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Calcic soils of the southwestern United States

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ABSTRACT

Calcic soils are commonly developed in Quaternary sediments throughout the arid and semiarid parts of the southwestern United States. In alluvial chronosequences, these soils have regional variations in their content of secondary calcium carbonate ($CaCO_3$) because of (1) the combined effects of the age of the soil, (2) the amount, seasonal distribution, and concentration of Ca^{++} in rainfall, and (3) the $CaCO_3$ content and net influx of airborne dust, silt, and sand. This study shows that the morphology and amount of secondary $CaCO_3$ (cS) are valuable correlation tools that can also be used to date calcic soils.

The structures in calcic soils are clues to their age and dissolution-precipitation history. Two additional stages of carbonate morphology, which are more advanced than the four stages previously described, are commonly formed in middle Pleistocene and older soils. Stage V morphology includes thick laminae and incipient pisolites, whereas Stage VI morphology includes the products of multiple cycles of brecciation, pisolite formation, and wholesale relamination of breccia fragments. Calcic soils that have Stage VI morphology are associated with the late(?) Miocene constructional surface of the Ogallala Formation of eastern New Mexico and western Texas and the early(?) Pliocene Mormon Mesa surface of the Muddy Creek Formation east of Las Vegas, Nevada. Thus, calcic soils can represent millions of years of formation and, in many cases, provide evidence of climatic, sedimentologic, and geologic events not otherwise recorded.

The whole-profile secondary $CaCO_3$ content (cS) is a powerful developmental index for calcic soils: cS is defined as the weight of $CaCO_3$ in a 1-cm^2 vertical column through the soil (g/cm^2). This value is calculated from the thickness, $CaCO_3$ concentration, and bulk density of calcic horizons in the soil. (See Soil Survey Staff, 1975, p. 45–46, for a complete definition of calcic horizon.) $CaCO_3$ precipitates in the soil through leaching of external Ca^{++} that is deposited on the surface and in the upper part of the soil, generally in the A and B horizons. The cS content, maximum stage of $CaCO_3$ morphology, and accumulation rate of $CaCO_3$ in calcic soils of equivalent age can vary over large regions of the southwestern United States in response to regional climatic patterns and the influx of Ca^{++} dissolved in rainwater and solid $CaCO_3$.

Preliminary uranium-trend ages and cS contents for relict soils of the Las Cruces, New Mexico, chronosequence show that 100,000- to 500,000-year-old soils have similar average rates of $CaCO_3$ accumulation. Conversely, soils formed during the past 50,000 years have accumulated $CaCO_3$ about twice as fast, probably because the amount of vegetative cover decreased in the Holocene and, hence, the potential supply of airborne Ca^{++} and $CaCO_3$ to the soil surface increased.

The quantitative soil-development index cS can be used to estimate the age of calcic soils. This index can also be used to correlate soils formed in unconsolidated Quaternary sediments both locally and regionally, to compare rates of secondary $CaCO_3$ accumulation, and to study landscape evolution as it applies to problems such as earthquake hazards and siting of critical facilities.

INTRODUCTION

Quantitative indices of soil development are powerful and fundamental tools for estimating ages of Quaternary soils, but such indices have not been widely applied in geology as yet. However, many soils and their parent materials can scarcely be dated otherwise and thus, inadequate age control limits the value of many geologic investigations. This paper describes a quantitative index that assesses the development of calcic soils: that is, those arid and semiarid soils that have significant accumulations of secondary calcium carbonate. This index can be used to (1) estimate the duration of soil formation, (2) correlate Quaternary sediments in which they are formed, and (3) analyze spatial and temporal variations in rates of secondary $CaCO_3$ accumulation.

Calcic soils are herein defined as having significant accumulations of secondary calcium carbonate. [Note: The term carbonate is used hereafter for both calcium carbonate and magnesium carbonate, which may occur as a minor constituent in calcic soils.] According to pedologic criteria they must have a calcic horizon. In the field, such soils are characterized by a layer (at least 15 cm thick) of secondary carbonate that is enriched in comparison to the soil's parent material.

If Quaternary sediments or soils contain appropriate material, they can be dated by one of several analytical methods. Organic or inorganic carbon can be dated by C^{14} or uranium-disequilibrium methods. Ages of volcanic rocks can be dated by the K-Ar method, and their associated tephra (ash and pumice) can also be dated by the fission-track technique or correlated using chemical and mineralogical characteristics (tephrochronology). These techniques, especially when used with stratigraphic and geomorphic evidence, help solve many problems in Quaternary geology. Because of advances in dating techniques, age control in many Quaternary geologic studies has been much improved. Unfortunately, most Quaternary sediments lack abundant datable material and thus their stratigraphies are commonly based on less exacting, yet widely applicable criteria.

Soils, however, mantle most land surfaces. These soils range from thin, incipient to weak profiles on young (Holocene) alluvium, to thick, strong profiles on old (Pleistocene and Pliocene) alluvium. The vast majority of soils, however, are between these extremes. Calcic soils are at the arid end-member of a broad spectrum of climates under which soils form. This study deals only with relict soils (as redefined by Ruhe, 1965, and as used by Birkeland, 1974). Relict soils are those that have formed continuously since their parent material was deposited. The age of a relict soil should closely approximate that of its parent material because the soil is the cumulative product of soil formation since the deposit became geomorphically stable, that is isolated from deposition or erosion.

Calcic soils are particularly well suited to quantitative assessments of soil development. In the United States, these soils are widespread in the Southwest, but they also extend into the northern Basin and Range province and into the Midwest (Fig. 1).

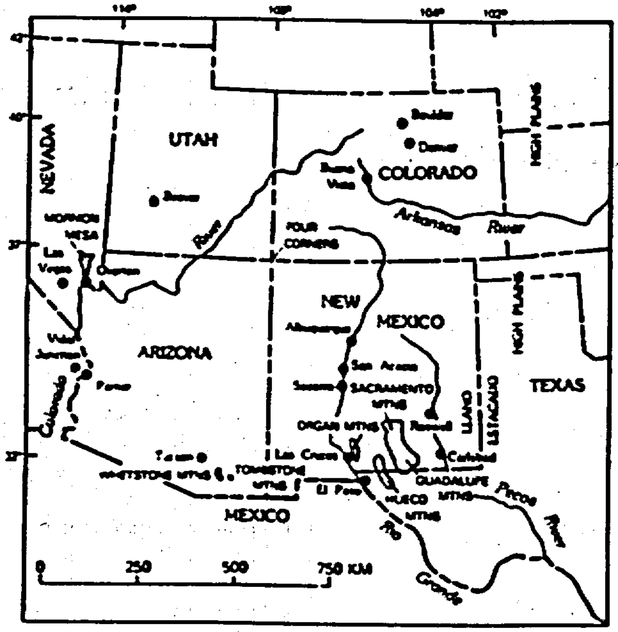


Figure 1. Geographic and cultural features of the southwestern United States mentioned in this report.

They form widely in unconsolidated sediments during periods ranging from as little as a few thousand years to as much as several million years. Most calcic soils in the Southwest have formed since middle and late Pleistocene time, but some highly advanced ones have been forming since Pliocene or late Miocene time on stable surfaces such as the Mormon Mesa of southern Nevada and the High Plains of Colorado, New Mexico, and Texas.

This report is based on reconnaissance and detailed soil studies in the southwestern United States during 1974 through 1977 under contract to the U.S. Nuclear Regulatory Commission. Preliminary results were published by Bachman and Machette in 1977. Since then, under numerous U.S. Geological Survey programs, further information has been collected in New Mexico and in the Basin and Range province near Beaver, Utah (Fig. 1; Machette, 1982).

NOMENCLATURE AND DISTRIBUTION OF CALCIC SOIL AND PEDOGENIC CALCRETE

Nomenclature

The term "caliche" (Blake, 1902) has been broadly applied to deposits of secondary calcium carbonate of various origins, often irrespective of their geomorphic and stratigraphic relations, physical and chemical characteristics, and genesis. Although geologists in the United States generally associate caliche with soil carbonate, the indiscriminate use of the term has created semantic problems. For example, the term has been applied loosely to the soluble salts of sodium in nitrate deposits of northern Chile and Peru and to gypsum deposits in Death Valley, California (cited in Goudie, 1973, p. 8-9). Such usage can lead to misconceptions, especially if comparisons and interpretations are made in either a stratigraphic or a genetic context. In general, the term caliche should be abandoned for more specific nomenclature.

Calcic soils (an informal term) are herein defined as those soils that contain a significant amount of secondary carbonate, generally in the form of calcic horizon(s). The term "horizon" is used to describe a three-dimensional body (a layer) of soil material. For the index developed here, such horizons should represent new additions of secondary carbonate to a soil profile, rather than redistributions of primary (allogenic) carbonate. Calcic horizons may range from layers of carbonate-coated pebbles or carbonate filaments and nodules to thick, massive, and indurated carbonate-enriched layers. With increasing age, calcic horizons become so well developed that their structural morphology and general appearance are dominated by the presence of carbonate.

The nongenetic term "calcrete," introduced by Lamplugh (1902) and popularized by Goudie (1973), refers to indurated masses of calcium carbonate. Calcrete is herein restricted to near-surface or shallow, terrestrial deposits of calcium carbonate that have accumulated in or replaced a preexisting soil, unconsolidated deposit, or weathered rock material, to produce an indurated mass (definition slightly modified from that of Goudie, 1973, p. 5). Following this usage, calcretes include indurated calcic soils (pedogenic calcrete) as well as lacustrine marls (lacustrine calcretes), ground-water deposits (ground-water calcretes), and spring or travertine deposits. Some calcic soils may result from a combination of pedogenic and nonpedogenic processes and their respective components may be virtually indistinguishable. For example, a ground-water calcrete that is exhumed and then modified by pedogenesis may form many of the same morphologic features commonly seen in pedogenic calcretes.

In the field, I use the terms "calcic soil" and "pedogenic calcrete" instead of "caliche" to denote those calcium-carbonate-enriched deposits that are formed exclusively by soil processes (pedogenesis). "Calcic soils" is a useful collective term that is roughly synonymous with the Pedocals of Marbut's (1935) soil classification; although many geologists favor the term pedocal (Birkeland, 1984), it has fallen from current pedologic usage.

Pedologists commonly recognize three master horizons in soils of arid and semiarid climates: the A, B, and C horizons, with increasing depth. Horizons with secondary carbonate are denoted by a "k" suffix, as in the Bk horizon (Guthrie and Witty 1982; Birkeland, 1984). Although this usage is consistent with modifiers used to describe other horizon types, it gives no indication of the amount of carbonate accumulation. Because calcic soils are characterized by carbonate, nomenclature that indicates the amount of carbonate accumulation would be useful for geologic purposes.

Gile and others (1965) recognized the need for descriptive nomenclature based on field criteria that would better describe calcic soils. They introduced the term "K horizon," a master soil horizon, to describe prominent layers of carbonate accumulation. The K-horizon nomenclature is particularly useful for geologic applications because it allows field differentiation of weak calcic horizons, such as Bk horizons, from moderate to strong K horizons. According to their definition, the K horizon must have more than 90 percent K-fabric, a diagnostic soil fabric in which ". . . fine-grained authigenic carbonate occurs as an essentially continuous medium. It coats or engulfs, and commonly separates and cements skeletal pebbles, sand, and silt grains . . ." (Gile and others, 1965, p. 74).

Distribution

Calcic soils are found in many areas of the western United States where warm and periodically to predominately dry climates result in torric, ustic, or xeric soil-moisture regimes (see Soil Survey Staff, 1975, for descriptions of soil-moisture regimes). Most calcic soils form under grassland or desert-type vegetation, but some may exist under pinon-pine and juniper forest vegetation where the present soil-moisture conditions differ from those that existed when carbonate was accumulating in the soil. Figure 2 shows major areas of calcic soils in the western United States as interpreted from the United States Soils Map (U.S. Soil Conservation Service, 1970). The main group of calcic soils includes only those soils that (1) are in the Entisol, Mollisol, Alfisol, or Aridisol orders (Soil Survey Staff, 1975); (2) have calcic or petrocalcic horizons; and (3) have ustic or torric soil-moisture regimes. Soils having xeric regimes receive mainly winter rainfall and are associated with Mediterranean climates such as that in California's San Joaquin Valley (Fig. 2). Most areas having these climates are too moist for soil $CaCO_3$ to accumulate; thus they are shown as marginal areas of accumulation (Fig. 2). However, soils formed in calcareous bedrock (such as limestone or dolomite) or alluvium are not included in Figure 2 because nonpedogenic accumulations of carbonate can form in these areas under almost any climate or can result strictly from high levels of ground water.

Within the United States, soils that continually accumulate carbonate generally are restricted to areas of arid and semiarid climate within low-altitude basins of the Southwest, although some soils accumulate carbonate periodically at higher altitudes in the northern Basin and Range province and in the lower altitudes of mountainous regions such as the Colorado Plateaus province. Gile (1975, 1977) has demonstrated that the increased rainfall associated with climatic gradients near mountain ranges has a profound effect on the distribution and concentration of carbonate in Holocene soils of the Las Cruces, New Mexico, area (Fig. 1). In the Southwest, Bk or K horizons formed in a single-age deposit generally become less calcareous or less continuous along soil transects from basins to mountains.

The boundary between soil that has accumulated carbonate and soil that is leached of carbonate is called the pedocal-pedalfer boundary. Jenny (1941) demonstrated that the pedocal-pedalfer boundary in the Midwest probably is controlled by the eastward

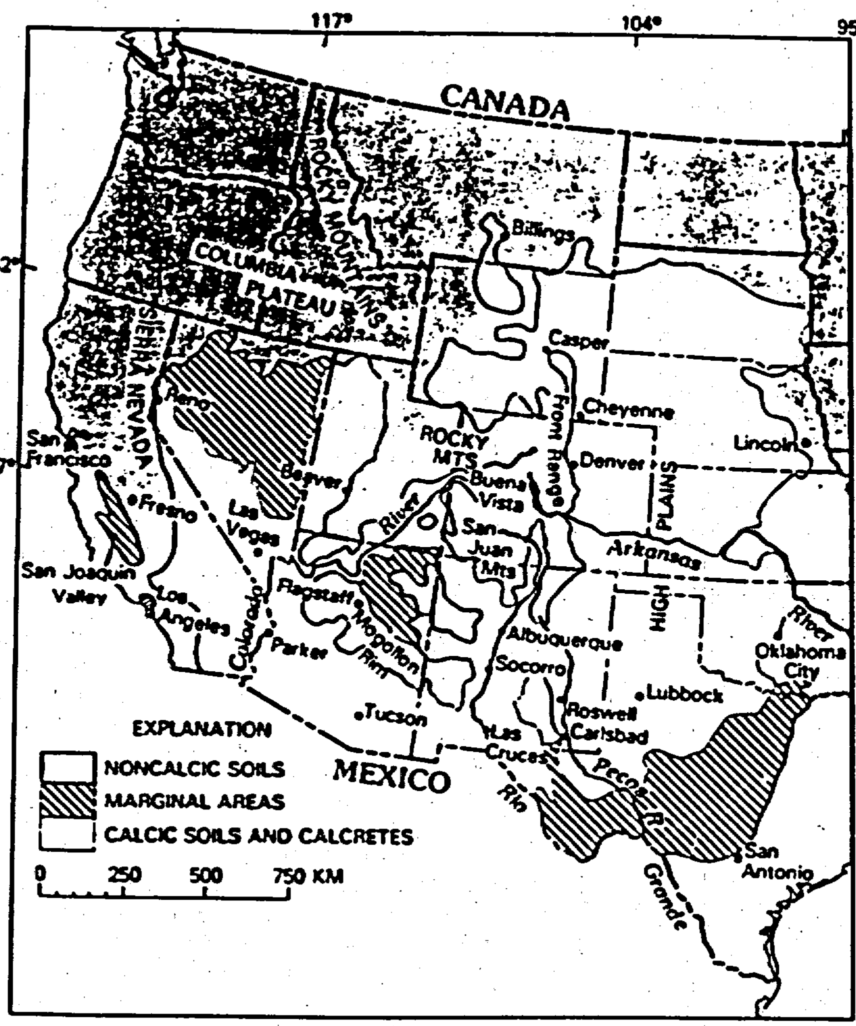


Figure 2. Areas where calcic soils may be present in the southwestern United States, as interpreted from the soils map of the United States (U.S. Soil Conservation Service, 1970). Areas of discontinuous or poorly preserved calcic soils are designated marginal.

increase in soil moisture, vegetative cover, soil organic-matter content, and soil acidity (decrease in soil pH). These factors, in combination, enable more carbonate to be leached from a soil than is supplied to its surface; the result is a pedalfer, a soil leached of carbonate. The eastern boundary of calcic soils shown in Figure 2, which I interpreted from the United States Soils Map, is similar to that of Jenny's (1941, Fig. 99).

MORPHOLOGY OF CALCIC SOILS

Gile and others (1966) described a morphological sequence for calcic soils in arid and semiarid regions of New Mexico based on the physical characteristics of pedogenic calcium carbonate. This sequence includes four stages of morphology (soil structure) that depend partly on the texture of a soil's parent material. Bachman and Machette's (1977) soil studies in the Southwest led to the recognition of two additional, more advanced stages of carbonate morphology (Stages V and VI, Table 1; modified from Bachman and Machette, 1977, Table 2). These two stages are characterized by thick laminae, pisolites, and multiple episodes of brecciation (physical disaggregation) and recementation. The diagnostic characteristics used to distinguish the six stages of carbonate morphology are shown in Table 1.

Gile and others (1965) proposed Stage IV as the maximum degree of carbonate morphology and included all thicknesses of laminae within this stage. However, during Bachman and Machette's reconnaissance, they recognized more advanced morphology in old calcic soils, particularly in pedogenic calcretes.

TABLE 1. STAGES OF CALCIUM CARBONATE MORPHOLOGY OBSERVED IN CALCIC SOILS AND PEDOGENIC CALCRETES DEVELOPED IN NONCALCAREOUS PARENT MATERIALS UNDER ARID AND SEMIARID CLIMATES OF THE AMERICAN SOUTHWEST
(Modified from Gile and others (1966, p. 348, Table 1) and Bachman and Machette (1977, p. 40, Tables 2 and 3))

Stage	Gravel content[1]	Diagnostic morphologic characteristics	$CaCO_3$ distribution	Maximum $CaCO_3$ content[2]
		CALCIC SOILS		
I	High------	Thin, discontinuous coatings on pebbles, usually on undersides.	Coatings sparse to common	Tr-2
	Low-------	A few filaments in soil or faint coatings on ped faces.	Filaments sparse to common	Tr-4
II	High------	Continuous, thin to thick coatings on tops and undersides of pebbles.	Coatings common, some carbonate in matrix, but matrix still loose.	2-10
	Low-------	Nodules, soft, 0.5 cm to 4 cm in diameter	Nodules common, matrix generally noncalcareous to slightly calcareous.	4-20
III	High------	Massive accumulations between clasts, becomes cemented in advanced form.	Essentially continuous dispersion in matrix (K fabric).	10-25
	Low-------	Many coalesced nodules, matrix is firmly to moderately cemented.	------------------do------------------	20-60
		PEDOGENIC CALCRETES (INDURATED CALCIC SOILS)		
IV	Any-------	Thin (<0.2 cm) to moderately thick (1 cm) laminae in upper part of Km horizon. Thin laminae may drape over fractured surfaces	Cemented platy to weak tabular structure and indurated laminae. Km horizon is 0.5-1 m thick.	>25 in high gravel content >60 in low gravel content
V	Any-------	Thick laminae (>1 cm) and thin to thick pisolites. Vertical faces and fractures are coated with laminated carbonate (case-hardened surface)	Indurated dense, strong platy to tabular structure. Km horizon is 1-2 m thick.	>50 in high gravel content >75 in low gravel content
VI	Any-------	Multiple generations of laminae, breccia, and pisolites; recemented. Many case-hardened surfaces.	Indurated and dense, thick strong tabular structure. Km horizon is commonly >2 m thick.	>75 in all gravel contents

[1]High is more than 50 percent gravel; low is less than 20 percent gravel.
[2]Percent $CaCO_3$ in the <2-mm-fraction of the soil. Tr, trace of carbonate.

Therefore, I propose that Stage IV morphology be limited to K horizons that have laminae or laminar layers less than 1 cm thick. The next stage of morphology, Stage V (Fig. 3A), is distinguished by laminae or laminar layers thicker than 1 cm and, in some cases, by incipient to thick, concentrically banded pisolitic structures. Pisoliths commonly have cores of fragments of Stage III soil matrix or Stage IV laminae, and these fragments suggest that brecciation is an integral part of pisolith formation in soils.

Calcic soils of Stage VI morphology are characterized by multiple episodes of brecciation and pisolith formation through relamination and recementation of breccia fragments (Figure 3B); the resulting products are thick, indurated masses of carbonate (pedogenic calcretes). These soils are the climax products of relatively continuous carbonate accumulation over perhaps millions of years. In eastern New Mexico, Stage V calcic soils have formed in middle to early Pleistocene alluvium that contains reworked clasts of older calcic soils (Stage VI) of the Miocene Ogallala Formation, indicating that the processes of soil brecciation and pisolization were active throughout the Quaternary, and possibly during the Pliocene.

Calcic soils that have Stage V and VI morphology result from varied conditions of carbonate accumulation during their prolonged formation. Bretz and Horberg (1949) considered calcic soils with Stage V and VI morphology to be self-brecciation features and named them collectively "Rock House structures" for outcrops near Rock House, New Mexico. Bryan and Albritton (1943) indicated that these structures are related to fluctuations in soil moisture caused by alternating climatic conditions, probably fluctuations between cool, moist conditions of the pluvials and warm, dry conditions of the interpluvials.

Stage V and VI calcic soils are particularly well preserved at numerous locations in the Southwest. The most spectacular of these soils are associated with the constructional geomorphic surfaces of the following geologic units:

$CaCO_3$ stage	Geomorphic surface and probable age	Geologic unit and probable age	Location
V	Upper La Mesa, early Pleistocene	Camp Rice Formation of Strain (1966), middle Pleistocene to Pliocene	Las Cruces, New Mexico
V	Mescalero middle Pleistocene	Gatuna Formation, middle Pleistocene	Southeastern New Mexico
VI	Mormon Mesa, early(?) Pliocene	Muddy Creek Formation, Miocene	Overton, Nevada
VI	Ogallala, late(?) Miocene	Ogallala Formation, Miocene	Eastern New Mexico and western Texas

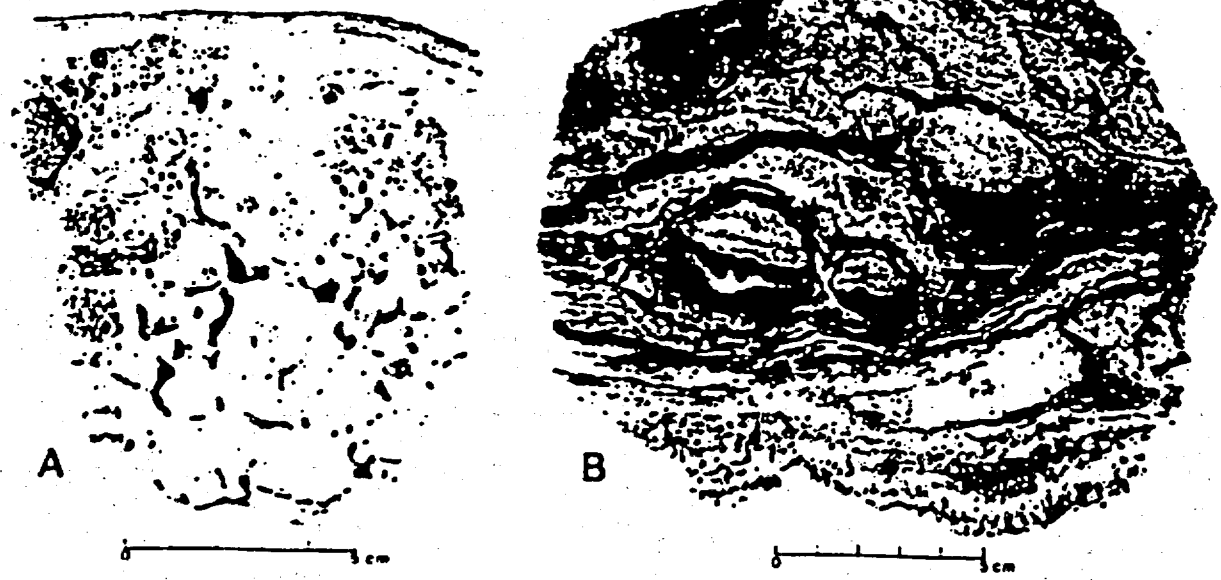


Figure 3. Slabbed samples of calcic soils showing advanced stages of carbonate morphology. A, Incipient Stage V morphology found in the upper part (K21m subhorizon) of the pedogenic calcrete of the upper La Mesa surface (early Pleistocene) near Las Cruces, New Mexico (U.S. Soil Conservation Service pedon 60-NMex7-7). B, Stage VI morphology typically found in the upper part of the Ogallala caprock (late? Miocene) in eastern New Mexico and western Texas.

Gile and others (1966) have shown that the difference in texture between gravelly and nongravelly parent materials greatly influences the time required to form Stage I, II, III, and IV morphologies (Table 1). However, parent-material texture is less significant in the two ultimate stages (V and VI), because of the great expansion that accompanies their formation. Stage V and IV horizons have so much $CaCO_3$—commonly more than 50 percent in gravelly materials and more than 75 percent in fine-grained materials—that the texture of the parent material is completely obscured in these horizons.

Volumetric calculations of the carbonate and noncarbonate fractions of calcic soils by Gardner (1972) and Bachman and Machette (1977, Table 7) indicate that K horizons of strong Stage III or greater morphology undergo marked and progressive expansion with continuing accumulation of $CaCO_3$. If the volume of carbonate that accumulates in a soil exceeds the original pore space of the soil's parent material, there must be a physical expansion of the detrital grains. Viewed in thin section, these K horizons have scattered detrital grains that appear to float in a matrix of carbonate. For example, there must be 400 to 700 percent volumetric expansion in the original framework of detrital grains to accommodate the carbonate found in some K horizons of Stage V and VI morphology.

As calcic soils accumulate carbonate and exceed Stage III morphology, their bulk density systematically and progressively increases with a concomitant decrease in porosity and permeability. Figure 4 shows the relation between carbonate content and bulk density for pedogenic calcretes having Stage IV, V, or VI morphology. Over millions of years of carbonate accumulation, these soils obtain carbonate concentrations (in percent) and bulk densities that approach those of limestones (Fig. 4). These physical characteristics and the gross similarity of laminar and pisolitic features to those produced by algal masses have led some investigators to consider the Ogallala caprock a lacustrine deposit rather than a calcic soil (compare Fig. 3B this report with Elias, 1931, pl. 21B; Price and others, 1946).

PROCESSES OF CALCIUM CARBONATE ACCUMULATION

Secondary carbonate may accumulate through several varied processes to form either calcic soils or other deposits that resemble soils. Although major processes leading to such concentrations have been discussed by Goudie (1973), four of these processes are briefly reviewed here, because some calcic soils can easily be confused with strictly nonpedogenic accumulations of carbonate.

Many calcic soils were once thought to form by "upward capillary flow of calcareous water, induced by constant and rapid evaporation at the surface in a comparatively rainless region" (Blake, 1902, p. 225). In the Southwest, ascending $CaCO_3$-rich water can and should precipitate some $CaCO_3$. However, this

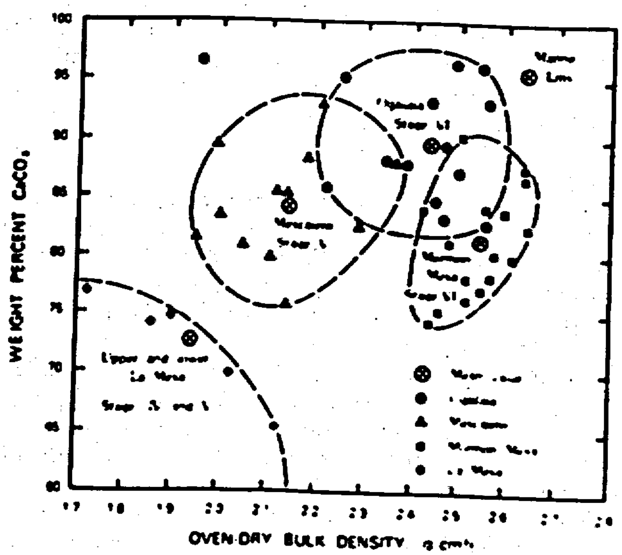


Figure 4. Percent calcium carbonate (whole-soil fraction) versus oven-dry bulk density (g/cm^3) of some pedogenic calcretes in the Southwest. Includes only data for K horizons of Stage IV, V, or VI morphology. The carbonate contents (Clarke, 1924) and bulk densities (Krynine and Judd, 1957) of marine limestones are also shown for comparison.

process is not likely to form calcic soils in areas of entrenched Pleistocene drainage, such as all along the Rio Grande in New Mexico. The ground water from which $CaCO_3$ might be derived has remained at levels well below the surface since the deposition of the soil parent material or shortly thereafter (Gile and others, 1981). Secondly, the concentration of Ca^{++} is usually low in ground water, thereby limiting the potential amount of carbonate that could be precipitated if ground water were to reach the surface and evaporate. Thirdly, in the Southwest many soils are formed in medium- to coarse-textured sediments that have little or no potential for capillary rise. Thus, the amount of rise postulated for this process requires an optimum combination of evaporative, ground-water level, and soil-texture conditions that does not commonly exist in the Southwest. The ascension process, as it is termed, does not appear to have contributed significant amounts of carbonate to most calcic soils of the Southwest.

A second process by which carbonate can accumulate involves the in situ weathering of Ca^{++} into soil water, and the subsequent precipitation of $CaCO_3$ in the soil. Ca^{++}-rich rocks such as basalt often are proposed as potential sources of Ca^{++} for this process. Such rocks, however, do not easily weather in semiarid to arid environments, nor do they provide abundant Ca^{++} if they are weathered. Gardner (1972) evaluated the likelihood that this process could have formed the Mormon Mesa calcrete of southern Nevada and concluded that the concentration of carbonate in the calcrete would require complete removal of Ca^{++} from 100 m of basaltic gravel. Studies of the chemistry of similar calcic soils (Vanden Hueval, 1966; Aristarain, 1970; Bachman and Machette, 1977) found little evidence of depletion of relatively mobile cations (such as Ca^{++}, Na^{++}, and K^{++}) in the detrital mineral fraction of the soil. These same soils lack residual accumulations of relatively immobile elements, such as Al, Si, or Ti, that should exist if the carbonate were concentrated by weathering. Thus, it seems that the process of in situ weathering is not involved in the formation of the majority of calcic soils in the Southwest. Obvious exceptions are soils formed on parent materials that contain limestone, calcareous sandstones, or dolomite. For example, the alluvium flanking the eastern side of the Sacramento and Guadalupe Mountains in southern New Mexico (Fig. 1) has soils formed partly by in situ weathering of limestones and partly by leaching of airborne calcareous dust (see following discussion of the per descensum model).

Laterally flowing, $CaCO_3$-rich ground water commonly forms deposits that are misidentified as calcic soils or pedogenic calcretes. This process calls for Ca^{++}-charged ground water to either discharge onto a stream bottom or reach a near-surface position where Ca^{++} is concentrated by evaporation. Supersaturation of Ca^{++} causes precipitation of $CaCO_3$ and subsequent cementation of relatively pervious sands and gravels. Such ground-water calcretes are typically well indurated to depths of 10 m or more, are characterized by gravel clasts that have grain-to-grain contact, and generally lack the horizonation and morphologic structures common in calcic soils. Ground-water calcretes form quickly but at differing times as the subsurface or surface flow shifts laterally into more permeable material. Surface runoff may add to or redistribute this same $CaCO_3$ and produce laminar zones that resemble pedogenic calcretes of Stage IV and V morphology. In southeastern New Mexico, Bachman and Machette (1977) found ground-water calcretes that had laminae as much as 1 cm thick along highway drainage culverts in limestone-rich alluvium. These laminae prove gulley-bed cementation can occur rapidly.

Lattman (1973) found that gully-bed cementation occurs during surface runoff on limestone-rich alluvial-fan sediments near Las Vegas, Nevada, and proposed that this process could form the laminar horizons (Stage IV and V) of many pedogenic calcretes. I disagree with his hypothesis, as it applies to most calcic soils, because laminar K horizons are commonly overlain by Bk horizons that are formed in material of the same age as the K horizon. However, my investigations of calcretes in the Las Vegas area suggest that many of them are pedogenically modified ground-water calcretes. Bachman and Machette (1977) found calcretes of similar origin west of Roswell and Carlsbad, New Mexico; near the Whetstone and Tombstone Mountains of southern Arizona; and south of the Hueco Mountains in west Texas (Fig. 1).

The fourth process, which involves airborne supply of calcareous material to the soil surface, has until recently not been widely accepted as an important formational process for calcic soils in semiarid and arid regions of the United States, partly because of the pervasive and subtle nature of airfall. Goudie (1973, p. 136) termed this the "per descensum model" because $CaCO_3$ is leached from the surface and upper horizons of the soil and subsequently precipitates and accumulates in lower soil horizons at a depth controlled by soil moisture and texture (see discussion by McFadden and Tinsley, this volume). The carbonate in the soil comes mainly from external sources such as minute amounts of solid carbonate in aerosolic dust, silt, and eolian sand, and Ca^{++} dissolved in rainwater (Gardner, 1972; Gile and others, 1979). Over thousands of years, the continual translocation of Ca^{++} and precipitation of $CaCO_3$ forms calcic horizons; over millions of years, the accumulation of carbonate forms thick, dense, indurated calcic soils (pedogenic calcretes). Almost a quarter of a century ago, Brown (1956, p. 14) recognized that the Ogallala caprock was pedogenic when he stated "the wind and rain bring in all the materials that form the soil and its associated caliche and deposit these materials on the soil surface."

I believe that airborne $CaCO_3$ and Ca^{++} dissolved in rainwater are the predominant sources of carbonate in calcic soils that have formed over thousands to millions of years in the Southwest. Four lines of evidence support this conclusion. (1) Many calcic soils are in noncalcareous sediments well above present and former levels of ground water. (2) A relict calcic soil's development is directly related to the age of the associated geomorphic surface (and parent material); this relation need not be true if the carbonate were derived from ground-water sources. (3) Local sources, such as calcareous alluvium or lacustrine sediment, and calcic soils themselves, provide abundant carbonate that is transported by the wind. Recent dust fall in the Las Cruces, New Mexico, area has averaged about 0.2 g of $CaCO_3$ per cm^2 per 1,000 years (Gile and others, 1979), which is only slightly less than the long-term average rate of carbonate accumulation in soils of this region (see section on "Rates of $CaCO_3$ Accumulation"). (4) Finally, the concentration of Ca^{++} in rainfall is high in the Southwest; values in the southern New Mexico area and the Four Corners region may exceed 5 mg of Ca^{++} per liter of water (Junge and Werby, 1958). The Ca^{++} in this rainwater alone would provide a major part of a soil's carbonate if all the rainwater entered the soil and the Ca^{++} was precipitated as $CaCO_3$. Gile and others (1979 and 1981) have been foremost in documenting these sources of soil carbonate and in popularizing the per descensum model for calcic soils of the Southwest.

ASSESSING THE DEVELOPMENT OF CALCIC SOILS AND THEIR CARBONATE CONTENT

Most assessments of soil development are based on systematic changes in soil properties in relation to those of the soil's parent material. Such assessments can be based on single properties such as soil structure, clay concentration, color, or horizon thickness, or on combinations of these soil properties. The soil-development index of Harden (1982) illustrates the importance of integrating multiple soil properties with soil thickness for quantitative assessments. Yet the results of even this powerful index are affected by variations in parent-material permeability, porosity, and texture, parameters that influence the distribution and concentration of many soil properties. To be widely applicable, an index must compensate for or equalize variations in parent-material characteristics.

Secondary Carbonate Content

This study and many past studies show that with age calcic horizons generally increase in degree of $CaCO_3$ morphology, in concentration of $CaCO_3$, and in thickness. But they also show that these horizons are strongly influenced by the character of the soil's parent material. For example, a calcic horizon in silt and another in gravel of the same age can have different stages of $CaCO_3$ morphology, different concentrations of $CaCO_3$, and different thicknesses, and therefore may appear quite dissimilar. For these reasons I believe that the whole-profile index of secondary carbonate is the best quantitative measure of calcic soil development.

Secondary carbonate (cS) is that component of the soil carbonate that has accumulated since deposition of the parent material. Any carbonate initially in the parent material is here considered to be a primary component (cP), even though some of this carbonate may be remobilized in the soil. The cS is a quantitative measure that integrates the concentration and distribution of carbonate throughout calcic horizons of the soil. For example, a soil in nongravelly sand could have 20 percent $CaCO_3$ (the secondary component) uniformly distributed over a ½-m thickness and still have the same cS content as a soil that has 50 percent gravel and 30 percent $CaCO_3$ (secondary component in the <2 mm fraction) uniformly distributed over a two-third-meter thickness. The soil in coarse-grained material appears stronger in outcrop, mainly because coarse sands and gravels have less surface area to coat with carbonate than do silts and clays. Therefore, by considering both the concentration and the distribution of secondary carbonate in a soil, the texture of a parent material can be controlled as a nonessential factor in Jenny's (1941) equation of soil formation.

Methodology

The whole-profile index of secondary carbonate (cS) is the difference between the soil's total carbonate content (cT) and the amount of primary carbonate (cP) initially present in the soil's parent material ($cS = cT - cP$). The total carbonate content of a single horizon or sample interval (ct) consists of two separate components: cs (secondary $CaCO_3$) and cp (primary $CaCO_3$), where $cs = ct - cp$. The sum of cs values is cS. Values of cs are computed for each sample interval (usually a soil subhorizon) from $CaCO_3$ content, thickness, and bulk density as follows: $cs = c_3 p_3 d_3 - c_1 p_1 d_1$ where,

c_3 is the present total $CaCO_3$ content (g $CaCO_3$/100 g oven-dry soil),

c_1 is the initial $CaCO_3$ content (g $CaCO_3$/100 g oven-dry soil),

p_3 is the present oven-dry bulk density (g/cm^3),

p_1 is the initial oven-dry bulk density (g/cm^3),
d_3 is the thickness (in cm) of the sampled interval, and
d_1 is the initial thickness (in cm) of the sampled interval.

Values for the soil's initial $CaCO_3$ content (c_1) and bulk density (p_1) have to be estimated. Although this requirement may seem to be a serious limitation to the technique, reasonable estimates of parent-material values can be made from unweathered and noncalcareous material (Cn horizons) exposed at the base of the soil. Also, because K horizons expand volumetrically, their initial thickness (d_1) should be less than their present thickness (d_3), even though one must use $d_3 = d_1$. This assumption will cause the cS values to be slightly overstated for some K horizons. A more complicated but realistic measure may be to use $d_1 = d_3 (p_1/p_3)$.

Values for cS, expressed in g/cm^2, are the weight of pure $CaCO_3$ in a 1-cm^2 column through all soil horizons that contain carbonate. Machette (1978b, Table 1 and Fig. 7) has an illustration of how cS values are calculated from laboratory and soil-description data for some surface and buried calcic soils. Note that the total $CaCO_3$ contents (cT) calculated by Gile, Hawley, and Grossman (1981, Table 25) for the Las Cruces soils are expressed in kg of $CaCO_3/m^2$, dimensional units that are 10 times larger than those discussed in this report.

Sampling Design

Jenny (1941) presented an equation for the formation of soil that was a function of five main factors: climate, landscape relief, biotic activity, parent material, and time. To relate soil development to soil age in his equation, one must control or equalize the four other factors of soil formation. Such control can be obtained by considering soils in a chronosequence, which Harden and Marchand (1977, p. 22) define as "a group of soils whose differing characteristics are primarily or entirely the result of differences in the age of the parent material from which they formed, the other soil-forming factors being held constant or nearly so." Calcic soils were sampled from chronosequences that extend over small geographic areas to control potential regional variations in the influx rates of airborne $CaCO_3$ and Ca^{++}. Most of the sampling sites have similar positions in the landscape, have similar amounts and types of vegetative cover, have low-carbonate parent materials, and are in areas of similar climate or have similar soil-moisture regimes. Through this sampling design, a calcic soil's age is directly related to its index of cS.

An assumption basic to this technique is that carbonate has continually accumulated in the soils of arid and semiarid environments. Some carbonate could have been periodically lost from the soil, because soil-moisture conditions probably varied during the Quaternary and late Pliocene. However, in the regions sampled, the climatic changes probably caused the zone of carbonate accumulation only to move deeper in the soil, not through the soil. If soils of these regions had lost carbonate through excessive leaching, one might expect to find the evidence as buried noncalcareous soils (pedalfers), but buried pedalfers are rare in these regions. The progressive burial of middle through upper Pleistocene calcic soils along the Organ Mountains of southern New Mexico (Gile and Hawley, 1966) provides clear evidence of continuous carbonate accumulation in southern New Mexico during this time.

Sampling and Analytical Techniques

To calculate cS, one needs to describe the properties of the soil and to determine soil horizon and subhorizon boundaries from pedogenic and parent-material changes. I use the K-horizon nomenclature of Gile, Peterson, and Grossman (1965) and the six-stage morphologic sequence to describe soil properties and horizon structures. Horizons and subhorizons thicker than 20 to 25 cm are subdivided into thinner units for sampling and laboratory analysis. The maximum sampling depth is restricted only to the base of the lowest calcic horizon, because the depth of carbonate accumulation varies according to the texture of the parent material. Samples are collected from vertical channels, and care is taken to include representative amounts of soil matrix and gravel. Peds and fragments of indurated material are collected and separately packaged for laboratory determinations of bulk density. If the soil is friable or does not contain peds, a piston-type sampling tube is used to extract a prescribed volume of material; the bulk density is then determined from the sample's dry weight and volume. Sampling must extend completely through the soil and into the underlying noncalcareous parent material (Cn horizon), commonly to several meters depth, to ensure reasonable estimation of c_1 and p_1 values for the soil. Soils should be sampled more than once if they vary considerably over lateral exposures.

Samples are air dried in the laboratory, pulverized by hand using a ceramic mortar and rubber pestle, and sieved to determine the amount of <2-mm- and >2-mm-size material. Because they will not constitute part of the total $CaCO_3$ in the soil, gravel clasts that are not calcareous and that are not coated with carbonate are discarded after sieving and after their weight percentage of the whole soil has been determined. Conversely, if the clasts have calcareous coatings, these coatings must be removed with acid to determine their contribution to cT. Samples of indurated calcic horizons are pulverized in a rotating-plate crusher and their carbonate data are reported on a whole-sample basis.

The < 2-mm fraction is oven-dried at 105°C and separated into several equal portions, and the $CaCO_3$ content of one or more of these portions is determined with the Chittick device using a gasometric $CaCO_3$-dissolution technique that requires 1 to 5 g of < 2-mm material per analysis. The standard operating technique and analytical precision of the method are discussed by Dreimanis (1962). This method provides quick, efficient, and inexpensive determinations of carbonate content (Bachman and Machette, 1977, appendix).

Bulk density (in g/cm^3) is determined by the paraffin-clod method as described by Chleborad and others (1975). Oven-dry peds are thinly coated with paraffin and weighed both in air and submerged in water. Bulk-density measurements of replicate samples generally vary by less than 10 percent of the average value of the samples.

Advantages and Limitations of the cS Index

The cS index is a superior measurement of calcic soil development because it integrates three soil parameters: $CaCO_3$ content, thickness, and bulk density. The procedure for calculating cS values is relatively straight-forward, and the analyses are simple and inexpensive to perform with equipment available in most earth science laboratories. Calcic soils formed in materials ranging from gravels to clays can be compared by this technique, and if parent materials that have little or no primary carbonate are selected, then most of the carbonate present in the soil (cT) must be a secondary component (cS), thereby enhancing the accuracy of the cS determination. Because the primary carbonate content of calcic soils is estimated from parent materials and can be controlled by sampling design, calcic soils differ significantly from other soils whose developmental indices are based on primary constituents such as clay. For example, clay in desert soils could be an original constituent of the parent material, an eolian contribution, or a product of in situ weathering of mineral grains; in most cases these three clays are analytically inseparable. Layered parent materials, such as alluvium, often have depositional variations in clay content and commonly become progressively finer-grained upwards. Thus, the initial distribution of clay in some parent materials can be masked or enhanced by pedogenic clay in B horizons.

There are two potential limitations to the cS index, both of which can be controlled by careful sampling design. The first limitation is the difficulty of determining the bulk density of weak calcic soils formed in coarse materials, many of which lack peds (coherent blocks). This problem is circumvented by taking a large sample and by determining both its extraction weight and its volume. Alternatively, in situ bulk density can be determined using a nuclear-density probe, as is done in road construction to measure the emplacement density and moisture content of compacted aggregate. Because nuclear-density probes do not disturb the soil, replicate measurements can be made on the same part of the soil.

A second, more serious limitation arises for soils in calcareous parent materials. Much of these soils' cT content is a primary component. Redistribution of primary $CaCO_3$ or errors in determining cP will decrease the precision of the computed cS value. In terms of this technique, soils in coarse-grained, calcareous parent materials are the most difficult to analyze: they are best avoided in favor of more suitable materials.

RELATION BETWEEN CARBONATE MORPHOLOGY CA^{++} INFLUX, AND CLIMATE

The time required to form successive stages of carbonate morphology in different regions is related to the age of the soil, the texture of the soil, the rate of influx of solid $CaCO_3$ and soluble Ca^{++}, and the amount and distribution of annual rainfall. By comparing the maximum stage of carbonate morphology in calcic soils from eight chronosequences in the Southwest, I found that significant regional differences in the time-dependent formation of these stages result primarily from various combinations of climate and Ca^{++} and $CaCO_3$ influx.

The eight chronosequences consist of noncalcareous, gravelly alluvium that has constructional geomorphic surfaces bearing relict calcic soils (Table 2). The vertical placement of these geologic units and (or) geomorphic surfaces in Table 2 reflects age estimates based on published and unpublished data. Correlations of units in different regions, however, are based partly on the climatic model of depositional and erosional cycles used by Hawley and others (1976).

Table 2 shows the maximum stage of carbonate morphology found in relict soils of each chronosequence. One of the points to illustrate here is the variation in stages observed in soils of the same age over broad geographic transects. For example, Stage IV morphology does not occur in any of the soils of the upper Arkansas River valley (column 1), yet Stage IV morphology is found on progressively younger soils southward into New Mexico. The areas in Table 2 form two geographic transects: a north-to-south transect from central Colorado to southern New Mexico (a distance of 800 km) and an east-to-west transect from eastern New Mexico to southeastern California (a distance of 850 km). The mean-annual precipitation and temperature values (Table 2; U.S. National Oceanic and Atmospheric Administration, 1978) are gross indicators of the soil-moisture regime in each of these areas and are included to aid in comparison of $CaCO_3$ morphologies. On the basis of their climate, the study areas are grouped in four broad categories: cool-arid, temperate-semiarid, warm-semiarid, and hot-arid.

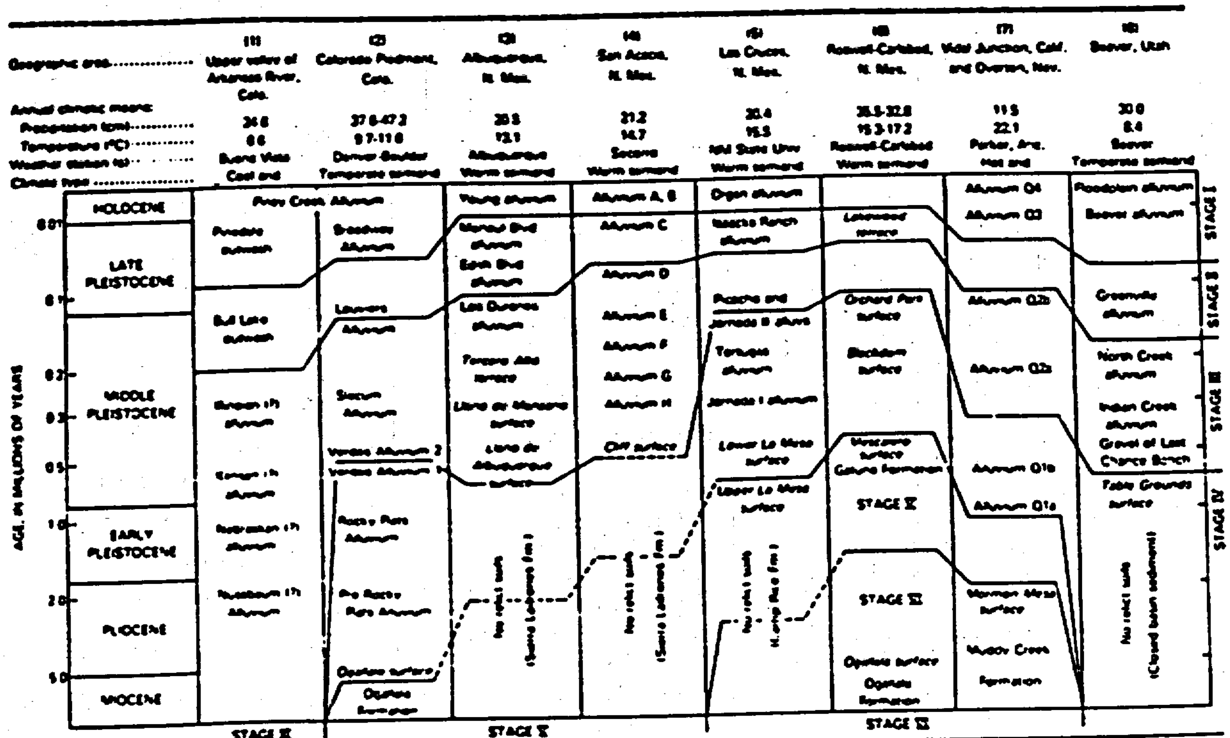
As one many expect, this regional study shows that most calcic soils cannot be correlated solely on the basis of $CaCO_3$ morphology. Even within the same climatic grouping, soils of a single age can vary by a full stage of morphologic development over large regions. For example, calcic soils in 200,000- to 400,000-year-old alluvium along the Rio Grande in New Mexico (Table 2, columns 3, 4, and 5) have a maximum Stage III morphology in the northern and central part of the State, but a maximum Stage IV morphology in the southern part.

Correlations based on morphology alone might be misleading because some morphologies form over intervals of as much as hundreds of thousands of years. Near San Acacia, New Mexico (Fig. 1 and Table 2, column 4), soils in late to middle Pleistocene alluvium (units D, E, F, G, and H, and the Cliff surface) all have Stage III morphology, and although the older units have thicker soils, $CaCO_3$ morphology fails as a distinguishing criterion for these soils, which range from about 100,000 to about 500,000 years in age.

Calcic soils formed in limestone-rich alluvium have a plentiful source of primary calcium carbonate for in situ leaching and thus develop faster than soils on noncalcareous alluvium. The fastest morphologic development we have seen in the Southwest

TABLE 2. MAXIMUM STAGES OF CARBONATE MORPHOLOGY IN GRAVELLY RELICT SOILS DEVELOPED IN ALLUVIAL UNITS OR BELOW CONSTRUCTIONAL SURFACES OF UNNAMED ALLUVIAL UNITS IN THE SOUTHWESTERN UNITED STATES

[Soils that have the same stages of $CaCO_3$ morphology are shown by tie lines. Alluvial units designated by letters and those shown with "alluvium" lowercased are informally named; all other names of alluvial units are formal. Names of geomorphic surfaces shown in italics. Ages are shown on a nonlinear scale. Climatic data from U.S. National Oceanic and Atmospheric Administration (1978).]



References for geologic and soils data used in the above columns: (1) Scott (1975); G.R. Scott and R.R. Shroba, written commun., 1977; (2) Modified from Scott (1963) and Machette and others (1976); (3) Modified from Lambert (1968), Bachman and Machette (1977). All alluvial units are informally named. (4) Bachman and Machette (1977), modified from Machette (1978a); (5) Modified from Gile and others (1979 and 1981), Machette, unpubl. data. All alluvial units are informally named. (6) Modified from Bachman (1976) and Hawley and others (1976); (7) Modified from Gardner (1972), Bull (1974), and Ku and others (1979); Machette unpubl. data; and (8) Machette (1982); Machette, unpubl. data. All alluvial units are informally named.

is in the Roswell-Carlsbad area of southeastern New Mexico, where relict soils on the three youngest surfaces, the Lakewood, Orchard Park, and Blackdom (Table 2, column 6), are underlain by alluvium derived from limestone-rich terrain in the Sacramento Mountains. Additionally, the Roswell-Carlsbad area has both relatively abundant rainfall (33 to 35 cm/year) and an extensive, upwind source area of calcareous rocks which provide airborne Ca^{++}. The southeastern New Mexico area has an optimum combination of climate, Ca^{++} influx, and limestone parent materials for in situ weathering.

Stages of $CaCO_3$ morphology are useful, though, for distinguishing and correlating soils and their associated geomorphic surfaces within local areas, such as individual drainage basins. $CaCO_3$ morphology can be used to differentiate some relict soils of less than 150,000 years age. In the Las Cruces region, soils in the Organ, Isaacks Ranch, Jornada II, and Picacho alluvial units (all informal terms) have diagnostic stages of morphology (Table 2, column 5). The latter units, the Jornada II and Picacho, are the same age and contain soils that have a maximum morphology of Stage III (in fine-grained material) to weak Stage IV (in gravel). The soils in the next significantly younger unit, the latest Pleistocene Isaacks Ranch, contain carbonate nodules (Stage II) in fine-grained materials, whereas soils in similarly textured Holocene Organ alluvium only have filaments of carbonate (Stage I). Thus, these groups of alluvium can be distinguished in the field on the basis of carbonate morphology. Many of the soils in the older alluvial units, such as the Jornada I, Tortugas, and parts of the Picacho, all have a maximum Stage IV morphology and are not so easily differentiated.

MODEL OF $CaCO_3$ ACCUMULATION

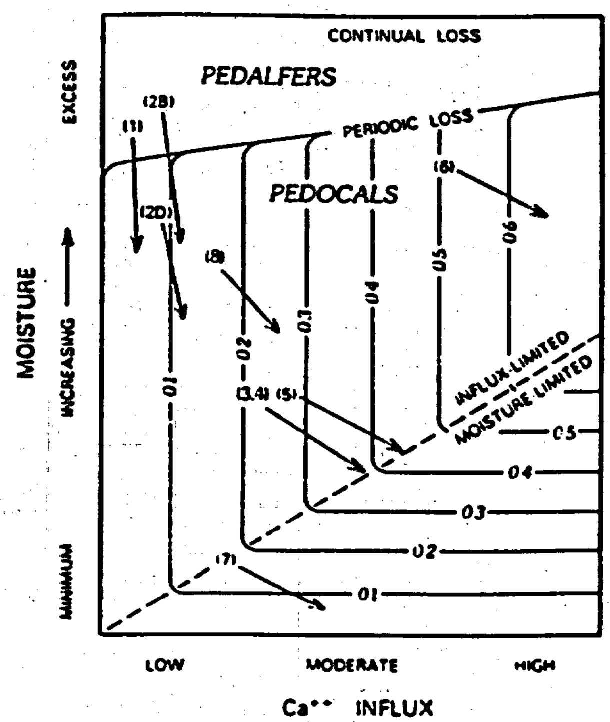
The maximum carbonate morphology in calcic soils (Table 2) observed along two geographic transects of the Southwest results from differences in their respective rates of $CaCO_3$ accumulation, which are controlled by a delicate balance between the supply of Ca^{++} ions and the amount and effectiveness of rainfall in moving Ca^{++} into the soil. Junge and Werby's (1958, Fig. 7) analyses show Ca^{++} is plentiful in rainwater of the Southwest, particularly in the Four Corners region. The rainfall component of Ca^{++} provides a broad regional base for calcic soil formation and this component can be a major part of the total Ca^{++} influx in many areas where sources of solid $CaCO_3$ are limited or not present.

Variations in the total Ca^{++} influx both between and within regions are also caused by locally derived solid carbonate. For example, there is a moderate difference between the average rate of Ca^{++} accumulation for central and southern New Mexico, yet these areas have similar amounts of rainfall and dissolved Ca^{++}. Therefore, the differences in rates of accumulation must be due to local sources of solid carbonate influx, such as the large areas of slightly calcareous eolian sand in the southern part of the state.

Rainfall and Ca^{++} Influx Control of Potential Rates

In the Southwest, the potential rate of carbonate accumulation appears to be controlled mainly by the supply of Ca^{++} to the soil surface and the amount of moisture (rainfall) available to move Ca^{++} in the soil. Because soil carbonate can form under greatly varying conditions of rainfall and Ca^{++} influx, the rates also vary widely under semiarid and arid climates of the Southwest. To illustrate these conditions, I have plotted rates of carbonate accumulation for soils of the eight chronosequences against a parameter that incorporates their relative amounts of moisture, largely as measured by annual rainfall ("moisture" shown on the y-axis of Fig. 5), and against their relative influxes of Ca^{++} (combined solid $CaCO_3$ and Ca^{++} in rainwater). The influx scale is open ended and ranges from no influx to high influx. Points on this diagram are plotted from long term accumulation rates (see also Table 2), partly on informed estimates of local and regional solid carbonate influx rates, and on the dissolved-Ca^{++} data of Junge and Werby (1958).

Leaching, however, is greatly dependent on the supply of Ca^{++}. Leaching can occur under moderate rainfall if the supply of Ca^{++} is low, but requires greater amounts of rainfall if the supply



EXPLANATION

1. *Buena Vista, CO*
2. *Boulder-Denver, CO*
3. *Albuquerque, NM*
4. *San Acacia, NM*
5. *Las Cruces, NM*
6. *Roswell-Carlsbad, NM*
7. *Vidal Junction, CA*
8. *Beaver, UT*

Figure 5. Carbonate accumulation rates (Ri, shown by vertical and horizontal lines, in g of $CaCO_3/cm^2/1{,}000$ years) under varying conditions of moisture and Ca^{++} influx. Soil data for the eight chronosequences (Table 2) are plotted under the inferred conditions and rates of accumulation during pluvial episodes; arrows show inferred conditions during interpluvial episodes. Most areas have higher accumulation rates during interpluvials; Vidal Junction (7), an exception, has slower accumulation rates during interpluvials.

of Ca^{++} is high. The upper limit of moisture under which pedocals form is shown by an inclined boundary in Figure 5.

The field of carbonate accumulation is divided into two subfields: moisture-limited and influx-limited (Fig. 5). The line separating these subfields represents equilibrium conditions at which there is a balance between Ca^{++} supply and moisture. When there is excess Ca^{++}, that is, Ca^{++} that is not being fully leached from the surface of the soil, the potential rate of carbonate accumulation is not realized, and the conditions are termed "moisture-limited." An increase in the limited factor, or a balanced increase in both factors, will result in a net increase in the rate of $CaCO_3$ accumulation.

Moisture-limited areas have a greater Ca^{++} influx than can be accommodated by local rainfall and soil-moisture conditions, hence the potential rate of carbonate accumulation is limited because all the supplied Ca^{++} cannot be translocated into the soil. In these cases, carbonate accumulation rates are increased by increasing moisture, but not the Ca^{++} influx, because there is already an overabundance of Ca^{++}. Soils from such areas typically have silt-rich calcareous A horizons that may or may not overlie noncalcareous B horizons. Soils of the Vidal Junction area (eastern Mojave Desert) and the Mormon Mesa area (southern Nevada, Fig. 1) are probably moisture-limited at present.

Conversely, influx-limited areas have a greater amount of moisture available for translocation of Ca^{++} than is supplied to the soil surface by rainfall and solid debris. Such areas, especially those where rapid snowmelt occurs each spring, can have excess leaching potential with respect to Ca^{++} influx, particularly if rates of Ca^{++} influx are low. The upper 1 to 2 m of soils in these areas are typically leached of carbonate. The field under which these conditions exist bounds the lower limit of the pedalfers (Fig. 5). Although the contours of equal rate parallel either the x- or y-axis in Figure 5, there may be an inherent dependence in the amount of rainfall and amount of dissolved Ca^{++} (Junge and Werby, 1958). Influx-limited conditions probably exist in areas such as the valley of the upper Arkansas River near Buena Vista, Colorado (Table 2, column 1), and the Colorado Piedmont between Denver and Boulder, Colorado (Table 2, column 2). These conditions also exist near the pedocal-pedalfer boundary throughout the Southwest, especially in mountainous areas, and are evidenced by laterally discontinuous accumulations of soil carbonate. Relict pedalfers and pedocals coexist in the middle Pleistocene Verdos Alluvium along the pedocal-pedalfer boundary northwest of Denver, Colorado (Machette and others, 1976). These pedocals are the remnants of extensive, continuous calcic soils that accumulated carbonate when the boundary was at higher elevations in the past.

On the basis of soils data (Gile, 1975, 1977; Machette, unpublished data, 1984) and regional studies of paleoecology (Spaulding and others, 1983) it seems plausible that semiarid areas in central and southern New Mexico have been more arid during interpluvial episodes (such as the Holocene) than during pluvial episodes, resulting in less vegetative cover and a greater influx of airborne Ca^{++} and $CaCO_3$. Although the potential for carbonate accumulation would have increased during the interpluvials because of higher influx of carbonate, the increase probably was partly offset by a decrease in rainfall. The New Mexico soils (Fig. 5; areas 3, 4, 5, and 6) are plotted on the basis of their average rates of carbonate accumulation ($R\bar{x}$) which, in these areas, are probably more indicative of pluvial conditions than interpluvial conditions as shown below. If this model based on Ca^{++} influx and moisture is correct, soils forming in these four regions would plot further down and to the right in the moisture-limited field during interpluvials (times of increased moisture but decreased Ca^{++} influx). Their plotted positions, which reflect conditions during pluvials, lie within the influx-limited field.

In other parts of the Southwest, the effects of climatic change on landscape stability and carbonate accumulation rates could be much different from those postulated for New Mexico. For example, the rainfall over much of the Southwest is less than 20 cm annually, and in some areas it is less than 10 cm. Calcic soils in moisture-limited areas, such as Vidal Junction (area 7 on Fig. 5 and Table 2), may have formed more slowly in the Holocene than in the late Pleistocene. Calcic soils in arid regions commonly have an excess supply of Ca^{++} relative to their limited amount of rainfall. Therefore, a substantial increase in the rainfall of these areas (such as during the pluvials) would allow more Ca^{++} to be leached into the soils and thereby increase the rate of carbonate accumulation.

Analyses of C^{14}-dated pack-rat middens from the Southwest suggest that vegetation zones during latest Pleistocene time were significantly lower than at the present (Van Devender and Spaulding, 1979; Spaulding and others, 1983) probably because a substantially wetter and (or) cooler climate prevailed during the late Pleistocene. The Vidal Junction area in the eastern Mojave Desert presently receives about 15 cm of rainfall, the majority of which falls during high-intensity summer storms. A modest increase of 15 cm (to a total of 30 cm) would double the amount of annual rainfall and probably would be accompanied by a marked increase in the amount of vegetational cover, to the extent that the potential sources of Ca^{++} would be greatly reduced. A climatic change of this magnitude could cause soil conditions to transgress the equilibrium line, such that there are influx-limited conditions during pluvials and moisture-limited conditions during interpluvials.

A condition not yet discussed is one of high accumulation under high Ca^{++} influx and moderate amounts of rainfall (annual mean of about 34 cm). The long-term rates of accumulation for soils of the Roswell-Carlsbad area (Fig. 5, area 6) indicate such conditions. Values for this area probably plot within the influx-limited field now (interpluvial), but during pluvials, the soil-moisture conditions may have approached those of the pedalfers (Fig. 5, upper part). Soil conditions in the Boulder-Denver area and in the upper Arkansas River Valley (Table 2) probably are analogous to those of the Roswell-Carlsbad area, except that they have a much lower supply of Ca^{++}.

RATES OF CALCIUM CARBONATE ACCUMULATION

Soil carbonate accumulation rates vary over time and between localities in response to geographic, geologic, and climatic controls. To make accurate soil-age estimates from cS data, one must understand the magnitude and frequency of these possible variations. These variations are detected by comparing the cS content of soils that have accumulated carbonate during several known time intervals (such as the past 10,000, 50,000, 100,000, and 500,000 years), thereby yielding rates of accumulation.

Rates of carbonate accumulation are influenced by changes in climate both in time and over regions. I used Gile and others'

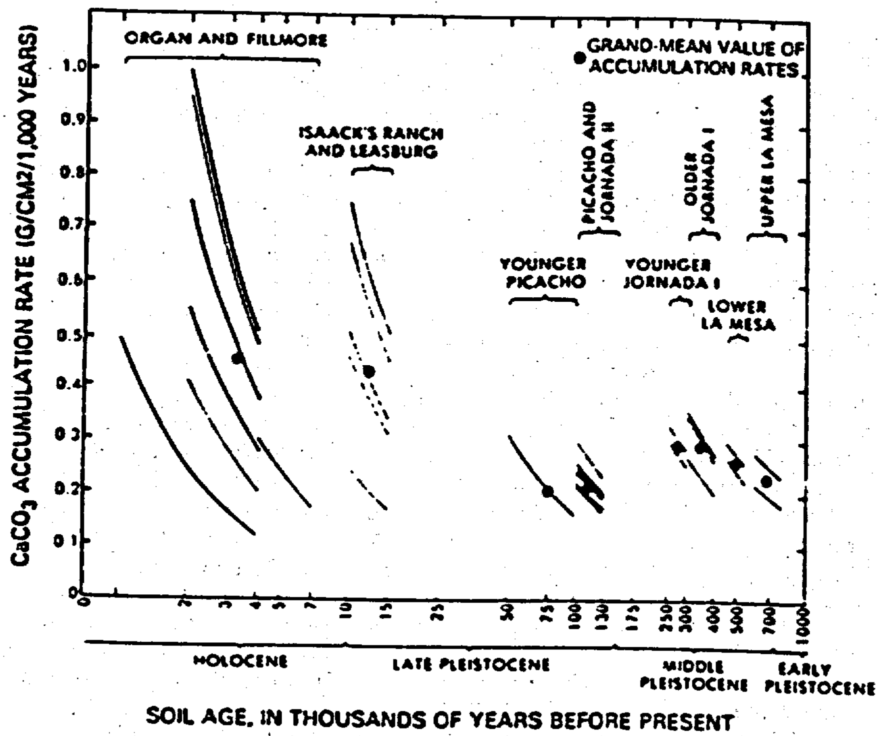


Figure 6. Average carbonate-accumulation rates ($R\bar{x}$) of soils formed in Pleistocene and Holocene alluvial units of the Las Cruces area, New Mexico. Alluvial units are those used by Gile and others (1979) and Gile and others (1981, Table 25) to calculate cT contents. Solid circles indicate the grand-mean values of possible average rates for soils in each alluvial unit.

(1981, Table 25) cT data to calculate rates of carbonate accumulation in the Las Cruces region. Data were selected for soils in noncalcareous parent materials, so that their cP component would be small. Their cT values would therefore approximate cS. However, the Las Cruces soils were not sampled specifically for analysis of carbonate. The older soils generally had thick sampling intervals in which there could be large but undetected variations in carbonate content or bulk density. Also, some of these soils are eroded and others were not sampled deeply enough to penetrate noncalcareous material (Cn horizon). Therefore, some of the Las Cruces soils may have cT values that are minimum estimates of cS, not maximum estimates.

Because the ages of some of the Las Cruces soils are not closely defined, I use a "probable age range" in calculating the average rates of carbonate accumulation. For example, the bulk of the Organ alluvial unit is considered to be between 1,000 and 4,000 years old, based on radiocarbon dates from organic carbon in the alluvium. To illustrate the effect that age ranges have on the calculation of accumulation rates, assume that a soil in this unit had 1.25 g of $CaCO_3$ per square-centimeter column. The carbonate accumulation rate for this soil is 0.125 to 0.50 g/cm^2/1,000 years (cS divided by age range). Such values represent the average rate ($R\bar{x}$) of carbonate accumulation because the soils are relicts; that is, they are the cumulative products of continuous soil formation. The ages used are those I consider geologically reasonable based on degree of soil development, C^{14} dates on inorganic and organic carbon, correlations of the Las Cruces chronosequence with other dated alluvial units in New Mexico, geomorphic considerations, and unpublished uranium-trend soil ages determined by J. N. Rosholt (written commun., 1981). Ages for the Las Cruces soils and alluvium are modified from those of Gile and others (1981).

Carbonate Accumulation Rates Through Time

One way to analyze the magnitude of change of carbonate accumulation rates is to compare Holocene soils with their next older counterparts, late Pleistocene soils, thereby contrasting soils formed during different parts of the most recent climatic cycle. The Las Cruces soils are ideal for such a comparison. The possible ranges in their ages against their potential accumulation rates are shown on Figure 6 as a series of lines whose upper end points represent maximum rates and minimum ages and whose lower end points show the opposite. The actual rate of accumulation for any of these soils should lie somewhere on the resultant line (these lines are curves because of the logarithmic scale used on

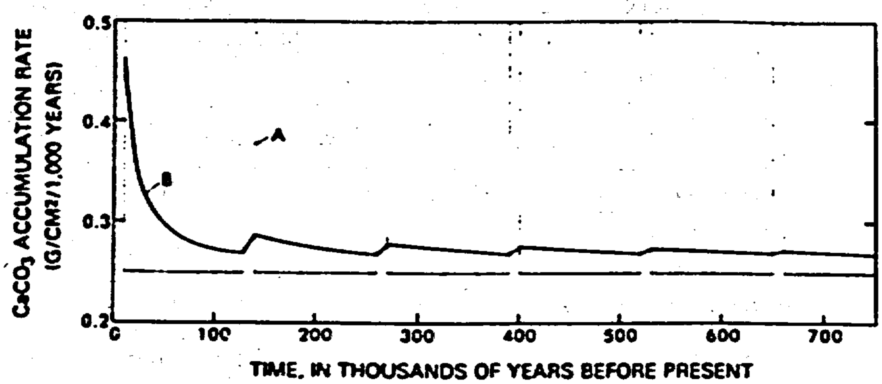


Figure 7. Model of calcium carbonate accumulation rates versus time. Line A shows the instantaneous rate (Ri) of $CaCO_3$ accumulation at a point in time. Line B shows average rate ($R\bar{x}$) through time. Model is based on interpluvial periods simulated by 10,000-year-long intervals in which Ri = 0.5 g/cm^2/1,000 years and pluvial periods simulated by 120,000-year-long intervals in which Ri = 0.25 g/cm^2/1,000 years.

the x-axis of Fig. 6). Figure 6 shows that the soils data plot as discrete groups of curves, and these groups range from Holocene and latest Pleistocene to middle Pleistocene age.

The young soils (Holocene and latest Pleistocene) have a wide range of possible accumulation rates for two reasons. First, they are weakly developed, and their cS contents are only a small part of their cT contents; hence, errors in determining their cP components greatly affect cS values. Secondly, the range of possible ages for each soil is large in comparison with the actual age. Conversely, the older groups of soils have smaller ranges of possible accumulation rates for exactly the opposite reasons.

Because of the range in values within any one group of soils, I computed the grand mean of $R\bar{x}$ values from the average value of each soil; the grand means are shown by large dots on Figure 6. The grand means clearly show that Holocene and latest Pleistocene calcic soils have average accumulation rates that are higher than those of older soils. The grand means for soils of Holocene and latest Pleistocene age are 0.46 and 0.43 g of $CaCO_3$/cm^2/1,000 years, respectively. These rates represent the accumulation of carbonate over intervals of less than 5,000 to as much as 18,000 years (the older limit for latest Pleistocene alluvium). Nevertheless, these rates largely reflect soil formation under Holocene interpluvial conditions (the past 10,000 years).

Soils in the Picacho and Jornada II alluvial units, the majority of which are between 75,000 and 150,000 years old, were formed mostly under pluvial conditions of the last complete climatic cycle, whereas older soils were formed under one or more complete climatic cycles. These soils, ranging back to middle or early Pleistocene age, have grand-mean accumulation rates of 0.21 to 0.29 g of $CaCO_3$/cm^2/1,000 years; values of about one-half of the younger rates. By using only grand means of accumulation rates, the effect of anomalous rates that could result from mistaken age calls or from errant determinations of cS should be minimized.

These data clearly show that soils in southern New Mexico have accumulated carbonate under conditions of an interpluvial climate at an average rate that is nearly twice that which prevailed during the preceding pluvial climatic episode. If one assumes that these rate changes are climatically controlled, then the average accumulation rate through time can be analyzed with an algebraic step function. To simply illustrate such a step function (Fig. 7), the interpluvial periods of southern New Mexico are simulated by 10,000-year-long intervals of high carbonate accumulation (0.5 g/cm^2/1,000 years) and the pluvial periods are simulated by 120,000-year-long intervals of low accumulation (0.25 g/cm^2/1,000 years). This model, although simpler in detail than most pluvial-interpluvial cycles currently being considered, calls for accumulation rates in southern New Mexico to double during interpluvials, an assumption I consider reasonable based on soil data (Fig. 6).

The instantaneous rate of carbonate accumulation (Ri) is herein defined as the accumulation rate at any point in time. In the step-function model (Fig. 7), the instantaneous rate changes between 0.25 and 0.50 g/cm^2/1,000 years as shown by line A. From these instantaneous values, I calculated the average rate of accumulation ($R\bar{x}$) for progressively longer intervals of time before the present (Fig. 7, line B). Soils that formed during one complete climatic cycle (130,000 years) or longer have similar $R\bar{x}$ values because fluctuations caused by short, high-rate interpluvials have little impact on the overall rate established during the long pluvial intervals.

A model based on these instantaneous rates shows that long intervals of low accumulation during pluvial episodes have a pronounced dampening effect on the short intervals of high accumulation during the interpluvials. Although one might disagree with the details of this model, any model that incorporates rate oscillations with long and short intervals of this amplitude will produce the same basic trend in carbonate accumulation rates. For example, increasing the number of short, high-rate intervals within the last climatic cycle superimposes minor fluctuations on

TABLE 3. AGE, MAXIMUM STAGE OF CARBONATE MORPHOLOGY, SECONDARY CARBONATE CONTENT (cS), AND AVERAGE RATE OF SECONDARY CALCIUM CARBONATE ACCUMULATION ($R\bar{x}$) IN CALCIC SOILS OF FOUR REGIONS OF THE AMERICAN SOUTHWEST

Area: Geomorphic surface	Soil age (m.y.)	Stage of $CaCO_3$	cS, in g/cm² Mean	cS, in g/cm² Range	$R\bar{x}$, in g/cm² per 1,000 years
Beaver, Utah: Last Chance Bench	0.5	III+	71	64-78	0.14±0.01
Albuquerque, New Mexico: Llano de Albuquerque	0.5	III	110	98-114	0.22±0.02
Las Cruces, New Mexico: Lower La Mesa	0.5	IV	129	120-137	0.26±0.02
Roswell-Carlsbad, New Mexico: Mescalero	0.5	V-	257	229-307	0.51±0.06

Data for soils near Beaver, Utah, are from Machette (1982) and Machette, unpublished data. Most of the data for the Las Cruces chronosequence are from Gile and others (1979). The remaining New Mexico data are from Bachman and Machette (1977) and Machette, unpublished data.

the basic curve and results in a slightly higher average rate of accumulation.

If the basic structure and assumptions of this model are valid, then soils that formed for more than about 100,000 years should have similar average accumulation rates and cS values that can be used to correlate soils locally and to estimate the ages of calcic soils older than about 100,000 years. The ages of soils younger than 100,000 years can also be estimated, although such estimates may be off because the average accumulation rate during this short-term interval and those used for the long-term (500,000-year) interval may be significantly different.

Regional Variations in Carbonate Accumulation Rates

The amount of regional variation in average $CaCO_3$ accumulation rates was determined by comparing cS values of relict calcic soils formed on correlative middle Pleistocene sediments of three areas in New Mexico. These values were also compared with one obtained from an area in central Utah, 600 to 1,200 km to the northwest, to determine their degree of similarity.

Relict middle Pleistocene calcic soils about 500,000 years old (Hawley and others, 1976; Bachman and Machette, 1977) are preserved along the Rio Grande between Albuquerque and Las Cruces, New Mexico (Fig. 1), just below the constructional surfaces of the Sierra Ladrones Formation and the Camp Rice Formation of Strain, 1966, and in correlative piedmont-slope sediments that rise gently mountainward from the Rio Grande. Likewise, east of the Pecos River in southeastern New Mexico, the "Mescalero caliche" (a pedogenic calcrete) is developed in the Gatuna Formation (Bachman, 1976). The Gatuna locally contains water-laid beds of the Lava Creek ash, a 600,000-year-old volcanic ash erupted from calderas in the Yellowstone area of northwestern Wyoming (Izett and Wilcox, 1982). Because the ash is interbedded with, rather than overlying, the Gatuna Formation, the Mescalero probably began to form immediately after deposition of the Gatuna Formation, about 500,000 years ago.

Calcic soils of the same age are present in unconsolidated alluvium near Beaver, Utah (Fig. 1), which is in an intermontane basin on the boundary between the Basin and Range and the Colorado Plateaus provinces. The basal part of the gravels of Last Chance Bench, a thin but widespread piedmont-slope deposit, is interbedded with a 530,000-year-old rhyolitic pumice (Machette, 1982). Antiformal uplift coupled with rapid lowering of base level within the basin caused dissection of the gravel soon after it was deposited, thereby preventing further deposition on the gravels after 500,000 years ago. A strong Stage III calcic soil has formed in the gravels of Last Chance Bench during the past 500,000 years.

The cS contents of 500,000-year-old calcic soils in these four areas are shown in Table 3. The soils near Beaver are the least calcareous; they have an average cS of 71 g/cm² and an average accumulation rate ($R\bar{x}$) of 0.14±0.01 g/cm²/1,000 years. Near Albuquerque and Las Cruces, New Mexico, soils of this age have cS contents of 110 and 129 g/cm² and $R\bar{x}$ values of 0.22 and 0.26 g/cm²/1,000 years, respectively. Along the Rio Grande, the 500,000-year-old soils show a slight southward increase in the maximum stage of carbonate morphology from Stage III+ to IV (Table 3). This increase must be primarily the result of a slightly higher solid-$CaCO_3$ influx in southern New Mexico than in central or northern New Mexico, inasmuch as the modern temperature and rainfall values (Table 2) and amounts of Ca^{++} dissolved in rainfall (Junge and Werby, 1958) are similar along the Rio Grande from Albuquerque to Las Cruces.

In the Roswell-Carlsbad area, the Mescalero has weak Stage V development (Tables 2 and 3) and thus, is more advanced than soils of the same age elsewhere in New Mexico. Both the amount of rainfall and the rate of Ca^{++} influx in southeastern New Mexico are higher than in central and southern New Mexico, and these conditions result in a high rate of carbonate accumulation. The Mescalero has an average cS content of 257 g of $CaCO_3$/cm^2; about 2.5 times that of soils of the Llano de Albuquerque. The Mescalero has accumulated carbonate at an average rate of 0.51 ± 0.06 g/cm^2/1,000 years for the past 500,000 years; this is the highest rate yet determined in the Southwest.

GEOLOGIC APPLICATIONS OF CARBONATE DATA

The stratigraphy and geomorphology of alluvial terraces and adjacent piedmont-slope sediments along the Rio Grande in New Mexico were recently correlated by Hawley and others (1976). To illustrate the potential that cS data have in such correlations, I suggest correlations for some of these same sediments based on new age control from uranium-trend ages by the method of Rosholt (1980), on K-Ar dates obtained from associated volcanic rocks, and on soil-age estimates. Soil ages are estimated from cS data and the long-term accumulation rates determined in each area (Table 3). For example, if a soil has a cS content of 25 g/cm^2 and an average accumulation rate ($R\bar{x}$) of 0.20 g/cm^2/1,000 years, the estimated soil age is 125,000 years. Estimated soil ages of less than about 50,000 years are probably maximum estimates, because their average accumulation rates were probably higher than the long-term rate used in the step-function model (Fig. 7).

Quaternary Geology along the Rio Grande

The Quaternary units of the Albuquerque area shown in Figure 8 are slightly modified from those established by Lambert (1968), but the conclusions concerning soil ages and correlations are my own. Lambert recognizes three major cut-and-fill alluvial units that form constructional surfaces: the alluviums of Menaul Boulevard (an unnamed surface), Edith Boulevard (the Primero Alto terrace), and Los Duranes (the Segundo Alto terrace). Bachman and Machette (1977) recognized alluvium that forms an additional terrace, the Tercero Alto, which is overlain by 190,000-year-old basalt flows of the Albuquerque Volcanoes (Bachman and others, 1975). An even higher, unnamed alluvium forms a widespread piedmont-slope surface, referred to either as the Sunport surface (Lambert, 1968) or the Llano de Manzano surface (Bachman and Machette, 1977), south of Albuquerque in the eastern part of the Albuquerque-Belen basin. The Llano de Manzano surface is graded to an alluvial terrace which lies 92 to 113 m above the modern Rio Grande; it is considerably lower than the Llano de Albuquerque surface (215 to 110 m) in the same basin. The Llano de Albuquerque, for the most part, is the upper constructional surface of the Sierra Ladrones Formation (Pliocene to middle Pleistocene). Although parts of the surface may have been isolated from further deposition in the early Pleistocene in response to local uplift, the majority of the surface is considered to have become geomorphically stable about 500,000 years ago in middle Pleistocene time (Hawley and others, 1976; Bachman and Machette, 1977).

At San Acacia, near the southern end of the Albuquerque-Belen basin, the Rio Grande is joined from the west by the Rio Salado, a major tributary stream that is flanked by middle to upper Pleistocene alluvial terrace units and piedmont-slope units (Fig. 8 and Machette, 1978a). The Cliff surface, a local fault-controlled erosion surface cut on the Sierra Ladrones Formation (Machette, 1978c), is the oldest geomorphic surface in this area. On the basis of the Cliff surface's elevation and its soil's cS content, Machette (1978c) considers it to be slightly younger than the Llano de Albuquerque surface, whose nearest outcrop is about 20 km north of San Acacia.

In the Las Cruces area, the alluvial stratigraphy of Hawley and Kottlowski (1969) and the soil-geomorphology studies of Gile, Peterson, and Grossman (1979) and Gile and others (1981) provide a detailed framework (Fig. 8) to which I correlate units in the San Acacia and Albuquerque areas. The upper La Mesa surface, one of the oldest geomorphic surfaces near Las Cruces, was isolated from the depositional plain of the Rio Grande by uplift along the Robledo fault in the middle(?) or early(?) Pleistocene. The next younger surface, lower La Mesa, is the widespread upper constructional surface of the Camp Rice Formation of Strain (1966) and is correlative with the Llano de Albuquerque surface to the north. The upper part of the Camp Rice Formation locally contains the 600,000-year-old Lava Creek ash bed (Izett and Wilcox, 1982); thus the lower La Mesa surface and the youngest part of the Camp Rice Formation must be slightly less than 600,000 years old. The lower La Mesa surface is here considered to be about 500,000 years old on the basis of depositional and geomorphic considerations. In the piedmont areas adjacent to but mountainward of the Rio Grande, the Jornada I alluvial unit is the youngest constructional part of the Camp Rice Formation; it was still being deposited after the Rio Grande started downcutting about 500,000 years ago. The Tortugas, Jornada II, and Picacho alluvial units record successively lower levels of downcutting along the Rio Grande and tributary drainages during middle and late Pleistocene time. The youngest alluvial units in the Las Cruces area include the Issacks Ranch and Leasburg (latest Pleistocene age) and the Organ and Fillmore (Holocene age).

Correlation and Age Estimates

The correlation of alluvial units along the Rio Grande is greatly enhanced if they are based on soil ages estimated from both secondary $CaCO_3$ contents and accumulation rates and more traditional criteria (Fig. 8). For example, the alluviums that form the Llano de Manzano and Jornada I surfaces and alluvial unit H (Fig. 8) appear to be correlative on the basis of their stratigraphic and topographic positions. Calcic soils below the Llano de Manzano surface (Fig. 8) have a cS content of about 70 g/cm^2, and yield soil ages of about 320,000 years, assuming that

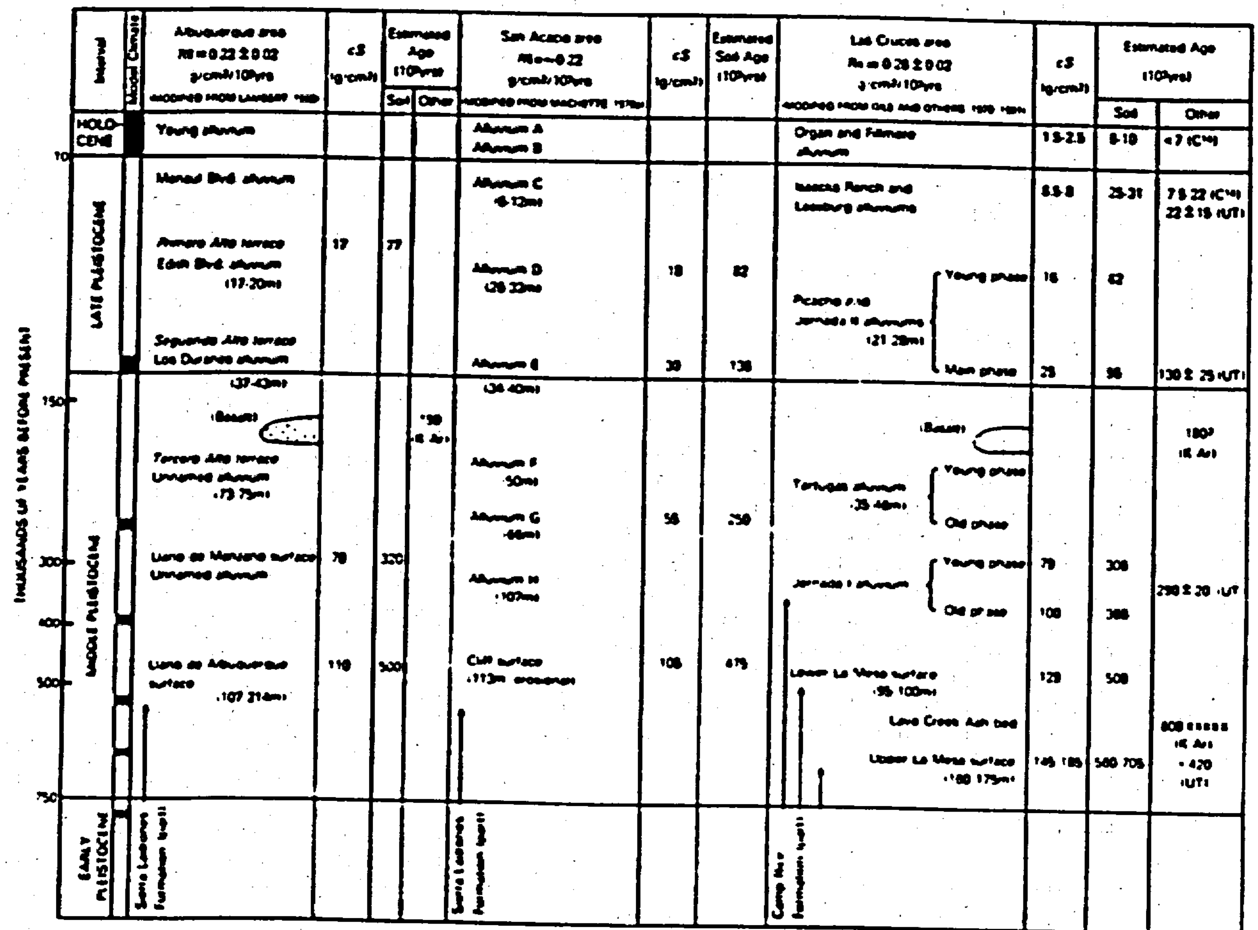


Figure 8. Tentative correlation of Quaternary alluvial units and constructional geomorphic surfaces (the latter shown in italics) along the Rio Grande in New Mexico. All of the alluvial units shown on here are informally named. Correlations are based on soil ages estimated from cS or cT contents, isotopic age data, relative position of unit in stratigraphic successions, and heights of constructional surface of units in meters above stream level (in parentheses) where applicable. $R\bar{x}$ is the average rate of carbonate accumulation (g of $CaCO_3/cm^2/1{,}000$ years) over the past 500,000 years. Time scale is nonlinear. Dark areas in "Model climate" column represent interpluvials; pluvials are white. This column is not intended to show the actual climatic chronology of the region, but reflects the simulation used in Figure 7.

$CaCO_3$ accumulated at an average rate of 0.22 $g/cm^2/1{,}000$ years ($R\bar{x}$ for Albuquerque). In the San Acacia area, I was unable to determine the cS content of the soil in alluvial unit H, but the soil is stronger than that on alluvial unit G (estimated to be 220,000 years old) and weaker than that below the Cliff surface (estimated to be 475,000 years old). Thus, I use the midpoint between these age limits, about 350,000 years, for the soil in alluvial unit H. In the Las Cruces area, soils in a young phase of the Jornada I alluvium have an average cS content of 79 g of $CaCO_3/cm^2$, which yields an age of about 305,000 years. Thus, the cS data for these three soils indicate ages that range from 305,000 to 350,000 years, and undoubtedly would lie within concordant error limits if one could assign such values.

The age of the upper La Mesa surface is poorly constrained, but it is clearly older than the lower La Mesa surface (500,000 years), and sediments underlying both surfaces contain Pleistocene, but not Pliocene, vertebrate faunas (Hawley and others, 1976). The soils of the upper La Mesa surface have Stage V morphology, which is significantly more advanced than those of the lower La Mesa surface (Table 3). On the basis of cS contents of 145 to 185 g/cm^2, the soils of the upper La Mesa surface have been forming for 560,000 to 720,000 years. More importantly, the disproportionately advanced morphology of the soils of the upper La Mesa surface strongly suggests that they either have been partly eroded or have lost $CaCO_3$ through excess leaching. If cS contents from soils of the upper La Mesa surface (Fig. 8) are considered as minimum values, then the age of the tectonically uplifted upper La Mesa surface may be closer to one million years.

Other Applications

The above examples illustrate how the cS content of calcic soils can be used in making local and regional soil correlations and in estimating the ages of these soils when they are in Quaternary sediments. These estimates of soil age also provide information useful in a wide range of geologic studies, such as assessments of earthquake hazards, landform evolution, and paleoclimatic interpretation.

The recurrence intervals and the recency of fault movements that displace calcic soils can be estimated from the quantitative differences in soil development across fault zones. Near Albuquerque, calcic soils were displaced by four episodes of movement along the County Dump fault during the past 400,000 years. Machette (1978b) estimated the timing and amounts of displacement along this fault by relating the cS contents of the buried soils to their combined surface equivalent and found that the soil overlying the fault (soil U of Machette, 1978b) required 20,000 years to accumulate its carbonate. In retrospect, this estimate seems too old because the age of soil U was calculated from the long-term average rate of accumulation, whereas if Holocene rates are about 2 times faster as I now suggest, soil U could be about 10,000 years old. However, the age estimates for buried (faulted) soils (90,000 to 190,000 years each) are probably reasonable, because they formed during time intervals equal to or more than one complete climatic cycle.

SUMMARY

Calcic soils, and to a lesser extent pedogenic calcretes, are widespread in the semiarid and arid parts of the Southwest. Although these soils have formed in unconsolidated sediments as old as late(?) Miocene age and as young as Holocene age, most of them have formed since middle or late Pleistocene time. Calcic soils form mainly by subaerial precipitation of carbonate that derived from Ca^{++} dissolved in rainwater and that is leached from solid airborne carbonate. As carbonate accumulates in the soil, its morphology develops progressively through recognizable stages that are reflected in enriched carbonate content, increased bulk density, and thickening of calcic horizons.

I have described a morphologic sequence of calcic soils that consists of six stages, the first four of which were originally defined by Gile and others (1966). Pedogenic calcretes are advanced forms of indurated calcic soils that display evidence of the three latter stages of morphology. Stage IV is characterized by carbonate-rich laminae less than 1 cm thick. The next stage of morphology, Stage V, is marked by thicker laminae and incipient to thick pisolites. The most advanced stage morphology, Stage VI, includes multiple generations of brecciation, pisolite formation, and recementation. Stage VI calcic soils can resemble marine limestones in both percent $CaCO_3$ and bulk density.

The total-profile index of secondary carbonate (cS) integrates three soil parameters: $CaCO_3$ content, thickness, and bulk density. Values of cS are easily computed from soil-description data and from simple laboratory analyses of soil carbonate content and bulk density. Many of the problems inherent in other types of quantitative soil indices can be minimized or negated by carefully selecting sampling sites in calcic soil chronosequences.

Long-term carbonate-accumulation rates reflect regional variations in the amount of soil moisture available for leaching of carbonate and in the airborne supply of Ca^{++} and $CaCO_3$. Carbonate accumulation rates in the Roswell-Carlsbad area of southeastern New Mexico over the past 500,000 years exceed 0.5 $g/cm^2/1{,}000$ years and are the highest in the Southwest. At the other extreme, calcic soils in the Beaver, Utah, area have accumulated carbonate at rates of about 0.14 $g/cm^2/1{,}000$ years; this rate is 25 to 75 percent of equivalent-age soils in New Mexico.

Soil cS contents can be used to correlate and differentiate Quaternary sediments and, in some cases, can be used to estimate the ages of relict calcic soils and pedogenic calcretes. Studies of calcic soils are relevant to geologic problems such as the siting of critical facilities, the evaluation of earthquake and other natural hazards, the analysis of landform evolution, and the understanding of surficial geologic processes.

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