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**Journal of Archaeological Science**journal homepage: <http://www.elsevier.com/locate/jas>**Pedogenetic dating of loess strata****Robert G. Bednarik\****International Federation of Rock Art Organizations (IFRAO), P.O. Box 216, Caulfield South, Victoria 3162, Australia***ARTICLE INFO****Article history:**

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**ABSTRACT**

Loess is an aeolian Pleistocene sediment of periglacial or arid origins, deposited without internal stratification in parcels representing geological periods. The contents of total as well as individual carbonates are comparatively uniform within a specific stratum, but the relative carbonate contents differ significantly between the various glacials as represented by loess facies. There is a consistent increase in the content of dolomite with decreasing age of stratigraphic units, which has traditionally been attributed to postdepositional alteration, notably the gradual removal of the calcite fraction by weathering. The explanation of pedogenetic enrichment in the course of aeolian recycling of glacial and glacio-fluvial deposits could convincingly account for the stepped profile of the dolomite's depth functions. The implication is that such recycled sediments can be attributed to specific cryoeratic phases simply by their characteristic dolomite fraction, i.e. they can be dated. In order to test this hypothesis against the competing weathering hypothesis, strata of the Gudenus Cave in Lower Austria were subjected to carbonate differentiation analysis. The results are presented, analyzed and discussed. It is shown that the dolomite contents of the unweathered strata provide a clear trend that is even more pronounced than that found at open-air sites.

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**1. Introduction**

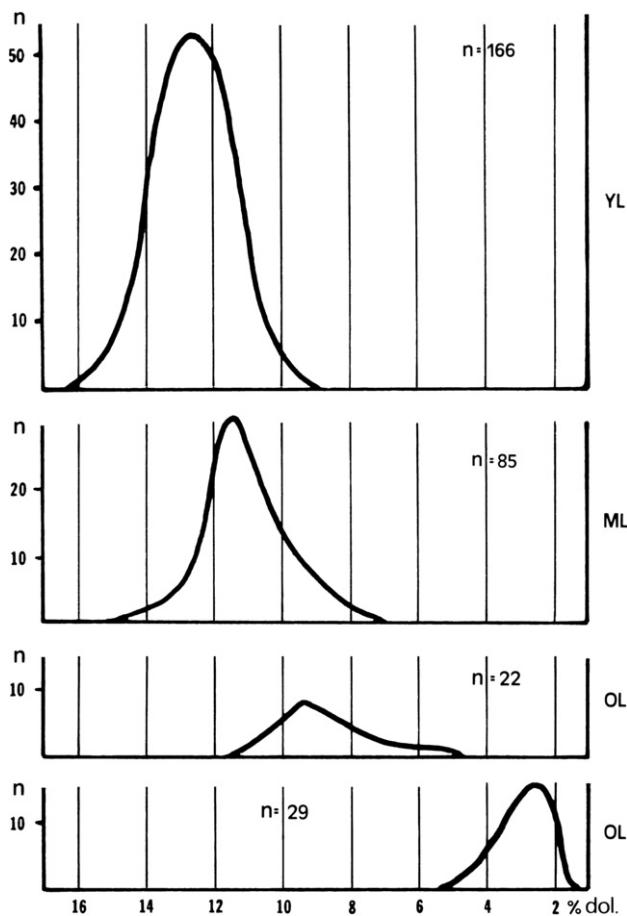
Prehistorians of the Pleistocene period of Eurasia have long had a special interest in loess deposits, an interest not generally shared by their American or Australian colleagues. A large proportion of Palaeolithic sites in Eurasia are sited in loess facies, and this is a major taphonomic factor determining the character of their material remains. It is the alkaline nature of loesses, defined by their carbonates, that has facilitated the preservation of the materials often determining our impression of the Middle and Upper Palaeolithic periods of much of Eurasia. Materials such as bone, teeth, ivory, shell and antler are particularly well preserved in these conditions, as well as ostrich eggshell in countries such as India and China. The sedimentary context of archaeological assemblages is therefore a taphonomic factor of considerable significance, and has a profound effect on the nature of regional archaeological evidence. Moreover, it is from loess deposits that prehistorians often obtained their concept of homogeneous sediment strata, the application of which is often invalid for other types of deposits.

Loesses lack internal stratification; they consist of essentially unconsolidated, calcareous silt. Their mineral composition is dominated by quartz (50–70%), followed by feldspars (15–30%). Carbonates account for less than 13%, but they are the subjects of

the present paper. Granulometrically, silts contribute 50–85%, clays 15–45%, and there is a small percentage of fine sands. Loesses are widespread in the Northern Hemisphere, particularly in former periglacial regions of the Pleistocene. They can form massive deposits of up to 200 m thickness in northern China. Other substantial deposits occur in Siberia, Russia and Ukraine, northern Africa, central North America, Argentina and New Zealand. Loess-like deposits in Australia, such as the clay-loam of the Murray basin known as *parna*, are derived largely from the arid interior, not from periglacial conditions. Loess is generally thought to be an aeolian sediment originating from flood plains and other poorly vegetated deposits, and sedimentation coincides with predominantly arid or glacial conditions.

In Europe, loesses have been subjected to detailed studies for well over a century, and it has long been noted that individual layers are fairly homogeneous, both in their morphology and their mineral composition. They are attributed to cold phases of the Middle and Late Pleistocene, and often separated by interstadial or interglacial soil strata indicating stabilization and climatic amelioration. Moreover, it was found that the relative carbonate contents of analyzed sections, that is, the relative contents of calcite and dolomite, differ consistently between the deposits of different glacials or stadials. Fig. 1 is a histogram-based set of curves indicating the frequency of dolomite contents as determined from a total sample of 302 analyses (Hädrich, 1975). On the top are Würmian loesses, followed by Russian ones. The two lower curves are from earlier deposits and may well correspond to Mindel and

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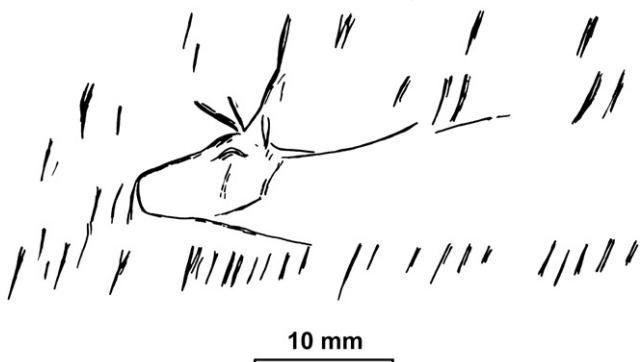


**Fig. 1.** Frequency distribution of dolomite contents for 302 loesses from open-air sites in central Europe. YL ('younger loess') is of the Würm glacial, ML ('middle loess') of the Riss, and OL ('older loess') is from two earlier facies (after Hädrich, 1975).

Günz, respectively (the traditional Alpine glacial sequence is applied in the study region). Relative content of dolomite consistently increases with decreasing age of loess strata.

The traditional explanation for this phenomenon had been that the loesses, once deposited, had been subjected to progressive weathering, with preferential mobilization of the more soluble calcite fraction. In other words, the younger loess is, the lower its residual calcite content.

Over 30 years ago, Friedhelm Hädrich from the Institut für Bodenkunde und Waldernährungslehre at the University of



**Fig. 2.** Engravings on an eagle ulna fragment from the Magdalenian horizon of Gudenus Cave, representing the only known Palaeolithic engravings found in Austria.

Freiburg examined this trend in the loesses of the upper Rhine valley. Arguing that the decrease in calcite could not be due to postdepositional alteration, he proposed the pedogenetic enrichment hypothesis, according to which the pronounced stepped profile in the physical as well as chemical characteristics of loess sequences is a function of source characteristics rather than weathering (Hädrich, 1975). There was either a progressively greater exposure of dolomite sources to loess-forming processes, or there was a re-cycling of older loesses, to which new material of higher dolomite content was being added, resulting in an apparent enrichment of dolomite in younger facies. A selective dolomite weathering in older deposits, attributable to the higher solubility in lower CO<sub>2</sub> pressure relative to calcite, as it has been proposed for Pleistocene gravels, does not seem to account for the carbonate ratio as a function of depth. A similar bias in favour of dolomite content with increasing age has even been observed in gravels from the Günz to the Würm (Fezer, 1969), and is also more likely to be due to enrichment than to differential weathering.

## 2. The Gudenus Cave in Austria

The remaining problem with Hädrich's otherwise persuasive hypothesis was that as long as it was only being confirmed by more analyses of terrace deposits that were exposed to weathering it remained effectively untested. It seemed to the author that to attempt refutation, one would have to analyze a sequence of loess deposits that had not been exposed to any significant weathering. The difficulty here was that most central European cave deposits with good loess components contain comparatively short sequences of sediments, most frequently limited to Würmian age (Lais, 1941; Schmid, 1958, 1969; Collcutt, 1979). Even at open-air sites, the frequency of surviving deposits decreases significantly with increasing antiquity, which is itself a possible indicator that older deposits have been re-cycled.

In the 1960s the author had secured suitable sediment samples from a site containing a long sequence of approximately known ages, and in 1976 he decided to use some of this material to test the hypothesis, with Hädrich's full co-operation. Although most analytical work was conducted prior to 1981, the results have not been made public so far. The site in question is one of the most important Palaeolithic sites of central Europe, the Gudenus Cave in Lower Austria. Located on the Kleine Krems river, not far above its confluence with the Grosse Krems, this cave is located in a deep gorge, about 8 m above the river, at the foot of a high vertical cliff of



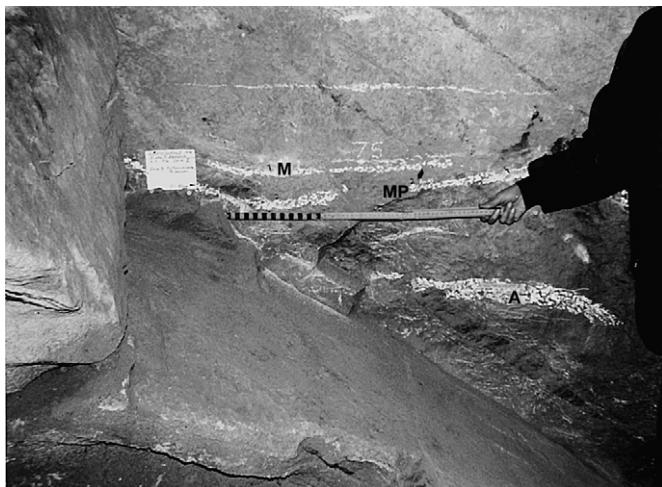
**Fig. 3.** The rock stack before its removal, in 1966. The top of the narrow sediment column concealed by it is where it meets the vertical cave wall. Three find sites of objects of the Mousterian occupation are indicated.



**Fig. 4.** Plan view of the excavation of part of the Mousterian layer within the narrow cleft formed by the cave wall (top) and the rock stack (bottom); five finds are shown in situ.

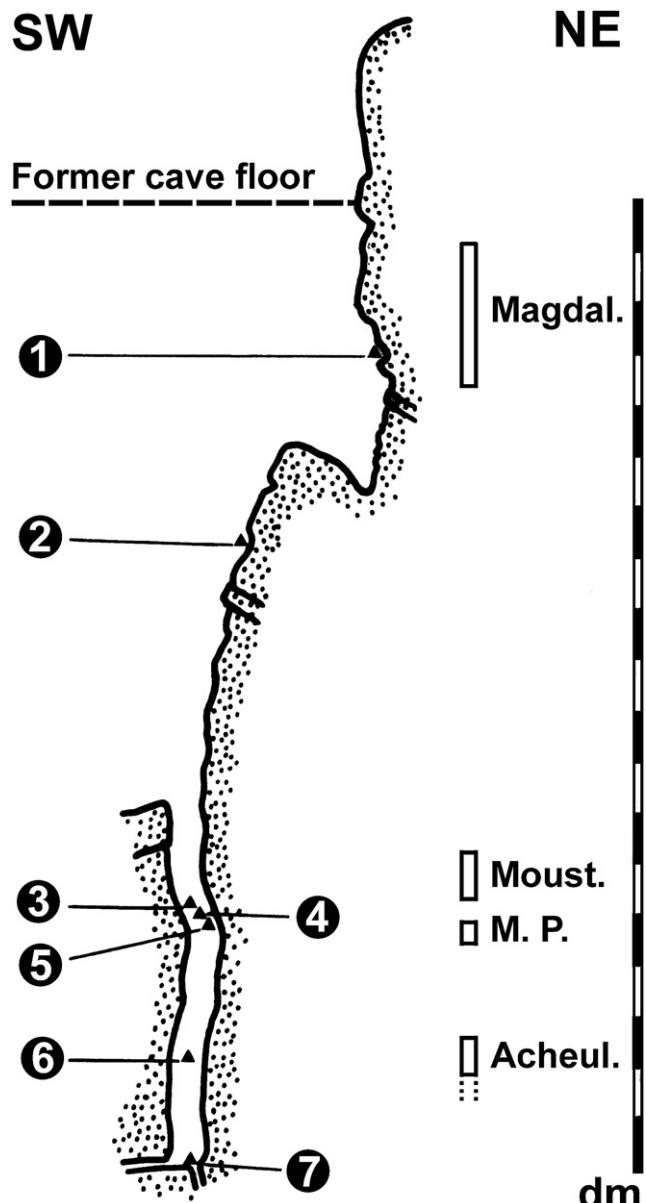
banded white marble (Hartensteiner Kalkmarmor, the major component) and blackish amphibolite (Late Palaeozoic). The cave, with its two large entrances 26 m apart, is exceptionally dry, free of condensation and seepage (even after heavy rainfalls), and it is entirely free of speleothems. Speleo-weathering is therefore thought to have been minimal.

The site is geographically close to major loess terrace deposits containing many occupation layers of the Upper Palaeolithic, including such famous sites as Willendorf, Krems and Galgenberg. The loesses of Lower Austria are among the most thoroughly studied in the world (Brandtner, 1950, 1954, 1956; Felgenhauer et al., 1959; Fink, 1954, 1956, 1962; Fink and Majdan, 1954; cf. Brunnacker, 1953; Zeuner, 1955). However, the Gudenus Cave is the district's only site with pre-Upper Palaeolithic occupation evidence, including the only major Acheulian biface industry of central Europe. The site's lowest of its four Palaeolithic occupations is Austria's earliest solid evidence of human presence (notwithstanding recent claims concerning the Repolust Cave, which are based purely on phylogeny of the ursine remains; cf. Bednarik, 1992: 34), and it contained the country's only Palaeolithic

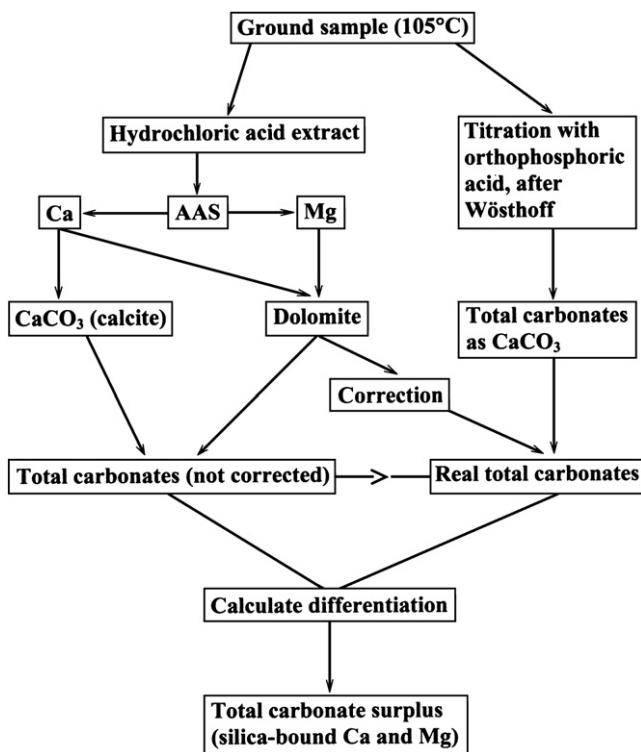


**Fig. 5.** Following the removal of the rock stack, nearly all sediment concealed by it has been excavated, the last remaining deposit is visible on the left. The course of the three lower occupation strata is marked on the vertical cave wall (M = Mousterian, MP = undetermined Middle Palaeolithic, A = Acheulian).

engraving (Fig. 2) and recovered Pleistocene human remains. Unfortunately, the cave was almost entirely excavated in 1883–1884 without separation of strata (Hacker, 1884), and much of what we know about the site stems from the subsequent detective work of Breuil and Obermaier (1908). They determined, from the stone implements and faunal remains, that there must have been two or more Palaeolithic occupations. Every one of their deductions has been shown to be correct by the author's research, begun in 1963. After the cave's flooding by a hydro-electric lake was announced in 1962, it was discovered that a rock buttress of the vertical cave wall consisted in fact of a rock stack (Fig. 3), concealing a narrow column of untouched sediment sequence representing the lower two thirds of the otherwise depleted cave fill (Fig. 4). In addition, several smaller pockets of primary sediment in recesses of the walls were discovered. Dozens of sediment samples were analyzed from the site during the subsequent 45 years, in order to reconstruct its stratigraphy, and this project is still continuing. It has produced the



**Fig. 6.** Section in Gudenus Cave at the location from which the seven samples being considered here were collected. The levels of the cultural deposits are shown (Magdalenian, Mousterian, undetermined Middle Palaeolithic, Acheulian).

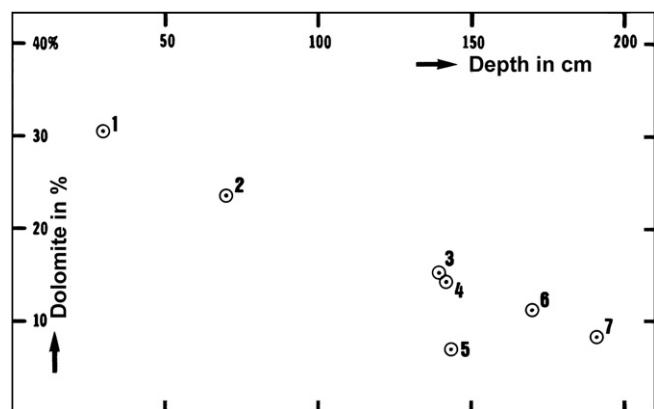


**Fig. 7.** Schematic depiction of the analytical procedures, carbonate differentiation analysis of Gudenus Cave sediment samples.

only palynological spectrum available from any Palaeolithic sequence in Austria (covering Rissian and Würmian deposits; **Bednarik, in preparation**), and has succeeded in reconstructing much of the cave's stratigraphy a century after the site had been effectively emptied of its sediment (Fig. 5).

### 3. Testing the pedogenetic enrichment hypothesis of loess formation

A series of stratigraphically secure samples (Fig. 6) collected in situ was subjected to carbonate differentiation analysis, to test the hypothesis of pedogenetic dolomite enrichment on an essentially unweathered series. Two principal methods were used to determine total carbonates (Hädrich, 1975: 97–8). One is titration, in which the pre-treated hydrochloric acid extract is buffered under addition of ammonium chloride (to keep the Mg in solution) and ammonium hydroxide. The Mg concentration obtained by titration allows the determination of dolomite, which is deducted from the total carbonates to establish the calcite fraction. In the second, more



**Fig. 8.** Dolomite fractions of total carbonates, plotted against absolute depths of the seven samples from Gudenus Cave.

accurate method, Ca and Mg were determined with an atomic absorption spectrophotometer (AAS). In this project, the instrument Perkin-Elmer 403 was used. Some known systematic error sources were allowed for, particularly the effect of cations derived from silicates or clays which was compensated for by applying Wösthoff's stoichiometric correction factor (dolomite fraction × 0.0855). This is essential because the treatment with hot HCl yields also Ca and Mg derived from clay minerals and readily weatherable primary silicates (such as the bedrock's minor amphibolite component), but the distortion is systematic and can be allowed for (see Hädrich, 1975: 98–9, and Fig. 1). A schematic depiction of the analytical procedures each sample was subjected to is provided in Fig. 7. The pre-treated sample was divided and subjected to AAS analysis, on the left, and parallel titration with orthophosphoric acid, on the right.

From among the available sediment samples, seven were selected because they had been recovered from vertically aligned exposures and from deposits not disturbed by any anthropic activity. The primary matrix resulting from their analysis (Table 1) shows, from left, the total carbonates by wet analysis, the corrected total carbonates and the AAS-derived CaCO<sub>3</sub>. This leads to the mathematical determination of MgCO<sub>3</sub>, and the dolomite and calcite fractions. The true carbonates were then obtained by a standard formula that corrects for Ca and Mg silicates, thus providing true carbonate differentiation as expressed by calcite and dolomite contents, as follows:

$$\text{MgCO}_3[\text{I}] = \frac{\text{real carb.}_{\text{B}} \times \text{MgCO}_3[\text{D}]}{\text{total carb.}_{\text{E}}} \quad (1)$$

The corrected calcium and dolomite fractions are then shown as percentages relative to real total carbonates. From this the

**Table 1**  
Primary matrix of results of the carbonate differentiation analysis, Gudenus Cave, Austria

No.	A Total carb. titrat.	B 'Real' carb.	C AAS- derived CaCO <sub>3</sub>	D AAS- derived MgCO <sub>3</sub>	E Total carb.	F Uncorr. dolomite	G Uncorr. calcite	H Corr. CaCO <sub>3</sub>	I Corr. MgCO <sub>3</sub>	J Corr. dolomite	K Corr. calcite	L (y) Dolomite of real carbonate	M (x) Depth in cm
1	13.47	13.47	14.73	2.39	17.12	5.23	11.89	11.59	1.88	4.11	9.36	30.5	30
2	4.84	4.84	7.87	0.94	8.81	2.06	6.75	4.32	0.52	1.14	3.70	23.6	70
3	18.09	18.09	17.63	1.32	18.95	2.89	16.06	16.83	1.26	2.76	15.33	15.3	140
4	17.66	17.66	21.22	1.46	22.68	3.19	19.49	16.52	1.14	2.49	15.17	14.1	142
5	23.18	23.18	24.85	0.83	25.68	1.82	23.86	22.43	0.75	1.64	21.54	7.1	144
6	11.69	11.58	10.86	0.59	11.45	1.29	10.16	10.98	0.60	1.31	10.27	11.3	170
7	20.27	20.27	20.15	0.80	20.95	1.75	19.20	19.50	0.77	1.68	18.59	8.3	191

In column B, only No. 6 is corrected because in all others, total carbonate (E) exceeds the values in column A, which is attributable to the silica-derived carbonate. Columns H–L are based on the mathematical correction for the effect of silica-bound Ca and Mg.

**Table 2**

Regression analysis of carbonate differentiation analysis of Gudenus Cave sediments

x (depth) in cm	30	70	140	142	144	170	191
y (%)	29.9	24.4	14.9	14.7	14.5	11.0	8.15
dol. (%)	30.5	23.6	15.3	14.1	7.1	11.3	8.3

Regression analysis matrix:  $n = 7$ ;  $y = 29.45 - 0.141x$ ,  $r^2 = 0.89$ ;  $n = 6$ ;  $y = 29.86 - 0.135x$ ,  $r^2 = 0.995$ ;  $y$  = dolomite fraction prognosis; dol. = actual dolomite fraction of real carbonates.

percentage of the dolomite of real total carbonate is derived ( $y$ ) and correlated with the absolute depth of the sample ( $x$ ).

The dolomite fractions can now be compared vertically, and for this purpose they are arranged in a scatterplot, in which the abscissa represents absolute depth in centimetres, and the ordinates depict dolomite fractions of total carbonates (Fig. 8). It demonstrates an unexpectedly strong trend, except for one sample, No. 5. However, this sample comes from a fluvially affected stratum that contains thin bands of clearly fluvial sand rich in mica, even small lenses of worn fine gravel, from the last flooding episode of the cave (which resulted in fluvial wear of both lithic and osteal materials in this sediment stratum). Hence its carbonate can be expected to be distorted and should perhaps not be considered here.

#### 4. Discussion

The final set of dolomite fractions has been subjected to a regression analysis and *ex post facto* prognosis of ideal values. It produced an exceptionally close correspondence between ideal predictions and actual dolomite fractions of real carbonates if sample No. 5 is disregarded. With that sample, the proportion of variance  $r^2$  is 0.89, but by deleting the anomalous sample of fluvial contamination,  $r^2$  rises to a near-perfect 0.995, or a correlation coefficient of 0.9975 (Table 2). This is much better than could possibly be expected under essentially perfect conditions, which would demand a constant rate of sedimentation together with an almost perfectly regular rate of pedogenetic dolomite enrichment. Therefore the correlation is regarded as extraordinarily and unexpectedly strong (Fig. 9).

This attempt to refute the enrichment hypothesis of loess formation has therefore failed convincingly. The observation that a continuous sequence of Rissian and Würmian deposits which has not been exposed to effective postdepositional weathering exhibits

such a pronounced enrichment of dolomite relative to total carbonate as a function of time provides very strong support for the hypothesis. Indeed, the author cannot perceive an alternative interpretation for this evidence than to accept that Pleistocene loesses consist largely of recycled sediments, to which dolomite has been preferentially added. This finding is likely to be valid elsewhere as well, and it is favoured by several empirical and logical observations. For instance, the argument of post-genetic weathering of calcite is illogical, because each loess stratum would have been subjected to weathering during the succeeding pluvial or stadial phase, the cumulative effect should be greatest on the lowest rather than the uppermost layer. Similarly, the concept of a re-cycling of sediment is supported by the increasing paucity of deposits with increasing age, and the concept of dolomite enrichment is corroborated by the similar trend in Pleistocene gravels (Fezer, 1969).

This result suggests also that loess strata can be roughly dated by this method, once local loess carbonate fractionation has been calibrated. Relative calibration would be achievable with cultural or palaeontological debris, as in the case of the Gudenus Cave; absolute calibration is possible by luminescence dating or one of the radiometric methods. It needs to be emphasized that the simplicity and economy of this potential pedogenetic dating method of aeolian sediments render it most attractive for Quaternary research, particularly in specific Northern Hemisphere regions. While the potential possibilities of application to loesses may not appear to be a great incentive for considering this method in other world regions, it should be noted that the theoretical principle applies wherever a compositional variable is a function of time. Quantification of such variables is likely to be of relevance to geochronology, which, after all, can often provide more reliable dating than the carbon isotope analysis of 'chronocentric archaeology' (Lewis-Williams, 1993: 49).

#### Acknowledgments

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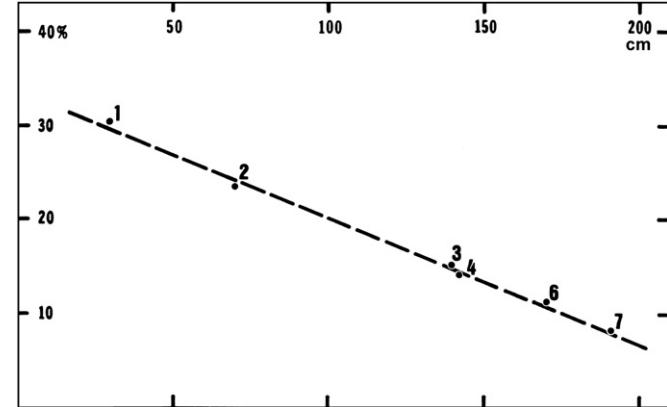


Fig. 9. Correlation of the dolomite fractions of carbonates of the six conforming samples, with the predicted trend as a function of relative age and dolomite enrichment.

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