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Growth rates of pedogenic carbonate coatings on coarse clasts

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Abstract

Growth rates of pedogenic carbonate coatings on clasts can be used as a simple quantitative index of soil and sediment age, as well as a chronological framework for palaeoecological reconstructions. They are also probably connected with general intensity of formation of Bk horizons in soils. Previously, data on coating growth rates were restricted ecologically and geographically to desert regions of North America. This paper presents growth rates of Holocene pedogenic carbonate coatings on clasts within an extended range of environments, calculated on the basis of archaeological and radiocarbon dating. The rates, in this study, are higher than in earlier reports. Carbonate coatings can thicken with rates up to 1 mm/1000 years or higher in semi-arid and semi-humid climates.

At least five factors are likely to control growth rates: (1) climate, (2) lithology of carbonate parent material, (3) depth under the soil surface, (4) clast size, (5) bulk density and composition of cutans. Favorable factors for comparatively rapid coating thickening seems to be climatic conditions, ranging from semi-arid to semi-humid, high carbonate content of parent material and large size of clasts. There is also an optimal depth of carbonate coating growth in a soil profile. Little information on bulk density and composition of cutans is available, but they appear to play an important role as one of the factors governing growth rates of pedogenic carbonate coatings on clasts.

1. Introduction

Pedogenic carbonate coatings on coarse clasts, otherwise called cutans or pendents, are common in stony soils of arid and semi-arid regions. In soils formed on limestones, they can occur also in humid climates. During the last two decades the process of formation of Bk horizons (Gile et al., 1966; Birkeland, 1984; Machette, 1985), palaeoenvironments (Courty et al., 1994; Wang et al., 1996; Monger et al., 1998; Pustovoytov, 1998; Buck and Monger, 1999) and the age of soils and sediments (Ku et al., 1979; Pierce, 1985; Amundson et al., 1994; Vincent et al., 1994) have been successfully studied, based on pedogenic carbonate accumulations on clasts. The thickness of carbonate coatings has been noticed to be a function of soil age (Gile et al., 1966; Machette, 1985; Pierce, 1985; Vincent et al., 1994; Treadwell-Steitz and McFadden, 2000). However, direct data on the growth rates of pedogenic carbonate cutans on clasts is rather rare in the literature and restricted ecologically and geographically to desert regions of North America (Ku et al., 1979; Pierce, 1985; Vincent et al., 1994).

Further assessment of the growth rates of pedogenic carbonate coatings on coarse clasts is important for two reasons. First, growth rate can be used as a simple quantitative index of soil and sediment age (Pierce, 1985; Vincent et al., 1994) as well as a chronological framework for palaeoecological reconstructions, based on the data recorded in the cutans (Courty et al., 1994; Wang et al., 1996; Monger et al., 1998; Pustovoytov, 1998; Buck and Monger, 1999). Second, the coating growth rates are probably connected with general intensity of formation of Bk horizon in soils, which is of great interest for pedologists (Gile et al., 1966; Birkeland, 1984; Machette, 1985; McFadden and Tinsley, 1985; Pendall et al., 1994).

The goal of the present study is to evaluate the growth rates of pedogenic carbonate coating on coarse clasts within an extended environmental range and to analyze some factors controlling them. Many of the calcareous cutans were collected in late Holocene soils formed on the surface of archaeologically dated earth and stone constructions or cultural layers. Such objects were, to my knowledge, not examined broadly by previous

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researchers in connection with pedogenic carbonate coatings. They provide a precise maximum age of carbonate accumulation on clasts and, on the other hand, suggest no dramatic environmental changes, which may introduce additional difficulties in interpreting the processes of carbonate cutan formation (Amundson et al., 1994; Wang et al., 1996).

2. Materials and methods

Only carbonate cutans of undoubtedly pedogenic origin were collected for the study. With very rare exceptions (Amundson et al., 1997), they are placed on the bottoms of the clasts within soil profiles. At least 10 clasts 3–15 cm in length were considered. The measurements of the coating thickness are based on the previously described approach (Pierce, 1985; Vincent et al., 1994; Treadwell-Steitz and McFadden, 2000). They were made with a simple ruler with mm-scale allowing a precision of about 0.25 mm. Although this resolution is lower than the one used in the cited works (0.05 mm), it is sufficient to demonstrate some principle features of rates of pedogenic carbonate cutan formation. An approximate carbonate content of soil matrix was inferred on the basis of reaction with 10% HCl ("carbonate-rich" $\geqslant$4–7% $CaCO_3$ and "carbonate-poor" $\leqslant$4–7% $CaCO_3$ (Finnern et al., 1996)).

In most of the samples pedogenic carbonate coatings were dated based on archaeological information. Only undestroyed artificial earthworks or cultural layers with well pronounced soil profiles on their surfaces were chosen for the study. In some cases radiocarbon dating with liquid scintillation spectrometry was involved. Radiocarbon analyses were carried out at the Institute of Geography RAS (Moscow, Russia) and the State Scientific Centre of Environmental Radiogeochemistry (Kiev, Ukraine).

3. Results and discussion

3.1. Sites and soils

The sites under investigation are listed below. All soils are classified according to the FAO (1990) system.

1. *Ipf, Nördlinger Ries* (*Germany*). A rendzic Leptosol (Fig. 1b) under a meadow vegetation developed on the

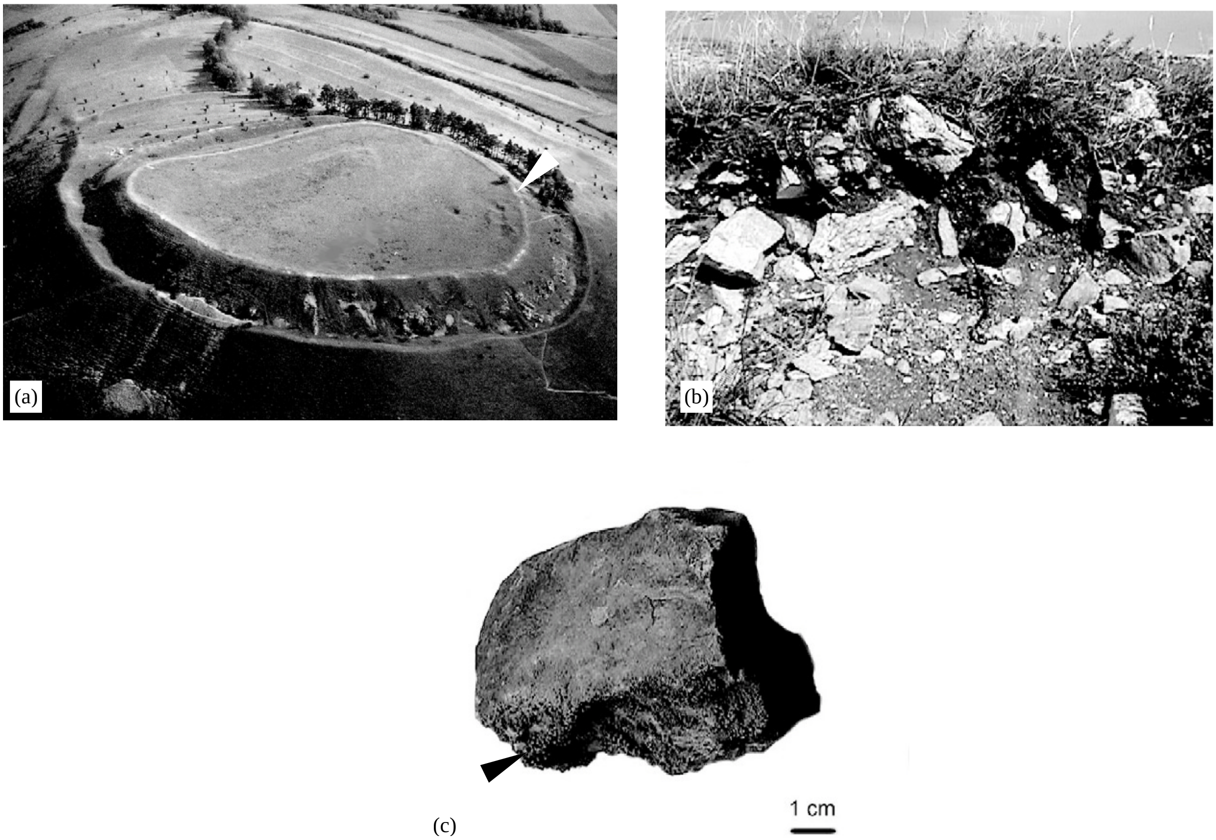

Fig. 1. Site Ipf, Nördliger Ries (Germany). (a) Air view of the settlement (photo from Krause, 1992). Ruins of a fortification wall embracing the mountain plateau are well seen. Arrow shows the position of a renzina-like soil profile considered (b). (b) A renzina-like soil profile developed at the surface of the wall ruins. Diameter of the black disk in the centre of picture is 5 cm. (c) A coarse clast from the soil profile.

ruins of a city wall made of limestone blocks. The wall had surrounded a settlement on the plateau of the mount Ipf (Fig. 1a). The soil development started presumably after the last settlement phase, 500–100 years BC (Krause, 1992). Pedogenic carbonate cutans occur below 20 cm depth down to the observed lower border of the soil profile, 50 cm below the soil surface. The cutans are about 2.0 mm thick.

2. *Novosvobodnaya*, *North-West Caucasus* (*Russia*). Carbonate coatings were taken from a weakly developed Luvisol under a deciduous forest on the surface of a ca. 5000 year old burial mound, studied by Alexandrovsky and Chichagova (1998). The coatings occur at 40–130 cm depth (lower border of the profile), and the coating thickness is about 1.5 mm.

3. *Berelekh*, *Upper Valley of Kolyma River* (*Russia*). The mollic Leptosol is situated on a steep southern slope in the Berelekh Valley. The vegetation is represented by a tundra-steppe. Pedogenic carbonate coatings, approximately 2.5 mm, are identified at 25–120 cm. Based on radiocarbon dating, these cutans have developed presumably through the major part of the Holocene (Pustovoytov, 1998).

4. *Troy*, *Western Anatolia* (*Turkey*). Pedogenic carbonate cutans were collected in a mollic Leptosol on the surface of the ca. 2000 years old burial mound Beshik–Sivritepe (Rose, 1999). The mound is covered by maquis vegetation. Coarse clasts with carbonate cutans of about 1.0 mm thick occur at a depth of 40–60 cm below the soil surface.

5. *Troy*, *Western Anatolia* (*Turkey*). The soil profile studied was a calcic Luvisol in the central part of the Troyan Plateau under maquis vegetation (Pustovoytov, 1999). Pedogenic carbonate coatings, about 5 mm thick, are found between 30 and 50 cm (bottom of the pit) below the soil surface.

6. *Hirbet ez-Zeraqon*, *North Jordan Highlands* (*Jordan*). Carbonate coatings, about 3 mm thick, were observed on undersides of bones and pottery within a 1–2 m thick cultural layer of an Early to Middle Bronze Age settlement. No pedological observation in the field was conducted and we have only samples at our disposal, so there is no exact evidence on localization of the coatings within the cultural layer. The final phase of sedimentation and the beginning of soil formation occurred about 4500 years BP (Mittmann, 1994).

7. *Tell Mozan*, *North Mesopotamia* (*Syria*). A tell of Bronze Age, about 20 m high (Fig. 2a) is situated on a broad plain to the south of the Taurus Mountains. Weakly developed calcic Luvisols have been formed on loamy substrate on the surface of the tell (Fig. 2b). According to archaeological estimates, pedogenesis began about 3300 years BP (Dohmann-Pfaelzner and Pfaelzner, 1999). Pedogenic carbonate coatings (Fig. 2c) on small pebbles and pottery are concentrated at a depth of 30–90 cm below the soil surface. They are about 1.5 mm thick.

8. *Emar*, *Northeast Mesopotamia* (*Syria*). This Bronze Age site is situated on a limestone residual mountain in the Euphrates Valley (Fig. 3a). Pedogenic carbonate cutans are found on pebbles within a 20 cm thick layer at the pit bottom within the site. The pebble layer is overlain by limestone blocks (Fig. 3b). The age of the pebble layer is about 4000 years BP (U. Finkbeiner, pers. comm.) and the thickness of coating is about 4 mm (Fig. 3c).

9. *Qatna*, *East Mesopotamia* (*Syria*). Weakly developed soil profiles (taxonomic range is unclear, only compaction and slight humus coloring in the uppermost 20 cm could be seen) are formed on the surface of 20 m high city walls made of sandy loam material. Pedogenic carbonate coatings are identified on stone undersides at 30–60 cm depth. The age of the walls is not precisely determined, but archaeological context suggests that the walls may have been erected roughly 3000 years BP (P. Pfaelzner, pers. comm.). Coating thickness is about 0.5 mm.

Additionally, data for pedogenic carbonate coatings on clasts for Brögger, Spitsbergen (#10) (Courty et al., 1994), Providence Mountains, USA (#11) (Wang et al., 1996) and Palo Duro Wash, Southwestern USA (#12) have been taken into consideration.

The sites described above were roughly grouped together according to climatic conditions (Table 1) and carbonate-related lithology of parent material. In relation to moisture conditions the main climatic groups are: humid (sites 1 and 2), semi-humid (sites 3–5 and 10), semi-arid (sites 6–9), and arid (sites 11 and 12) whereas in relation to temperature: cold (sites 3 and 10), temperate (sites 1, 2 and 11) and warm (sites 4–9 and 12). The subdivision with respect to lithology of carbonate parent material was as follows: primarily limestone (sites 1, 8 and 11), no or little limestone and carbonate-rich matrix (sites 2, 4, 6, 9 and 12) and no or little limestone and carbonate-poor matrix (sites 3, 5 and 7).

These subdivisions are rather tentative. However, such a scheme seems to be reasonable for the relatively small number of estimations in this work and can serve as basis for further, more detailed studies of growth rates of pedogenic carbonate coatings.

3.2. *Values of growth rates of pedogenic carbonate coatings*

The age of pedogenic carbonate pendents on coarse clasts, their thickness and duration of their formation, together with calculated mean growth rates are presented in Table 2. Some data published previously are included also (Ku et al., 1979; Pierce, 1985; Courty et al.,

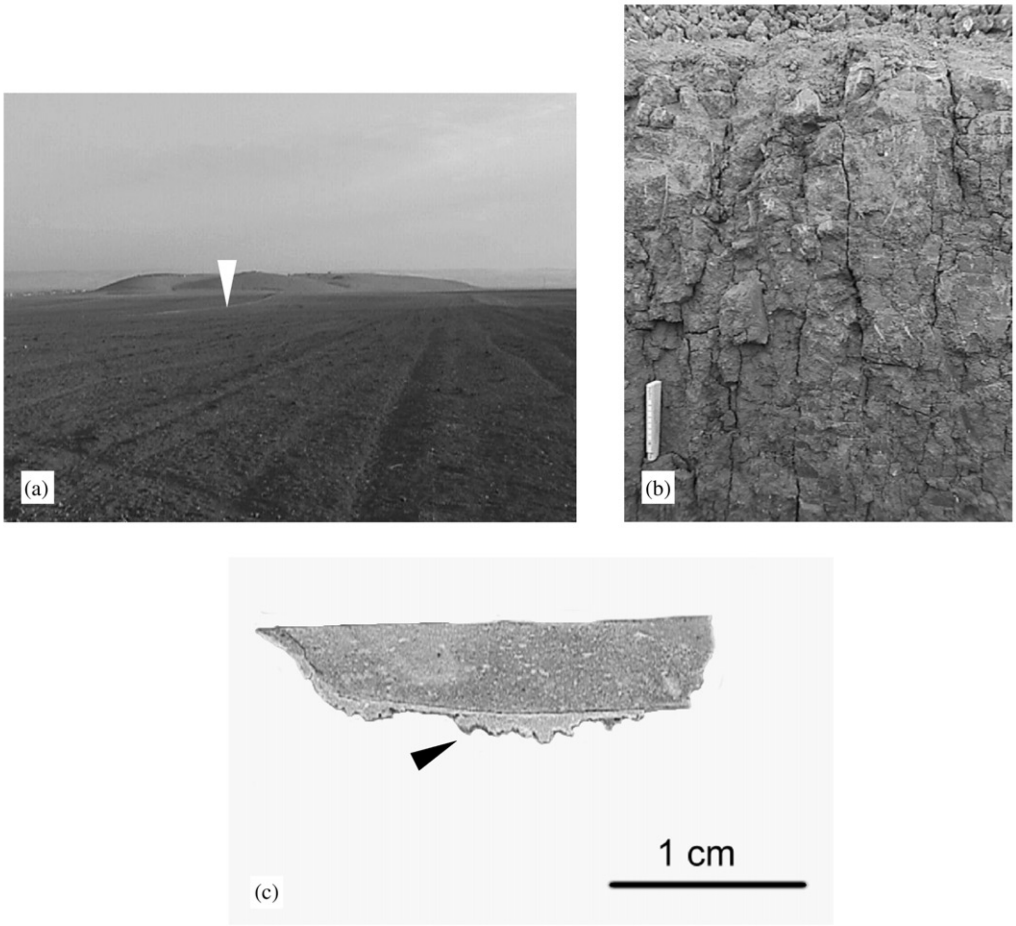

Fig. 2. Site Tell Mozan, North Mesopotamia (Syria). (a) General view of the tell from south. The Taurus Mountains are seen on the background. Arrow indicates the location of excavation area with weakly developed calcic Luvisols in the upper part of cultural layer. (b) The upper ca. 80 cm part of cultural layer with a weakly developed calcic Luvisol profile. A Bk horizon with carbonate concretions is located at 25–40 cm depth. (c) Pottery fragment from the profile.

1994; Vincent et al., 1994; Wang et al., 1996; Pustovoytov, 1998; Treadwell-Steitz and McFadden, 2000).

Ideally, if a clast-bottom coating thickens steadily in time, its growth rate can be worked out through dividing the coating thickness by the time of coating formation. However, in reality coating formation on clast undersides is a process with unknown dynamics, which may include not only accumulation of calcium carbonate but also its re-dissolution. Hence, in the absence of any other chronological information, only average rates can be calculated. Furthermore, archaeological ages of artificial earth constructions and cultural layers provide, in the strict sense, maximum ages of soils and pedogenic carbonate coatings.

In some cases, radiocarbon ages of calcium carbonate were invoked. Interpretation of radiocarbon dates of pedogenic carbonates faces two major problems. The first was referred to as "limestone dilution effect", which was supposed to be responsible for too old ^{14}C-dates (Ruhe, 1967; Williams and Polach, 1971; Chen and Polach, 1986). Later, it has been found, however, that for pedogenic carbonates this mechanism plays a limited role if any, because secondary carbonates in soils are formed in isotopic equilibrium with CO_2 of the soil atmosphere (Cerling, 1984, 1991; Cerling et al., 1989; Cerling and Wang, 1996). This suggests that the $^{14}C/^{12}C$ ratio in pedogenic carbonates at the moment of precipitation corresponds to the atmospheric one (Wang et al., 1994, 1996; Amundson et al., 1994). Too old radiocarbon ages of pedogenic carbonates can be explained alternatively by mechanical incorporation of limestone particles of parent material (Amundson et al., 1989) and/or a high concentration of "old" carbon CO_2 fraction in the soil air introduced through the microbial activity (Wang et al., 1994, 1996; Amundson et al., 1994).

Another problem encountered is that pedogenic carbonate may be contaminated by ^{14}C after precipitation. The intensity of ^{14}C exchange between carbonate material and environment depends on the depth below

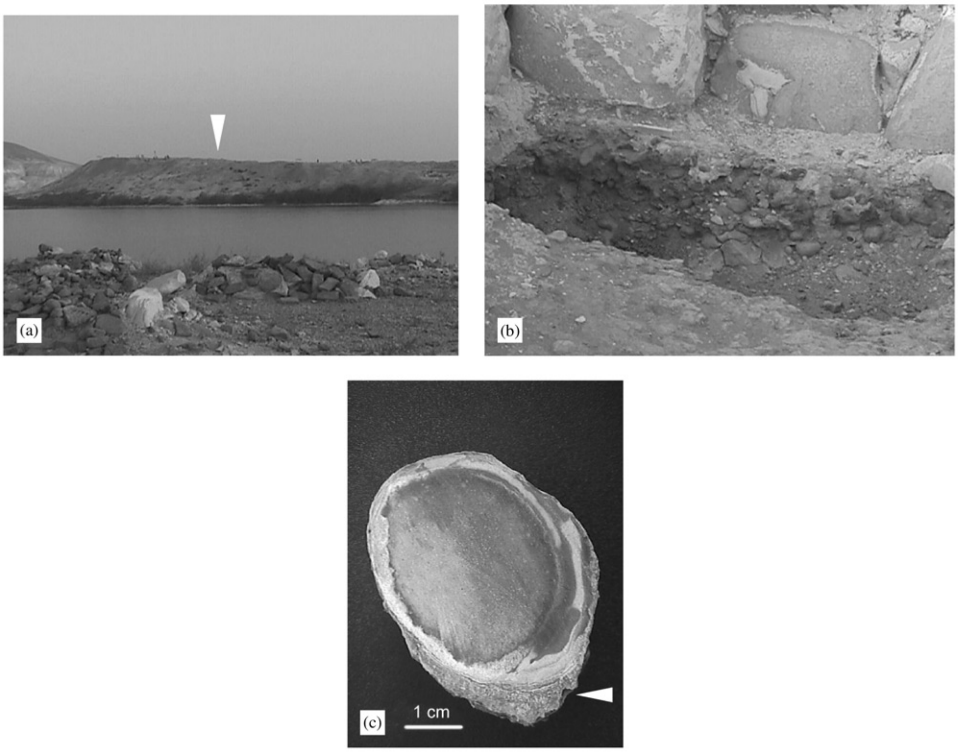

Fig. 3. Site Emar, Northeast Mesopotamia (Syria). (a) General view of the site from west. Arrow indicates the position of the excavation area with pedogenic carbonate coatings on pebbles. (b) Cultural layer in the excavation area with pedogenic carbonate coatings on pebbles. The upper unit of cultural layer consists of limestone blocks, whereas the lower one is presented by an estrich layer with pebbles. (c) A cross section of a pebble from the estrich layer.

Table 1
Climatic conditions of study areas

Site	Key station	Mean annual precipitation (mm)	Coefficient of moisture[a]	Mean annual temperature (°C)	Source
1. Ipf	Heidenheim	879	> 1.33	6,8	World Atlas (1964), Klimadiagramme Baden-Württemberg (2000)
2.Novosvobodnaya	—	ca. 800	1–1.33	8	Shashko (1961), Alexandrovsky (2000)
3. Berelekh	Berelekh	313	1–0.5	−13.0	Shashko (1961), Climate reference book of the USSR (1966)
4 and 5. Troy	Canakkale	680	0.45–0.68	15.2	World Atlas (1964), Alex (1985)
6. Hirbet ez-Zeraqon	Irbit	482	0.35	18.0	Perrin and Wallen (1968), Zohary (1973)
7. Tell Mozan	Qamishlieh	430	0.31	no data	Perrin and Wallen (1968), Zohary (1973)
8. Emar	Aleppo	358	0.28	17.7	Perrin and Wallen (1968), Zohary (1973)
9. Qatna	Homs	364	0.25	16.7	Perrin and Wallen (1968), Zohary (1973)

[a] Ratio precipitation/evapotranspiration.

the soil surface. There are several factors controlling this process. The aridity of climate and a high density of carbonate material seems to suppress the ^{14}C contamination (Bowler and Polach, 1971; Chen and Polach, 1986; Amundson et al., 1994; Pendall et al., 1994). On the other hand, a number of radiocarbon dates on carbonate materials with independently determined ages indicates that the carbonate may be preserved in soils without any diagenetic ^{14}C contamination (Evin et al., 1980; Haas and Haynes, 1980; Folk and Valastro, 1985;

Table 2
Growth rates of pedogenic carbonate coatings on clasts

Site	Coating thickness (mm)	Age of parent substrate (years BP)	^{14}C-age of carbonate material (years BP, uncalib.)	Assumed duration of coating formation (years)	Calculated growth rate of coating (mm/1000 years)	Source
1. Ipf (W-Germany)	2	ca. 2000 (Krause, 1992)		⩽2000	⩾1	This study
2. Novosvobodnaya (Russia, NW-Caucasus)	1.5	ca. 5000 (Alexandrovsky, 2000)		⩽5000	⩾0.3	This study
3. Berelekh (Russia, NO-Siberia)	4	Holocene		10,000[a]	0.4	Pustovoytov (1998)
4. Troia, Beschik-Sivritepe (NW-Turkey)	1	ca. 2000 (Rose, 1999)	1050±80 (KI-5174)[b]	⩽2000	0.5	This study
5. Troia, Low Plateau (NW-Turkey)	5	No data	2390±95 (KI-5176)[c] 2250±100 (KI-5177)[d] 2040±105 (KI-5178)[e]	500	10	This study
6. Hirbet ez-Zeraqon (N-Jordan)	3	ca. 4500 (Mittmann, 1994)		⩽4500	⩾0.67	This study
7. Tell Mozan (NO-Syria)	1.5	ca. 3300 (P Pfälzner, pers. comm.)		⩽1300	⩾0.45	This study
8. Emar (NW-Syria)	4	ca. 4000 (Finkbeiner, pers. comm.)		⩽4000	⩾1	This study
9. Qatna (W-Syria)	0.5	ca. 3000 (P Pfälzner, pers. comm.)		⩽1500	⩾0.17	This study
10. Brögger (Spitsbergen)	1	130,000–290,000		⩾200, 000[f]	⩽0.005	Courty et al. (1994)
11. Providence Mountains (SW-USA)	⩾1	Quaternary		7000[g]	⩾0.14	Wang et al. (1996)
12. Palo Duro Wash (SW-USA)	1	8000–15,000		⩽10, 000	⩾0.1	Treadwell-Steitz and McFadden (2000)

[a] Interpretation of Pustovoytov (1998).

[b] ^{14}C-dating by Dr. N. Kovalykh and Dr. V. Skripkin (State Scientific Centre of Environmental Geochemistry, Kiev, Ukraine).

[c] Inner layer.

[d] Middle layer.

[e] Outer layer.

[f] Interpretation of Courty et al. (1994).

[g] Calculated on the basis of ^{14}C-datings of inner and outer layers of coatings under assumption of a linear growth over the whole time of coating formation; the Pleistocene coatings were not considered.

Zouridakis et al., 1987; Freundlich et al., 1989; Amundson et al., 1994; Wang et al., 1996; Monger et al., 1998; Buck and Monger, 1999; Pustovoytov, 1999).

Calculated coating growth rates are plotted in Fig. 4. It is evident that the coatings grow more rapidly in semi-arid to humid than in arid climates. Under semi-arid to semi-humid climatic conditions, growth rates can reach 1 mm/1000 years or higher.

An exceptionally rapid coating thickening is calculated for site 5. For calculation purposes the time of carbonate coating here was restricted to the ^{14}C ages of the inner and outer carbonate laminae. A linear coating growth over time was assumed. Until the processes of radiocarbon exchange in soils are proved sufficiently, it is very difficult to explain this extremely high value. It could be indeed a very high rate of carbonate accumulation. Furthermore, the carbonate coatings at this site were covered by a thin layer of clay cutans, which indicates an intensification of clay illuviation and as a rule a deeper leaching of carbonates (Birkeland, 1984). Therefore, a contribution of partial re-crystallization and radiocarbon contamination to the resulting ^{14}C age cannot be excluded.

As already mentioned, most of the values represent minimal carbonate coating growth rates, whereas actual rates and their dynamics remain to be explored. For the moment it can be only presumed that the pedogenic carbonate coatings studied grow mainly more or less linear in time and actual growth rates are not much higher than the calculated minimal ones. First, all the sites are of Mid- to Late Holocene age, and so did not experience dramatic environmental changes, as took place, for example, at the Pleistocene–Holocene transition in the Mojave Desert (Wang et al., 1996). Second, the ^{14}C age of carbonate coatings on stones from the soil on the Beshik–Sivritepe mound (site 4) was approximately the half of the age of the monument, the latter being 2000 years. This radiocarbon age correlates perfectly with the model for ^{14}C ages of carbonate pendents thickening linear in time without any contribution of "old" carbon and diagenetic contamination (Amundson et al., 1994).

3.3. Factors controlling growth rates of pedogenic carbonate coatings

Among numerous factors controlling the growth rates of pedogenic carbonate cutans on coarse clasts, only several ones of paramount importance are considered below: climate, lithology of carbonate parent material, depth below the soil surface, clast size, and bulk density and composition of cutans.

1. *Climate.* Pedogenic carbonate coatings from semiarid to humid climates show basically higher growth rates than those developed under arid climatic conditions (Fig. 4). An exclusively high value of coating thickening at site 5 falls within this climatic range as well, although this growth rate cannot be interpreted unambiguously (see above). One of the reasons for

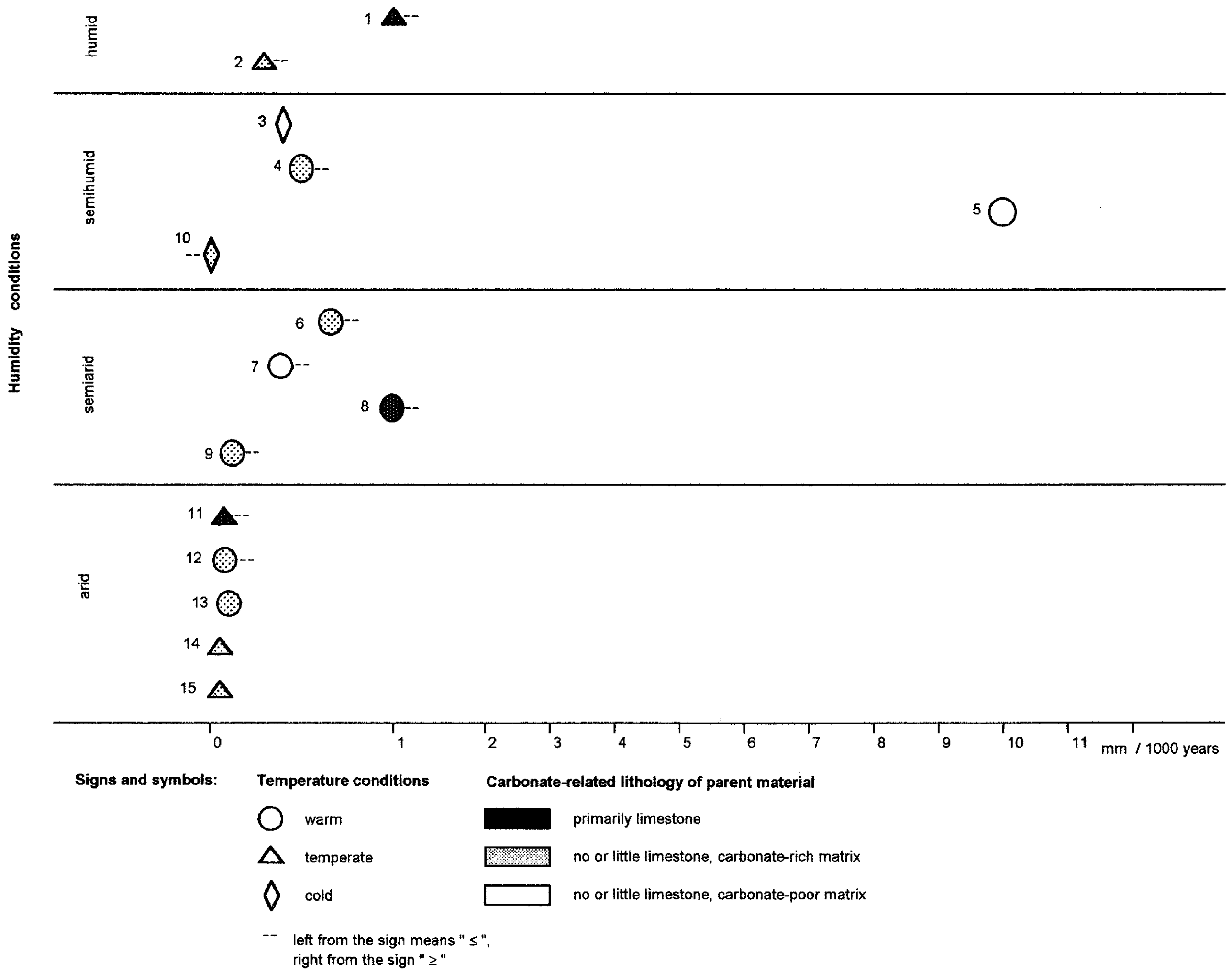

Fig. 4. Growth rates of pedogenic carbonate cutans on clasts. Approximate differentiation into climatic groups and carbonate richness of parent substrates are also plotted. Data from Ku et al. (1979) (13), Pierce (1985) (14) and Vincent et al. (1994) (15) are given for comparison.

higher growth rates of carbonate coatings in non-arid climates could be more intensive leaching of carbonate from the upper part of soil profile (Arkley, 1963; Birkeland, 1984; Machette, 1985). The influence of temperature conditions is less evident, but the cutan thickening in warm climates seem to be somewhat more rapid. Temperature can affect the intensity of calcium carbonate accumulation on clasts in several ways. First, higher temperatures may promote evaporation in soil and increase concentration of carbonate solution, which, in turn, intensifies the process of coating formation. Second, calcium carbonate solubility in water decreases with growing temperature (Butler, 1982) and a warmer temperature regime should favor precipitation of carbonates. On the other hand, an increase of partial pressure of CO_2 in soil under higher temperatures makes soil solutions more aggressive in relation to carbonates (Jakucs, 1977). The cumulative effect of temperature on growth rates of pedogenic carbonate may be a complex combination of these phenomena.

2. *Carbonate content of parent material.* There are few data on dependence of coating growth rates on lithology of parent material. Vincent et al. (1994) found no definite relationship between thickness of carbonate coatings and content of limestone pebbles in soils of similar age. Treadwell-Steitz and McFadden (2000), however, demonstrated that the values of coating thickness on limestone pebbles and non-calcareous pebbles are statistically different for 120–240 ka years old desert soils. In younger soils (75–120 and 8–15 ka years old) these relationships were not statistically different. The data, in this study, suggest that minimal values of growth rates of pedogenic carbonate coatings are slightly higher in soils on primary limestone substrates (Fig. 4).

3. *Depth below the soil surface.* In this study, as in some previous works (Pierce, 1985; Vincent et al., 1994; Treadwell-Steitz and McFadden, 2000), only carbonate coatings from a depth with their maximum thickness were taken into account (at the sites 1 and 5 soil pits were not deep enough to make sure that the coatings observed were the thickest in the soil profiles). Generally, growth rates of pedogenic carbonate coatings on clasts are presumably dependent on depth under the soil surface. The thickness of carbonate cutans on stones varies within a soil profile reaching its maximum at a certain depth (Vincent et al., 1994; Pustovoytov and Targulian, 1996; Treadwell-Steitz and McFadden, 2000). It suggests that the coatings thicken with different rates at different depths. Optimal depths for carbonate cutans formation are most probably lower in less arid climates (Arkley, 1963; Birkeland, 1984; Retallack, 1994). Carbonate accumulation on clasts may persist at one depth while it is already over at another (deeper) one. According to radiocarbon dates, carbonate coatings in lower parts of soil profiles in the Mojave Desert have developed in Late Pleistocene, whereas in the upper parts of soil profiles the coating formation took place during the Pleistocene–Holocene transition (Wang et al., 1996).

Table 3
Bulk density and carbonate content of coatings

Site	Bulk density (g/cm^3)[a]	$CaCO_3$ content (%)[b]
3. Berelekh	1.68	70
5. Troy	1.95	94

[a] Determined by the paraffin-clod method (Chleborad et al., 1975).
[b] Determined by dissolution in 10% HCl.

4. *Clast size.* Rates of thickening of carbonate coatings may be influenced by size of clasts on which they form. Treadwell-Steitz and McFadden (2000) showed a linear relationship between clast diameter and coating thickness. This dependence becomes more pronounced with older soil age.

5. *Bulk density and composition of coating material.* Growth rates of carbonate pendants on clasts considered above are related to their thickness, i.e. a merely morphological property. Bulk density and composition of carbonate coatings may vary in a broad range and are probably dependent on parent material and some other local conditions of a site (Table 3). Exact relationships between bulk density, composition of coatings and the growth rates are not known. However, it seems to be plausible that, with all other factors being equal, coatings with higher porosity and concentration of admixtures show higher growth rates.

4. Conclusions

Growth rates of Holocene pedogenic carbonate coatings on clasts within an extended range of environments, in this study, were principally higher than reported previously. Carbonate coatings can grow with a rate of 1 mm/1000 years or higher in semi-arid to semi-humid climates.

At least five factors control growth rates: (1) climate, (2) lithology of carbonate parent material, (3) depth below the soil surface, (4) clast size, (5) bulk density and composition of cutans. Favorable factors for comparatively rapid coating thickening seems to be climatic conditions, ranging from semi-arid to humid, high carbonate content of parent material, and large size of clasts. There is also an optimal depth of carbonate coating growth in a soil profile. Little information on bulk density and composition of cutans is available, but they appear to play an important role as one of the factors governing growth rates of pedogenic carbonate coatings on clasts.

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