# Genesis of a Late-Holocene Soil Chronosequence at the Lubbock Lake Archaeological Site, Texas

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**Abstract. Field and laboratory data combined with geochronological information were used to investigate the nature and rates of pedogenesis of three late Holocene soils at the Lubbock Lake archaeological site (Southern High Plains of Texas). A variety of pedologic characteristics become better expressed with time, and aerosolic additions and burial of the soils significantly affect the development of these characteristics. Organic carbon accumulates rapidly in initial stages of development of the A horizon: mollic epipedons form in about 100 years and steady-state conditions of organic carbon content are attained in about 1000 years. Upon burial, organic carbon content of the A horizon quickly decreases. Calcic horizons form in 200 years and minimally developed argillic horizons form in 450 years, the result of infiltration of clay and carbonate derived from aerosolic dust. Horizonation is better expressed with time, and B-horizon hues redden from 10YR to 5YR in 3500 years. Locally, landscape position is an important factor: along the valley axis A horizons become cumulic and mixed-layer illite-smectite clays form at the expense of illite because more moisture is available and there are strong seasonal contrasts in wetting and drying.**

**Key Words: chronosequence, pedogenesis, buried soils, late-Holocene soils, dust, Southern High Plains, soil-geomorphology.**

A chronosequence of late Holocene soils was defined at the Lubbock Lake site, an archaeological locality on the Southern High Plains of Texas (Holliday 1985a) (Fig. 1). Considerable field and laboratory data are available for the soils (Holliday 1982, 1985a) along with excellent age control resulting from the archaeological research. The ages of the soils are firmly established by about 40 radiocarbon determinations and much archaeological data (Holliday et al. 1983, 1985; Haas et al. 1986; Johnson 1987). Combined, this information provides the database necessary to study the nature and rates of genesis of the soils. This examination is significant for several reasons. There are very few studies of Holocene pedogenesis on the Great Plains or studies of Holocene pedogenesis in fine-grained sediments in semi-arid environments. In addition, soils in settings similar to that at Lubbock Lake occur elsewhere on the Southern High Plains (Holliday 1985b, c) and the information from Lubbock Lake will be very useful for stratigraphic correlations and for age estimation of deposits and surfaces at other sites.

On a broader scale, the nature of the pedologic research at Lubbock Lake is rare among soil-geomorphic studies. All four kinds of chronosequences defined by Vreeken (1975) are present at Lubbock Lake: post-incisive, where soils began development at different times in the past and all now exist at the surface; pre-incisive, where soils began forming at the same time but were buried at different times; and time-transgressive chronosequences with and without historical overlap. As Vreeken (1975, 393) notes concerning the study of soil development based on chronosequences: "comparisons of conclusions from post-incisive and . . . pre-incisive sequences appear to be a necessity although they have hardly been attempted."

This paper discusses the nature and rates of pedogenesis of the late Holocene soils at Lubbock Lake including a review of macro- and micromorphological development and chemical and mineralogical trends. The site setting, stratigraphy, chronology and soil morphological, physical and chemical characteristics are

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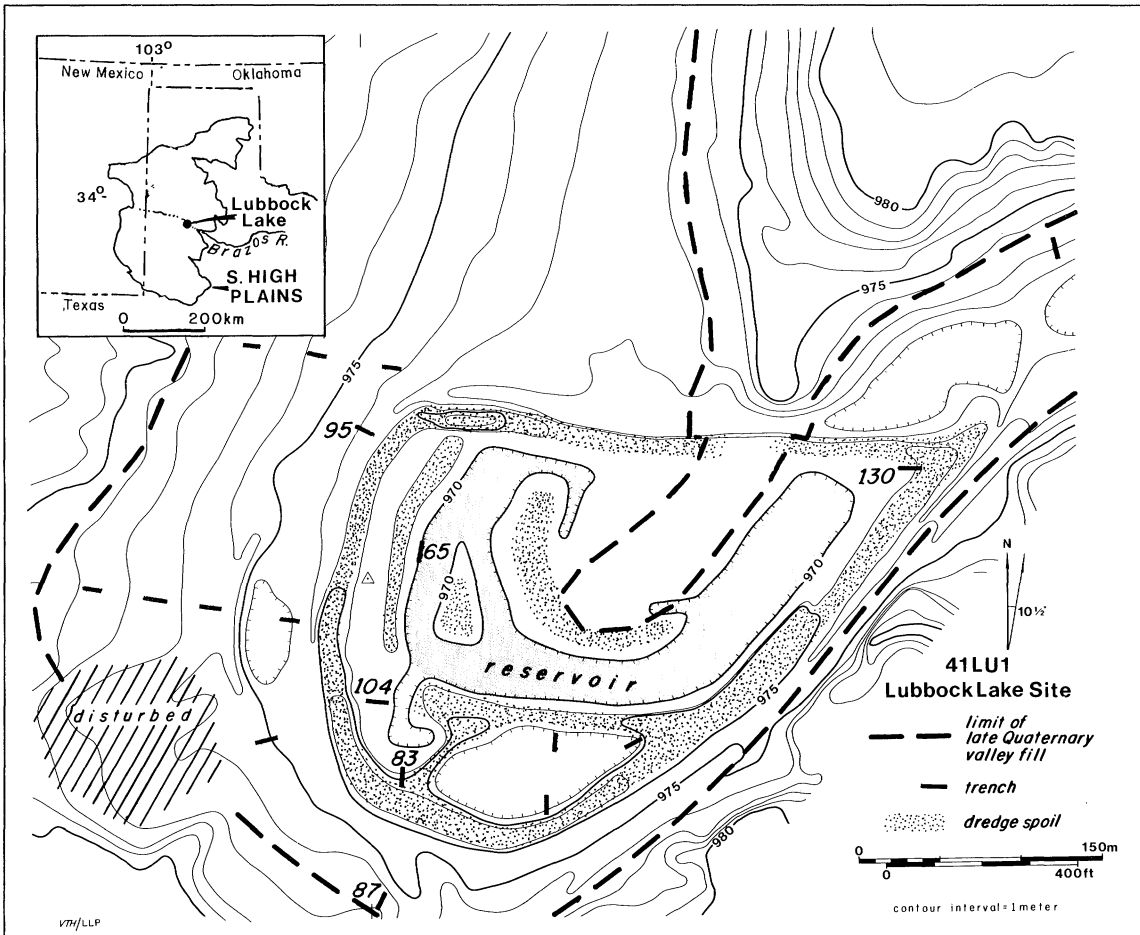


**Figure 1.** Yellowhouse Draw in the area of the Lubbock Lake site with locations of dust traps (1–3) and backhoe trenches in which soil profiles were described and sampled (modified from Holliday 1985a, Fig. 1). Trenches for which analytical data are presented are identified by number. Inset shows the location of Lubbock Lake on the Southern High Plains.

discussed in detail by Holliday (1982, 1985a, d, e), although a brief summary is presented here. The terminology used generally follows that of the U.S. Department of Agriculture (Soil Survey Staff 1975; Guthrie and Witty 1982). The stages of morphology of calcic horizons follow the terminology of Gile et al. (1966).

## Setting and Soils

The Lubbock Lake site is in Lubbock County (33°37′N latitude, 101°54′W longitude) on the Southern High Plains of northwest Texas (Fig. 1). The climate is continental and semiarid with an ustic soil moisture regime. Average annual precipitation in Lubbock (992 m elevation) is 46.8 cm, although there is considerable inter-annual variability. Most of the precipitation falls as rain in the spring and summer, generally from thunderstorms (Haragan 1970; NOAA 1982).

Lubbock Lake is in Yellowhouse Draw, a dry tributary of the Brazos River entrenched into the High Plains surface (Fig. 1). The valley has been aggrading episodically for the past 11,000 years with alluvial, lacustrine, paludal, eolian and slopewash sediments, which provide a well-dated, late-Quaternary cultural, floral, faunal, depositional, and pedological record (Johnson 1987) (Fig. 2). There are five principal late-Quaternary strata numbered 1 through 5 from oldest to youngest, each divided into substrata

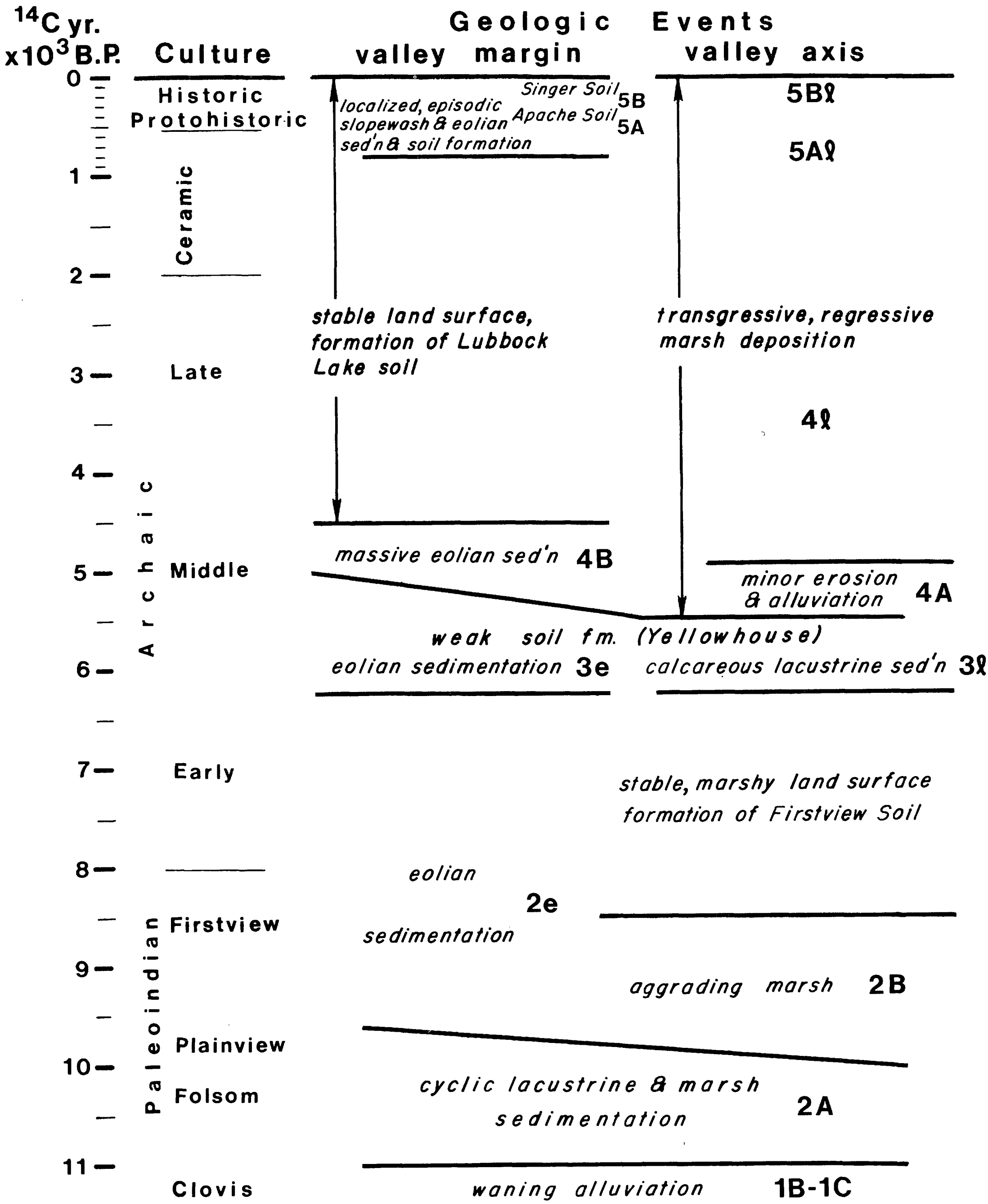


**Figure 2.** Summary diagram of the late-Quaternary depositional, pedological, and cultural history of the Lubbock Lake site (modified from Holliday 1985d, Fig. 7).

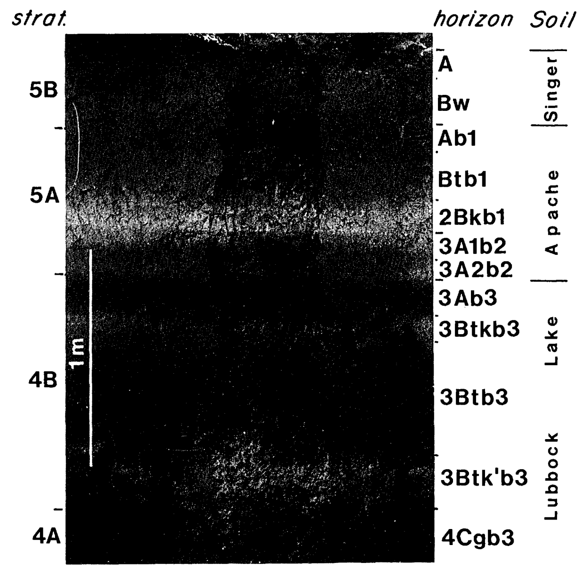


**Figure 3.** The late-Holocene soil sequence at Lubbock Lake in Trench 95 (Fig. 1) with excellent examples of the Singer Soil, buried Apache Soil and buried Lubbock Lake Soil (with multiple calcic horizons) (see Table 1 for description) (modified from Holliday 1985d, Fig. 5).

based on localized lithologic variation and identified by letters (e.g., 1A, 1B, 4A, 4B) (Figs. 2, 3). Five major Holocene soils developed in the valley fill, each given informal soil-stratigraphic names: Firstview, in stratum 2; Yellowhouse, in stratum 3; Lubbock Lake, in stratum 4; and Apache and Singer, both in stratum 5 (Figs. 2, 3).

The three late Holocene soils (Lubbock Lake, Apache and Singer) formed in quartzose, sandy loam to sandy clay loam, dominantly eolian sediments derived from the High Plains surface (Holliday 1985a, d). Sand-size grains of feldspar and calcium carbonate are also present, and the carbonate is common in localized deposits of slopewash. The clay mineralogy of the soils is chiefly illite and mixed-layer illite-smectite (ML-IS) with lesser amounts of smectite and kaolinite. The Lubbock Lake Soil formed in sediments deposited between 5000 and 4500 years B.P. (substratum 4B) and has had 4500 years to form or, where buried, about 3500 years to form. The soil exhibits mollic and, where buried, ochric epipedons, cambic and argillic and locally, a partially gleyed B horizon and Stage I or II, often multiple, calcic horizons (Fig. 3). The Lubbock Lake Soil is classified as either a Calciustoll, Haplustoll, Haplustalf, or Ustochrept, depending on which horizons characterize it in different locations.

The Apache Soil was formed in sediments deposited between 800 and 450 years B.P. (substratum 5A) and has had 450 years to form where not buried and 200 years to form where buried. The soil usually has mollic epipedons but in some buried situations, the epipedon is ochric. The B horizon is typically cambic but sometimes qualifies as argillic. Secondary carbonate accumulation, sometimes qualifying as a calcic horizon, commonly attains a Stage I morphology (Fig. 3). The Apache Soil is classified as either an Ustochrept, Haplustoll, or Calciustoll or possibly as a minimally developed Haplustalf.

The Singer Soil was formed in sediments deposited between 250 and 100 years B.P. (substratum 5A) and developed in the past 100 years. The soil has an ochric epipedon that overlies either a C, Bw, or cambic horizon. Stage I carbonate horizons are common but never qualify as calcic (Fig. 3). The Singer Soil is classified as an Ustorthent.

The theoretical approach taken in this study of soil genesis follows that of Jenny (1941, 1980) and Birkeland (1984) whereby soil formation is considered the result of the influence of climate, biota, relief, parent material, and time,

**Table 1.** Field Descriptions[a]

| Soil | Substrata | Horizon | Depth cm | Munsell color Dry | Munsell color Moist |
|---|---|---|---|---|---|
| Trench 95; Singer Soil (Ustorthent), buried Apache Soil (Ustochrept), Lubbock Lake Soil (Ustochrept) | | | | | |
| Singer | 5B | A | 0—15 | 7.5YR 5/2 | 7.5YR 3/2 |
| | | Bw | 15–42 | 10YR 5.5/3 | 7.5YR 4/4 |
| Apache | 5A | Ab1 | 42–59 | 10YR 6/2.5 | 10YR 3/3 |
| | | Btb1 | 59–80 | 7.5YR 5.5/3 | 7.5YR 4/4 |
| | | 2Bkb1 | 80–102 | 7.5YR 7/2 | 7.5YR 5/4 |
| | | 3A1b2 | 102–114 | 7.5YR 6/2 | 7.5YR 3/2 |
| | | 3A2b2 | 114–118 | 7.5YR 6/2 | 7.5YR 3/2 |
| Lubbock Lake | 4B | 3Ab3 | 118–137 | 7.5YR 5/2 | 7.5YR 3/2 |
| | | 3Btkb3 | 137–149 | 7.5YR 6/2 | 7.5YR 5/4 |
| | | 3Btb3 | 149–200 | 7.5YR 5.5/4 | 7.5YR 4/4 |
| | | 3Btk'b3 | 200–226 | 7.5YR 7/2 | 7.5YR 6/2 |
| | 4A | 4Cgb3 | 226–274 | O = 7.5Y 5/4 | 7.5YR 4/4 |
| | | | | G = 2.5Y 6/2 | 2.5YR 5/3 |
| | | 5Cgkb3 | 274–292 | 2.5YR 6/2 | 2.5YR 5/2 |
| Trench 130: Lubbock Lake Soil (Calciustoll) | | | | | |
| Lubbock Lake | 4B | A1 | 0–14 | 7.5YR 4/2 | 7.5YR 3/3 |
| | | A2 | 14–33 | 7.5YR 4/3 | 7.5YR 3/3 |
| | | Bt | 33–68 | 7.5YR 6/3 | 7.5YR 5/4 |
| | | Btk1 | 68–88 | 7.5YR 6/3 | 7.5YR 5/4 |
| | | Btk2 | 88–120 | 7.5YR 7/3 | 7.5YR 5/4 |
| | | 2Bgk | 120–149 | O = 7.5Y 7/3 | 7.5YR 5/3 |
| | | | | G = 5Y 7/1 | 5Y 6/2 |
| Trench 87: Apache Soil (Haplustalf) | | | | | |
| Apache | 5A | A | 0–11 | 10YR 4/2 | 7.5YR 3/2 |
| | | 2Bt | 11–28 | 10YR 5/2 | 10YR 4/3 |
| | | 2C1 | 28–40 | 10YR 6.5/2 | 10YR 5/3 |
| | | 2C2 | 40–54 | 10YR 6/3 | 10YR 5/3 |
| | | 2C3 | 54–64 | 10YR 6/4 | 10YR 5/3 |

[a] Modified from Holliday 1985a, Table 1.
[b] Abbreviations for soil profile descriptions: Texture: LS = loamy sand; SL = sandy loam; SCL = sandy clay loam; L = loam; CL = clay loam; f = fine. Structure: Grade, 1 = weak; 2 = moderate; 3 = strong. Class, f = fine; m = medium; c = coarse. Type, sbk = subangular blocky; abk = angular blocky; pr = prismatic; sg = single grain. Dry Consistence: h = hard; sh = slightly hard;

plus unspecified factors unique to a site or region, the so-called "dot factors" (Jenny 1980, 202). In a chronosequence time is the principal variable and the other factors must be held constant or accounted for. At Lubbock Lake there are some differences in topographic settings of the soils, and locally this exerts some influence on pedogenesis, as is discussed below. There is also slight, local variability in the texture of the parent materials of the soils, but this variability appears not to affect soil formation (Holliday 1982). Available data indicate that the climate, flora, and fauna of the area have not changed appreciably in the late Holocene during periods of landscape stability and pedogenesis with one minor exception noted below (Holliday 1985d; Johnson 1987). The principal variable among the late Holocene soils at Lubbock Lake is time. Soils of five ages are present: 4500-year-old Lubbock Lake Soil, 3500-year-old Lubbock Lake Soil (buried), 450-year-old Apache Soil, 200-year-old Apache Soil (buried), and 100-year-old Singer Soil. Important dot factors are burial and aerosolic dust, which is quite common and contains considerable amounts of clay and some carbonate, as discussed below.

## Procedures

Approximately 30 soil profiles in Yellowhouse Draw in the area of Lubbock Lake were described (Table 1), and samples from 16 of these profiles were analyzed in the laboratory. A variety of analytical methods was employed to study and quantify pedogenic processes and trends (Tables 2, 3). The field procedures and

**Table 1.** Continued

| Texture | Structure | Dry consis-tence | Reaction | Boundary | Comments[b] |
|---|---|---|---|---|---|
| SCL | 1msbk | h | ev | cs | common carb. clasts |
| SCL | 1msbk&2cpr | vh | ev | gs | common carb. clasts |
| SCL | 1msbk&1cpr | vh | ev | cs | |
| SCL | 1msbk&2cpr | h | ev | gs | |
| CL | 2msbk&1mpr | vh | ev | cs | few carb. clasts |
| L | 1msbk | vh | ev | cs | few carb. clasts |
| fSL | 1msbk | h | ev | cs | few carb. clasts |
| fSL | 1msbk | h | ev | cs | |
| SCL | 1msbk&1mpr | vh | ev | cs | |
| SCL | 2csbk&1mpr | h | ev | gs | |
| CL | 1msbk | vh | ev | gs | |
| SCL | m | h | es | cs | 40% G mottles |
| CL | m | vh | ev | cw | |
| SL | 2csbk | vh | ev | cs | |
| SL | 1mpr&2csbk | h | es | gs | |
| SL | 2cpr&2csbk | vh | ev | cw | |
| SCL | 1mpr&2csbk | vh | ev | gw | |
| SCL | 2csbk | h | ev | ci | |
| SiL | 1fpr&2fabk | h | es | aw | 40% O mottles<br>60% G mottles |
| CL | 2msbk&2fgr | vh | ev | ai | few carb. clasts |
| SCL | 2csbk | vh | ev | cw | 1–2 cm carb. gravels at base |
| SL | m&1msbk | h | ev | cw | few carb. clasts |
| SL | 1msbk&sg | sh | ev | cs | disc. carb. pebble lens at base |
| LS | 1msbk&sg | sh | ev | cs | disc. carb. pebble lens at base |

vh = very hard. Reaction (w/dilute HCl): es = strongly effervescent; ev = violently effervescent. Boundary: Distinctness, a = abrupt; c = clear; g = gradual. Topography, s = smooth; w = wavy; i = irregular. Remarks: G = gleyed; O = oxidized (for soils with mottled horizons); carb = calcium carbonate; disc = discontinuous.

basic methods for determination of bulk density (BD), particle-size distribution (PSD), and content of illuvial clay, organic carbon (OC), $CaCO_3$, and clay mineralogy are described by Holliday (1985a).

Three dust traps were set out at Lubbock Lake (Fig. 1) for one year (1979–80), and the recovered sediments were analyzed for selected physical and chemical characteristics (Table 4). Dust and eolian sediment on the Southern High Plains is locally derived (Holliday 1987), and therefore the traps provide semiquantitative data indicative of the physical, chemical and mineralogical characteristics of the soil parent-material, which is eolian (Holliday 1985d), and the dust falling on the soils (Tables 3, 4). The data from the traps is not used for absolute quantification of these characteristics of the parent material or dust because the traps were set out for only one year and because of artificial modification of the local and regional landscape.

The basic field and laboratory data were combined with a variety of other qualitative and quantitative approaches in order to investigate the processes of soil formation and pedologic development. For quantifying development of the A horizon and OC build-up, the amount of OC per unit volume was calculated by multiplying OC × BD. Where the A horizon was subdivided, a weighted mean of OC/cm$^3$ was calculated.

Various characteristics of clay-films coating sand grains were measured in thin sections in order to quantify rates of clay illuviation. The PSD data could not be used for this because only approximate amounts of illuvial clay could be measured due to subtle parent material vari-

**Table 2.** Laboratory Data[a]

| Soil | Horizon | Particle size distribution (%): Sand: Very coarse | Coarse | Medium | Fine | Very fine | Total: Sand | Silt | Clay | Organic carbon (%) | $CaCO_3$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trench 95 | | | | | | | | | | | |
| Singer | A | — | 0.3 | 8.6 | 30.6 | 21.8 | 61.3 | 21.7 | 17.0 | 1.1 | 12 |
| | Bw | 2.8 | 1.6 | 8.8 | 26.4 | 20.6 | 60.2 | 22.5 | 17.3 | 0.2 | 12[b] |
| Apache | Ab1 | — | — | 5.9 | 29.9 | 24.1 | 59.9 | 22.6 | 17.5 | 0.7 | 8[b] |
| | Btb1 | — | — | 5.4 | 29.5 | 22.7 | 57.6 | 21.9 | 20.5 | 0.6 | 14[b] |
| | 2Bkb1 | — | — | 4.2 | 21.4 | 16.7 | 42.3 | 29.0 | 28.7 | 0.5 | 20[b] |
| | 3A1b2 | — | — | 7.1 | 33.1 | 25.0 | 65.2 | 22.7 | 12.1 | 0.6 | 9[b] |
| | 3A2b2 | — | — | 7.8 | 37.8 | 26.9 | 72.5 | 19.5 | 8.0 | 0.4 | 5[b] |
| Lubbock Lake | 3Ab3 | — | — | 7.3 | 42.2 | 33.4 | 82.9 | 8.7 | 8.4 | 0.1 | 3[b] |
| | 3Btkb3 | — | — | 6.2 | 38.3 | 26.2 | 70.7 | 12.3 | 17.0 | 0.3 | 9[b] |
| | 3Btb3 | — | — | 6.4 | 37.2 | 25.8 | 69.4 | 19.6 | 11.0 | 0.2 | 7[b] |
| | 3Btk′b3 | — | 0.9 | 7.3 | 33.9 | 24.0 | 66.1 | 14.7 | 19.2 | 0.2 | 15[b] |
| | 4Cgb3 | — | — | 14.6 | 54.1 | 17.3 | 86.0 | 6.7 | 7.3 | 0.1 | 2 |
| | 5Cgkb3 | — | — | 1.8 | 10.3 | 18.0 | 30.1 | 49.8 | 20.1 | 0.5 | 5 |
| Trench 130 | | | | | | | | | | | |
| Lubbock Lake | A1 | — | — | 2.4 | 25.5 | 29.6 | 52.5 | 33.6 | 13.9 | 0.7 | 9[b] |
| | A2 | — | — | 2.7 | 27.3 | 23.6 | 53.6 | 33.6 | 12.8 | 1.3 | 8[b] |
| | Bt | — | — | 2.3 | 25.8 | 26.5 | 54.6 | 31.2 | 14.2 | 1.1 | 10[b] |
| | Btk1 | — | — | 2.3 | 29.3 | 22.8 | 54.4 | 29.0 | 16.6 | 0.9 | 15[b] |
| | Btk2 | — | — | 2.7 | 28.3 | 24.2 | 55.2 | 31.5 | 13.3 | 0.6 | 10[b] |
| | 2Bgk | — | — | 0.5 | 11.5 | 28.8 | 40.8 | 55.1 | 4.1 | 1.1 | 5[b] |
| Trench 87 | | | | | | | | | | | |
| Apache | A | — | — | 1.3 | 14.5 | 17.1 | 32.9 | 35.8 | 31.3 | 1.6 | 17[b] |
| | 2Bt | — | — | 4.1 | 40.5 | 22.9 | 67.5 | 16.0 | 16.5 | 1.0 | 12[b] |
| | 2C1 | — | — | 4.6 | 45.1 | 25.3 | 75.0 | 13.3 | 11.7 | 0.6 | 17 |
| | 2C2 | — | — | 4.7 | 44.1 | 27.7 | 76.5 | 11.8 | 11.7 | 0.5 | 13 |
| | 2C3 | — | — | 3.3 | 49.0 | 29.1 | 81.4 | 11.1 | 7.5 | 0.4 | 12 |

[a] Modified from Holliday 1985a, Table 2.
[b] Secondary carbonate.

ations. Grain argillans were chosen for clay-film measurements because very few coatings along voids were noted. Point counts were made for each thin section, usually 200 points. When a skeleton grain was counted, the presence or absence of clay films around the grain was noted. If clay films were present, an estimate was made of the percentage of the perimeter of the grain coated by clay. Thickness of the clay films was also determined by scanning across the slide and randomly measuring 20 films. Weighted means were then calculated for each soil from the data on each horizon for the percentage of the grains with clay films, percentage of the perimeter of the grains coated with clay, and the thickness of the films. This technique does not yield data on absolute amounts of illuvial clay but does permit quantitative comparisons of clay accumulation over time.

Carbonate accumulation was assessed by calculating $CaCO_3$ content in a centimeter-square column of soil the thickness of the solum ($CaCO_3 \times$ BD $\times$ solum thickness). The amount of carbonate in the parent material, subtracted from $CaCO_3$ content before the calculation was made, was estimated as 5 percent, based on data from only a very few C horizons, dust traps (Table 4), and thin sections.

Overall profile development was quantified using the field morphology rating scale of Bilzi and Ciolkosz (1977) (BC values). The BC system can determine distinctiveness of a horizon in a profile, and a comparison of BC values with time may indicate horizon and profile development over time. Horizon distinctiveness involves the comparison between horizons of the color, texture, structure, and boundary of each horizon. Because of textural variations in the

**Table 3.** Clay Mineralogy of Late Holocene Soils and Sediments, Lubbock Lake Site[a]

| | Sample | % Clay minerals | | | | ML-IS composition | | ML-IS: Illite | Weighted means of ML-IS: Illite |
|---|---|---|---|---|---|---|---|---|---|
| | | Kaolinite | Illite | Smectite | ML-IS[b] | I | S | | |
| | Dust Trap #2 | 5 | 85 | 5 | 5 | 65 | 35 | .13 | .09 |
| | Dust Trap #3 | 5 | 85 | 5 | 5 | 65 | 35 | .04 | |
| Soil (length of pedogenesis) | Horizon | | | | | | | | |
| Singer (100 yr) | A | 5 | 75 | 10 | 10 | 60 | 40 | .23 | .30 |
| (Tr 104) | A/Bw | 5 | 70 | 5 | 20 | 60 | 40 | .32 | |
| Apache (200 yr) | Ab2 | 5 | 70 | 10 | 15 | 55 | 45 | .32 | .35 |
| (Tr 104) | Btb2 | 10 | 65 | 5 | 20 | 60 | 40 | .35 | |
| | Bw1b2 | 10 | 60 | Tr | 30 | 65 | 35 | .45 | |
| | Bw2b2 | 10 | 70 | 5 | 15 | 60 | 40 | .30 | |
| Lubbock Lake (3500 yr) | Ab4 | 5 | 40 | 10 | 45 | 55 | 45 | 1.53 | 1.13 |
| (Tr 65) | Btk1b4 | Tr | 50 | 10 | 40 | 55 | 45 | 1.04 | |
| | Btk2b4 | Tr | 50 | 10 | 40 | 65 | 35 | .96 | |
| | Bgkb4 | 10 | 40 | 5 | 45 | 65 | 35 | 1.28 | |
| | Cgb4 | 5 | 70 | 5 | 20 | 60 | 40 | .31 | |
| | 2Cgkb4[c] | 20 | 50 | 5 | 25 | — | — | — | |
| | 3Cgb4 | 5 | 80 | 5 | 10 | — | — | — | |
| | 4Cgkb4 | — | — | — | — | — | — | — | |
| | 4Cgb4 | 10 | 80 | 5 | 5 | — | — | — | |
| | 4Cb4 | 5 | 50 | 10 | 35 | — | — | — | |

[a] Modified from Holliday 1985a, Table 4.
[b] Mixed-layer illite-smectite.
[c] Parent material change.

parent material of the soils at Lubbock Lake, only color, structure, and boundary characteristics could be compared.

# Pedogenic Trends

## Organic Carbon Content and A-Horizon Formation

The OC-content of A horizons and formation of epipedons in all late Holocene soils was compared with soil age (Fig. 4). This comparison indicates that OC content (gm/cm$^3$) increases rapidly in the A horizon as soon as pedogenesis begins. Mollic epipedons form within 100 years. Steady-state conditions (Lavkulich 1969; Birkeland 1984), where gains in OC are approximately equal to losses in OC, are reached within a few thousand or even a few hundred years. Upon burial OC content decreases rapidly, probably as a result of oxidation and microbial activity. The data from the A horizons of the Lubbock Lake Soil show that within 1000 years after burial, the buried surface-horizons still meet the color and thickness requirements for mollic epipedons, but seldom the OC requirement. These data support Yaalon's (1971, 33–34) argument that A horizons, and mollic epipedons in particular, are "relatively rapidly adjusting [pedologic] features."

Landscape position has locally affected genesis of the A horizons. Along the valley margins, the A horizons of some buried soils were eroded prior to burial, indicated by abrupt, irregular upper boundaries and thin epipedons. Near the

**Table 4.** Field and Laboratory Data for Dust Trap Samples

| Dust trap | Trap area (cm$^2$) | Dust deposition/yr (gm) | Particle size distribution | | | $CaCO_3$ % | Color | |
|---|---|---|---|---|---|---|---|---|
| | | | Sand % | Silt % | Clay % | | Dry | Moist |
| #1 | 441 | 14.59 | 21 | 49 | 30 | 4 | 10 YR 5/2 | 10 YR 3/4 |
| #2 | 875 | 64.97 | 37 | 41 | 22 | 4 | 10 YR 5/3 | 10 YR 3/2 |
| #3 | 875 | 52.50 | 49 | 31 | 20 | 2 | 10 YR 5/3 | 10 YR 3/4 |

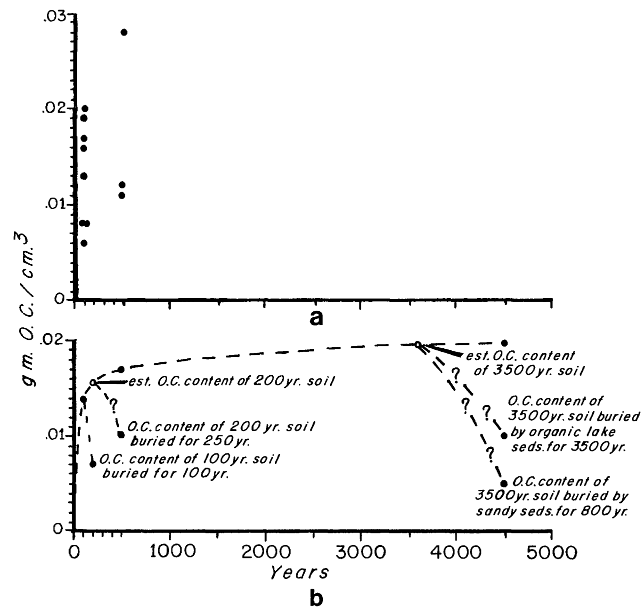


**Figure 4.** Plots of organic carbon buildup per unit volume of an A horizon. (a) Comparison of all OC data points for A horizons of unburied soils with time; (b) Plot of averaged values of OC content over time showing buildup in unburied soils and decline following burial (dashed lines are estimated, not calculated, curves).

valley axis, the soils have pachic or cumulic epipedons which are apparently the result of episodic accumulation of slopewash and eolian sediment. Along the valley axis, the A horizon of the Lubbock Lake Soil is often cumulic and clayey. This morphology is probably the result of slow accumulation of paludal sediments; such sediments are common along the valley axis throughout the site, often resting unconformably on middle Holocene sediments (Holliday 1985d). Typically the lower portion of this cumulic zone exhibits the dark colors of an A horizon, but prismatic to subangular blocky structure more characteristic of a B horizon. Additionally, thin section and particle-size data show the presence of translocated silicate clay in the lower part of the cumulic A horizon. Apparently, the original A was converted into a B horizon as the A horizon aggraded. A similar genetic history is apparent in soils of similar age, parent material, and landscape position in Running Water Draw, north of Lubbock (Holliday 1985c).

The valley-axis variant of the buried Lubbock Lake Soil is an exception to the process of OC destruction after burial. In these soils the buried A horizon maintains higher OC relative to the more typical buried valley-margin facies, though not usually as high as the unburied Lubbock Lake Soil (Fig. 4). The organic-rich paludal sediments and perhaps the reducing conditions of the associated waters probably contribute to OC retention in this setting.

## Clay Illuviation and Argillic Horizon Formation

Illuvial clay content as determined from PSD and thin-section observations increase over time. From the particle-size data, the older soils generally show more translocated clay than the younger ones (Fig. 5), and in thin-section clay films, become better expressed with increasing age (Figs. 6, 7). Very generally this relationship is apparent from the classification of the fabric of the plasma (discussed in detail by Holliday 1985a; following the terminology of Brewer 1976), particularly the redistribution and orientation of the clay. The younger soils have argillasepic fabric with flecked orientation (i.e., skeleton grains in a fine-grained matrix with no redistribution of clay) and the older soils have skel-argillasepic to skelsepic fabric with weakly to moderately striated orientation (i.e., oriented clays are apparent around the skeleton grains) (Fig. 6). All characteristics measured on the clay films in thin section increase with time (Fig. 7).

The clay films in thin section could be the result of a variety of mechanisms, but several lines of evidence suggest that most are due to clay translocation. The clay films increase in number and thickness with time and are better expressed in the B horizons, which appear to mirror the data from PSD. At other localities in the region, soils of similar age in a similar landscape setting but with different parent materials (some with more sand, others with more silt and clay) exhibit similar clay film development (Holliday 1985c).

A few clay films may have come in with skeleton grains of aerosolic dust. Clay films are common on the skeleton grains of the soils on the uplands surrounding the site (Fig. 8a), the source area for most of the Holocene sediments. A thin section of a dust sample from the area, however, shows very few preserved clay films (Fig. 8b). During windstorms in the area, the sand-sized skeleton grains move by saltation and argillans generally do not survive such transport (Gillette and Walker 1977). Finally, if many clay films came in with the grains, it would not be possible to explain clay film development with time, which is clearly demonstrated from the data.

There are few argillans lining voids, which suggests a mode of clay film development other than illuviation, such as orientation of primary clay as water films dry around the grains. Such primary coatings would be expected to contain silt and carbonate, but this has not been observed and would not necessarily produce a maximum expression of clay films in the B horizon. Absence of argillans along voids and channels is common in soils of the region (e.g., Allen and Goss 1974) and is probably a result of disruption due to slight shrinking and swelling. Soils of the semiarid and arid central and western United States are often very dry for long periods of the year, then undergo rapid wetting during intense rainstorms followed by rapid drying. These intense cycles of wetting and drying appear to be quite sufficient to inhibit or disrupt clay film development within the matrix of the soils (Nettleton et al. 1969; Nettleton and Peterson 1983; Allen and Wilding 1985). Some shrinking and swelling therefore appear to take place in the soils, but the

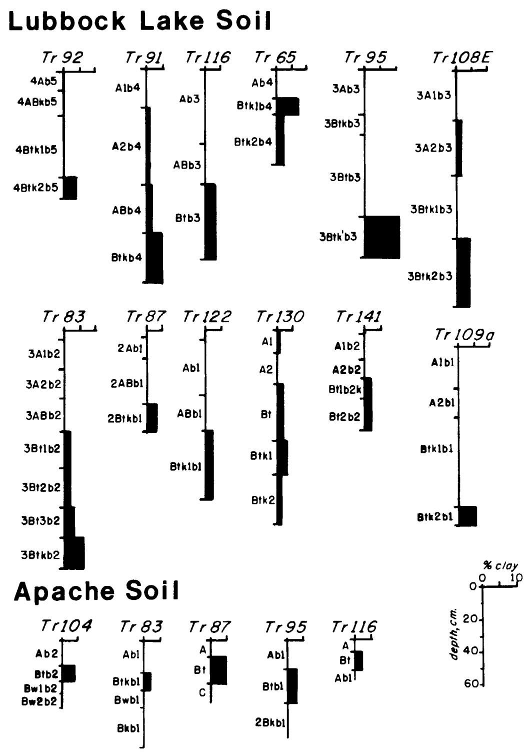


**Figure 5.** Graphs of illuvial clay contents calculated for the Lubbock Lake Soil (all profiles are buried except Trench 130) and Apache Soil (Trenches 104, 83 and 95 are buried). Actual contents of illuvial clay are at least that shown and may be higher. (source: Holliday 1985a, 4; reproduced from *Soil Science Society of America Journal* 49(4):938–46).

clay films do not appear to be stress cutans. The argillans have sharp outer boundaries and are often present as free grain argillans (Fig. 6).

The rate of argillic horizon development is quite rapid. Horizons meeting the minimal requirements for argillic formed in 450 years (e.g., Trench 104, Btb2, Fig. 5; Trench 87, Bt, Fig. 5), and as much as a 6 percent increase in clay content from A to B horizon occurs within 3500 years (Fig. 5; Holliday 1985a). The only comparable rates in a somewhat similar setting are in Bailey County, Texas, where Gile (1979) reports minimally developed argillic horizons in 3500 year-old Haplustalfs formed in noncalcareous dune sands. In contrast, in the Las Cruces, New Mexico, area Gile and Grossman (1979) report development of Haplargids in low-gravel, low-carbonate parent material in 4000

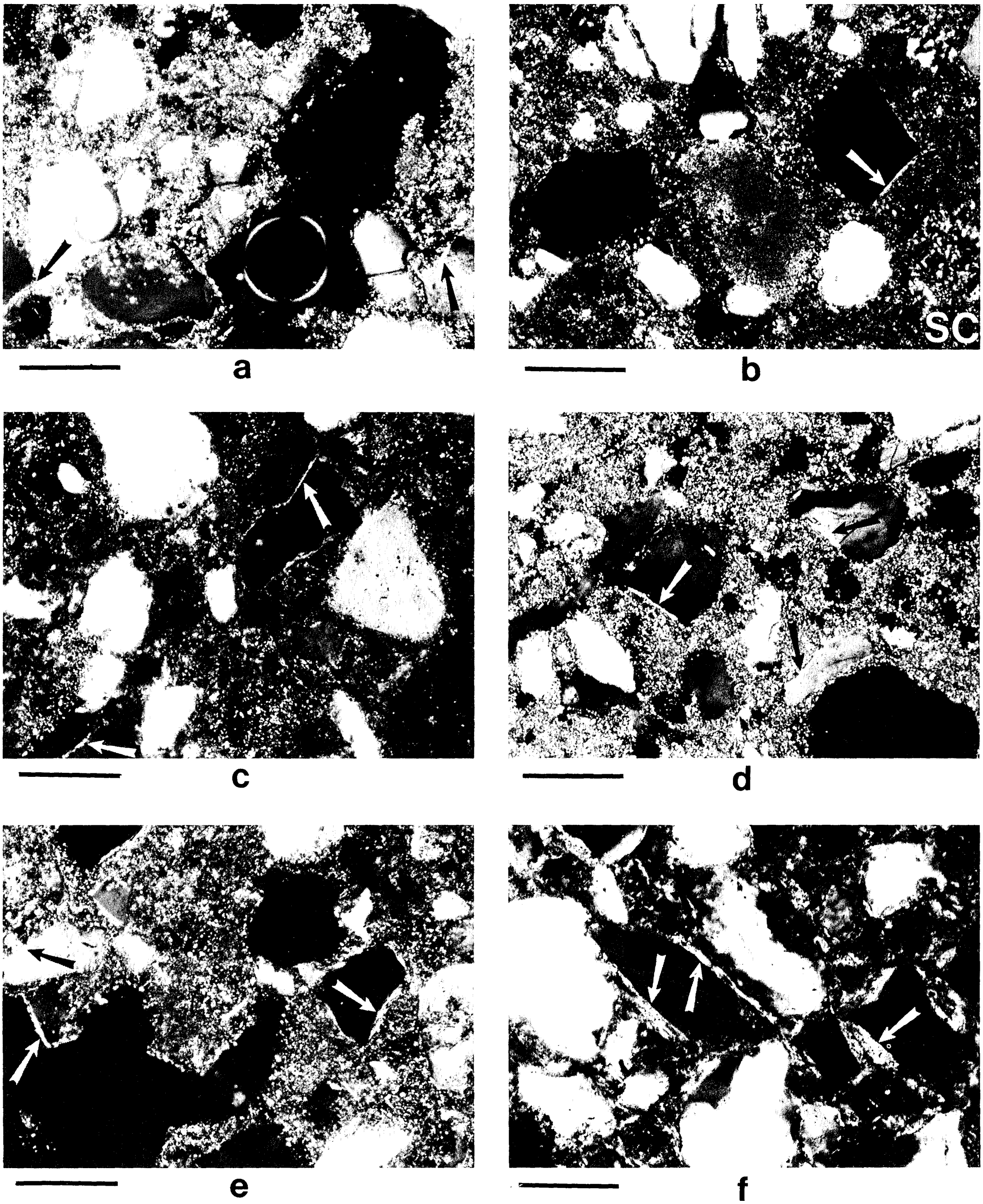


**Figure 6.** Photomicrographs of thin sections (crossed nicols) showing evidence for clay illuviation (arrows indicate argillans; bars are 10 microns): Singer Soil (a = A horizon, Trench 104; b = B horizon, Trench 95); Apache Soil (c = A horizon, Trench 87; d = Btb1, Trench 104); Lubbock Lake Soil (e = A horizon, Trench 130; f = 2Btk1b2, Trench 83) (from Holliday 1985a, Fig. 3; reproduced from *Soil Science Society of America Journal* 49(4): 938–46).

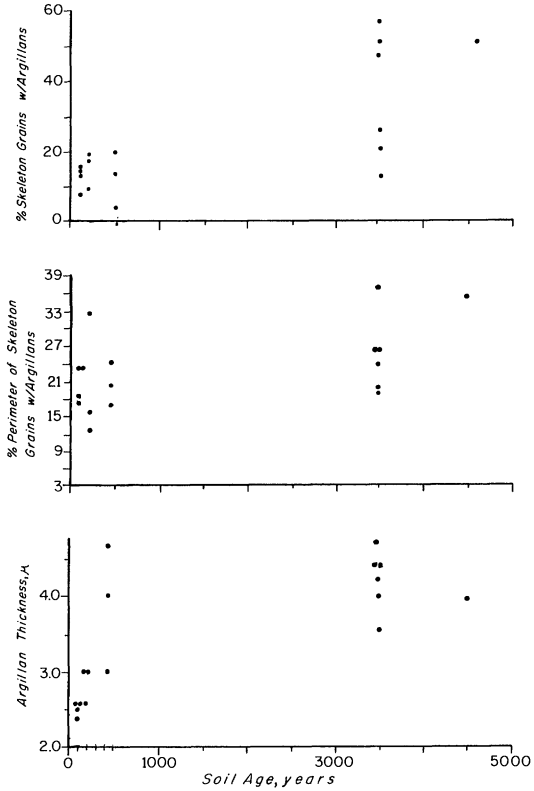


**Figure 7.** Comparisons of various argillan characteristics with time.

years. In the Panamint Valley, California, Peterson (1980) identifies Natriargids developed in sandy alluvium well within 3500 years due to the presence of sodium from aerosolic dust.

Such rapid development of argillic horizons on the Southern High Plains is considered to be the result of mechanical infiltration of aerosolic clays. The best evidence for such aerosolic input at Lubbock Lake is the presence of clay films in A horizons (Fig. 6). In buried soils some of the clay films in the A horizons may be due to illuviation from overlying soils. Clay films are also present, however, in the surface horizons of soils never buried, and the older surface soils show better expressed argillans in the A horizons (Fig. 6).

The availability of aerosolic clays is well demonstrated from particle-size distribution of dust trapped at Lubbock Lake (Table 4) and from several other independent studies of dust in the area (Warn and Cox 1951; LaPrade 1957; Gillette and Walker 1977). The clays are mainly derived from the abrasion of clay films on saltating sand grains during windstorms (Gillette and Walker 1977; Gillette 1981). Goss et al. (1973), in experiments about 160 km north of Lubbock, demonstrate that clay coatings on sand grains can be formed easily from slurries of clay and water injected into the soil. They suggest that such slurries form naturally as a result of dust storms that are associated with convective or frontal thunderstorms; the rain incorporates

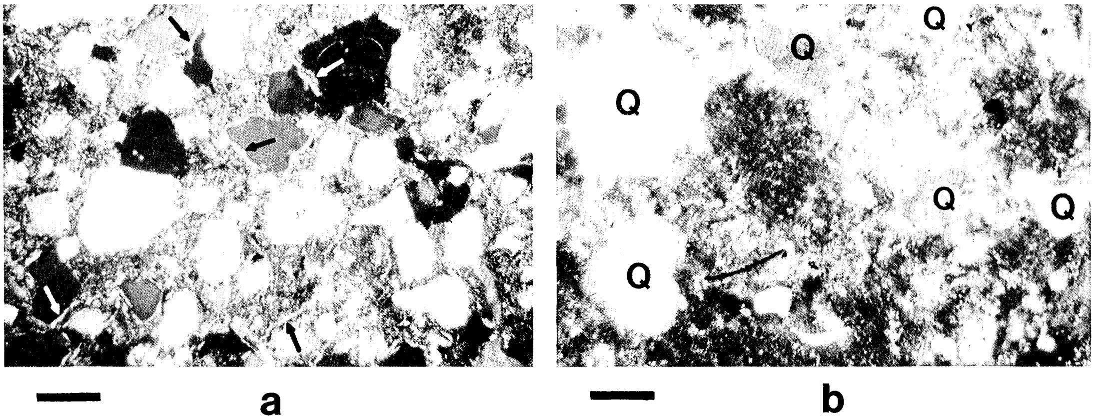


**Figure 8.** Photomicrographs (with crossed nicols) of thin sections from (a) the Bt horizon of a Paleustalf (Amarillo series) formed in the High Plains surface showing common, well-developed argillans (arrows) coating skeleton grains and (b) impregnated dust trapped at Lubbock Lake (trap 3, Table 4) showing clean quartz grains (Q) (bar is 10 microns).

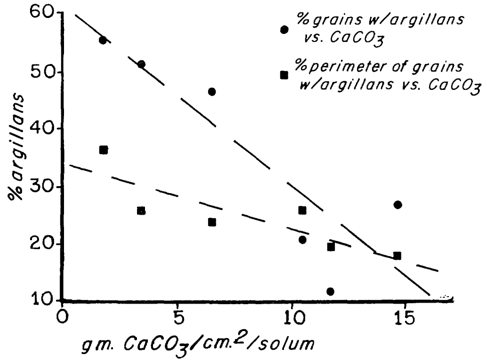


**Figure 9.** Plot of various argillan characteristics as linear functions of total, secondary $CaCo_3$ content ($gm/cm^2$/solum). Each regresssion has an r significant at the 0.5 level using linear regression equation $Y = a + bX$ (where X is total $CaCO_3$ and Y is argillan data; for % skeleton grains w/argillans, b, slope, is −3.167, a, intercept is 61.806; for % perimeter of skeleton grains coated b is −1.145 and a is 34.392).

the associated dust, creating a "mud rain," as noted by Warn (1952) and observed by the writer on numerous occasions.

Finally, the data from Lubbock Lake suggest that clay can be translocated into a calcareous medium, which was also documented for the early Holocene soils at the site (Holliday 1985e), in similar Holocene soils at Plainview, Texas (Holliday 1985c), from experimental work in the area (Goss et al. 1973), and from other regions (Aguilar et al. 1983). At Lubbock Lake all of the late Holocene soils were calcareous throughout their profiles, and illuvial clay films were observed in thin sections from most horizons. There was no evidence that the soils were ever decalcified, then recalcified following clay illuviation. The experimental work of Goss et al. (1973) suggests that clays can move through calcareous soils by mechanical infiltration, i.e., as mud-rain slurries. There is, however, a statistically significant inverse relationship between clay film content and amount of $CaCO_3$ ($gm/cm^2$/solum), indicating that there is more clay film development where there is less calcium carbonate (Fig. 9), probably because clay translocation is facilitated when carbonate is removed from the solum (Buol et al. 1980; McKeague 1983).

## Calcium Carbonate Accumulation and Calcic Horizon Formation

Horizons of carbonate accumulation are the most visually obvious pedogenic features in the soils at Lubbock Lake. Zones of carbonate accumulation typically appear in the lower B horizons of the late Holocene soils. Carbonate accumulation is quite rapid (Fig. 10a), and calcic horizons are present in the buried Apache Soil (i.e., forming in about 200 years). Morphologically, the films and threads of $CaCO_3$ become more common and thicker over time.

Carbonate is available from the parent material of the soils, from aerosolic additions, and from rainwater. As noted earlier, the parent material of the late Holocene soils probably had about 5 percent primary $CaCO_3$. The source of much of the rest of the carbonate is most likely dust. Dust in the Lubbock area is calcareous; the sediments from the dust traps at Lubbock Lake contained from 2–4 percent $CaCO_3$ (Table 4). Warn and Cox (1951) and LaPrade (1957) also report calcareous dust in the area. The aerosolic carbonate is probably derived from calcareous lacustrine sediments exposed in many of the lake basins in the region (Holliday 1985b) and from extensive exposures of calcretes along the western and southwestern (upwind) portion of the Southern High Plains. Meteoric water also provides some calcium. Junge and Werby (1958) show that rainwater over the Southern High Plains is relatively high in calcium content (between 2.0 and 3.0 mg/l), which they relate to high dust content of the air. Their data could be somewhat misleading in considering rates of $CaCO_3$ accumulation, because the collection period (1955–56) was a time of above-average dust storm activity (Wigner 1984).

The buried Lubbock Lake Soil often exhibits carbonate accumulation in the upper B horizon in addition to the more typical Bk lower in the profile (e.g., 3Btkb3, Trench 95, Fig. 3, Table 1). This accumulation is believed to be due to variations in influx of aerosolic $CaCO_3$, resulting from minor climatic changes, just prior to burial of the soil. A drier climate just after 1300 yr B.P. is indicated by evidence for wind deflation of a playa just north of Lubbock Lake (Holliday 1985b); Hall (1982) presents paleontological and paleobotanical evidence for a drying trend on the Southern Plains about 1000 yr B.P. A drier climate would lead to reduced vegetative cover

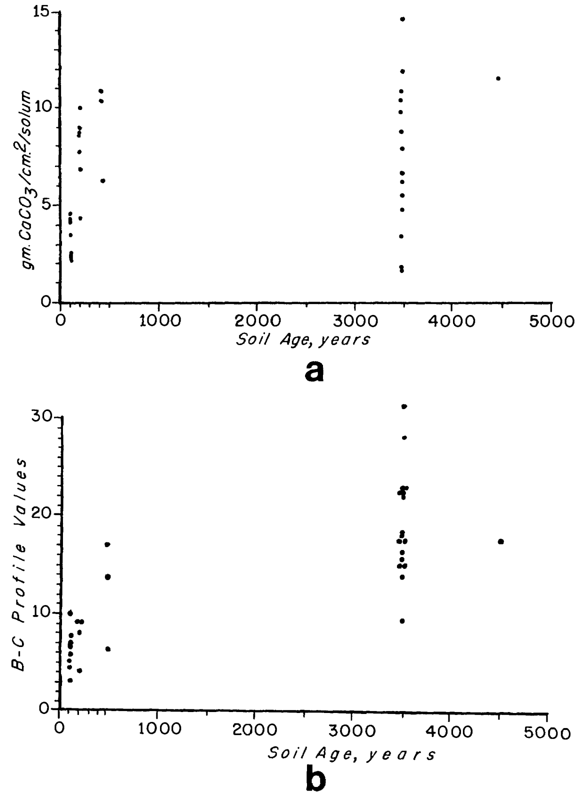


**Figure 10.** Comparisons of: (a) total, secondary $CaCO_3$ with time; (b) BC values with time.

and increase wind erosion and dust. Deflation of lake basins with calcareous sediments, common in the region (Holliday 1985b), would increase the amount of carbonate dust. Drying would also result in formation of carbonate horizons nearer the surface of soils because less water would be available to move carbonates deeper in the profile.

## Color

The soils show an increasing redness with time at Lubbock Lake. The $CaCO_3$ in the soils tends to mask the colors, however, most often affecting the color value. In order to establish trends in color with time, colors of the samples from the dust traps were determined. The dust-trap sediments are considered to be similar to the original parent material and have hues of 10YR (Table 4). The Singer and Apache Soils have hues of 10YR and 7.5YR. The Lubbock Lake Soils have hues of 7.5YR and one profile has a hue of 5YR (this profile also has low $CaCO_3$ content).

## Clay Mineralogy

There is a significant trend in the clay mineralogy of the soils at Lubbock Lake that is considered to be a function of landscape setting. Weighted-mean ratios of mixed-layer illite-smectite (ML-IS) clays to illite were calculated for dust samples and for the Singer, Apache, and Lubbock Lake Soils. There is an increase in ML-IS clays in the older soils (Table 3). Similar trends are reported from soils developed in tills in Illinois (Frye et al. 1960; Willman et al. 1966). This trend is considered to be the result of clay redeposited in an environment with more effective moisture. The uplands surrounding the site, the source of the clays, are very well drained and receive moisture directly from rain. In the redeposited (valley) setting, where the clays are incorporated into the soils, there is an increase in effective moisture from two sources: runoff that is concentrated along the drainage and springs or seeps documented for the Holocene, including modern times (Holliday 1985d). This situation would tend to exaggerate seasonal wetting and drying relative to the uplands. Wetting and drying have been proposed as one of the conditions under which K in the inner layers of illite becomes exchangeable with other cations, leading to the formation of ML-IS clays (Fanning and Keramidas 1977, 232). Through time, more ML-IS clays would be produced and ML-IS clays already present would tend to have increased amounts of smectite.

### Overall Morphology and BC Profile Indices

A trend toward stronger morphological development with time is generally apparent in the late Holocene soils. Such a chronosequence can be described by classifying the soils to the Great Group level of the *Soil Taxonomy* (Soil Survey Staff 1975) and grouping them into three general age categories. The soils start as Entisols, but minimally developed Inceptisols and Mollisols form very rapidly (within 100 years). Within 450 years, all soils are Inceptisols with calcic horizons, Mollisols with calcic horizons, or minimally developed Alfisols. Within 4500 years, soils are Inceptisols with calcic horizons, Mollisols with calcic and argillic horizons, or Alfisols with calcic horizons.

In the field morphology rating, the BC values show an increase in horizon distinctiveness through time (Fig. 10b). This development probably largely reflects $CaCO_3$ buildup because the distinctiveness of each horizon is due to color, and the maximum color difference in the profiles is due to the presence of carbonate.

## Summary and Conclusions

The presence of buried and unburied soils at the Lubbock Lake archaeological site, formed in similar parent materials and topographic position under uniform vegetation and a basically uniform climate, provide an opportunity to study a late-Holocene chronosequence. Moreover, outstanding age control is available from numerous radiocarbon ages and archaeological data, owing to the long-term archaeological research. This situation exemplifies the potential that archaeological sites possess for soil chronosequence studies.

Time is considered to be the most important variable in the genesis of late Holocene soils at Lubbock Lake formed under otherwise similar conditions. Significant trends with time are observed for argillan development, $CaCO_3$ and OC accumulation, and overall development and field morphology rating (BC values). Less significant trends with time are noted for B horizon thickness and color development. There are some differences in A horizon development and clay mineralogy that appear to be functions of landscape position.

There are two other factors ("dot factors" of Jenny 1980) that have a considerable influence on development of Holocene soils examined as part of this study: burial and eolian additions. Burial affects the soils in two ways. First, in the buried A horizons, the OC content decreases rapidly. Second, soil development in sediments burying older soils may impart different pedologic characteristics to the buried horizons, e.g., a buried A horizon may take on some of the characteristics of a B horizon. The result is termed a composite profile by Morrison (1967) or a welded soil by Ruhe and Olson (1980).

Eolian additions had a significant effect on pedogenesis. Minimally developed argillic horizons formed in 450 years, probably due to mechanical infiltration of clays derived from dust. In addition, $CaCO_3$ accumulation is quite rapid because of calcareous dust infiltration. Multiple k and calcic horizons are seen in the Lubbock Lake Soil, probably caused by minor climatic fluctuations. The region appears to have optimal environmental conditions for promoting clay and carbonate translocation and accumulation: abundant dust, precipitation of adequate frequency and intensity contrasting with strong seasonal drying, and soils that allow relatively rapid infiltration.

In conclusion, time is a significant factor in explaining the variations in the late Holocene soils on the Southern High Plains. An important contributing factor is the timing and availability of aerosolic additions which enhance certain significant pedological characteristics.

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