Depth to gypsic horizon as a proxy for paleoprecipitation in paleosols of sedimentary environments

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ABSTRACT

Pedogenic accumulations of crystals and nodules of gypsum are common in desert soils, especially extreme deserts such as the Atacama Desert, Chile. Some soils with both pedogenic gypsum and calcite have the gypsic (By) horizon below the calcic (Bk) horizon. Here we present a compilation of 88 gypsic soils from around the world to derive a relationship ($R^2 = 0.63$, standard error = ±129 mm) between depth to the By horizon (*D*, in centimeters) and mean annual precipitation (*P*, in millimeters) as follows: $P = 87.593e^{0.0209D}$. This relationship can be used to derive paleoprecipitation estimates from paleosols, once depth to the gypsic horizon is corrected for compaction due to overburden. Application of this technique to Early Permian paleosols near Gilliland, Texas, confirms paleoprecipitation estimates in the same sequence derived from depth to the calcic horizon. Barite is another sulfate mineral that forms nodular horizons in paleosols, but not in modern soils. Miocene paleosols in Panama with both calcareous and barite nodules suggest that this weakly soluble salt forms at levels in paleosols unlike those of either pedogenic carbonate or gypsum.

INTRODUCTION

A climofunction relating mean annual precipitation and depth to carbonate (Bk horizon) in soils was proposed at the inception of quantitative pedology (Jenny and Leonard, 1935; Jenny, 1941), and has survived challenges based on uncontrolled data (Retallack and Royer, 2000). Similar climofunctions still serve as proxies of former precipitation (Retallack, 2005a, 2009; Sheldon and Tabor, 2009), or what may be called paleohyetometers (from Greek παλαιος for ancient, ὑετός for rain, and μετρον for measure). A comparable relationship between mean annual precipitation and depth to gypsum accumulations (By horizon) was noted for desert soils of Israel (Dan and Yaalon, 1982), and this paper expands this relationship with data from soils around the world (Figs. 1 and 2). The gypsic climofunction derived here is not only a statement of controls on modern soil formation, but can be used as a paleohyetometer with paleosols, in a way comparable with the calcic paleohyetometer. Permian gypsic paleosols of Texas are interpreted here as an application of this technique; we also consider the paleoclimatic significance of paleosol nodules of barite, another sulfate salt of By horizons.

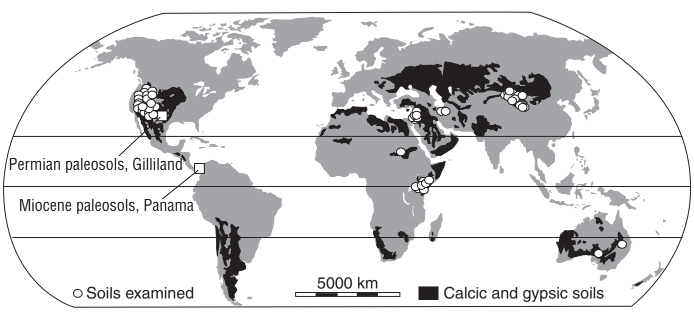

Figure 1. Distribution of modern and fossil soils used in this study.

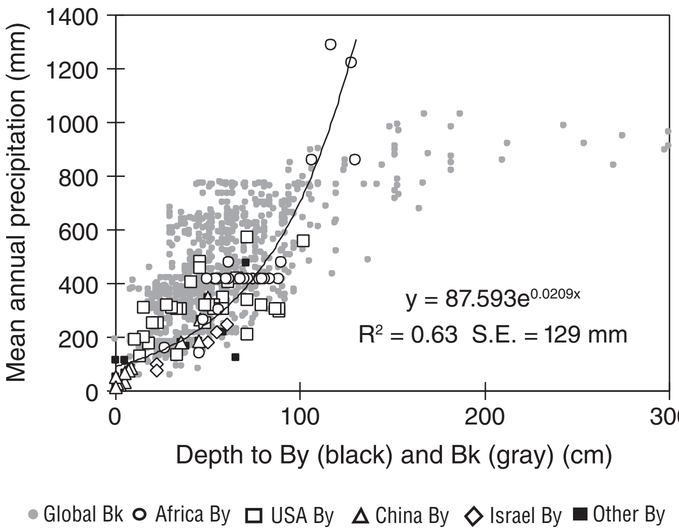

Figure 2. Correlation between depth to By horizon and paleoprecipitation in modern soils of the world (for sources and localities data see the Data Repository [see footnote 1]). Gray circles in background show depths to Bk horizon in modern soils (from Retallack, 2005a). S.E.—standard error.

MATERIALS AND METHODS

The primary activity of this study was compilation of depths to By horizons from published soil descriptions (see the GSA Data Depository[1]), additional to the pioneering study of Dan and Yaalon (1982). Following the experimental design outlined by Jenny (1941), soils were accepted into the database only if within a limited range of competing factors in soil formation other than climate and vegetation, which is strongly related to climate. Parent materials, for example, were limited to unconsolidated sediments, not soils on claystones, bedrock, or lava. Geomorphic setting was limited to low-gradient but well-drained sedimentary environments, such as floodplains and loess blankets. Soils of swamps and saltpans were avoided, because gypsum in them may reflect local water table rather than regional climate. Soils of slopes or incised surfaces also were avoided because of soil erosion reducing depth to the By horizon. Time for soil formation was limited to postglacial, ca. 13 ka or younger, thus excluding middle Pleistocene and older soils. Such ancient land surfaces have benches and beds of gypsum, which can be difficult in the fossil record to distinguish from beds of lacustrine, sabkha, playa, and marine gypsum. At the other extreme, very young soils (Entisols) were rejected if they had only isolated crystals, which may have been redeposited with alluvium (Khademi and Mermut, 2003). Between these extremes of isolated crystals and thick benches is a variety of gypsum forms: powdery mottles, small

[1]GSA Data Repository item 2010112, Table DR1 (gypsic soils in postglacial sedimentary environments), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

to hard nodules, crystal clusters, and sand crystals ranging up to ~28% by volume of the soil (Dan et al., 1973; Khademi and Mermut, 2003). Our compilation has trusted published field identifications of By horizons, which are the depths at which gypsum crystals characterize a discernibly distinct horizon. This is not necessarily the highest individual salt nodule or crystal, sometimes encountered above the gypsic horizon because of unusually dry years, redeposition, or bioturbation. The distribution of the modern soils used is global (Fig. 1), embracing both summer-dry (Mediterranean) and summer-wet climates and a variety of chemically distinct parent materials, but our compilation does not include high-latitude soils (known Antarctic gypsic soils, for example, are older than 13 ka; Campbell and Claridge, 1987).

These criteria for data selection are not only a rigorous experimental design, but tailor the relationship for use with gypsic paleosols in sedimentary environments. For example, gypsum ($CaSO_4 \cdot 2H_2O$)–bearing paleosols of the Early Permian (Leonardian) Choza Formation, Clear Fork Group, were observed in a road cut to the east of County Highway 262 (N33.822842° W99.595278°), 18 km north of Gilliland, Foard County, Texas (Retallack, 2005b). The relationship presented here does not work for paleosols with By horizon of other sulfate salts, such as barite ($BaSO_4$)–bearing paleosols of the Middle Miocene (Barstovian) Cucaracha Formation, observed on the west bank of the Panama Canal south of El Centenario Bridge (N9.04560° W79.65079°), Canal Zone, Panama (Retallack and Kirby, 2007).

NEW GYPSIC CLIMOFUNCTION

The 88 modern soils of our database (see the Data Repository) show a clear relationship between mean annual precipitation (P, in millimeters) and depth to the By horizon (D, in centimeters) according to the following relationship:

$$P = 87.593e^{0.0209D}. \quad (1)$$

These data were culled from horizon identifications published in soil descriptions and meteorological records. The coefficient of variation (R^2) is 0.63, and standard error is ±129 mm. An F test of ANOVA regression of these data returned a probability of $1.5 \cdot 10^{-20}$. The depth to the By horizon is lower in the soil than the depth to the Bk horizon, as indicated by 806 modern calcic soils (gray circles in Fig. 2; after Retallack, 2005a) in the range of P 100–800 mm, but diverges strongly from the calcic relationship at higher precipitation.

INTERPRETATION OF THE CLIMOFUNCTION

Our new climofunction quantifies what had been suspected from soil geography. Gypsic soils are best known from desert regions (Dan and Yaalon, 1982), but gypsic horizons can be found at depth in soils of humid climates, especially in tropical highly evaporative climates (van Kekem, 1986). In the Atacama Desert of Chile, arid calcic soils under desert shrubs pass downslope into hyperarid soils under biological soil crusts with gypsum and a variety of other salts (Ewing et al., 2006). Similarly gypsic soils were more common in sedimentary rocks of Cambrian than later Phanerozoic age (Retallack, 2008, 2009), and are the best-known relict paleosols on Mars (Retallack, 2001). These observations suggest a role for biota and soil productivity in the observed relationship between mean annual precipitation and depth to the gypsic horizon. This may explain why soils from Israel plot along the lower edge of the data cloud (Fig. 2); because their dry growing season is a hardship for primary productivity. The spread of data from the United States (Fig. 2) may also reflect productivity enhancing summer rain from the Gulf of Mexico versus less effective winter rain from California in soils across the desert southwest. Regressions from particular regions may be more accurate for application to paleosols in which these other climatic parameters are known: China for summer-wet temperate soils, Africa for monsoonal tropical soils, and Israel for summer-dry temperate soils (see the Data Repository).

Soils with both gypsic and calcic horizons (Dan et al., 1973; Buyanovsky et al., 1982) have the gypsic horizon below the calcic horizon. This may reflect the higher solubility of gypsum compared with calcite (Hanor, 2000), but something else is needed to explain the substantial overlap of calcic and gypsic depths in different sites (though not in individual pedons) under very low precipitation (Fig. 2). Biological effects may explain this overlap, because gypsic soils of the Atacama Desert have much lower microbial abundance and diversity than calcic soils (Navarro-González et al., 2003). Subhumid soils with deep gypsic horizons were only found in monsoonal equatorial Africa (van Kekem, 1986), and may reflect limited soil respiration during the monsoonal dry season. Pedogenic carbonate is also precipitated during onset of the dry or cold season, but in soils of greater biological productivity than gypsic soils (Breecker et al., 2009). A relationship between depth of gypsic and calcic horizons and soil productivity is not surprising, because soil productivity also is correlated highly with mean annual precipitation (Brook et al., 1983).

APPLICATION TO PERMIAN PALEOSOLS OF TEXAS

Permian red beds of Texas, famous for fossil tetrapods (Olson, 1967), also include a variety of gypsic and calcic paleosols (Tabor and Montañez, 2004). Both are present south of Gilliland, in the Early Permian (Leonardian) Choza Formation of the Clear Fork Group (Nelson et al. 2001), at a stratigraphic level of 916–940 m in the composite section of Hentz (1988). The section exposes 10 gypsic and 2 calcic paleosols (Fig. 3), and was buried by 273 m of overburden (Hentz, 1988). Compaction due to overburden (C as a fraction) for both gypsic and calcic paleosols can be calculated from this burial depth (K, in kilometers) using the equation for Aridisols from Sheldon and Retallack (2001) as follows:

$$C = \frac{-0.62}{\left[\frac{0.38}{e^{0.17 \cdot K}} - 1\right]}. \quad (2)$$

Decompacted thicknesses using the transfer function (Equation 2) for gypsic paleosols, and another transfer function for calcic paleosols (Retallack, 2005a), yields comparable estimates of mean annual precipitation from both calcic and gypsic paleosols (Fig. 4): 6 gypsic paleosols yield averaged mean annual precipitation of 577 ± 129 mm, and 2 calcic paleosols yield 615 ± 147 mm. The raw depths also are similar: mean and

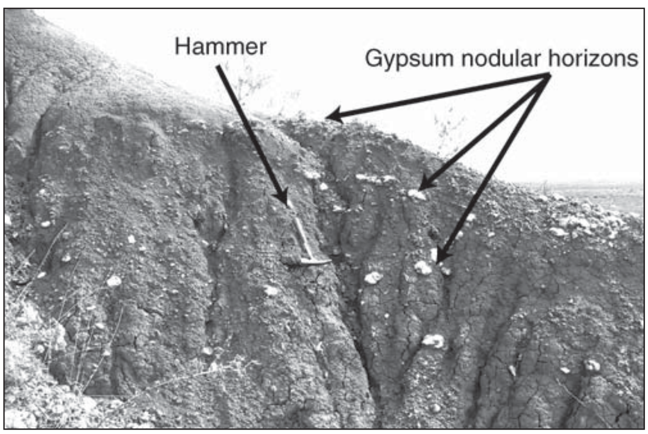

Figure 3. Gypsic horizons in paleosols of Early Permian (Leonardian) Choza Formation (upper Clear Fork Group), near Gilliland, Texas. Hammer handle is 25 cm long.

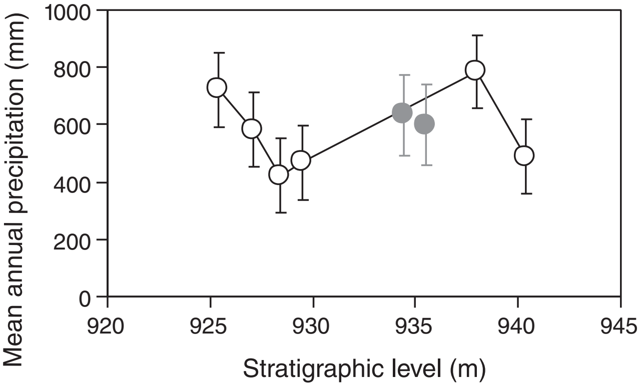

Figure 4. Inferred paleoprecipitation from depth to calcic (Bk, gray circles) and depth to gypsic (By, open circles) horizons in Permian paleosols from the Choza Formation near Gilliland, Texas. Stratigraphic level is from the composite section of Hentz (1988).

standard deviations of 6 depths to By are 87 ± 12 cm, and of 2 depths to Bk are 89 ± 6 cm.

Short-term variation in Early Permian paleoclimatic estimates (Fig. 4) may reflect variation on Milankovitch time scales (10^3–10^5 yr): the age model of Retallack (2005b) gives a geological age range of 282.1–281.6 Ma for this local sequence of paleosols. Four of the paleosols not used for paleoclimatic determination had thick benches of gypsum at the base of Vertisols, like relict gypsic soils of the Atacama Desert (Ewing et al., 2006), that exceed the age limits of the training set of modern soils (see the Data Repository). The other eight paleosols have nodular gypsum or dolomite comparable with soils of the training set, and their climatic variation (Fig. 4) is on the time scale of Milankovitch obliquity or precession (35.6–45.0 or 17.7–21.2 k.y. for the Permian, according to calculations of Berger et al., 1992; the considerable uncertainty of these estimates was outlined by Laskar, 1999).

The Texas Permian example (Figs. 3 and 4) demonstrates that our transfer function can add reasonable estimates of paleoprecipitation to the calcic paleohyetometer (Retallack, 2005a). The new gypsic paleohyetometer can now be applied to Cambrian and Precambrian gypsic paleosol sequences without pedogenic carbonate (Retallack, 2008).

ARE BARITE NODULAR HORIZONS SIMILAR?

Barite is another sulfate salt that forms nodules and sand crystals and By horizons in paleosols (Retallack and Kirby, 2007), but not in modern soils, where barite is present as microscopic microbiologically produced crystals (Lynn et al., 1971; González-Muñoz et al., 2003; Stoops and Zavaleta, 1978) or redeposited from diagenetic or hydrothermal barite (Shacklette and Boerngen, 1984; Torres et al., 1996). In Middle Miocene (Barstovian) paleosols of Panama (Retallack and Kirby, 2007), mean and standard deviations of 44 depths to Bk are 97 ± 24 cm, and those of 2 barite nodular horizons are 83 and 56 cm (70 ± 19 cm). Thus barite nodular horizons are distinctly shallower in depth than calcic horizons in the same paleosol sequence, and calcic horizons are generally shallower than gypsic horizons (Fig. 2). This difference may be related to the low solubility of barite (Hanor, 2000). This and the general rarity of barite nodules in paleosols, but local abundance in paleosols of unusual greenhouse climates (Retallack and Kirby, 2007), suggest that barite did not behave like other salts in soils of the past.

CONCLUSIONS

Like the depth to the Bk horizon in soils, the depth to the By horizon in soils is related to mean annual precipitation (Fig. 2), and also to its correlate, biological productivity (Brook et al., 1983). Application of the newly derived climofunction, from depth to gypsic horizon, to Permian paleosols of Texas gives paleoclimatic estimates similar to a previously published climofunction from depth to calcic horizon in paleosols (Retallack, 2005a). There are no modern barite nodular soils to derive a comparable climofunction for application to barite nodular paleosols, but Miocene examples of barite nodular horizons in paleosols from Panama (Retallack and Kirby, 2007) show shallower depths than calcic horizons of paleosols in the same sequence, and are also shallower than gypsic horizons of comparable climates.

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ERRATUM

Lake-sediment geochemistry reveals 1400 years of evolving extractive metallurgy at Cerro de Pasco, Peruvian Andes

Colin A. Cooke, Alexander P. Wolfe, and William O. Hobbs
(*Geology*, Vol. 37, No. 11, p. 1019–1022)

There is an error in the value for the accumulation of Pb on p. 1020. As published, the sentence reads: For nearly a millennium prior to ca. A.D. 600, the accumulation of Pb is stable and low, averaging 0.07 (±1) mg m^{-2} a^{-1}. The value reported should actually be 0.07 (± 0.01) mg m^{-2} a^{-1}.

ERRATUM

Learning to recognize volcanic non-eruptions

Michael Poland
(*Geology*, Vol. 38, No. 3, p. 287–288)

The Author name "Geshi" is incorrectly written as "Geishi" in the Focus Article text and in the References Cited. The correct Reference is:

Geshi N., Kusumoto S., and Gudmundsson A., 2010, Geometric difference between non-feeder and feeder dikes: Geology, v. 38, p. 195–19, doi: 10.1130/G30350.1.