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Three-Dimensional Imaging in Paleoanthropology and Prehistoric Archaeology

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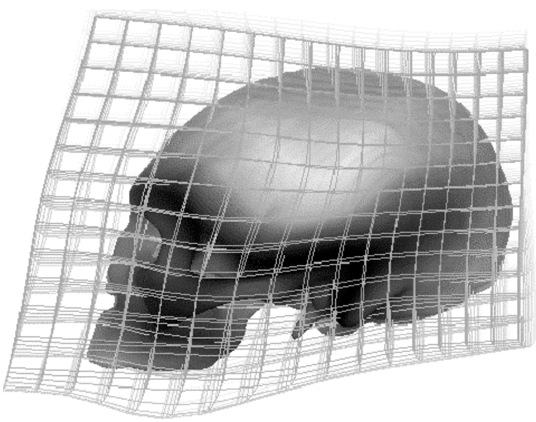

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SIMULATION AND 3D-LASER-SCANNING OF DENTAL ABRASION

Irene Luise GÜGEL & Karl-Heinz KUNZELMANN

Résumé: La perte d'émail dentaire sous l'effet des particules abrasives contenues dans l'alimentation peut avoir des conséquences importantes pour la santé et le bien–être des sujets. Les connaissances actuelles sur les processus de formation de cette abrasion sont encore limitées. Dans le cadre de nos recherches, une étude expérimentale a été conduite pour mieux simuler et quantifier l'usure dentaire obtenue avec des céréales pour des modes de broyages différents. Des échantillons d'émail de molaires humaines extraites ont été utilisées comme matériel expérimental dans un simulateur de mastication. Les surfaces de l'émail ont été scannérisées avant et après cette mastication expérimentale, avec un Laserscanner Pro 3D. L'importance de l'usure totale a été quantifiée à partir des données tridimensionnelles par superposition des images numériques pré et post procédure grâce à un algorythme des moindres -carrés sans utilisation de points de référence. L' « image de la différence » était obtenue par soustraction digitalisée des deux images numériques 3D superposées.

Abstract: The loss of dental enamel caused by abrasive particles in the diet can have serious consequences for human health and well-being. With regard to the formation process of abrasion, current knowledge is still limited. In the course of our research, an experimental approach served for a better simulation and quantification of dental abrasion, depending on different cereal species and milling techniques. Enamel samples of impacted human molars were used as agonists in a chewing simulator. The enamel surfaces were scanned before and after the chewing simulation by a Laserscanner Pro 3D. Absolute abrasion was determined by this 3D-data set, by numerically superimposing the baseline and follow-up image with a least-squares matching algorithm without reference points. The "difference image" was calculated by digital substraction of the superimposed 3D-data sets of loss.

INTRODUCTION

The pattern of tooth wear is related to cultural, dietary, occupational, and geographical factors. Tooth wear analysis continues to play an important role in the understanding of the biological consequences of subsistence change, which is but one component in this complex analysis. The abrasiveness of food is a key determinant in the rate of physiological dental wear in humans (Molleson et al., 1993, Molnar 1971, 1972, Powell 1985, Rose et al. 1985, Rose & Ungar, 1998, Smith, 1984, Teaford & Lytle, 1996). With increasingly refined food processing methods through time, the rate of physiological dental wear on human teeth has changed markedly.

Many investigators share the opinion that a certain degree of dental wear is beneficial for dental health. This was demonstrated by the elimination of cuspal interferences to excursive movements and the reduction of caries and periodontal diseases by the removal of stagnating areas (Ainamo, 1972, Berry and Poole, 1976). A lack of occlusal and approximal dental wear may also lead to crowding, rotation and overlapping of anterior teeth (Lombardi 1982, Wolpoff, 1971).

The analysis of abrasion on teeth of pre-modern human populations led to important data about the degree and patterns of abrasion (for review: Vötter, 1973, Larsen, 1997). However the underlying causes of different abrasion rates and patterns, and also the wear formation process as such are far from being clear. The aim of the following study was to further investigate the process of abrasion on human enamel by use of a chewing-device for a simulation of abrasion, and subsequent analysis of enamel loss by 3D-Laser-Scanning (Kunzelmann, 1997).

MATERIALS AND METHODS

In vitro simulation of abrasion

In vitro enamel abrasion on human enamel samples was performed with the Academic Center for Dentistry Amsterdam (ACTA) device (DeGee et al., 1986, Gügel et al., 2001). The ACTA chewing simulator consists of both a sample wheel and an antagonistic wheel with different diameters (Gügel et al., 2001). 20 chambers of the sample wheel were filled with dental filling material, and a cavity was cut into 10 separated chambers each. Ten prepared human enamel samples of impacted teeth were cemented into these cavities. The "occlusal" part of the enamel insert was lifted up to 850 mm maximum above, while the "cervical" part was left at the polished surface. SEM investigations after the simulation process did not reveal any significant signs of fatigue, indicative of a possible rise of pressure exceeding physiological biting forces. The chambers without enamel served as internal controls. During the experiments, the wheels were completely covered by the diet slurry. The wheels rotated against each other with different velocities, so that their sliding motion simulates the lateral sliding of antagonistic teeth in the jaws during the crushing phase of the chewing cycle. The antagonistic wheel works with a constant load of 15 N to simulate physiological biting forces. The slurries included cereal species which were expected to induce rapid (millet), moderate (spelt and wheat) and low (spelt) enamel loss according to their differing abrasiveness. The slurries contained amounts of phytoliths, amorphous silica particles, the occurance of which is largely plant-specific and contaminating particles which are one factor for abrasion caused by diet (Teaford and Lytle, 1996, Gügel et al., 2001). Wheat and spelt were ground on historical sandstone, millet was ground with its silica-rich husks, and a negative control without debris consisted of modern prepared spelt. To simulate the course of abrasion on human enamel in the ACTA-device, first experiments were performed with slurry consisting of spelt, which was roughly ground in a modern mill with korund-ceramics. High resolution replicas were taken as baseline before the chewing simulation, and follow-up after every 50 000 cycles of the simulation until 200 000 cycles. It was expected that this procedure would induce a loss of small quantities of enamel, which could already be detected stepwise after every 50 000 cycles by the 3D-Laser-Scanning method.

3D-Laser-Scanning of experimentally abraded enamel surfaces

The measurement on the abraded areas of the samples was achieved by scanning high resolution replicas of the enamel surface (Beynon 1987) by the 3D-Laser Scanner (Mehl et al., 1997). The preparation of replicas was necessary to overcome translucency of natural enamel. A light line created by a laser diode enables the measurement of about 512 surface points within 40 msec (that is 500x faster compared to a profilometric method) which are projected onto a CCD-chip under a defined triangulation angle. The information of height for any surface point is encoded within the lateral displacement of the light line. By shifting the enamel sample on a stepper motor along the y-axis, the entire 3D-surface can be measured line by line (Figure 1a, b). The CCD-image is stored in a frame-grabber. To measure small surface changes, the two digital images (from the baseline, Figure 1a, and follow-up, Figure 1b, scannings) were superimposed (Figure 1c).

The software (Mehl et al., 1997) was developed as a reference-free 3D-superimposing algorithm. The fitting region of reference points in corresponding images can now be defined by the operator. Areas of wear and other differences between baseline and follow-up model can thus be excluded. The matching process is considered successful when the difference values in known identical regions show a “noisy” pattern with its standard deviation close to the sensor accuracy. The loss of enamel was finally made visible by presentation in counter-colours. The mean loss of height and volume was calculated for each wear region on the basis of the difference-image. The results obtained were compared with the results achieved by the much more timeconsuming and therefore limited method of profilometry with a perthometer on the identical samples.

RESULTS

Absolute abrasion loss

Cereal species with different phytolith contents and contaminating particles from the grinding process show differences in their abrasiveness (Gügel et al., 2001). Wheat and spelt ground on historical sandstone show abrasion values which fall between a negative control without debris consisting of modern prepared spelt and the highly abrasive millet, which was ground with its silica-rich husks in both scanning procedures (Table 1). According to nonparametrical statistical analysis with SPSS 10.0 (Kruskal-Wallis-Test) no significant differences in the ranking of abrasion due to the scanning method occured (Table 2a).

The differences (U-Mann Whitney, >2 independent samplings) in total abrasion between the control and all the cereal species tested are significant on the 5% level for all parameters analysed by the 3D-Laser-scanning and the

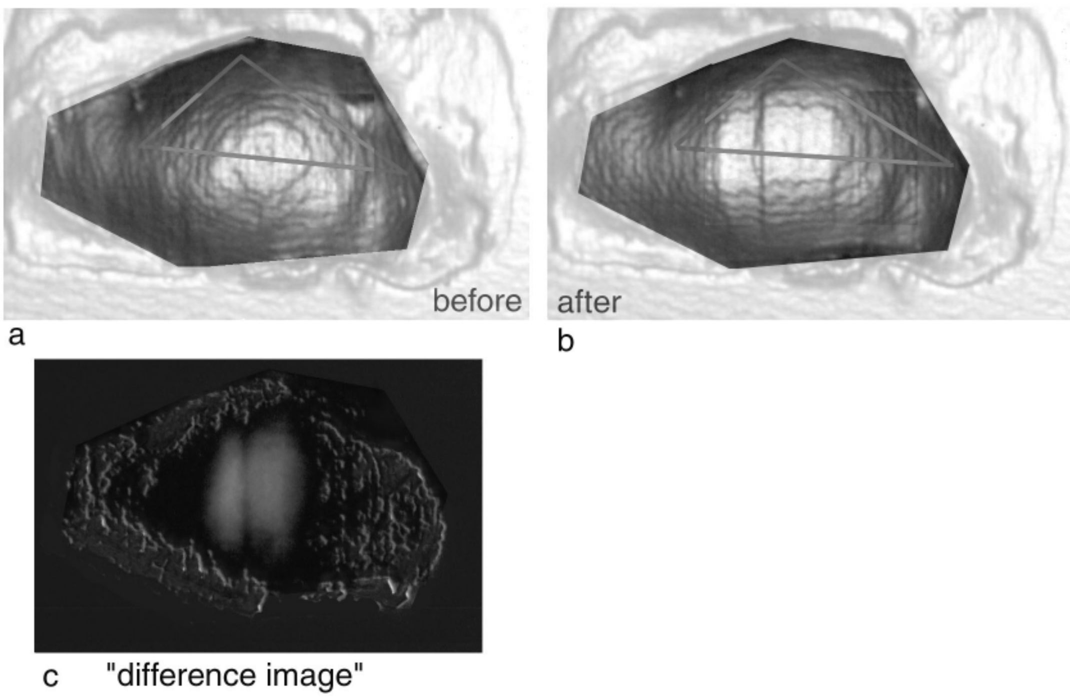

Figure 1 - 3D-Laser-Scanning of experimentally abraded enamel surfaces:
a: before abrasion, b: after abrasion, c: difference image

Table 1 - Median enamel abrasion after 200,000 cycles of chewing simulation with ACTA device using two different scanning procedures

		Spelt (b)[2]	Spelt (m)[2]	Wheat (m)[2]	Millet (h)[2]
% ash residue per dry weight[1]		< 0.01	0.20	n.d. [3]	1.46
3D-Laserscanning	Median abrasion loss (μm) ± 1sd[4]	-7.6 (1,5)	-21.8 (4.1)	-22.1 (6.7)	-33.2 (6.2)
Profilometry	Median abrasion loss (μm) ± 1sd[4]	-8.3 (3.1)	-24.6 (4.2)	-17.8 (2.3)	-27.1 (5.4)
	N (samples)	4	4	4	4

[1] After both wet and dry ashing, consisting mainly of silica. (cf. Gügel et al. 2001)

[2] b, bioshop, ground in mill with korund-ceramics; m, ground in historical mill; h, ground in modern householdmill;

[3] Not detected, but usually similar to rye and oat, 0.01 – 0.03; Runge pers. comm

[4] Standard deviation in parenthesis

Table 2a - Nonparametrical test (Kruskal-Wallis-Test) to compare two different scanning procedures by ranking the abrasivity of cereals (median abrasion loss).

Ranking in average	Spelt (b)	Spelt (m)	Wheat (m)	Millet (h)
3D-Laserscanning	28,50	15,25	13,75	4,50
Profilometry	28,50	12,00	19,75	9,75
Level of significance 0,1 %.				

Table 2b - Nonparametrical test (Mann-Whitney-U-Test) to compare the abrasivity of cereals (median abrasion loss).

	3D-Laserscanning			Profilometry		
	Spelt (m)	Wheat (m)	Millet (h)	Spelt (m)	Wheat (m)	Millet (h)
Spelt (b)	0,029*	0,029*	0,029*	0,029*	0,029*	0,029*
Spelt (m)		0,886	0,029*		0,200	0,686
Wheat (m)			0,029*			0,114
Level of significance* 5 %.						

(b), (m), (h) see Table 1.

profilometric method (Table 2b). In contrast the differences between wheat or spelt to the high abrasive millet remained insignificant after the application of the profilometric method, whereas there is a significant difference on the 5% level after the application of the 3D-Laser-Scanning method (Table 2b). Though the homogeneity of the variances between the scanning methods cannot be statistically rejected, there is a higher statistical security for homogeneity for different cereal species in the 3D-Laser-scanning method opposed to the profilometry. The results indicate that the 3D-Laser-Scanning method permits a more reliable analysis of simulated abrasion on human enamel samples in a very short time.

The abrasion process

In addition these results allowed for an experimental approach to the abrasion process. Table 3 and Figure 2a and 2b show the interrelationship between the number of chewing cycles and four different abrasion parameters: the median, the mean, the maximum and the volume of enamel abrasion loss of every individual enamel sample.

The results of 150 000 cycles are missing because of technical problems. Though the mean tends to be slightly higher than the median, indicative of an asymmetrical distribution of abrasion on the enamel area, all values show a continuing decrease of enamel height and volume with increasing chewing-cycles, as expected. The linear regression of enamel loss of height for every individual enamel sample shows a high correlation between abrasion value and chewing cycles, 3 out of five samples correlate with a coefficient better than -0,900. The analysis of the median abrasion loss of the five data sets leads to a linear regression with a slope of –0,0001 and a constant of –4,567. The linear regression of the mean and the median enamel loss is highly significant on the level of 0,1 % and the loss of volume on the level of 1 %. The

Table 3 - Quantitative enamel loss during the abrasion process.

sample	cycles	maximum abrasion loss (µm)	mean abrasion loss (µm)	median abrasion loss (µm)	volume of abrasion loss ($µm^3$)
1	50000	-84,6	-17,7	-17,1	-5,07E+07
	100000	-103,3	-22,6	-22,9	-7,64E+07
	200000	-126,2	-37,5	-34,7	-1,40E+08
				r = 0,919	
3	50000	-332,7	-27,6	-20,3	-1,53E+08
	100000	-367,0	-38,5	-28,3	-2,57E+08
	200000	-387,7	-52,6	-27,1	-3,75E+08
				r = 0,618	
4	50000	-61,3	-13,1	-13,2	-6,72E+07
	100000	-89,7	-14,1	-14,9	-1,02E+08
	200000	-105,7	-22,0	-21,1	-1,13E+08
				r = 0,824	
5	50000	n.d.	-47,4	-25,1	-3,02E+08
	100000	n.d.	-57,9	-35,3	-3,83E+08
	200000	n.d.	-84,3	-72,7	-4,86E+08
				r = 0,986	
6	50000	-52,0	-6,3	-5,1	-2,04E+07
	100000	-81,8	-10,6	-11,3	-5,07E+07
	200000	-92,9	-18,7	-14,6	-7,64E+07
				r = 0,918	
linear regression	50000	-94,5	-14,2	-14,6	-6,25E+07
	100000	-139,5	-24,2	-24,6	-1,05E+08
	200000	-229,5	-44,2	-44,6	-1,90E+08
r (correlation)		0,214	0,559	0,598	0,401
slope		-0,0008	-0,0002	-0,0001	-849,09
constant		-49,534	-4,223	-4,567	-2,00E+07
Significance on the level of 1%*, 0,1%**		0,071	0,001**	0,000**	0,008*

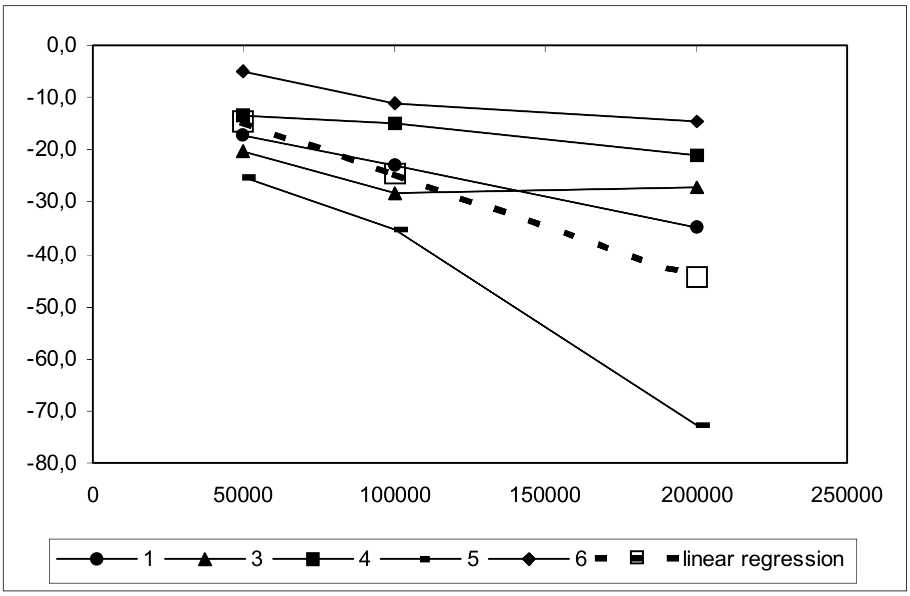

Figure 2a - Median enamel height loss (µm) during the abrasion process (n = 5).

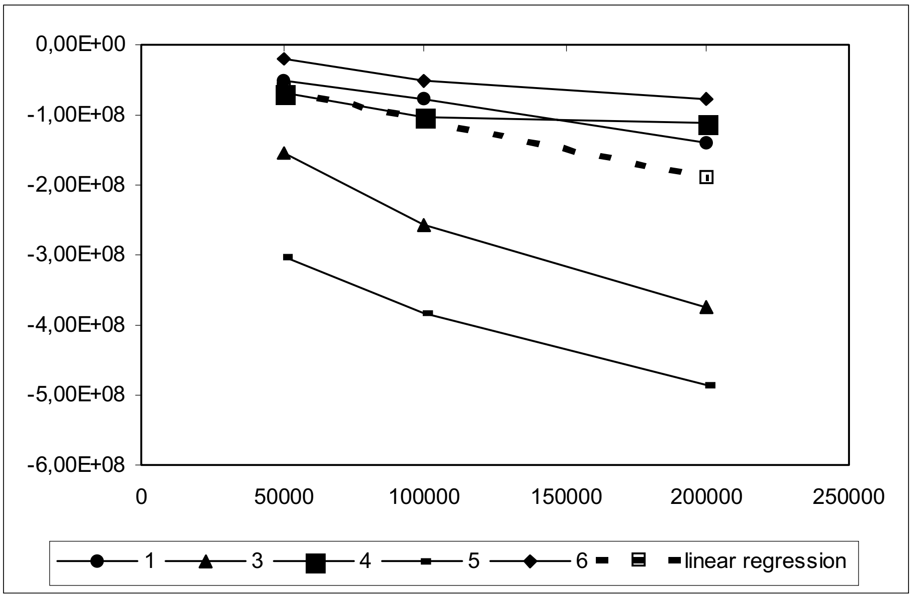

Figure 2 b - Loss of enamel volume (µm^3) during the abrasion process (n = 5).

linear regression of maximal enamel height loss is not significant. The low correlation coefficient of –0,598 also indicates the high variability of individual resistance of enamel towards the abrasive effect of diets.

SUMMARY

Our first results on the experimental investigation of the effect of diets on the rate of abrasion are encouraging. We were able to show that the 3D-Laser-Scanning method can replace the profilometric scanning of abraded surfaces, and that a continuous loss of small amount of enamel is detectable on high resolution replicas of enamel samples with experimentally induced wear. The necessity of replica preparation, because of the translucency of natural enamel, does not prevent the detection of little abrasion which is necessary for the discrimination between both different rates of abrasion and different abrasivity of diets. The preparation of high resolution replicas permits at the same time insights into the experimental formation process of dental microwear. The time consuming procedure of profilometry (which needs nearly 16 h for one sample wheel) did not permit the collection of this data set. Further experiments are needed for the establishment of the 3D-Laser-scanning method on abraded areas resulting from different abrasive foodstuffs and debris.

With the ACTA-simulation and the analytical procedure presented in this paper we introduce the application of a methodological spectrum used in modern dentistry suitable for getting access to experimentally produced data on the abrasivity and, in particular, the rate of abrasion in relation to different diets and subsistence strategies on human enamel, independent of the age of the tooth or dental disease. The results of further experiments with a different chewing device to better simulate physiological conditions are in preparation and will be published soon.

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BIBLIOGRAPHY

AINAMO, J., 1972, Relationship between occlusal wear of the teeth and periodontal health. *Scandinavian Journal of Dental Research* 80, p. 505.

BERRY, D. C. & POOLE, D. F. G., 1976, Attrition: possible mechanisms of compensation. *Journal of Oral Rehabilitation* 3, p. 201-206.

BEYNON, A. D., 1987, Replication technique for studying microstructure in fossil enamel. *Scanning Microscopy* 1, p. 663-669.

DE GEE, A. J., PALLAV, P., DAVIDSON, C. L., 1986, Effect of abrasion medium on wear of stress-bearing composites and amalgam in vitro. *Journal of Dental Research* 65, p. 654-658.

GÜGEL, I. L., GRUPE, G., KUNZELMANN, K.-H., 2001, Simulation of dental microwear: Characteristic traces by opal phytoliths give clues to ancient human dietary behavior. *American Journal of Physical Anthropology* 114, p. 124-138.

KUNZELMANN, K.-H., 1997, Verschleißanalyse und -quantifizierung von Füllungsmaterialien in vivo und in vitro. München: Habilitationsschrift LMU.

LARSEN, C. S., 1997, Masticatory and non-masticatory functions. In *Bioarchaeology: interpreting behavior from the human skeleton*, edited by C. S. Larsen. Cambridge University Press, p. 227–269.

LOMBARDI, A. V., 1982, The adaptive value of dental crowding: A consideration of the biologic basis of malocclusion. *American Journal of Orthodontics* 81, p. 8-42.

MEHL, A., GLOGER, W., KUNZELMANN, K.H., HICKEL, R., 1997, A new optical 3-D device for the detection of wear. *Journal of Dental Research* 76, p. 1799-1807.

MOLLESON, T., JONES, K., JONES, S., 1993, Dietary change and the effects of food preparation on microwear patterns in the Late Neolithic of abu Hureyra, northern Syria. *Journal of Human Evolution* 24, p.455-468.

MOLNAR, S., 1971, Human tooth wear, tooth function and cultural variability. *American Journal of Physical Anthropology* 34, p.175-190.

MOLNAR, S., 1972, Tooth wear and culture. *Current Anthropology 13*, p. 511-526.

MOLNAR, S., MCKEE, J. K., MOLNAR, I. M., PRZYBECK, T. R., 1983, Tooth wear rates among contemporary australian aborigines. *Journal of Dental Research* 62, p. 562-565.

POWELL, M. L., 1985, The Analysis of dental wear and caries for dietary reconstruction. In *The Analysis of prehistoric diets,* edited by R. J. jr. Gilbert, J. H., Mielke. Academic Press, Inc. p. 307-338.

ROSE, J. C., CONDON, K. W., GOODMAN, A. H., 1985, Diet and Dentition: Developmental Disturbances. In *The Analysis of prehistoric diets*, edited by R. J. jr. Gilbert, J. H., Mielke. Academic Press, Inc. p. 281-306.

ROSE, J. C. & UNGAR, P. S., 1998, Gross dental wear and dental microwear in historical perspective. In *Dental Anthropology, Fundamentals, Limits and Prospects*, edited by K. W. Alt, F. W. Rösing, M. Teschler-Nicola, Springer, p. 349 - 386.

SMITH, B. H., 1984, Patterns of molar wear in hunter-gatherers and agriculturalists. *American Journal of Physical Anthropology* 63, p. 39-56.

TEAFORD, M.F., LYTLE, J.D., 1996, Brief communication: Diet-induced changes in rates of human tooth microwear: a case study involving stone-ground maize. *American Journal of Physical Anthropology* 100, p. 143-147.

VÖTTER, W., 1973, Zeitliche und Geographische Unterschiede in der Abrasion der Zähne. Dissertation, Ludwig-Maximilians-Universität München.

WOLPOFF, M. H., 1971, Interstitial wear. *American Journal of Physical Anthropology* 34, p. 205-228.