Depth to pedogenic carbonate horizon as a paleoprecipitation indicator?

Dana L. Royer*

Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, Connecticut 06520-8109, USA

ABSTRACT

An analysis of 1168 modern soil profiles from the U.S. Natural Resources Conservation Service yields no correlation between mean annual precipitation and depth to the top of the carbonate horizon ($r^2 = 0.03$; $p < 0.001$). Parent material and soil texture both play negligible roles in this regression. When combined with similar published studies (n = 1481), r^2 improves slightly ($r^2 = 0.31$; $p < 0.001$). Caution is therefore advised in using this or any previously published regression for inferring paleoprecipitation from paleosols. However, in the combined data set, carbonate horizon–bearing soils correlate with a mean annual precipitation of < 760 mm ($p < 0.05$). Thus the presence vs. absence of pedogenic calcium carbonate is a good indicator of paleoprecipitation above or below this value.

INTRODUCTION

Pedogenic (secondary) calcium carbonate is, by definition, a product of soil processes (Soil Survey Staff, 1996). The primary sources of calcium in such deposits are wind-carried particulates, usually in the form of carbonates, and dissolved Ca^{2+} in rain water (Gardner, 1972; Gile et al., 1979). On the basis of both mass-balance considerations of calcium and the lack of residual accumulations of refractory elements (e.g., Al, Si, Ti) in parent material, the weathering of calcium silicates is typically only a minor calcium source (Gardner, 1972; Bachman and Machette, 1977; Machette, 1985). In the southwestern United States, for example, it has been shown that the atmosphere is the primary source of calcium for pedogenic calcium carbonate (Gile et al., 1979). In regard to the source of the carbonate ion, assuming equilibrium with the soil CO_2, the decomposition of soil organic matter supplies most of the carbon; at shallow soil depths and in regions with low respiration rates, the atmosphere can also directly supply some of the carbon. Stable isotope research principally supports the organic matter pathway, as the $\delta^{13}C$ of pedogenic carbonate is usually offset from the surrounding organic matter by 14‰–16‰, consistent with the fractionations within this pathway (Magaritz and Amiel, 1980; Cerling et al., 1989; Quade et al., 1989).

Because pedogenic calcium carbonate is readily soluble, its depth in a soil profile is partially a function of rainfall. Jenny and Leonard (1934), the first to quantify this relationship, used mean annual precipitation (P) and depth to the top of the carbonate horizon (D) as variables. They established and analyzed soil pits at 5–10 km intervals along the 11 °C mean annual temperature

isotherm from eastern Colorado to western Missouri (n = 104). Regression analysis of their data treating P as the dependent variable yields an r^2 value of 0.64 and a standard error (σ) of 109 mm. Treating P as the dependent variable is necessary for work involving paleosols where P is unknown. Subsequent work has both refined (Arkley, 1963; Gile, 1977; Retallack, 1994a) and applied (Blodgett, 1988; Retallack, 1992, 1994a, 1994b, 1997; Quade and Cerling, 1995; Caudill et al., 1996) this relationship. In particular, Retallack (1994a) compiled a data set (n = 317) from 41 sources, including Jenny and Leonard (1934) and Arkley (1963), reporting an r^2 value of 0.62 and a σ of 141 mm, and then used this relationship to infer paleoprecipitation changes (range 250–650 mm·yr^{-1}) across the Eocene-Oligocene boundary in South Dakota. If it is robust and simple to implement, this relationship would represent a powerful paleoprecipitation indicator, because paleopedologists cannot confidently incorporate as many criteria (e.g., soil age, paleogeomorphic context, paleovegetation, seasonal distribution of paleoprecipitation, soil CO_2 concentrations) as can modern soil researchers. To test this model, an exhaustive generalized search of official U.S. soil type localities (n = 1168) was conducted.

METHODS

The U.S. Natural Resources Conservation Service (NRCS) regulates the classification of U.S. soils. Each soil series, the finest division within the NRCS classification, is referenced by an intensely studied official type locality. More than 19000 soil series exist and are accessible via the World Wide Web (www.statlab.iastate.edu/soils/osd).

All soil series containing calcic horizons (designated as Ak, Bk, Ck) were analyzed. The calcic

horizon is defined by the NRCS as "an illuvial horizon in which secondary calcium carbonate, or other carbonates have accumulated to a significant extent" (Soil Survey Staff, 1996, p. 13–14). Calcic horizons must be ≥15 cm thick, neither indurated nor cemented, ≥15% $CaCO_3$ by weight, and either ≥5% $CaCO_3$ by weight than the underlying horizon or ≥5% secondary carbonates by volume (Soil Survey Staff, 1996).

For all qualifying soils, depth to the top of the uppermost calcic horizon (D) and associated mean annual precipitation (P) were recorded. The NRCS reports both D and P in inch increments; for type localities where a range of P was given, means were calculated. Parent material (dominance vs. nondominance of calcium carbonate), soil texture (dominance by sand, silt, or clay), and the taxonomic class in which the calcic horizon was reported (suborder, family, or great group) were also recorded. Soils with anthropogenically disturbed epipedons were avoided, as were buried calcic horizons, which often are influenced by ground water (Birkeland, 1984). Soils with surficial calcic horizons (D = 0) showed a large range in mean annual precipitation (508 mm). Because equivalent paleosols can be easily avoided in the field, they were excluded from the data set (n = 33). Consideration was not given to soil age (e.g., Holocene, Pleistocene) or geomorphic context (e.g., slope, aspect, elevation, drainage, slope stability), because such parameters are difficult to control in paleopedological work.

The use of calcic horizons as the parameter for calculating the depth to carbonate horizon is reasonable (Birkeland, 1984). Nodules are considered the most robust form of secondary calcium carbonate, because they typically are not influenced by parent material, ground water, soil age, or diagenesis (Birkeland, 1984; Ma-

*E-mail: dana.royer@yale.edu.

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chette, 1985; Retallack, 1985, 1994a). About 94% of the NRCS data used here show strong evidence for secondary carbonate accumulation; most are described as containing carbonate masses, nodules, accretions, flakes, or weakly cemented grains. This strong correlation is not surprising, because the definition for calcic horizons selects for the translocation and precipitation of calcium carbonate.

Because the database of Retallack (1994a) includes Jenny and Leonard's (1934) data, "Retallack + Jenny" hereafter refers to the complete data set of Retallack (1994a), and "Retallack" excludes the data of Jenny and Leonard (1934) (Table 1).

RESULTS AND DISCUSSION

Analysis of NRCS data (n = 1168) yields an r^2 value of 0.03, a σ of 143 mm, and a regression equation of P = 1.187D + 297.2 (Table 1; Appendix 1[1]). Previous work suggests that parent material and soil texture influence D (Arkley, 1963; Gile, 1977; Birkeland, 1984; McFadden and Tinsley, 1985); however, in this data set, both the single (e.g., removing all soils with a calcium carbonate-dominated parent material) and interactive (e.g., removing all soils with a calcium carbonate-dominated parent material and sandy texture) effects of parent material, texture, and taxonomic class fail to raise r^2 above 0.07. The addition of the Jenny and Leonard (1934) data ("NRCS + Jenny") increases r^2 to 0.25 (n = 1272; σ = 151 mm; P = 2.602D + 263.8) (Table 1). Incorporation of the remainder of Retallack's (1994a) data set (NRCS + Retallack + Jenny) marginally increases r^2 to 0.31 (n = 1481; σ = 150 mm; P = 2.775D + 257.8) (Fig. 1; Table 1).

The data of Jenny and Leonard (1934) clearly anchor the regression shown in Figure 1. The addition of their data to the NRCS + Retallack database almost doubles the r^2 from 0.18 to 0.31 with a < 8% increase in sample size (Table 1). If the Jenny and Leonard (1934) data with a D > 100 cm are removed (n = 35) from Retallack's (1994a) complete data set, r^2 drops to 0.44 (data not shown) and is closer in character to the NRCS + Retallack + Jenny results. Thus Jenny and Leonard's (1934) data have a great influence on the regressions, particularly their deep-to-carbonate-horizon soils (D > 100 cm).

If a random subset of NRCS data (n = 213) is analyzed with Jenny and Leonard's (1934) data for a combined sample size of 317, the same size as Retallack's (1994a) data set, r^2 jumps to 0.53 and is comparable to the r^2 of Jenny and Leonard

(1934), Arkley (1963), and Retallack (1994a) (Table 1). This strongly suggests that previous data sets did not have sufficient sample sizes.

The NRCS data set contains few soils with a D > 100 cm (n = 7), which likely suppresses its r^2 (see previous discussion). This finding is surprising, given that NRCS protocol calls for analysis down to at least 200 cm in soil depth (Soil Survey Staff, 1996). Three possible explanations are discussed here. First, some previous studies do not base their depth measurements (D) on the presence of secondary carbonates. In cases where the concretion zone was not discernible, Jenny and Leonard (1934, p. 367–368) measured the "zone nearest the surface which exhibited the strongest effervescence with dilute HCl" (n ≤ 104 samples). Furthermore, Jenny and Leonard (1934) noticed large concretions and channels of $CaCO_3$ abnormally deep in profiles with a P > 914 mm and cast doubt on their worth as precipitation indicators (Fig. 1). Of their soils with a D > 100 cm, 29% fit this precipitation pattern, and therefore should be considered carefully. In light of this observation, the regression in Figure 1 is extended only to a P of 914 mm (D = 236 cm). Ruhe (1984) measured $CaCO_3$ concentrations in the laboratory by gravimetric loss of CO_2 (n = 9 samples), whereas Arkley (1963) did not report a methodology (n = 26 samples). These same studies account for > 65% of soils with a D > 100 cm in the combined data set (NRCS + Jenny + Retallack), and thus the robustness of these deep-to-carbonate-horizon soils is questionable. This conclusion concurs with the observations of Shantz (1923), who measured the "lime zone" across the Great Plains (as far east as eastern Kansas) and reported a maximum depth of 122 cm for a P between 762 mm and 1016 mm.

Second, several studies (e.g., Jenny and Leonard, 1934; Ruhe, 1984) are based on single transects and therefore do not reflect the spatial distribution of soil and climatic features. In contrast, the NRCS database is designed to reflect both the ranges of features (like the transect studies) and distribution of features along those ranges. Whereas transects simply highlight differences, the NRCS data emphasize which nodes along the transect are significant. Figure 1

illustrates this point well; although the NRCS and previously published data show similar ranges, the NRCS data contain a high density bull's-eye pattern at shallow depths and low mean annual precipitations.

Third, the geographical ranges in previous studies that report deep-to-carbonate-horizon soils are far more restricted than this study's (Table 2). For example, Jenny and Leonard (1934) only analyzed soils from eastern Colorado to western Missouri, whereas Ruhe (1984) sampled from western Kansas to eastern Iowa. The thorough sampling methodology of the NRCS better represents the distribution of calcic paleosols that will be encountered in the field and thus yields a more robust data set. Furthermore, the low percentage of carbonate horizon-bearing soils east of Colorado (Table 2) casts doubt on the sampling techniques of some previous studies.

Independent of the question of deep-to-carbonate-horizon soils, data in all data sets (not just NRCS) are compressed toward the soil surface (Retallack, 1994a). Even in the combined data set, 95% of soils have a D < 98 cm and 56% of soils have a D < 50 cm and P < 400 mm. An additional important point is that a log-log regression does not improve r^2 over a linear fit in this data set ($r^2 = 0.22$). Because most paleoprecipitation studies focus on shallow-to-carbonate-horizon paleosols (they are the most common), typically <100 cm deep (Retallack, 1992, 1994a, 1994b, 1997; Caudill et al., 1996), statistical analyses should be based on the behavior of soils at these same depths. Thus, regardless of which data set is chosen, correlation at shallow depths is poor. For example, removing all data with a D > 100 cm from Retallack's (1994a) complete data set reduces r^2 to 0.38 (n = 246; p < 0.001). Conversely, if deep-to-carbonate-horizon paleosols (D > 100 cm) are found, the regression is also not improved by restricting the combined data set to D > 100 cm (n = 72; $r^2 = 0.24$; p < 0.001). Thus correlation is poor at depth as well.

Only soil texture, parent material, and buried calcic horizons were controlled. It must be emphasized that it is possible to construct a more robust relationship if stricter criteria are imposed.
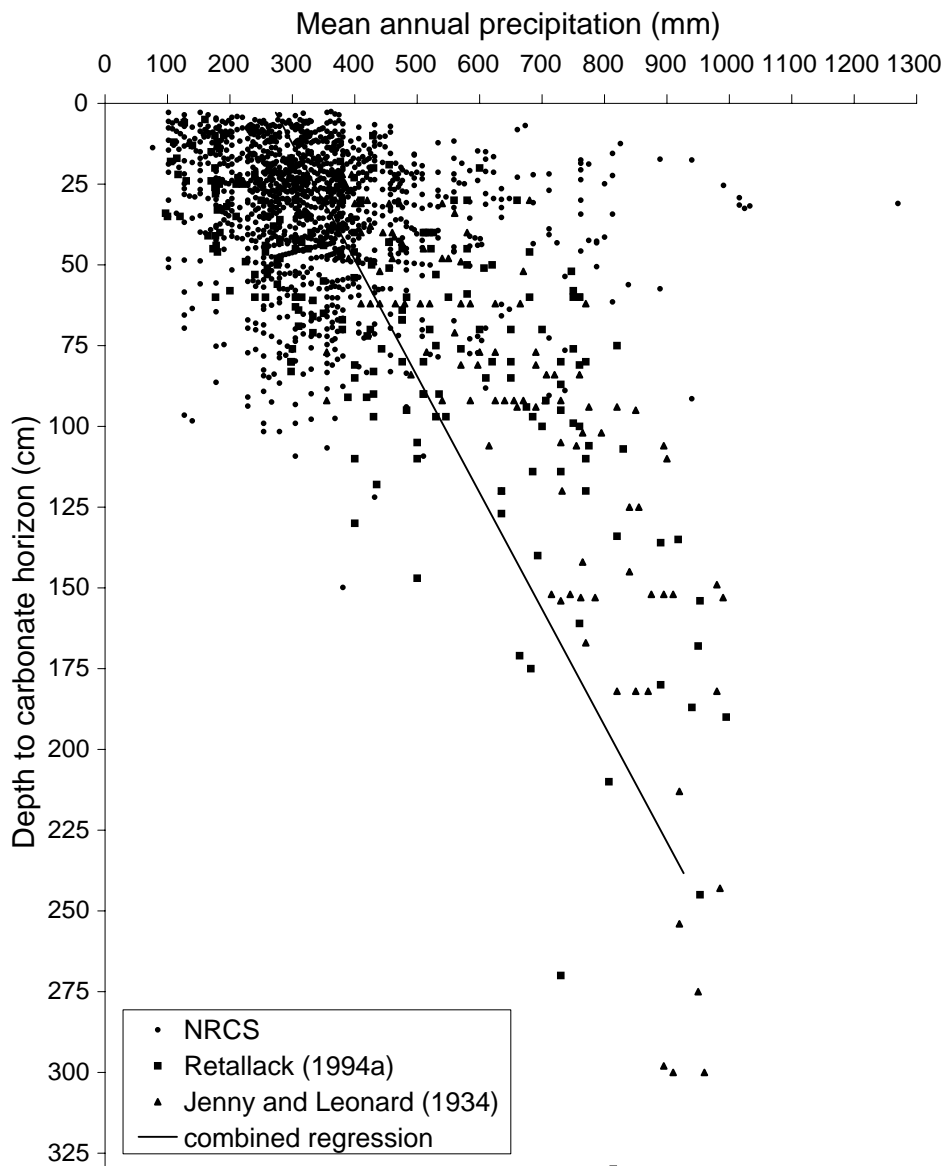
TABLE 1. REGRESSION ANALYSIS OF KEY DATA SETS

Data set analyzed	r^2	p	σ (mm)	Regression equation
NRCS; n = 1168	0.03	<0.001	143	P = 1.187D + 297.2
NRCS + Jenny; n = 1272	0.25	<0.001	151	P = 2.602D + 263.8
NRCS + Retallack; n = 1377	0.18	<0.001	148	P = 2.318D + 265.7
NRCS + Retallack + Jenny; n = 1481	0.31	<0.001	150	P = 2.775D + 257.8
Jenny (Jenny and Leonard, 1934); n = 104	0.64	<0.001	109	P = 2.324D + 420.2
Retallack + Jenny (Retallack, 1994a); n = 317	0.62	<0.001	141	P = -0.01303D^2 + 6.388D + 139.6
Arkley (Arkley, 1963); n = 26	0.56	<0.001	87	P = 3.730D + 106.0
Random NRCS + Jenny; n = 317	0.53	<0.001	146	P = 3.117D + 274.0

Note: P = mean annual precipitation (mm); *D* = depth to carbonate horizon (cm). Standard errors (σ) calculated by using *P* as dependent variable. Statistics of Jenny and Leonard (1934) and Arkley (1963) recalculated for this paper.

Figure 1. Results from combined data set (NRCS + Retallack + Jenny): $r^2 = 0.31$; $\sigma = 150$ mm; regression equation is P = 2.775D + 257.8, where P = mean annual precipitation (mm) and D = depth to top of carbonate horizon (cm). Regression line only extended to P = 914 mm (see text for details). NRCS is Natural Resources Conservation Service.

TABLE 2. GEOGRAPHIC DISTRIBUTION OF NRCS LOCALITIES

State	Percentage of soil type localities
Utah	19.4
Idaho	14.8
Nevada	13.7
Texas	11.8
Arizona	10.7
New Mexico	9.3
Colorado	3.9
California	3.6
Montana	3.3
Wyoming	2.8
Oregon	2.3
Washington	1.7
Other*	2.4

*North Dakota (7 type localities), Minnesota (4), Oklahoma (4), Virgin Islands (4), Kansas (3), South Dakota (3), Puerto Rico (2), and Nebraska (1).

sociated P > 760 mm exist (Jenny and Leonard, 1934; Soil Correlation Committee for South America, 1967; Ruhe, 1984), but based on the combined data set presented here (which includes the data from these three references), such soils comproise < 5% of all carbonate horizon–containing soils. Although ~150 mm less than previous estimates (Jenny and Leonard, 1934; Retallack, 1994a) because of the factors discussed in this paper, this correlation is offered here as a statistically robust ($p < 0.05$), albeit broad, paleoprecipitation indicator.

CONCLUSIONS

Data presented here suggest that the depth to the top of the carbonate horizon should not be used as a paleoprecipitation indicator vis-à-vis Retallack (1992, 1994a, 1994b, 1997) and Caudill et al. (1996), particularly in data sets in which data are compressed toward the soil surface and the range of inferred paleoprecipitation is narrow. At the very least, this indicator should be combined with other paleoprecipitation indicators such as modern analogues to fossil floral assemblages (e.g., Hickey, 1977), multivariate leaf physiognomy (e.g., Wolfe, 1993), leaf area (e.g., Wilf et al., 1998), and soil mineral content (e.g., Retallack, 1992).

Alternatively, a significant correlation ($p < 0.05$) exists between the presence of carbonate horizons and a mean annual precipitation of < 760 mm. Although broad, this relationship nevertheless offers an accurate, first-order estimation of paleoprecipitation.

For example, Arkley (1963) analyzed 28 soils of equal age and distribution of rainfall from California and Nevada, yielding an r^2 value of 0.56. If the water-holding capacity of the soil was normalized, r^2 improved to 0.90. Other potential confounding factors not incorporated include climate change during pedogenesis (Birkeland, 1984; Ruhe, 1984; Marion et al., 1985; McFadden and Tinsley, 1985), vegetation type (Semeniuk and Meagher, 1981), significance of dust inputs (Machette, 1985), evapotranspiration (ET), seasonality of rainfall (e.g., winter precipitation leaches more effectively owing to lower ET rates; Arkley, 1963), amount of organic matter (organic matter aids in $CaCO_3$ translocation; Jenny, 1941), and soil CO_2 concentrations (Mayer et al., 1988). Coupled with these many vagaries inherent in the

P vs. D relationship are complications associated with paleosols such as diagenesis, erosion, and compaction (including differential packing among horizons). Although some of these factors can be estimated in paleosols (Retallack, 1994a; Caudill et al., 1997), they nonetheless further dull the relationship (Sobecki and Wilding, 1982; Blodgett, 1988; Mayer et al., 1988; Quade and Cerling, 1995), particularly in older paleosols where such estimates typically become increasingly difficult.

Although the depth to carbonate horizon is not sound as a high-resolution paleoprecipitation indicator, in the combined data set (NRCS + Retallack + Jenny), more than 95% of the soils correlate with a P < 760 mm. This precipitation value corresponds with a D of 181 cm. Soils with an as-

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