series ages were obtained on dentine and cementum from four different teeth. These MSUS ages are generally older than in Level 1, indicating that the teeth absorbed the uranium over a longer period of time. The cementum and dentine ages for individual teeth are

TABLE 13-2
Starosele, Mass Spectrometric U-Series Ages for Cementum (Cem) and Dentine (Den)

Sample	*Level*	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	*U [ppm]*	*U-series Age [ka]*	*% of corresponding ESR EU age*
94107 Den U	1	1.080 ± .007	0.078 ± .001	121 ± 1	31.3 ± 0.2	8.8 ± 0.1	44
94107II Den	1	1.083 ± .007	0.068 ± .001	418 ± 3	41.1 ± 0.2	7.6 ± 0.1	38
94103 Den 5	1	1.081 ± .006	0.044 ± .001	64 ± 1	21.5 ± 0.1	4.9 ± 0.1	18 to 22
94104 Den U	1	1.083 ± .004	0.040 ± .001	260 ± 1	31.7 ± 0.1	4.4 ± 0.1	19
94117 Den U	1	1.089 ± .007	0.046 ± .001	235 ± 7	36.5 ± 0.2	5.1 ± .1	not dated by ESR
95115 Den U	3	1.143 ± .009	0.071± .001	180 ± 1	27.6 ± 0.2	8.0 ± 0.1	not dated by ESR
95115 Cem U	3	1.131 ± .013	0.097 ± .001	199 ± 1	60.4 ± 0.7	11.0 ± 0.1	not dated by ESR
95116 Den 8	3	1.177 ± .005	0.147 ± .001	100 ± 1	7.8 ± 0.1	17.2 ± 0.2	49 to 59
95116 Cem U	3	1.124 ± .008	0.126 ± .001	316 ± 1	54.4 ± 0.4	14.6 ± 0.1	42 to 50
94118 Den U	3	1.137 ± .006	0.070 ± .001	17 ± 1	6.5 ± 0.1	7.8 ± 0.1	37
95114 Den	3	1.152 ± .005	0.194 ± .001	93 ± 1	2.7 ± 0.1	23.3 ± 0.1	61

quite similar, suggesting that this may also be true for Level 1. The cementum and dentine MSUS results range from 7.8 to 23.3 ka, which are 37 to 61% of the ESR EU ages. Based on Figure 13-1, this means that they fall into zones 3, 4, and 5, clustered near zone 4. Thus, the true burial age for this level will lie near the average LU age of 38 ± 5 ka. A mean coupled ESR/MSUS age of 41.9 ± 4.1 ka, based on the old style of beta dose modeling was also reported (Monigal et al. 1997) for this level. As is true for Level 1, these ages will also increase when the new coupled ROSY age calculations are made, but the increase will be greater in this level than in Level 1. This derives from the fact that the influence of the U on the ages is larger here because it has been absorbed over a longer period of time, rather than in Level 1 where it was absorbed closer to the end of the burial period (based on the younger MSUS ages). Thus, the statistically indistinguishable coupled ESR/MSUS ages reported earlier may spread apart enough to discriminate the relative time difference between the deposition of these two archeological assemblages. As in Level 1, this previously reported age must be considered a minimum age.

Starosele: Dosimetry in Level 3

For these teeth, the approximate ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is quite variable and ranges from 3/36/50/11 % to 1/62/30/7 % (EU model). The total annual doses ranged from 873 to 1471 μGy/a (EU model). The gamma plus cosmic dose (contributing from 37 to 61% of the total annual dose) was determined using a single in situ CaF_2 thermoluminescence dosimeter (TLD 100), which gave an annual dose rate of 534 μGy/a using a burial depth assumed to be 1 meter greater than the present day. Neutron activation analysis of sediment from the same hole (Gam Hole 5 in square I22, elev. -443 cm) yields a gamma plus cosmic dose rate of 423 μGy/a, which is about 21 % lower than the TLD value which was used in the age determinations. The hole was in a thin gravelly layer sandwiched by finer grained sediment. The gravel is less radioactive than the sediment, thus explaining the slightly lower value obtained by NAA. The in situ TLD measurement value was used for the age calculations.

Starosele: Ages in Level 4

Four teeth have been analyzed by ESR (Table 13-1) but no MSUS results are yet available in this level. Consequently, the EU and LU ages must be considered more preliminary than those reported above. The mean EU and LU ESR ages are 37 ± 10 and 48 ± 8 ka respectively. The LU model ages are stratigraphically consistent with the rather firmer age estimates for the overlying levels, however, it should be remembered that the true burial ages will most likely range from about 40 to values of greater than 48 ± 8 ka. Considering that the U concentrations are lower in this level than those in the overlying level (especially in the cementum), it suggests that the U-bearing waters that percolated through the site after deposition of the overlying levels were being depleted of U by the teeth and bones in those levels during the later part of the burial history of Level 4. It is not possible to judge what effect this might have on the uptake history in lieu of the MSUS ages. The minimum ages of ca. 41 ka for the overlying levels constrain the minimum age for this level to about 41 ka.

Starosele: Dosimetry in Level 4

For these teeth, the approximate ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is quite variable and ranges from 3/27/52/18 % to 1/70/22/7 % (EU model). The total annual doses ranged from 574 to 1329 μGy/a (EU model). No thermoluminescence dosimetry was done in Level 4. Due to the consistent yearly thefts of TLD's from other levels, it was decided to implant most of the dosimeters in the levels that had yielded the most teeth (many of these were also stolen), namely 1 and 3. The annual dose from gamma and cosmic radiation could have only been constructed from the sediment removed from two holes (Gam

Holes 7 in square I22, elev. -509 cm and Gam Hole 8 in square G21, elev. -519 cm). The relatively large distance from the dated teeth to Gam Hole 8 required that we use the sediment from Gam Hole 7 to reconstruct this dose, which was calculated to be 399 μGy/a, including a cosmic dose based on a burial depth assumed to be one meter greater than that of the present day burial level of the teeth. This gamma plus cosmic dose makes up from 29 to 70 % of the total dose received by teeth in this level.

Starosele: Ages in the "Below 4" Level

Two teeth were dated by ESR from this level, but no MSUS series ages are yet available. Consequently the EU and LU ages are preliminary, just as in Level 4. The mean EU and LU ages are 39 ± 5 and 55 ± 3 ka respectively. Again, these LU ages are stratigraphically consistent with the LU ages in the overlying level and the more refined ages for Levels 1 and 3. It is important, however, to remember that even the teeth from this level might only date to around 40-45 ka, or may date to >55 ± 3 ka. In this level, and in Level 4, the ages have been calculated assuming that the U in the enamel is real zero, as was observed in Levels 2 and 3. The last stage of the normal procedure of testing for U in the enamel is underway.

Starosele: Dosimetry in the "Below 4" Level

For these teeth, the approximate ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is quite variable and ranges from 3/52/31/14 % to 1/71/19/9 % (EU model). The total annual doses ranged from 655 to 1090 μGy/a (EU model). The single TLD implanted here gave uninterpretable results, so we used NAA of sediment to reconstruct the gamma plus cosmic dose rate. The sediment came from Gam Hole 1 (Square J22, elev. -598 cm) and yielded a dose rate of 298 μGy/a based on a burial depth assumed to be one meter greater than that of the present day burial level of these teeth. This gamma plus cosmic dose makes up from 28 to 45% of the total dose received by teeth in this level.

Discussion of Starosele Results

Effects of Moisture on Calculated Ages

One of the most criticized aspects of ESR dating of tooth enamel is the concern over the effect of fluctuating moisture content on the assumption of constant gamma and beta dose rate from the external environment of the tooth. This is much more important in sites where there has been little U-uptake into the teeth because the external dose then dominates over the internal doses. At Starosele, the relatively large U-uptake minimizes this effect, but to show how small the effect is, the ages were also calculated with a different moisture content in order to demonstrate the possible effect posed by inevitable moisture content fluctuations over time. The average moisture content measured for all samples taken from Levels 1 and 3 was 12.9 ± 2.8 %, which was used for ages reported in Table 13-1. For Levels 4 and "Below 4," a similar value of 10 ± 10% was used. For all the levels, the ages were recalculated using a moisture content value of 20 ± 10%. The results are reported in Table 13-3.

The increase in mean age with increased moisture content is only 1-2 ka in all cases, and the same reduction would occur if the moisture content was assumed to have been near zero for most of the burial history. These variations lie well within the standard deviation of the mean ages quoted for each level.

Comparison with other Published Ages for Starosele

Level 1. AMS ^{14}C ages of 41.2 ± 1.8 and 42.5 ± 3.6 ka BP (Hedges et al. 1996; Marks et al. 1997) were obtained on bone collagen from the same vicinity as our teeth, although another bone sample from the collections of Formozov's excavations in the 1950s yielded an age of 35.5 ± 1.1 ka. The former ages are consistent with the coupled ESR/MSUS age of 41.2 ± 3.6

TABLE 13-3
Starosele, Effects of Moisture Content on ESR ages

Level	*Mean EU ESR ESR Age (ka)*	*Mean EU ESR ESR Age (ka)*	*Mean LU ESR ESR Age (ka)*	*Mean LU ESR ESR Age (ka)*
	12.9% Moisture	20% Moisture	12.9% Moisture	20% Moisture
1	23 ± 3	24 ± 3	31 ± 3	32 ± 4
3	30 ± 6	31 ± 7	38 ± 5	39 ± 6
	10% Moisture	20% Moisture	10% moisture	20% Moisture
4	37 ± 10	38 ± 11	48 ± 8	50 ± 9
Below 4	39 ± 5	40 ± 5	55 ± 3	57 ± 3

ka based on old-style beta dose calculations (Monigal et al. 1997) which is a minimum age as mentioned above. The standard EU and LU model ages in Tables 13-1 and 13-3 have clearly been shown to be underestimates of the true age through use of U-series dating. Earlier reported preliminary mean ESR LU ROSY ages of 35.6 ± 3.9 (Marks et al. 1997) were based only on gamma dose reconstructions using sediments, but are statistically indistinguishable from the mean LU ROSY ages reported herein. The best ESR age estimate for this level at the present time is >41.2 ± 3.6 ka, which is entirely consistent with the expectation that ^{14}C ages of this time range should underestimate the true age by only a few thousand years (Mazaud et al. 1991) if they have not been contaminated by younger carbon.

Level 3. A single U-series age of 46.0 ± 2.5 ka on tooth enamel obtained by C. McKinney was reported by Marks et al. (1997). This age is based on a closed system assumption (early uptake) for the alpha-spectrometric U-series dating. This age is consistent with the previously reported coupled ESR/MSUS age of 41.9 ± 4.1 ka, which has to be considered a minimum age because of the beta dose calculation method, as discussed above. Thus the early uptake assumption for the enamel is very likely correct, based on verification through the coupled ESR/MSUS approach. Interestingly, this approach also shows that the correct uptake model for the dentine is near linear (see section above), as would be expected based on its structural and chemical similarity to bone, which is known to absorb uranium in a gradual fashion (linear uptake is a special case of gradual uptake). The early uptake situation for enamel has virtually no effect on the coupled ESR/MSUS ages because there is so little uranium dose within the enamel. The previously reported ESR ROSY LU age of 42.0 ± 4.7 ka (Marks et al. 1997) was a preliminary age based on gamma doses reconstructed from sediment, and is statistically indistinguishable from the ESR ROSY LU value of 38 ± 5 reported herein. In contrast to Level 1, the LU model ages have been shown to be approximately correct. The spread between the ages of Levels 1 and 3 can only be determined once the coupled ESR ROSY/MSUS ages are available.

Levels 4 and Below 4. C. McKinney reported an alpha-spectrometric age of 104.0 ± 8.5 ka using the closed system assumption of early uptake for the U-series dating. Until MSUS dating of our teeth from these levels is completed, it is not possible to properly compare the burial age estimate by ESR with this date. Nonetheless, the existing model ages of 37 ± 10 (EU) and 48 ± 11 (LU) are certainly much younger than this date, and the mean recent uptake (RU) age for this level is only 77 ± 6 ka, which provides an absolute maximum ESR age regardless of the MSUS ages obtained on these teeth (the RU model assumes that all of the U was absorbed in the last day of the burial period). Thus, this very old age will remain inconsistent with the ESR ages for this level, and there is no obvious explanation for this observation.

There are no other existing published ages for the "Below 4" level. The EU and LU model ages of 39 ± 5 and 55 ± 3 are older than those of the overlying levels, but the true burial age cannot be estimated until the MSUS ages are available.

Summary of Starosele Results

At this stage of the dating program, ESR dating results refined using MSUS dating have shown that Levels 1 and 3 are older than about 40 ka, consistent with the results of AMS ^{14}C and U-series dating done by independent laboratories. Through this intercomparison, these results for the first time prove beyond the shadow of doubt that the coupled ESR/MSUS dating approach is accurate even when relatively large amounts of U have been absorbed. Results for the lower Levels 4 and "Below 4" give age estimates which cannot be properly interpreted until the MSUS results are available, but the single U-series age from an independent laboratory on enamel for Level 4 is clearly older than any possible ESR-based age estimates. Based strictly upon the ESR and MSUS dating evidence, the age difference among these four levels may be as small as 1 ka, but may also be somewhat larger than about 5 ka.

Although it is clear that AMS ^{14}C dating of the in situ bone samples would have provided accurate age estimates for Level 1 in the absence of ESR and MSUS dating, only limited confidence could have been ascribed to the AMS ^{14}C dates because they extend beyond the practical range of this method (generally considered to be about 40 ka). Moreover, it would have been difficult to distinguish between the younger AMS ^{14}C age for the Formozov collection Level 1 sample and those ages from in situ material recovered from the recent excavations of Level 1 by Marks and collaborators, which now appear to be more correct. In Level 3, AMS ^{14}C dating was not successful because no bone collagen could be extracted. Thus, here ESR dating was essential and proved useful for confirmation of the single U-series date on enamel from another laboratory. In the lower levels, the ESR results stand in disagreement with the single U-series date on enamel from another laboratory for Level 4, and currently provide the only age estimates for the "Below 4" level.

KABAZI II RESULTS

ESR dating results (Table 13-4) were obtained on teeth from five archeological levels designated in descending stratigraphic order as II/1A, II/7B, II/8, III/2, and III/3. MSUS results (Table 13-5) for a limited number of dentine samples were obtained from Levels II/1A, II/7B, and III/3). Even larger amounts of U were taken up in these teeth than at Starosele, with the U concentration ranging from 47 to 88 ppm in the cementum, and 48 to 117 ppm in the dentine of the uppermost levels in the site. As was seen at Starosele, there is a distinct decrease in U in the teeth with deeper burial. For example, the average U in cementum and dentine were 14 and 19 ppm respectively for Level III/2. The dentine proved to be the dominant source of U-based dose to the enamel for almost every tooth in the site, and thus its U-series age is the most important to the interpretation of the EU and LU model ages. All of the teeth were *Equus hydruntinus* molars.

Kabazi II: Ages in Level II/1A

The mean EU and LU ages were 21 ± 5 and 32 ± 6 ka, respectively. Tooth 94207 had an MSUS dentine age of 15.0 ± 0.1 ka which was 58 and 71% of the two EU ESR ages of this tooth (subsamples A and B). Assuming that the cementum MSUS ages do not prove to be vastly different from the dentine result, this places the sample in the older range of ESR age zone 3 (sublinear uptake), suggesting that the true burial age is somewhat younger than the LU ESR age of 32 ± 6 ka. The large difference of 9 ka between the two subsamples of this tooth may be related to loss of some of the cementum in subsample A, which was quite pitted at the

TABLE 13-4
Kabazi II, ROSY ESR Ages on Enamel and Analytical Data

Sample	*Level*	*Square*	*Elev. (cm below datum)*	*Cementum U (ppm)*	*Enamel U (ppm)*	*Dentine U (ppm)*	*Early Uptake ESR Age (ka)*	*Linear Uptake ESR Age (ka)*
94206A	II/1A	Д9	-265	82.9	0.6	116.6	17 ± 1	28 ± 2
94207A	II/1A	Д9	-270	48	0.8	58.9	26 ± 2	38 ± 3
94207B	II/1A	Д9	-270	46.7	0.7	47.8	21 ± 2	29 ± 2
	Mean Level II/1A			**59.2 ± 20.5**	**0.7 ± 0.1**	**74.4 ± 36.9**	**21 ± 5**	**32 ± 6**
94212A	II/7B	М5	-415	64.5	0.6	53.8	22 ± 2	34 ± 2
94208A	II/7B	М4	-424	88.1	0.3	83.9	18 ± 2	29 ± 3
	Mean Level II/7B			**76.3 ± 16.7**	**0.5 ± 0.2**	**68.9 ± 21.3**	**20 ± 3**	**32 ± 2**
95100A	II/8	Н5	-465	36.2	0.9	26.6	27 ± 2	39 ± 3
95105A	III/2	Г8	-671	20.9	< 0.1	25.5	48 ± 3	62 ± 5
95104A	III/2	Г8	-680	7.4	0.1	12.4	53 ± 5	60 ± 6
	Mean Level III/2			**14.2 ± 9.5**	**0.1**	**19.0 ± 9.3**	**51 ± 3**	**61 ± 1**
95101A	III/3	Г8	-698	17.1	0.3	26	53 ± 4	69 ± 5

time of recovery. The state of preservation of the teeth in Kabazi II was not as good as the teeth from Starosele, and we suspect that some of the cementum layer may have disintegrated during the burial period. But the age spread may also be an artifact related to the use of the linear uptake assumption for both cementum and dentine. In any case, the true ages will depend to some extent upon the uptake in cementum, too. The average EU and LU ages in Table 13-4 should not be regarded as accurate age estimates, although it is likely that the LU ages are more correct based on the MSUS dating of the single tooth studied thus far. The coupled ROSY ESR/MSUS ages will provide the best age estimate for this level.

TABLE 13-5
Kabazi II, Mass Spectrometric U-Series Ages for Dentine (Den)

Sample	*Level*	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	*U [ppm]*	*U-series Age [ka]*	*% of ESR EU age*
94207 Den	II/1A	1.045 ± .011	0.129 ± .001	625 ± 4	60.7 ± 0.6	15.0 ± 0.1	58 to 71
94205 Den	II/7B	1.112 ± .011	0.128 ± .001	3582 ± 24	45.7 ± 0.4	14.9 ± 0.1	75
94209 Den	II/7B	1.039 ± .014	0.131 ± .003	337 ± 7	58.6 ± 0.7	15.3 ± 0.3	77
95101 Den	III/3	1.119 ± .011	0.463 ± .002	2575 ± 7	24.1 ± 0.2	66.7 ± 0.5	126

Kabazi II: Dosimetry in Level II/1A

For these teeth, the approximate ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is quite variable and ranges from 9/63/20/8 % to 3/84/9/4 % (EU model). The total annual doses ranged from 1258 to 2770 μGy/a (EU Model). A CaF_2 TLD (105) located in the same level near the two dated samples gave a gamma plus cosmic dose rate of 361 μGy/a, which was much lower than the values obtained by sediment analyses taken from the same hole, located directly within the thin occupation horizon (Gam Hole 4, square Д9, elev. -270 cm). The sediment gave a value of 897 μGy/a (including a calculated cosmic dose based on depth). This large discrepancy may be due in part to the high levels of U, Th, and K which were also found in the sediment collected with the teeth and used for the beta sediment dosimetry. The TLD sensed the gamma dose from a sphere of 30 cm radius which contained some larger limestone elements of lower radioactivity, but it is clear that the high radioactivity in the closest areas to the teeth should be considered as part of the influence of the dose rate. This high radioactivity was also found in another sediment from the same level (Gam Hole 2, at the corner of square Γ8/Γ9, elev. -250), which yielded a dose rate of 620 uGy/a. The average of the gamma plus cosmic dose rate of the two sediments from the holes (based on a moisture content value of 10%) and that found using the TLD was 626 μGy, and this average value from the three measurements was used for gamma plus cosmic dose in the age calculations.

Kabazi II: Ages in Level II/7B

The mean EU and LU ages are 20 ± 3 and 32 ± 3 ka, respectively. Thus far, two teeth from this level, which could not be dated by ESR because of crumbling weak enamel, have been dated by MSUS. They gave dentine ages of 14.9 ± 0.1 and 15.3 ± 0.3 ka, which are 75 and 77% respectively of the mean EU ESR age for this level. Normally, the comparison is made with the exact same tooth, but in this case, this is the best available comparison. However, the cementum is a rather more significant contributor of dose in this case, so the MSUS ages on cementum are quite important to the interpretation. These results are similar to those of Level II/1A and suggest that the probable burial age of this level would lie somewhere between the EU and LU ages. These ages, however, may be slightly underestimated due to lack of thermoluminescence dosimetry for this level (see below).

Kabazi II: Dosimetry in Level II/7B

For these teeth, the ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses ranges from 1/67/21/7 % to 2/75/17/6 % (EU model). The total annual doses to the tooth enamel ranged from 1908 to 2369 μGy/a (EU model). The two TLD's implanted in this level were stolen, thus the gamma plus cosmic dose had to be reconstructed from the sediments recovered from these positions (Gam Hole 5, square M3, elev. -428 and Gam Hole 6, square H3, elev. -412). These sediments yielded gamma plus cosmic dose rates of 471 and 630 μGy/a. The average value of 551 μGy/a was used for the gamma plus cosmic dose in the calculations, which constituted between 23 and 28 % of the total dose to the teeth. This level did show significant amounts of limestone rocks which may have caused the teeth to receive somewhat lower dose rates than those represented by the sediments. This would make the apparent ages too young.

Kabazi II: Ages in Level II/8

The mean EU and LU ages of a single tooth studied from this level are 27 ± 2 and 39 ± 3 ka. Although it is only a single tooth, its ages are older than any EU or LU ages in the overlying levels. Should the uptake model for this level be proven similar to that of the overlying levels, its age would lie between the EU and LU ages.

Kabazi II: Dosimetry in Level II/8

No TLD's were emplaced into this level, which was about 40 cm deeper than II/7B. The same sediments that were used in Level II/7B were used to reconstruct the gamma plus cosmic dose rate to this tooth. For this tooth, the ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is 9/53/28/10% (EU model). The total annual dose to this tooth was 1459 μGy/a (EU model).

Kabazi II: Levels III/2 and III/3

These levels are considerably deeper than the overlying levels, separated by a considerable thickness (almost 2 m) of sterile material above III/2. Hence it was expected that the ages might be considerably older than those for the overlying levels, which is probably the case based on the ESR and MSUS results. Taking the lowest of the two levels first, the MSUS age for dentine of tooth 95101 is 66.7 ± 0.5 ka, which is 126% of the EU ESR age. This suggests U-loss from the dentine which indicates that the true burial age lies within ESR Age zone 1 (fig. 13-1), which would make it younger (by an unknown amount) than the EU ESR age of 53 ± 4 ka. Teeth exhibiting U-loss are difficult to date because a reliable coupled ESR/MSUS age will not be calculable.

The teeth in overlying Level III/2 have not yet been dated by MSUS, and consequently their true burial age cannot yet be estimated. Although these EU and LU model ages are apparently older than those in the overlying levels, they should not yet be interpreted as providing confirmed ages for these levels. Nonetheless, the EU and LU ages also closely match the single age in Level III/3. Hopefully these teeth will yield MSUS ages that are younger than corresponding EU ESR ages, which will make ESR/MSUS ages calculable.

Kabazi II: Dosimetry in Levels III/2 and III/3

For the teeth in Level III/2, the ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses ranges from 3/26/66/5 % to 0/42/54/4 % (total annual dose range: 825 to 1023 μGy/a), while the tooth in Level III/3 had a ratio of 6/42/48/4 (total annual dose: 1133 μGy/a) (EU model). In the lower of the two levels (Level III/3) a TLD (107) was placed in Gam Hole 3 (square И9, elev. -700 cm). The gamma plus cosmic dose rate obtained by TLD was 599 μGy/a, which was very similar to the dose rate of 539 μGy/a based on NAA of the sediment taken from this hole and a cosmic dose rate based on an overburden of 8 meters. The age was calculated using the TLD value. In the overlying Level III/2, a reconstructed gamma dose based on sediment alone from a single hole (Gam 1, square K9, elev. -670 cm) was only 317 μGy/a, while the sediment collected with the teeth in both levels (used for the beta dosimetry) gave values closer to the TLD value from the nearby dosimeter in Level III/3. The best estimate of the gamma plus cosmic dose rate to the teeth in Level III/2 is the TLD from Level III/3, which was used for the age calculations in that level.

Discussion of Kabazi II Results

Effects of Moisture Content on ESR Ages

A moisture content of 10 ± 10% was used for the age calculations, which was assumed to be true for the whole burial period. If we assume that the moisture content was only 1% over the whole history of burial, the measured gamma doses would increase slightly, while the relative change in the sediment beta doses would have almost no effect on the ages because the cementum shields the enamel from nearly all of the sediment beta dose in almost every tooth. The slightly increased gamma doses would reduce the calculated ESR ages by 2-5% in the site, with the exception of a single tooth (95104A) where the low U in the cementum and dentine would let the age decrease by 8%.

Comparison with other Published Ages for Kabazi II

A single AMS ^{14}C age of 31,550 ± 600 years BP was reported (Hedges et al. 1996) for Level II/1, which lies in close contact with the overlying Level II/1A containing the dated teeth. This is consistent with the ROSY ESR age of tooth 94207 (see above) of < 34 ka in this level. Chabai (1996b) reported conventional alpha-spectrometric U-series dates by C. McKinney (McKinney and Rink 1996) on tooth enamel from Level II/1A of 30 ± 3 ka and from Level II/1 of 32 ± 6 ka which are based on the closed system assumption for U-series dating. These are also in good agreement with the burial age based on MSUS and ESR dating, which appear then to substantiate the closed system assumption for the teeth dated by that method in this level. In the same publication, Chabai reported our preliminary mean ROSY ESR LU age of 31.7 ± 2.2 for Level II/1A, which is now updated by the results in this paper. Hedges et al. (1996) also reported ^{14}C ages on bone collagen of 35,100 ± 850, 32,200 ± 900, and 33,400 ± 1000 BP for Levels II/2, II/4, and II/5 respectively, which is the sequence just below Level II/1, and an age of 34,940 ± 1020 BP for the cultural layer I/3 which overlies Level II/1A. Although the AMS ^{14}C dates are clearly out of stratigraphic order, there is general agreement among all the methods that the age of these levels in the site (II/1 down to II/5) lies in the range of 30-35 ka.

There are no comparative dating results published for Level II/7a.

Chabai (1996b) reported our (McKinney and Rink 1996) preliminary ROSY LU ESR date of 51.6 ± 4.4 ka (LU) for Level II/8, which is now updated by the new ROSY ESR ages of 27 ± 2 (EU) and 39 ± 3 ka for this same tooth. This significantly younger age results from the problems encountered with the original teeth used in reporting the preliminary age for Level II/8, which had preliminarily included mixtures of different parts of the enamel of a single tooth, a method which has been rejected as inviable through the new work with the beta attenuation studies in tooth enamel. (The Equus enamel from Kabazi II splintered apart very easily, which led us to make this approach in this instance.) The age reported in this paper utilizes a new tooth prepared in the standard way. This age is preliminary since no MSUS dating has been done to refine the true burial age. Chabai (1996b) also reported a conventional U-series alpha spectrometric date of 47.7 ± 7.5 ka by C. McKinney (McKinney and Rink 1996) on enamel from this level, based on the closed system assumption for U-series dating. This age is older than but statistically indistinguishable from our new ROSY LU age of 39 ± 3 ka for this level, but both of these ages are based on assumptions which have not yet been verified.

Chabai (1996b) reported our (McKinney and Rink 1996) preliminary ROSY ESR LU ages of 84.0 ± 1.6 and 82.0 ± 6.4 ka for two teeth from Level III/2, which are updated in this paper by new results for the same two teeth. The new mean ROSY ESR ages of this level (based on the same two teeth) are 51 ± 3 EU and 61 ± 1 LU; thus, the new LU ages are about 20 ka younger than the preliminary ages. This results from refined dosimetry (using a TLD) for this level, whereas the preliminary dates were based on gamma plus cosmic dose reconstructed from nearby sediments. No MSUS dates are available to determine whether the EU or LU model is more correct, but the data for the underlying level (see below) is relevant. Chabai (1996b) also reported a much older conventional alpha-spectrometric U-series age by C. McKinney on enamel from this level of 117 ± 13 ka, which is based on the closed system assumption for U-series dating. This age is much older than any of the ESR ages, but the ESR results cannot be properly compared against this age until MSUS ages are available. This result, however, seems too old in light of the relevant lithological and pollen data (see below).

There are no comparative dating results published for Level III/3, but the MSUS results and ESR results in this level constrain its age to < 53 ± 4 ka. The overlying level must predate this time and thus the mean LU ROSY ESR age in that Level (III/2) of 61 ± 1 ka is too old. The EU ages in that level agree closely with the EU ages in this level, but see the discussion below regarding ambiguities in the ages of these levels.

The reported ages in Levels III/2 and III/3 are based on the best dosimetry available (TLD), but they are somewhat ambiguous in that use of sediment for gamma dosimetry would place them into the 70 (EU), 80 (LU) ka range. In that scenario, the MSUS ages of 66 ka for the dentine of the tooth in Level III/3 would lead to the interpretation that an age of 70 ka is the correct age of burial (see fig. 13-1). It is not clear at the present time whether the true age is < 53 ± 4 (as reported above) or about 70 ± 5 ka. More MSUS dating of the enamel from Level III/2 may help in this regard. The lithology and the pollen data suggest that stratigraphic layer 11, which contains Levels III/2 and III/3, was deposited during persistent cold winters after a warmer wetter period (Chabai 1996b). If we accept that the Crimean temperatures fluctuated directly according to the global climate reflected by the marine oxygen-isotope record, this immediately suggests that the true burial age of the level might lie within the global cold period of oxygen isotope stage 4, but it does not rule out deposition during a colder part of stage 3. This age range of about 75 to 45 ka is consistent with the possible range of ESR ages we have just described.

Summary of Kabazi II Results

There is good agreement between the dating methods in Level II/1A, although the ESR result remains poorly constrained until the ROSY ESR/MSUS coupled ages can be calculated. The lack of thermoluminescence dosimetry in Level II/7B reduces our confidence in the ESR ages for this level, because the lack of dosimetry may bias the ages in the direction of being too young. In Level III/2 and Level III/3, the large discrepancy between independent U-series dating of enamel and our combined efforts with ESR and MSUS dating of dentine is problematic. There is also ambiguity associated with the wide range of results possible in Levels III/2 and III/3 based on choices about gamma dosimetry. Further MSUS dating and gamma dosimetry may possibly resolve these issues.

KABAZI V RESULTS

Dating results (Tables 13-6 and 13-7) were obtained using teeth from two different levels in the site: III/1 and III/1A. The uranium uptake was not as severe as at Kabazi II, but was similar to that observed at Starosele. U concentrations in cementum and dentine ranged from 10 to 50 ppm, while the enamel contained the same low levels (<0.4 ppm) seen in most of the teeth from the other two sites (except for a single saiga tooth in Level III/1A with U = 1.19 ppm in the enamel). All of the other teeth were *Equus hydruntinus* molars.

TABLE 13-6
Kabazi V, ROSY ESR Ages on Enamel and Analytical Data

Enamel Sample	*Level*	*Square*	*Elev.* †	*Cementum U (ppm)*	*Enamel U (ppm)*	*Dentine U (ppm)*	*ESR EU Age (ka)*	*ESR LU Age (ka)*
94301 IIA	III/1	Д9	-539	49.6	0.3	29.5	23 ± 1	32 ± 2
94303 IIA	III/1	39	-571	18.5	0.1	21.4	24 ± 2	31 ± 2
94303 IIIA	III/1	39	-571	33.7	< 0.1	10.2	26 ± 2	30 ± 3
Mean Level III/1				**33.9 ± 15.6**	**0.2 ± 0.1**	**20.4 ± 9.7**	**24 ± 2**	**31 ± 1**
94304 IIIA	III/1a	B9	-538	N/A	1.19	38.0	41 ± 2	55 ± 4

N/A: not applicable (no cementum layer present on the Saiga tooth), † cm below datum.

Kabazi V: Ages in Level III/1

In this level, three teeth were dated by ESR, with supporting MSUS data on dentine and cementum from one of those teeth. The mean ESR ages are 24 ± 2 (EU) and 31 ± 3 (LU) ka. The tooth dated by MSUS gave a cementum age of 22.1 ± 0.1 ka and a dentine age of 10.8 ± 0.1 ka, which were 96 to 47% of the EU ESR age of 23 ± 1 ka for that tooth. Figure 13-1 shows that this places the enamel into the entire range of ESR age zone 3, since the cementum age lies just over the boundary of zone 2, while the dentine is just over the boundary into zone 4. The relative dose contributions are about 50/50 because the cementum is about 1/2 the thickness of the dentine, but has twice as much U in it. Thus the true age should be roughly halfway between the EU and LU ages, which is about 28 ± 2 ka. This will approximately be the ROSY ESR/MSUS coupled age. The other teeth in this level show similar ESR ages, and thus, they might also have the same uptake behavior as the well-studied tooth.

TABLE 13-7
Kabazi V, Mass Spectrometric U-Series Ages for Cementum (Cem), Dentine (Den), and Enamel (Enam)

Sample	*Level*	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	*U [ppm]*	*Age [ka]*	*% of ESR EU age*
94301AII Cem	III/1	1.029 ± 0.731	0.184 ± .001	736 ± 2	48.8 ± 0.3	22.1 ± 0.1	96
94301AII Den	III/1	1.015 ± .005	0.095 ± .001	424 ± 2	26.6 ± 0.1	10.8 ± 0.1	47
94304III Enam	III/1A	1.069 ± .004	0.325 ± .026	220 ± 18	1.71 ± 0.1	42.6 ± 4.2	104
94304III Den	III/1A	1.063 ± .005	0.421 ± .002	708 ± 2	31.4 ± 0.1	59.1 ± 0.4	144

Kabazi V: Dosimetry in Level III/1

For the teeth in Level III/1, the ratio of time-averaged alpha/ beta/ gamma/ cosmic annual doses ranges from 0/34/53/13 % to 3/49/39/9 % (EU model). The total dose to teeth ranged from 1004 to 1366 μGy/a (EU model). One TLD was implanted within Level III/1 in Gam Hole 2 (square 8Д, elev. -584). It was within 90 cm of tooth 94303, while sediment was extracted both from this hole and another hole in this level (Gam Hole 1, square 83, elev. -544 cm), which was 60 cm away from tooth 94301. The CaF_2 TLD (97) yielded a gamma plus cosmic dose of 663 μGy/a, while the sediments yielded doses based on NAA and moisture contents of 1% (as measured) of 598 μGy/a and 687 μGy/a. The close agreement increases our confidence in the accuracy of the ESR age estimates, and suggests the sediments in the site are very homogeneous with respect to gamma radiation dose. The TLD value was used for the age calculations.

Kabazi V: Ages in Level III/1A

This level is stratigraphically very close to the overlying Level III/1 and thus would be expected to have a similar age. Only a single tooth from this level was dated—a saiga tooth—that did not have a thick layer of outer cementum like most of the Equus teeth. Interestingly, it had the highest U content of all of the teeth, indicating that exposed enamel area is important to the earlier stages of U uptake into teeth. The same tooth was studied using MSUS, which gave an enamel age of 42.6 ± 4.2 ka and a dentine age of 59.1 ± 0.4 ka which are 104% and 144% respectively of the ESR EU age of 41 ± 2 ka. The enamel age is indicative of ESR age zone 2, suggesting early uptake in the enamel. If we were to use the closed system model for U-series dating, as often invoked by C. McKinney, the age of the burial would be considered 41.2 ka, but this is at least 9 ka older than the layer just above and in contact with Level III/1A. Hence, it would appear that the closed system assumption for enamel might not hold in this case. The dentine MSUS ages suggest that there has been U-loss (ESR age zone 1) from the dentine. From Figure 13-1, this suggests that the true burial age would be younger than the EU ESR age (by an unknown amount). This would require that the U-concentration in the dentine of the tooth had been higher than the present-day value of 38 ppm, and that the calculated ESR EU age might then be overestimated (by an unknown amount) due to the unaccounted for additional dose that it had imparted before it was lost. An extreme interpretation would have been that very recent uptake followed by some loss had occurred, which would lead to an interpretation that the ESR EU age would be too young. The best estimate of age is <41-43 ka, based on all of the available evidence, including stratigraphic evidence that suggests no depositional or erosional hiatus between Levels III/1 and III/1A. The ESR LU age can be confidently ruled out as the correct burial age. Because of the U-loss observed here, ROSY ESR/MSUS coupled ages cannot be calculated because the possible modes of U-uptake in the calculation are only allowed to involve U-uptake, but not U-loss.

Kabazi V: Dosimetry in Level III/1A

For this tooth, the ratio of time-averaged alpha/ beta/ gamma/cosmic annual doses is 14/42/36/8 % (EU model). The total dose rate was 1492 μGy/a. No TLD was buried in this level, but a sediment sample just in contact with the tooth was collected for beta dosimetry. This sample had extremely high U content upon analysis in the lab, indicating that breakdown of the tooth during shipment had contaminated the sediment with the high U of the cementum and dentine (the tooth was not well preserved and easily broke apart during preparation for ESR dating). We therefore reconstructed the beta dose using the sediment from Level III/1 and used the TLD value from that level to reconstruct the gamma plus cosmic dose. In the case of this rather homogeneous site, this is not a seriously problematic assumption for reconstruction of the doses. An additional sample of sediment collected from a zone within 10 cm of the tooth is under analysis now to confirm this.

Discussion of Kabazi V results

Effects of Moisture on ESR ages

All of the age calculations were based on a moisture content of 1%, as measured at the site in summer. If we assume that the average moisture content over the entire burial was much higher, then the mean EU ESR ages in Level III/1 increase to 26 ± 2 ka and the mean LU ages increase to 33 ± 2 ka. The age of the single tooth in Level III/1A increases to 43 ± 3 (EU) and 58 ± 4 (LU) ka. These changes are 4 to 6% of the age and lead to very slight increases in the possible ages for the levels discussed above: about 29 ka for Level III/1 and <43 ka for Level III/1A.

There are no published ages for Kabazi V for intercomparison with these ages.

Summary of Kabazi V Results

The best age estimates are about 26 to 30 ka for Level III/1 and <41 ka for Level III/1A. We have strong confidence in the dates from Level III/1 because of the homogeneity of the gamma dose in the sediment and because of the MSUS results. Although the U-loss problem does not allow us to make a confident assessment of the true absolute age of Level III/1A, it appears that it cannot be more than 10-14 ka older than the overlying level, and stratigraphic evidence suggests that this difference is probably less than 9 ka.

SUMMARY OF RESULTS FOR STAROSELE, KABAZI II, AND KABAZI V

Figure 13-2 shows the results of the dating program thus far. The entire site of Starosele is clearly older than Level III/1 at Kabazi V and Level II/1A at Kabazi II. Level III/1 at Kabazi V appears to be slightly younger than Level II/1A at Kabazi II, although they might overlap. The middle range of levels at Kabazi II (II/7B and II/8) may or may not overlap with the lower Level at Kabazi V, and it is difficult to say if these Kabazi II levels post-date the Starosele deposit, or are contemporaneous with it. It is not possible to say if the Level 4 or "Below 4" deposits at Starosele are much older than the rest of the deposit, and hence it is not yet possible to say if they pre-date any of the Kabazi II deposits. Levels III/2 and III/3 at Kabazi II may be older than, but are possibly contemporaneous with, some of the Starosele deposit. Given the data in its present form, we can conclude that there is a large degree of overlap in time among the various Paleolithic industries in the area. We can also conclude that all of the occupational levels which have been studied could have been deposited within a time span as short as 20,000 years (about 30-50 ka) or as long as 40 ka (about 30-70 ka).

At the outset of this program, ESR dating in the time range of 25-40 ka remained completely untested. Through this study, which allowed a number of comparisons with AMS ^{14}C dating, it has been made clear that even under the conditions of significant U-uptake, the combination of ESR and mass spectrometric U-series dating can provide reliable, accurate results. Although there are clearly situations where this approach fails to give results with a sufficiently small uncertainty that render them better than an uncalibrated ^{14}C age, it has become clear that this approach is particularly useful in the time range of 35-45 ka, where ^{14}C results are susceptible to contamination and where no bone collagen or charcoal can be found.

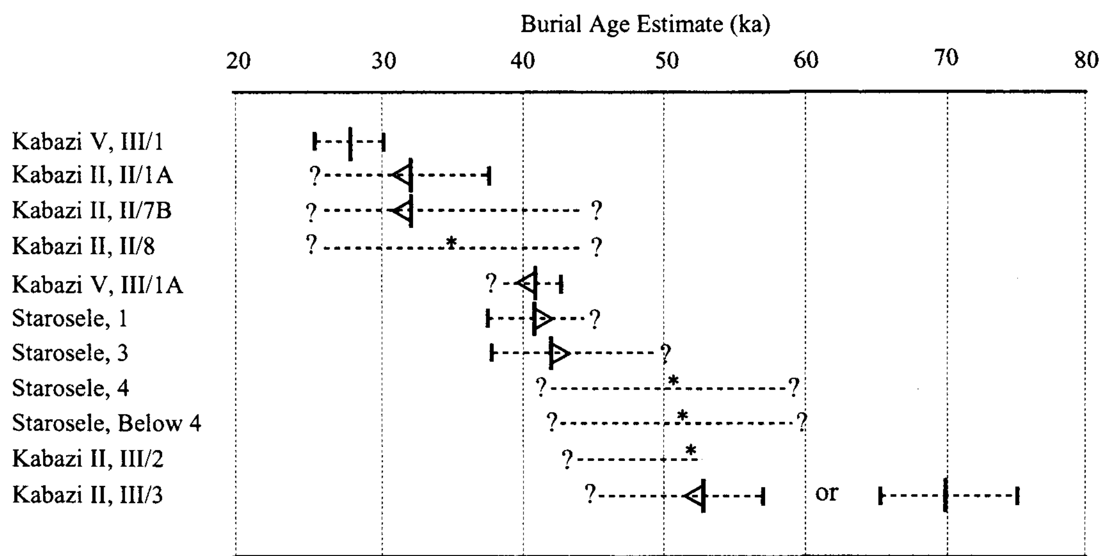

Fig. 13-2—Best estimates of burial age based on ESR and MSUS dating arranged in approximate chronological order. Large solid vertical lines are benchmark ESR ages constrained by MSUS dating (except for Starosele 1 and 3, where this line is the benchmark minimum coupled ESR/MSUS age based on old beta attenuation calculations). The attached arrow on the large vertical lines indicates the direction of the true burial age from the benchmark value. Smaller solid vertical lines represent the uncertainty range of the benchmark ESR age. The question marks on the same side as the arrow indicate that the distance from the benchmark is not yet known but should be better constrained later by coupled ROSY ESR/MSUS ages. The asterisks indicate that the age range (represented by the dotted horizontal line) is essentially constrained by the age in a level above or below it in the same site, because no MSUS data is available for that level. When no arrow is present, the age is the best estimate based on combined ESR and MSUS data that does not have a directional dimension. The dotted line and question mark on the older age side of the Kabazi II, Level II/7B benchmark is related to ambiguity regarding the lack of in situ dosimetry.