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Thermoluminescence dating of heated silex – Method and application

Abstract

The method of Thermoluminescence (TL) dating of heated siliceous rocks from archaeological sites is briefly described and a summary of the requirements for obtaining successful age estimates for prehistoric occupations is given. A focus is set on the archaeologists' need to understand the variables used in TL dating. This paper should enable archaeologists to assess the potential of the method as well as of their site and the samples for dating. To demonstrate the power of TL-dating an example is given from the Upper Palaeolithic stratigraphy of the Geißenklösterle Cave, Baden-Württemberg, Germany. TL-dating results on heated silex give a very early age for the arrival of modern humans, who are believed to be the bearers of the first Upper Palaeolithic culture in Central Europe.

Keywords: *Thermoluminescence Dating, heated silex, Early Upper Palaeolithic, Geißenklösterle, Radiocarbon Dating.*

Introduction

Establishing ages of sites and chronologies in archaeological research is essential. The basis of age estimates are often typological and geostratigraphic correlations, which, by their nature, are sometimes rather imprecise. Thus chronometric dating methods are necessary.

The most commonly used method is ^{14}C-dating of organic material, but it has a lower limit of approximately 40-60,000 years. As it is the archaeological event, that is of interest, the association of bone and charcoal samples with such an event must be demonstrated by unambiguous evidence of human use, like cut marks (Richter *et al.* 2000). Many finds could have been introduced to the archaeological record by non anthropogenic processes as the prey of predators, or even as the remains of predators themselves, like cave bears. In addition to the potential of sample contamination, the results in ^{14}C-dating have to be corrected for past isotopic variations of C. So far, this can be achieved routinely only for the last 20,000 years (see for example Laj *et al.* 1996; Kitegawa & van der Plicht 1998). ^{14}C results of older samples can be given in ^{14}C-years, but not in solar years, as required in archaeology and supplied by other chronometric methods, like thermoluminescence (TL) dating of heated silex.

Thermoluminescence (TL) dating

When organic materials are not preserved or the site is too old for ^{14}C-dating Thermoluminescence (TL) dating is a suitable tool for chronometric dating. It is applicable to burnt rocks, usually termed flint, chert or silex, but also sandstone and quartzite, as well as certain sediments. The application limit of TL dating is given by the properties and saturation of the TL-signal, which are determined by the site environment and the sample itself. The lower limit of the method for the most commonly used material, silex, lies at approximately 1 Ma, although only ages of up to a few 100 ka are reported, while the upper limit is found to be at a few ka. The method is also applicable to more unusual context, like the dating of the rock material from quarrying and mining if fire was used. In contrast to many other archaeological finds, the archaeological event itself (last heating) is dated by using heated artefacts for chronometric dating.

Method

TL-dating is based on structural damages in the crystal lattice of minerals and ionizing radiation. Energy from omnipresent ionizing radiation is stored in crystal defects. The sources for this radiation are radioactive elements from the surrounding sediment and from the sample itself, as well as secondary cosmic rays. Thus a radiation dose

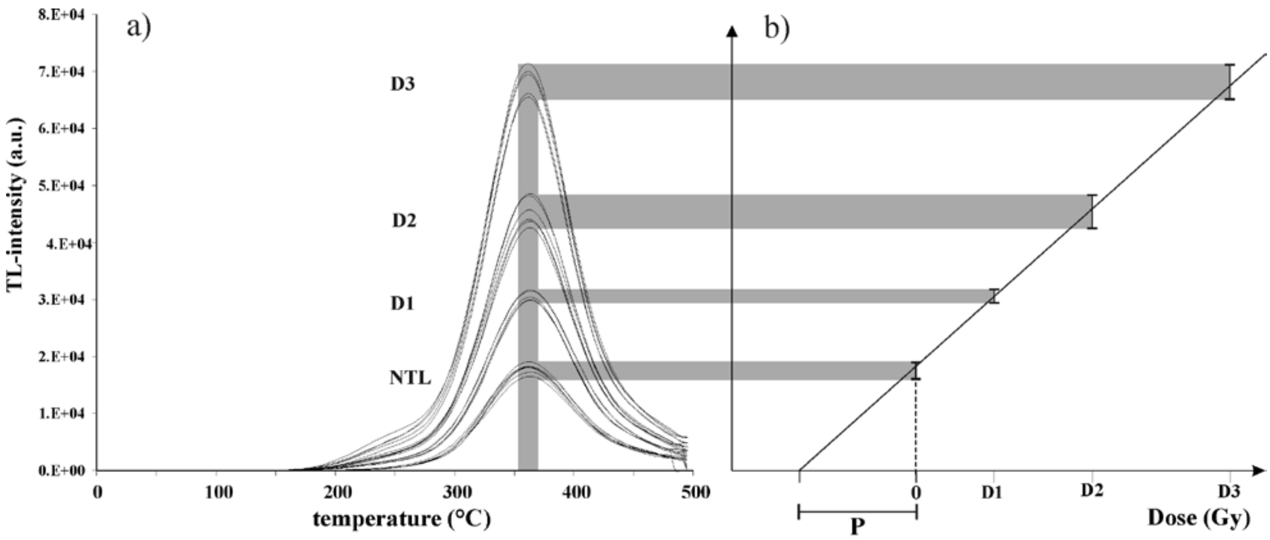


Fig. 1: A TL glow curves of a silex sample (temperature versus TL signal intensity, where 0 is the natural TL (NTL) and D1-D3 is the TL signal after applying the artificial doses D1-D3; b Regression analysis of the integrated TL intensities (arbitrary units) versus applied doses (0 and D1-D3 in Gy) to determine the palaeodose P.

(palaeodose = P) accumulates in the crystal. This dose is proportional to time for a constant dose rate (D), which means that a continuous clock is running. Heating of the crystal releases some of the stored energy as light, hence it is called thermoluminescence. The luminescence intensity (number of photons) increases with the total deposited energy (palaeodose) in a crystal and is therefore a function of exposure time to radiation.

The storage of the TL signal starts with the mineral formation. Therefore the rock had to be heated thoroughly in antiquity, as the interest lies in establishing the age of an archaeological event. A temperature of the prehistoric fire of about 400°C is required, where it is unimportant if the heating was deliberate or unintentional. The TL-clock is set to zero by this process. After cooling and sedimentation the TL-clock starts running again and the last heating of the artefact can be dated after excavation.

Two variables have to be determined, to solve the age equation,

$$\text{age} = \frac{\text{palaeodose}}{\text{dose - rate per year}} = \frac{P}{D}$$

The palaeodose (P) is proportional to the stored energy, which is measured in the form of the TL-signal by heating of sample aliquots at a constant rate (Fig. 1a). Aliquots of the sample are irradiated with a radioactive source to increase the TL-signal (arbitrary units) in order to determine the sample's sensitivity to radiation (Fig. 1b). The TL intensities of the natural and the artificially increased signal are plotted versus the applied doses (in Gy) to yield a growth curve. Regression analysis of such a growth curve gives the palaeodose P (Fig. 1b). In order to correct for the supralinear behaviour of some materials like silex, a second growth curve has to be established in the same manner with artificially zeroed material in order to determine the appropriate palaeodose (P). Such an approach is probably not necessary for very old samples, as the supralinear fraction of the palaeodose is often small.

A basic assumption in this formula is the constancy of the dose rate per year (D), which consists of three main components: the internal dose rate ($D_{internal}$, from radioactive elements within the sample), the cosmic dose rate (D_{cosmic}) and the external γ-dose-rate ($D_{external-\gamma}$), which is mainly a function of the mineral composition of the sediment and moisture content.

$$\text{age} = \frac{P}{D} = \frac{P}{D_{internal} + D_{cosmic} + D_{external - \gamma}}$$

The relative proportions of the three components of the dose rate (D) vary from site to site and from sample to sample. The precision and accuracy of dating results are highly dependent on these proportions. As only the geochemical stable parts of the samples are used for dating, the $D_{internal}$ can be considered as constant over the time span of interest in archaeological dating. In order to take the different TL efficiency of alpha radiation into account, a conversion factor (expressed as a-value, b-value or S-alpha) has to be determined for each sample as part of the internal dose-rate. The small contribution to the total dose-rate by the cosmic dose-rate D_{cosmic} is regarded as constant (Prescott & Hutton 1994). The external γ-dose-rate ($D_{external-\gamma}$), however, could have undergone fluctuations. Sediment moisture fluctuates with climate, thus the γ-dose-rate varies, as water absorbs γ-rays. The possibilities of evaluation and modeling of such changes are limited. Thus, a large error is usually assumed for the external γ-dose-rate, in order to incorporate any fluctuation like changes in the water content of the sediment (Fig. 2). The influence of any variation in the external γ-dose-rate ($D_{external-\gamma}$) on the age is proportional to its fraction of the total dose-rate (D).

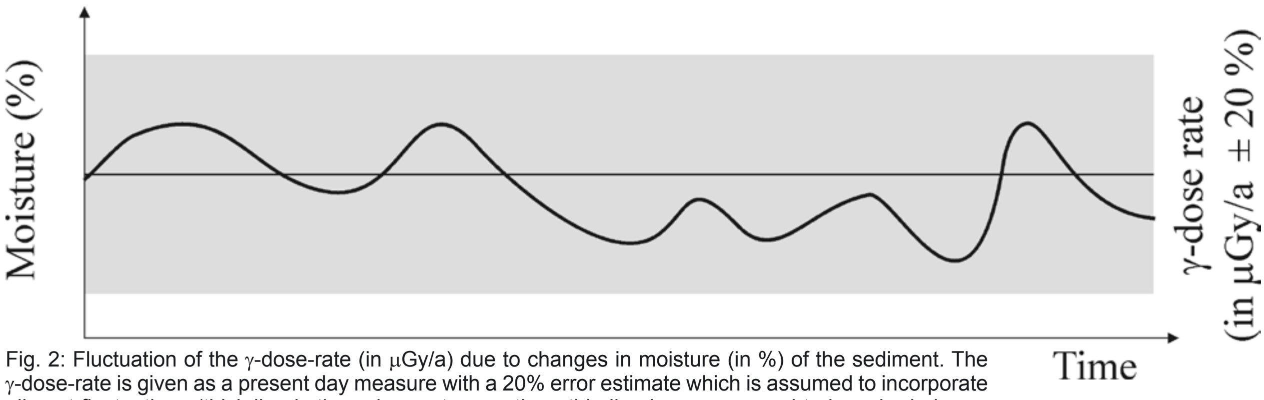


Fig. 2: Fluctuation of the γ-dose-rate (in μGy/a) due to changes in moisture (in %) of the sediment. The γ-dose-rate is given as a present day measure with a 20% error estimate which is assumed to incorporate all past fluctuations (thick line is the γ-dose-rate over time; thin line is as measured today; shaded area indicates ±20% fluctuation relative to the present day measurement).

TL dating results

The accuracy of any chronometric dating of archaeological sites is dependant most of all on the relation of the sample to the archaeological event, but also on the depositional environment and the quality of the samples. The precision of a dating result depends on the latter two and on the method used. In general the errors associated with TL dating results are rarely better then 8-10%. Ages are usually given with a one sigma standard deviation estimate, which means that there is only a 68% probability that the true age lies within this age range. In order to compare dates from any chronometric dating method, the 2-sigma range should be used.

TL dating results give age estimates of the last heating of an artefact/rock. Such heating is assumed to represent the anthropogenic manipulation of the sample. The heating is verified by TL analysis, resulting in the determination of the palaeodose. Natural fires are a frequent occurrence. This is probably not true for caves, which are the most common type of Palaeolithic sites in Europe. The occurrence of the self ignition of guano is reported (Binford & Ho 1985), but as the depth penetration of natural fire in sediment is generally very small (Bellomo 1994), this would be only of concern in very special cases. The TL dating result on samples buried more then 2-3 cm below the surface would only be affected by burning roots, though the low temperatures (Bellomo 1994) most likely are insufficient to erase the TL signal as required for TL dating. Only artefacts on the surface or very close to it are affected by fire. Such samples are either contemporary with the fire, or were previously exposed on the surface for some considerable time. TL dating assumes undisturbed position and full coverage by sediment soon after deposition. Artefacts exposed at the surface for some time before the fire would thus violate this assumption.

These hypothetical scenarios emphasise the importance of close work between archaeologist, sedimentologist and dating specialist, in establishing and interpreting TL dating results. It has to be noted that unintentional heating of an artefact occurs either if it was on the ground surface previous to the fire or if the artefact was dropped accidentally into the fire. Therefore it is possible that the artefact was abandoned during a previous occupation, and not by the one responsible for its heating. Considering the time resolution of archaeology and sedimentology, the time difference between such occupations is very small. Thus such events, which have led to the deposition of one archaeological unit, have to be regarded as contemporary anyway.

The accuracy and precision of dating results also depends on the proportions of the various dose-rates. Samples with a high internal dose rate can be rated as more reliable then those where the external γ-dose-rate is the major contributor to the dose rate. In the latter cases the error of the dating results are generally higher, because of the uncertainties associated with the external γ-dose-rate from the sediment in the site. In addition to this decreased precision, the accuracy can also be affected in case of disturbed or inhomogeneous sediments.

The lack of knowledge of the precise radiation environment of each sample leads to some variation in the dating results of samples from the same level. Under the assumption of contemporaneity, which has to be shown by other means then the TL results, weighted mean ages with a considerably reduced error can be calculated for multiple results from one level.

Sites

Only samples from undisputed context and clear relation to the occupation should be dated. It is essential, that the samples can be related clearly to the sediment used for the determination of the external γ-dose-rate. The exact three-dimensional position of the samples thus should be known. Disturbed sediments or displaced pieces have to be avoided. On the other hand it is possible to show a disturbance in a site by TL analysis of heated artefacts, if they are of significant different age (Debenham 1994).

The sample should be surrounded since deposition by a sphere of sediment at least 30 cm in radius. In case of a

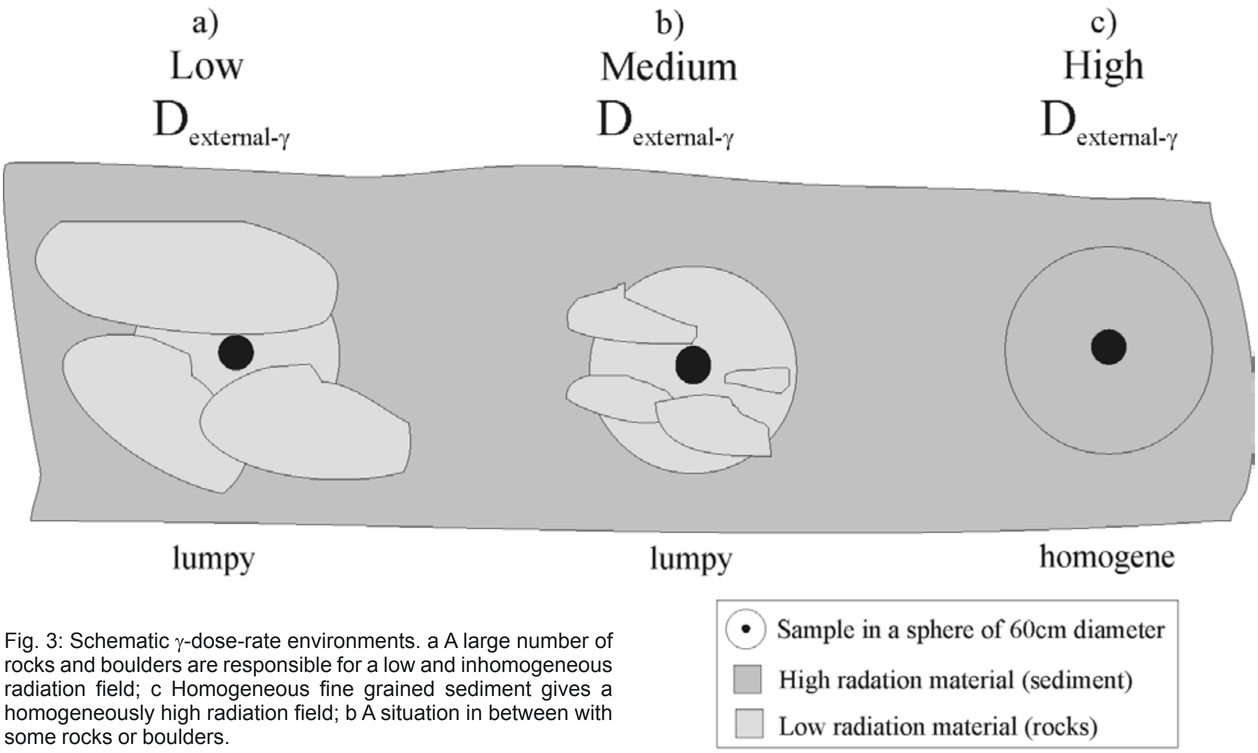


Fig. 3: Schematic γ-dose-rate environments. a A large number of rocks and boulders are responsible for a low and inhomogeneous radiation field; c Homogeneous fine grained sediment gives a homogeneously high radiation field; b A situation in between with some rocks or boulders.

cave site the walls and the floor should be at least 30 cm from the sample. To assess the dose rate from the radioactive elements in the sediment access to a standing profile as close to the sample locations as possible is needed. The measurement(s) has to be made in a similar configuration in the same sediment/stratigraphical unit as the sample. Thus the profile has to be at least a cube of 60 cm side length (for one measurement) in order to guarantee the measurement of a sediment sphere of 30 cm radius.

There are two major types of sites in TL dating, with regard to their radiation environment (Fig. 3). Sites with a homogeneous fine grained sediment provide a homogeneous external gamma radiation field (Fig. 3c), with little variation from sample position to sample position. This is in contrast to sites with a lumpy radiation environment (Brennan *et al.* 1997), usually found in caves with many rocks and boulders (Fig. 3a,b). On the one hand this requires more dose-rate measurements due to possible variation and a larger error estimate on the external γ-dose-rate has to be applied. On the other hand such sites tend to have a lower contribution of the external γ-dose-rate, giving more weight on the internal dose rates. It is possible to date older sites in such environments due to saturation effects of the TL signal at higher doses.

Samples can originate from any random location within a layer. The precise radiation field usually cannot be reconstructed, thus the measurements of the radiation field have to be performed before excavation or in places with a very similar field. It is essential to have a good knowledge of the depositional history of the sediments in order to assess any changes which might have had an effect on the γ-dose-rate. Long exposure of samples to the surface or near surface position results in underestimation of the ages, thus the sample should have been buried soon after its heating, and not been exposed or nearly exposed until recently.

In situ measurements

In order to establish the external γ-dose-rate from the sediment of a site, several measurements are needed. Spatial variation in radiation levels occurs due to lumpy radiation environments resulting from mixtures of rock boulders, stones, and fine sediment. Two methods are usually combined. Measurement with a portable gamma spectrometer requires holes of 8 cm diameter and 30 cm depth at several locations in the site for each level. A denser grid of measurements is obtained by placing several 1 cm thick plastic tubes with dosimeters 30 cm deep in the profile(s). These dosimeters have to be left in the site for a few weeks or up to one year, depending on the type of dosimeter.

The optimum strategy is to implant dosimeters at the end of a field season and retrieve them before excavation the following year. A sediment sample has also to be taken for a test of the equilibrium of the Uranium decay chain. If the sediment is very homogeneous (an ideal situation) a sediment sample is sufficient for the determination of its radioactive element concentrations. Thus such sites which already have been excavated can be dated under certain circumstances as well.

Samples

Archaeological materials datable by TL are heated flint, chert, silex, quartzite or sandstone. Some promising developments on the dating of heated limestone are under way (Roque *et al.* 2000). Macroscopic signs of heat alteration are reddish or pink colour, glossy scars or glossy (lustre) surface, heat crazing (craquelation, a net of very fine cracks) and potlids (Richter 1998). But all these features can equally be attributed to other causes like frost action (potlids and craquelation), use (lustre) and iron oxidation (red/pink colour). Empirical results with TL analysis show that samples having potlids and any other sign of heating are usually sufficiently heated for dating purposes. Without careful experimental studies, the prehistoric temperature can not be determined by visual inspection (Richter 1995). Even physical methods can produce only rough temperature estimates, as their basis are usually heating experiments under certain conditions, for certain raw materials. A translation of such laboratory heating results on archaeological samples requires the assumption of a very similar heating rate and length of the prehistoric firing process. It has to be noted, however, that the required heating to approximately 400°C does not necessarily produce any macroscopicaly detectable traces.

As the outer 2 mm surface of the sample has to be cut off with a water cooled diamond saw to remove all parts of the sample which had been exposed to α- and β-radiation from the surrounding sediment, the samples will usually be completely destroyed for dating. The minimum size is 20 by 30 by 7 mm, but has to be larger for samples with irregular shape. Usually 15-20 g total weight of a sample is sufficient, unless it is heavily patinated or a large portion consists of cortex.

Exposure to light is not critical for most samples, as the outer surface is cut away, but as a precaution samples should be wrapped in aluminium foil. Any exposure to direct bright sunlight must be avoided. The analysis of the artefact under artificial light is not critical, except for translucent samples, which should be avoided for dating on reasons of irregular signal behaviour anyway.

A small portion of each sample is subjected to the plateau test (Aitken 1985) to determine if it was sufficiently heated and thus suitable for TL dating before the actual sample preparation. Frequently only a small portion of samples from a site pass this test.

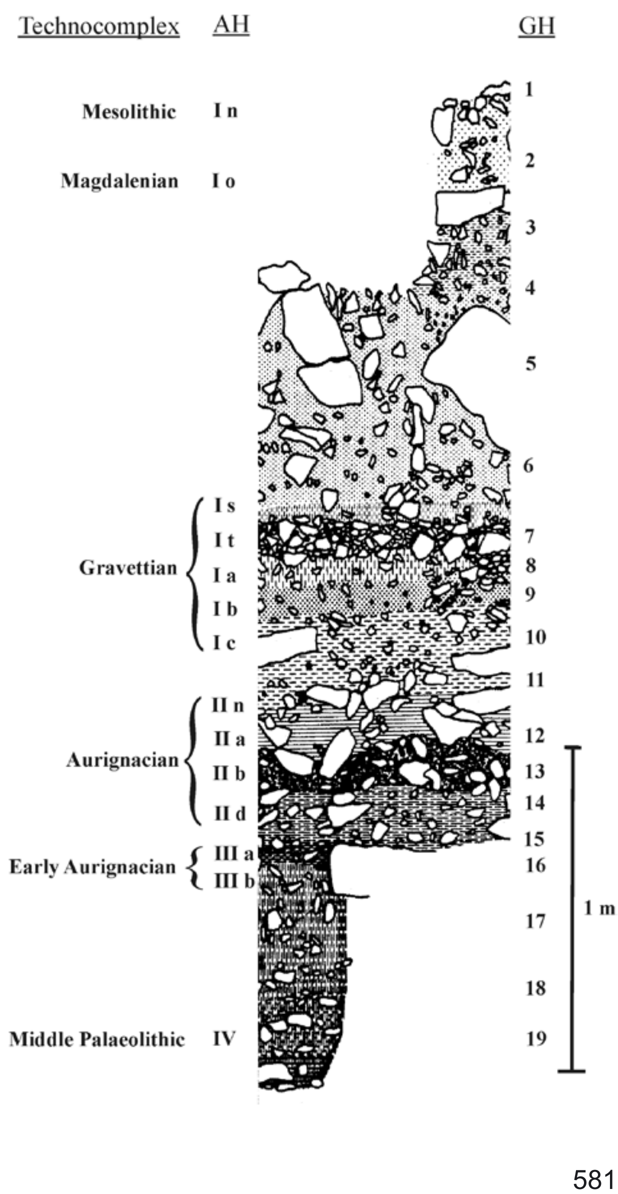
In order to achieve the highest possible accuracy the three-dimensional position of each sample should be known, in order to avoid samples from disputed context or intermediate layers, which can not be securely attributed to one occupational layer. A minimum of six or more samples should be successfully dated for each occupation or layer in order to obtain a good age estimate for the occupation. Therefore a number of samples several times the number of desired results should be submitted for analysis.

Case study: the Geißenklösterle Cave

The Geißenklösterle Cave (near Blaubeuren, SW-Germany) is situated in the Achtal, a former valley of the Danube, 60 m above the valley floor at ca. 550 m above sea level. It is one of the few Central European stratigraphies (Fig. 4) comprising levels from the Middle Palaeolithic to the Mesolithic.

The basal occupation of the Geißenklösterle Cave yielded only a few artefacts which cannot be attributed to a technocomplex. Due to its stratigraphical separation from the Upper Palaeolithic layers by 10-20 cm of deposit free of artefacts, the difference in raw materials, and changes in the faunal composition, it is assigned to an undefined Middle Palaeolithic (Hahn 1988; Waiblinger in prep.). Electron-Spin-Resonance dating on four bear teeth gave a mean age of 43,300±4000 a (Richter *et al.* 2000). The overlying

Fig. 4: Profile of the Geißenklösterle Cave, indicating the technocomplexes, archaeological layers (AH) and geological layers (GH) (after Hahn 1985; 1988).



Early Aurignacian layer (AH III) is defined by carinated and nose ended scrapers, blades, splintered pieces and simple bone points (Hahn 1988). Its typology can be regarded as equivalent to the Aurignacian 0 as defined by Djindjian (1992). Palaeoecological analysis places this level in the Hengelo Interstadial (Hahn & Kind 1997; Campen 1990). Another Aurignacian archaeological complex (AH II) with split base points is located stratigraphically higher and can be linked with the French Aurignacian I (Hahn 1988). This layer is famous for its large number of unusual objects like an anthropomorphic half relief on ivory, a flute made of swan bone, ivory figurines of mammoth, feline, bear, bison and several other pieces of symbolic representation, as well as jewellery made of ivory (Hahn 1988; 1993; 1995b; Hahn & Münzel 1995). The overlying Gravettian of the Geißenklösterle can be directly linked to the nearby sites of Brillenhöhle and Hohle Fels by refitting of stone artefacts (Scheer 1990; 1993), suggesting the contemporaneous use of these three caves by a single group or by different groups of people during a rather short period of time. Furthermore, this assemblage shows links to East Europe (ivory pendants and worked antler) as well as to the Western European Gravettian (flechettes, microgravettes and Font Robert points) (Scheer in press). The late Magdalenian and Mesolithic occupations of the Geißenklösterle represent only short events with small lithic assemblages.

The spatial distributions of artefacts, especially those of worked ivory, allow the reconstruction of the primary occupation horizons and the activities of Palaeolithic humans at this site (Scheer in press; Christensen 1996). The presence of hearths (two in the Gravettian and one in the Early Aurignacian) also indicate the preservation of the living floors to a high degree, despite the minor displacement (mainly vertical) of the artefacts. Extensive refitting showed that six major occupations of the cave took place (Scheer in press; Hahn 1988; 1989).

Radiocarbon (^{14}C-AMS) dating

A large number of ^{14}C dates were produced for the various layers of the Geißenklösterle. Here only ^{14}C-AMS results on samples with a clear association to human activity are presented (Tab. 1). Criteria were the following: The bones had to show cut marks and/or are from species considered to belong to human prey (reindeer size or bigger). Results on samples from stratigraphically intermediate positions between the archaeological occupations, or on cave bear bones, are not presented here. The incorporation of such results in the analysis led to the misinterpretation of the Aurignacian layers of the Geißenklösterle Cave of being mixed, as proposed by Zilhão & d'Errico (1999).

Such a careful AMS sample selection allows the calculation of weighted means, using the assumption of contemporaneity of all the samples from one layer. These results can be taken as accurate age estimates for the Palaeolithic occupations, at ~35,000 bp for the Early Aurignacian, 31,000 bp for the Aurignacian and 28,000 bp for the Gravettian in Radiocarbon Years before present. But the fluctuations of atmospheric carbon isotope production suggest an even older real age by several thousand years (see for example Mazaud *et al.* 1991 or Bard *et al.* 1990) especially for the Early Aurignacian.

Tab.1: ^{14}C Dating results from the Geißenklösterle Cave. Only AMS data on samples from secure stratigraphic position and showing either human modification or belong to human prey are presented here. (Data from Housley *et al.* 1997; Hahn 1995a; Münzel *et al.* 1994; Richter *et al.* 2000; Conard & Bolus 2003).

laboratory	number	arch. horizon	Species	age (a)	± (a)
OxA	5226	It	reindeer	26540	460
OxA	4855	Ir	reindeer	27000	550
OxA	4857	Ir	horse	27500	550
OxA	5229	It	mammoth	27950	550
OxA	5227	Is	reindeer	28050	550
OxA	5228	It	mammoth	28500	550
OxA	4592	It	reindeer	29200	460
OxA	5706	It	red deer	29200	500
OxA	5161	Ic	reindeer	30300	750
OxA	4856	Ir	equus	30950	800
KIA	8960	IIb	mammoth	29800	240
OxA	6629	IIa	reindeer	30300	550
KIA	8958	IIb	horse	31870	+260-250
OxA	5708	IIb	mammoth	32300	700
OxA	5707	IIa	horse	33200	500
OxA	4594	Iib	reindeer	36800	1000
OxA	6256	III	reindeer	30100	550
OxA	6255	III	rhinocerus	32900	850
OxA	5705	IIIa	reindeer	33150	1000
KIA	8961	IIIb	reindeer	33210	+300-290
KIA	13076	IIIb	reindeer	34080	+300-290
KIA	13075	IIIa	reindeer	34330	+310-300
KIA	13074	IIIa	reindeer	34800	+290-280
KIA	16032	IIIb	roe deer metacarpal	36560	+410/-390
OxA	5163	III	ibex	37300	1800
ETH	8267	III	large mammal	37800	1050
OxA	4595	III	horse	40200	1600
OxA	6076	IV	red deer tibia	33600	1900
OxA	6077	IV	ibex	32050	600

Thermoluminescence (TL) dating

Due to the very old ^{14}C-dates for the Early Aurignacian of the Geißenklösterle, which are at the limits of the dating method, Thermoluminescence (TL) dating was performed as an independent chronometric dating method.
Sample selection for TL dating followed the strategy used for ^{14}C-AMS-dating by not including samples from intermediate layers where the artefacts could not securely be attributed to one of the major occupational layers. The Early Upper Palaeolithic assemblage yielded 33 stone artefacts, which seemed to be suitable for TL dating, being of sufficient size and showing macroscopic signs of heating. None turned out to be suitable for dating the Gravettian layer, but two silices from the Aurignacian and seven silices from the Early Aurignacian passed the plateau test. A more detailed description of the dating procedure can be found in Richter *et al.* 2000.

High sensitive gamma spectrometry on the fine-grain sediment portion of the layers revealed radioactive equilibrium of the ^{238}U-chain for all layers. Measurement of the external γ-dose-rate of the sediment was performed by Thermoluminescence dosimetry with $CaSO_4$:Dy, CaF_2 and LiF:Mg,Cu,P dosimeters. Due to the removal by the excavation of most of the sediment of the upper levels, only two measurements of the external γ-dose-rates for each Aurignacian layer were possible. The external γ-dose-rates of the sediment ($D_{external-\gamma}$) are very similar within the Aurignacian layer (AH II: 62 and 51 µGy a^{-1}), but rather diverse for the Early Aurignacian layer (AH III: 39 and 87 µGy a^{-1}). This reflects the inhomogeneous 'lumpy' dose environment of this sediment. Nevertheless, the average of the readings (57 µGy a^{-1} for AH II and 63 µGy a^{-1} for AH III) were used for each layer as the best available estimates of the external γ-dose-rate for all samples from the corresponding layers. A 20% error estimate for the external γ-dose-rate was employed in order to account for any variation in soil moisture which would have affected the γ-dose-rate. The unusual geometry of the Geißenklösterle Cave and the rather large contribution of the cosmic dose (formulas from Prescott & Stephan 1982; Prescott & Hutton 1994; Barbouti & Rastin 1983) required the modelling of the cosmic dose-rate for each individual sample (Richter *et al.* 2000). Internal dose-rates were calculated from element concentrations determined by Neutron Activation Analysis (NAA). The major contribution to the total dose-rate comes from the internal dose-rate (Tab. 2) which makes the age results less prone to variations and uncertainties in the external γ-dose-rate. Sample GK5 is exceptional for two reasons. A high proportional contribution from the external dose-rate is paired with a low internal dose-rate. This results in a much higher age (61,600±3,800 a) than measured for the other samples. It is significantly different and thus has to be rejected. All the other results cluster between 38,300 and 44,700 a (Tab. 2)

According to the geological and archaeological record, the prehistoric burning of all these samples took place within a short period of time and is considered to be one archaeological event of a time length much below the error limits of the method. This allows the calculation of a weighted mean age for the TL dating results from the Early Aurignacian of

Tab. 2: Sample numbers, provenance, results of TL measurements and age for all samples from the Geißenklösterle.
[1] The palaeodose (P) includes the supralinearity correction.
[2] The internal dose-rate ($D_{internal}$) is corrected for the alpha sensitivity.
[3] The cosmic dose-rate (D_{cosmic}) is determined by burial depth, thickness of cave roof, altitude and latitude, and was calculated using the formulas provided by Prescott & Stephan (1982), Prescott & Hutton (1994) and Barbouti & Rastin (1983).
[4] The external γ-dose-rate ($D_{external-\gamma}$) is corrected for the form and weight of the sample (Valladas 1985).
[5] The palaeodose (P) divided by the sum of the dose-rates[2,3,4] gives the age.

sample #	square #	Tübingen #	Archaeol. horizon (AH)	P[1] (Gy)	$D_{internal}$[2] (µGy a^{-1})	D_{cosmic}[3] (µGy a^{-1})	$D_{external-\gamma}$[4] (µGy a^{-1})	age[5] (a)
GK4	87	533	II	8.58 ± 0.25	130	45	50	38,100 ± 2,500
GK6	46	271	II	8.30 ± 0.32	117	66	50	35,600 ± 3,900
GK2	35	236	III	11.84 ± 0.13	145	99	56	39,500 ± 2,100
GK3	67	1759	III	11.05 ± 0.34	171	45	54	40,900 ± 4,700
GK5	48	83	III	10.78 ± 0.36	91	29	55	61,600 ± 3,800
GK7	68	592	III	11.49 ± 0.65	162	39	56	44,700 ± 5,600
GK8	57	1361	III	11.04 ± 0.46	197	37	54	38,300 ± 5,400
GK9	37	199	III	11.73 ± 0.44	195	54	54	38,700 ± 3,900
GK12	37	65	III	10.08 ± 0.10	121	54	56	43,600 ± 5,400

40,200±1,500 a, whereas the occupation of the Aurignacian level took place around 37,000 a.

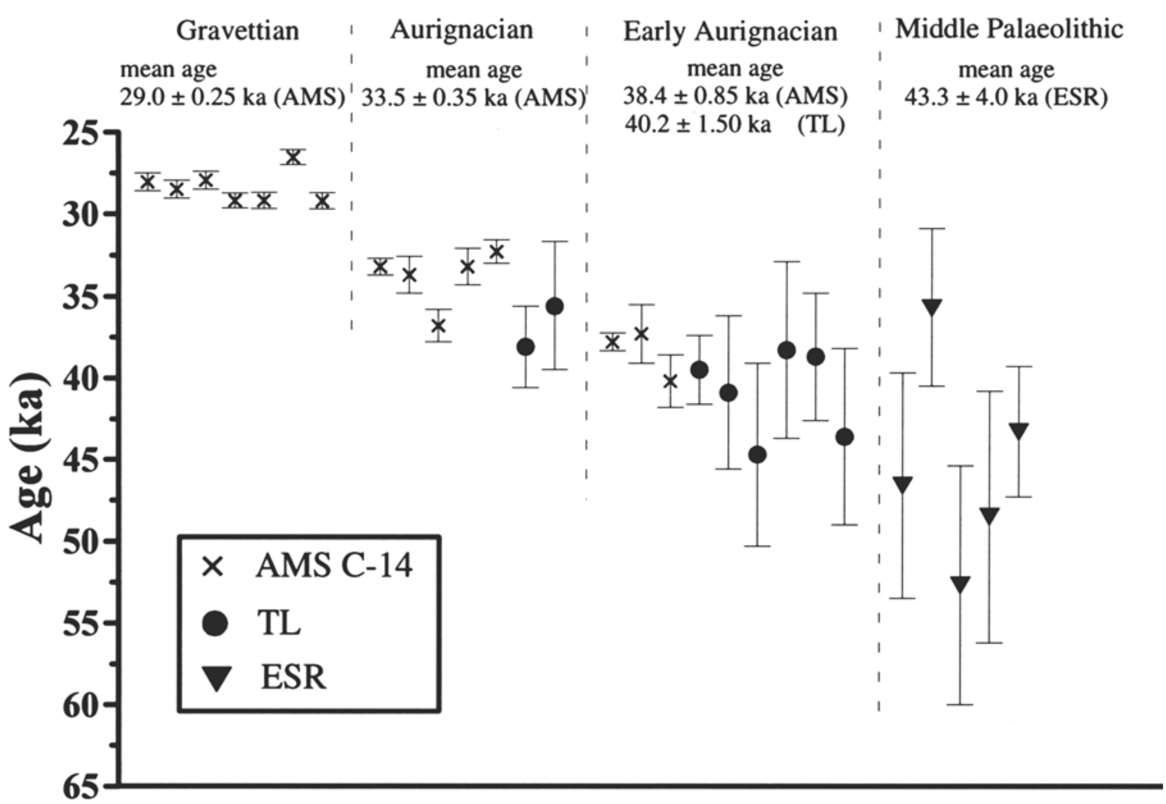
Summary

More reliable age estimates of stone age sites can be obtained by applying several independent chronometric dating methods. By comparison of age estimates (Fig. 5) from TL and ^{14}C linked with palaeoecological data, the Early Upper Palaeolithic of the Geißenklösterle can be placed in the Hengelo Interstadial in Oxygen Isotope Stage (OIS) 3.

Although the chronometric dating results are coherent with the stratigraphy, the overlaps within the error limits are considerable (Fig. 5), giving more weight on the relative age information obtained by stratigraphic superposition. The quality of dating results as well as any archaeological chronology in general is based on the careful verification of such superpositions and the clear affiliation of samples to occupational layers.

The age difference of TL results on burnt flint to ^{14}C-AMS dating on bone can be taken as an estimation of the lack of calibration of ^{14}C-dating results in this time range. Dating results of similar age were obtained from other Central European Aurignacian sites as well. Unfortunately they are either flawed, the integrity of the site is unclear or the nature of the assemblage as Upper Palaeolithic is questioned (Richter *et al.* 2000). The reported dating results for the Early Aurignacian occupation of the Geißenklösterle to 40,200±1,500 a by TL of burnt silex must therefore be taken as one of the earliest firmly dated Early Upper Palaeolithic occupations in Central Europe. This dating result sheds new light on the appearance of modern humans in Europe, who are believed to be associated with this first Upper Palaeolithic culture (Aurignacian). The TL age estimate of 37,000 a for the Aurignacian layer in the Geißenklösterle Cave shows a very early appearance of sophisticated Palaeolithic art, probably earlier than elsewhere reported. Being situated in a former Danube valley, the Geißenklösterle is located at an obvious route for the colonisation of Central Europe by modern humans. Dating results for other Aurignacian as well as Gravettian sites are younger to the East as well as to the West. Therefore a simple colonisation model for Europe from East to West in one direction is not applicable. The Geißenklösterle might be a first venture, from which this new technology spread, maybe even in both directions (Richter *et al.* 2000). This idea was developed and a hypothesis formulated (Conard & Bolus 2003).

Fig. 5: Chronometric dating results from the Geißenklösterle Cave (from Richter *et al.* 2000).



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