Pedogenic carbonate proxies for amount and seasonality of precipitation in paleosols

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ABSTRACT

The depth to carbonate nodular (Bk) horizon in soils (*D* in cm) is correlated with mean annual precipitation (*P* in mm), so that Bk horizons are deep in subhumid regions, but shallow in semiarid regions. Previous quantifications of this relationship are unchanged by this new compilation of 807 soils: $P = 137.24 + 6.45D + 0.013D^2$, where $R^2 = 0.52$, and standard error (S.E.) = ±147 mm. In most North American postglacial soils, the Bk horizon is thin and well defined, whereas in monsoonal tropical soils of Pakistan and Kenya, the Bk horizon is thick and diffuse. Data from 675 modern soils define the relationship between the thickness of soil with nodules (*T* in cm) and mean annual range of precipitation (*M* in mm difference between monthly means of wettest and driest months): $M = 0.79T + 13.71$, where $R^2 = 0.58$, and S.E. = ±22 mm). The relationship between carbonate nodule size (*S* in cm) and soil age (*A* in ka) is quantified by 9 radiocarbon-dated soils from Las Cruces, New Mexico: $A = 3.92S^{0.34}$, where $R^2 = 0.57$, and S.E. = 1.8 k.y. These transfer functions are applied to reconstructing paleoclimatic change from Paleocene–Eocene paleosols of the North Horn Formation and Flagstaff Limestone of Axhandle Canyon, Utah. The terminal Paleocene spike of warmth recorded by fossil plants in nearby Wyoming was coincident with a brief peak in both mean annual precipitation and mean annual range of precipitation in Utah.

Keywords: pedogenic carbonate, paleosol, precipitation, seasonality, Paleocene, paleoclimate.

INTRODUCTION

Hans Jenny (1899–1992), Berkeley soil scientist and conservationist, came to the U.S. as a Rockefeller Fellow in 1926 from his native Switzerland. On a 1927 transcontinental train excursion following the First International Soil Congress in Washington, D.C., he was inspired by the Great Plains. "There the rolling plains, I fancied, must harbor the secret of mathematical soil functions. At times I could hardly sleep thinking about it" (Jenny interviewed by Maher and Stuart, 1989, p. 98). He quantified the relationship between depth to carbonate nodular (Bk) horizon (Fig. 1) and mean annual precipitation of the Great Plains (Fig. 2B) (Jenny and Leonard, 1935; Jenny, 1941) and established a new approach to quantitative pedology. Soils of the Great Plains are a good natural experiment in the role of climate in soil formation because they show great variation in climate, yet modest variation in other soil forming factors: mainly grassy vegetation, rolling to flat topography, uniform calcareous loess parent material, and postglacial age (younger than 14 ka).

The relationship between depth to Bk horizon and precipitation (Fig. 2B) remains a useful pedogenic climofunction (as defined by Jenny, 1941), widely applied to rangeland management (Munn et al., 1978), interpreting paleoprecipitation from paleosols (Mack and James, 1992; Caudill et al., 1996; Retallack, 2000; Retallack et al., 2004), and amenable to modeling (McFadden and Tinsley, 1985; McFadden et al., 1991). Challenges to Jenny's Bk depth–precipitation relationship first emerged in a study of Mojave Desert soils (Arkley, 1963), which fell on a different linear trend. However, Great Plains and Mojave data are continuous (Fig. 2B) and can be fit by one nonlinear function (Retallack, 1994). Another challenge came from Ruhe (1984), who pointed out the different ages (14 ka vs. 9 ka) of loess in different parts of the Great Plains. This contributes scatter (Fig. 2B), but does not invalidate the relationship. A final challenge came from an uncritical download of digital soil survey data by Royer (1999), who failed to detect any relationship. His scattershot graphs are not surprising, because they included soils of great age, steep slopes, bedrock, and other compromising soil factors (Retallack, 2000), ignoring basic principles of experimental design (Jenny, 1941).

A new compilation of depth to Bk data is

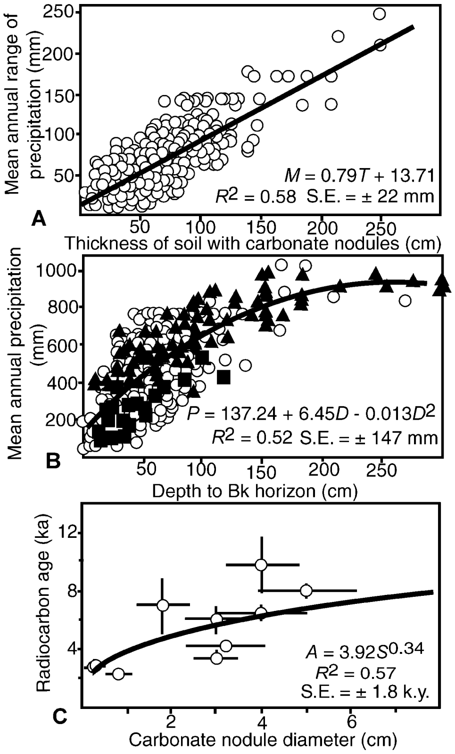

Figure 2. Modern soil correlations between (A) mean annual range of precipitation and thickness of soil with nodules (675 soils, global), (B) mean annual precipitation and depth to Bk horizon (807 soils, global, including data of Jenny and Leonard [1935], as solid triangles, and of Arkley [1963], as solid squares), and (C) radiocarbon age and carbonate nodule diameter (9 soils of Gile et al., 1981; complete data set in Table DR1 [see footnote 1 in text]).

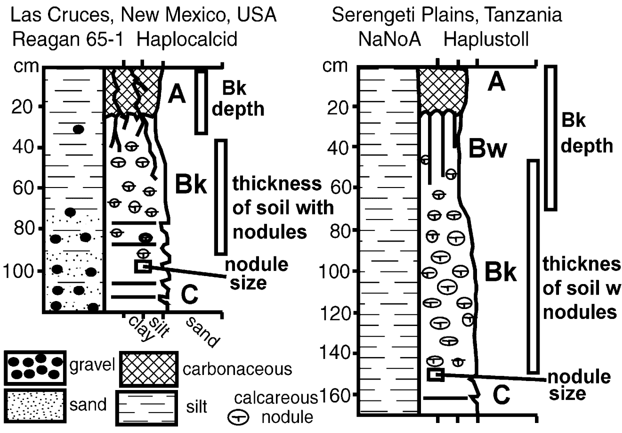

Figure 1. Measured features of soil and paleosol Bk horizons indicated on modern temperate soil from Las Cruces, New Mexico, U.S. (soil profile Reagan 65–1 from Gile et al., 1981) and monsoonal tropical soil from Serengeti, Tanzania (soil profile NaNoA from de Wit, 1978). Soil names are from Soil Survey Staff (2000).

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offered here, including data on the thickness of soil with carbonate nodules and monthly mean, as well as mean annual precipitation (Table DR1[1]). Unlike most North American postglacial soils in which the Bk horizon is thin (<50 cm) and well defined, soils of the monsoonal tropics of Pakistan and Kenya have very thick (~1 m) and diffuse horizons of nodules (Fig. 1). These observations (Retallack, 1991) led me to examine a new relationship between thickness of soil with nodules and mean annual range of precipitation (Fig. 2A). Also attempted was an age-size correlation (Fig. 2C) of radiocarbon-dated pedogenic carbonate nodules from the Desert Project of New Mexico (Gile et al., 1981). A terminal Paleocene spike in precipitation and seasonality at Axhandle Canyon, Utah (Talling et al., 1994), is offered as an application of these new proxies.

RESULTS OF A NEW COMPILATION

The new compilation of soils includes most records of my previous compilation (Retallack, 1994), now expanded to 675 soils, gleaned from county soil surveys and other soil monographs with comprehensive descriptions of soils and their setting. Data of Jenny and Leonard (1935) and Arkley (1963) do not include Bk thickness or monthly precipitation, but increase the database for the relationship between calcic depth and mean annual precipitation to 807 soils. The depth to the Bk horizon is defined as the depth to the horizon where nodules or other forms of carbonate dominate the fabric of the profile, but thickness of soil with nodules is taken as the interval between the shallowest and deepest nodules. Neither measure corresponds to the calcic horizon as strictly defined (Soil Survey Staff, 2000), and the thickness of soil with nodules is equal to, or greater than the thickness of the Bk and calcic horizon. In most North American soils the top of the Bk horizon coincides with the uppermost nodules, but in monsoonal tropical soils it is common to have nodules above the horizon normally designated Bk on the basis of nodule abundance (Sehgal and Stoops, 1972; de Wit, 1978; Retallack, 1991).

Stringent criteria must be applied in the selection of data in order to limit effects of competing factors in soil formation (Jenny, 1941). The selected soils are all postglacial (younger than 14 ka), as determined by radiocarbon dating (Fig. 2C), or small nodules (Fig. 2C). Over time, Bk horizons evolve from wisps and filaments of carbonate, which take 1–2 k.y. to differentiate. These grow into small nodules, then larger nodules, until nodules coalesce into tabular carbonate (K) horizons after ~12 k.y. (Gile et al., 1981). Tabular, laminated, and brecciated carbonate horizons were excluded from the compilation.

The compiled soils all developed on sedimentary parent materials, although these range in grain size from clay to gravel. Bedrock soils, including beachrock and welded tuff, were excluded. The soils all developed in young, but not the youngest, land surfaces. Lowland swampy soils with evidence of waterlogging were excluded. Soils and buried soils of sand dunes, streamsides, high terraces, and steep slopes were excluded, because they were subjected to multiple climatic and sedimentary regimes. Loess soils of some rolling uplands were included if there was independent evidence of postglacial age (Ruhe, 1984). Included soil orders were Aridisol, Mollisol, Vertisol, Gelisol, Andisol, and Alfisol. Entisols and Inceptisols were excluded because they were too young, and other orders because they were noncalcareous or too old.

Nevertheless, there is a range of vegetation and climate among the compiled calcareous soils. Vegetation ranges from desert scrub to woodland. Climates range from hyperarid in southern Israel to subhumid in India, from frigid in Antarctica and Greenland to tropical in Pakistan and Kenya. While this range in other soil-forming factors introduces some variance, it enables global application to calcareous paleosols in sedimentary sequences.

The new compilation includes mean monthly precipitation for nearby climate stations from the original soil surveys and from standard references (Ruffner, 1980; Muller, 1982). The variable that showed the strongest correlation with thickness of the nodule-containing soil was mean annual range of precipitation, calculated as the highest mean monthly precipitation minus the lowest mean monthly precipitation (Fig. 2A). Also tried were a variety of proportional measures, such as mean precipitation of the wettest month as a percentage of mean annual precipitation, but none showed significant correlation.

The new compilation doubles the database of a previous compilation (Retallack, 1994) of calcic depth and mean annual precipitation, but does not offer significant improvement in accuracy or precision over that compilation, or over data of Jenny and Leonard (1935) and Arkley (1963). This suggests that the new compilation is not severely biased by variation in soil-forming factors such as parent material, topography, and vegetation, which were more tightly constrained by Jenny and Leonard (1935) and Arkley (1963).

WHY THE CORRELATIONS?

Correlation need not mean causation, but reasons for increased depth and thickness of carbonate nodule-containing soil with increased amount and seasonality of precipitation are apparent from theory and observations of soil formation. These correlations (Figs. 2A, 2B) are not due to simple leaching of the profile to a climatically determined wetting front by seepage from the top down, because nodules were precipitated in both decalcified and calcareous soil matrices, and in places are scattered throughout the profile (Sehgal and Stoops, 1972; Retallack, 1991). Depth of soil matrix decalcification is controlled more by time for formation than by climate (Ruhe, 1969). Nor are these relationships (Figs. 2A, 2B) due to deepening water table in more arid climates, because most of these soils are many meters above water table (Jenny, 1980).

Instead, both correlations may be related to soil respiration (secondary productivity), which in turn is related to primary productivity and rooting depth (Jenny, 1980; Retallack, 2001, Figs. 4–11). Modeling has shown that soil profile water balance and alkaline earth (Ca, Mg) supply is important, but carbonate precipitation is critically dependent on atmospheric and soil partial pressures of CO_2 (McFadden and Tinsley, 1985; McFadden et al., 1991). Respired CO_2 within the soil, when it comes alive after rain, is 5–100 times atmospheric CO_2 partial pressure. Carbonic acid, from dissolved CO_2, hydrolyzes soil minerals, and is neutralized to precipitate carbonate just below this acidic zone of biological activity. Microbes may mediate the observed micritic carbonate replacement of soil matrix (Monger et al., 1991). Both secondary and primary productivity increase with mean annual precipitation and mean annual temperature (Munn et al., 1978). In monsoonal tropical soils, there are pronounced differences in root activity between wet and dry seasons (Singh and Singh, 1981), and fine root (<4 mm) biomass peaks a full month before large root (4–8 mm) biomass (Singh and Srivastava, 1986). Carbonate precipitated at shallow depths during the dry season is partly dissolved by respiration of fine shallow roots, then further dissolved by respiration of deeper roots later in the wet season, as indicated by dissolution rinds and interlaminated goethite in carbonate nodules and concretions of monsoonal soils (Sehgal and Stoops, 1972) and paleosols (Retallack, 1991).

APPLICATION TO PALEOCENE-EOCENE PALEOSOLS IN UTAH

These new climofunctions (Figs. 2A, 2B) are here used to assess paleoclimate of a sequence

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[1] GSA Data Depository item 2005054, Table DR1, soil and climate data, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

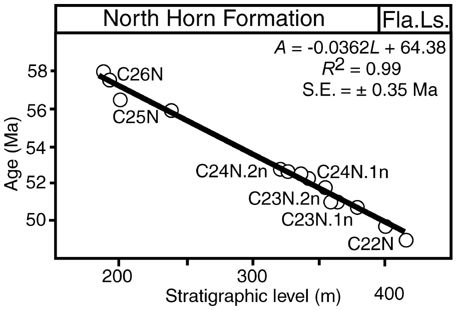

Figure 3. Age model for Paleocene–Eocene North Horn Formation and Flagstaff Limestone in Axhandle Canyon, Utah, using magnetostratigraphic data of Talling et al. (1994) and time scale of Cande and Kent (1995).

of paleosols in the Paleocene–Eocene North Horn Formation and Flagstaff Limestone in the steep ridge at the northeast entrance of Axhandle Canyon, near Wales, Sanpete County, Utah (N39.40268°, W111.68204°). This sequence was chosen because of its excellent age control: magnetostratigraphic chrons of Talling et al. (1994) include 14 geochronological tie points in the time scale of Cande and Kent (1995) to stratigraphic level (Fig. 3). My section was measured using the method of eye heights with a Brunton compass, and nodule size, thickness of paleosol with nodules, and Bk depth of 132 paleosols were measured with a milliner's tape.

Any application of these relationships to soils of the past must account for preburial erosion of paleosols and postburial compaction due to overburden. Soil erosion is unlikely to compromise this record for three reasons: (1) converging surficial root traces, (2) high rock accumulation rate (27 m/m.y.), and (3) constant accumulation rate (Fig. 3). The simplest way of factoring out reduction in thickness and depth of Bk horizons is to apply a standard burial-compaction formula to known sedimentary overburden (Sheldon and Retallack, 2001), which was 1.615 km at Axhandle Canyon (Hintze, 1988).

Higher atmospheric CO_2 of the past can also deepen and thin the Bk horizons, and thus alter the relationship between mean annual precipitation and mean annual range of precipitation, respectively. Modeling of McFadden and Tinsley (1985) showed that increasing atmospheric CO_2 from 500 to 3000 ppmV increased Bk horizon depth only 5 cm. A CO_2 correction was not applied here because the CO_2 spike at the Paleocene-Eocene boundary only reached 1034 ppmV (Royer, 2003, recalculated using formula of Wynn, 2003).

The paleosol sequence at Axhandle Canyon demonstrates an abrupt and short-lived (450 ± 350 k.y. duration of 7 successive paleosols) spike of subhumid precipitation (663 ± 147 mm yr^{-1}), and barely enhanced seasonality of precipitation (42 ± 22 mm yr^{-1}) beginning at 55.62 ± 0.35 Ma, which contrasts with arid and weakly seasonal climate before (mean annual precipitation 393 ± 66 mm, and mean annual range of precipitation 38 ± 6 mm for 51 paleosols) and after (mean annual precipitation 429 ± 83 mm and mean annual range of precipitation 31 ± 5 mm for 64 paleosols). This paleoclimatic spike (Figs. 4A–4B) is not compromised by the time for formation of the nodules, which shows little variance during that interval (Fig. 4C) by comparison with Holocene radiocarbon dated calcic horizons near Las Cruces, New Mexico (Fig. 2C). The abrupt paleoclimatic spike also created clayey rather than conglomeratic and red rather than brown paleosols. This striking red clayey band at Axhandle Canyon is a marker of the Eocene–Paleocene humidity spike, and is traceable 5 km west into Axhandle Canyon, and 15 km north from Axhandle to Petes and Wales Canyons (Talling et al., 1994). Although the Paleocene and Eocene have been considered greenhouse periods of widespread rainforest, these and other calcareous paleosols (Koch et al., 2003) confirm local dry rangeland within the rain shadow of mountains created during Laramide uplift (Norris et al., 2000).

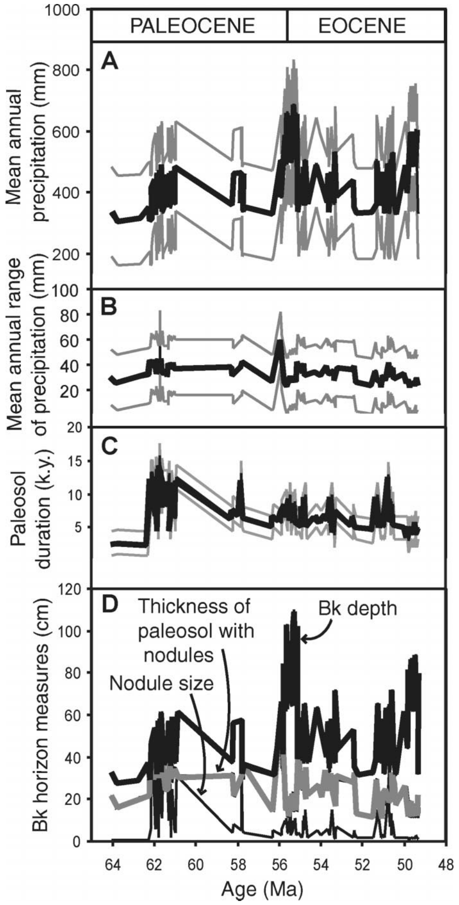

Figure 4. Inferred paleoclimatic variation and duration of Bk horizons during Paleocene and early Eocene in Axhandle Canyon, Utah (A–C), using transfer functions of Figure 2, and raw observations of Bk horizon depth, thickness of paleosol with nodules, and nodule size in Axhandle Canyon (D). Fine gray envelopes in A–C are 1 standard error.

IMPLICATIONS FOR GLOBAL CLIMATE CHANGE

The terminal Paleocene thermal climatic optimum is known to have been global in extent, because of the spread of laterites and bauxites to Ireland (McAlister and Smith, 1997) and southeastern Australia (Taylor et al., 1992). Tropical mangrove palms (*Nypa*) grew north as far as England and Belgium and south as far as Tasmania and New Zealand (Morley, 2000). Turtles and alligators lived as far north as Ellesmere Island (Tauxe and Clark, 1987).

The mechanism for this dramatic global warming is thought to have been dissociation of ~1.1–2.1 Gt (1 Gt = 10^{15} g) of methane from clathrate reservoirs, as estimated from a global carbon isotopic anomaly (Dickens et al., 1995). Methane is a potent greenhouse gas, and it oxidizes to another greenhouse gas, CO_2, within 7–24 yr (Khalil et al., 2000). Independent evidence for a terminal Paleocene spike in atmospheric CO_2 comes from stomatal index studies of fossil *Ginkgo* leaves (Royer, 2003) recalibrated to the transfer function of Wynn (2003), which suggest concentrations of 1034 ppmV CO_2, or 3.7 times the current level. Isotopic anomalies can also be perceived in paleosol carbonate of Wyoming (Koch et al., 2003), where fossil floras indicate a rise in mean annual temperature to 18.4 ± 0.8 °C from 12.9 ± 0.8 °C (Wing, 1998). The catastrophic release of methane has been considered a culmination of volcanic gas–induced global warming (Bralower et al., 1997), but is more likely due to local igneous intrusion (Svensen et al., 2004) or bolide impact into methane reservoirs (Kent et al., 2003).

Pedogenic carbonate proxies of Axhandle Canyon terminal Paleocene paleosols (Fig. 4) indicate that global warming was associated in this area with substantial increases in mean annual precipitation and modest increases in seasonality of precipitation. Even modest increases in precipitation seasonality could exacerbate storm intensity. Such relationships would be expected consequences of warmer atmosphere with higher latent heat capacity, and greater potential for moisture retention and dissipation (Ulbrich and Christoph, 1999). Further study of Paleocene–Eocene paleosols is needed to determine the global reach of such climatic effects.

ACKNOWLEDGMENTS

I thank Brooks Britt for help during field work. This work was funded by National Science Foundation grant EAR-0000953.

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Manuscript received 12 October 2004
Revised manuscript received 24 November 2004
Manuscript accepted 24 November 2004

Printed in USA