Structure and Function of Chihuahuan Desert Ecosystem
The Jornada Basin Long-Term Ecological Research Site
Edited by: Kris Havstad, Laura F. Huenneke, William H. Schlesinger
Monger, H. C. 2006

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# 4

# Soil Development in the Jornada Basin

**H. Curtis Monger**

Soils of the Jornada Basin are the substrate on which Jornada ecosystems reside and interact. Understanding soils and plant–soil feedback processes have been integral to understanding vegetation change and desertification (Buffington and Herbel 1965; Schlesinger et al. 1990). Formal studies of Jornada soils extend back to 1918 (figure 4). The most detailed study of Jornada soils is the USDA-SCS Desert Soil-Geomorphology Project (Gile et al. 1981), a 400-mi$^2$ study area that includes the southernmost areas of the Jornada Experimental Range (JER) and Chihuahuan Desert Rangeland Research Center (CDRRC) (refer to figure 2-1). This chapter highlights findings of soil and geomorphology studies, discusses factors and processes of soil development, and lists several ways soils of the Jornada Basin carry a memory of past climates.

## Types of Soils

In addition to the Veatch (1918) study and the Desert Soil-Geomorphology Project, other investigations of soil types in the Jornada Basin include three soil surveys by the Soil Conservation Service: the first was of Jornada Experimental Range (SCS 1963), the second was of the White Sands Missile Range that includes the eastern Jornada Basin and San Andres Mountains (Neher and Bailey 1976), and the third was of Doña Ana County (Bulloch and Neher 1980).

**The 1918 Map**

The 1918 investigation by J.O. Veatch of soils of the Jornada Basinwas a reconnaissance study of the Jornada physical landscape. The purpose of the investigation was to make observations on the relation between soils and native vegetation and of the effect of overgrazing on different soil types. Veatch divided the study area into the higher mountain slopes, the foothills, and the Jornada Plain (as he described it, the plain included the currently recognized basin floor and piedmont slope). He recognized that the Jornada Plain was of Pleistocene age and contained extinct lakes with gypsum precipitated from desiccating water. He wrote that little change existed between the soil and subsoil, that "in reality a description of 'soils' here is but little more than a description of the various lithologic phases, appearing at the surface of a recent geologic formation." Still, he made the important observation that development of caliche depends on the age of the soil, greatest in old soils.

The 1918 soil map contains 13 units (figure 4-1). Some of the main characteristics of these units are paraphrased next, beginning with the western units of the Jornada Plain and progressing eastward to the San Andres Mountains. The Jornada Plain west of the gypsiferous playas had three units. The first, West Well Gravelly Sand (WGS), was an area where "whitish limestone-like caliche" of at least 6 feet in thickness occurred at depths of 2–6 feet beneath sandy and gravelly surface soils. In 1918, the WGS unit was predominately covered with a threeawn (*Aristida)* grama (*bouteloua)* association with no brush except for a few mesquites (*Prosopis glandulosa*) in wind-eroded areas. To its east, the Jornada Red Loamy Sand (RLS) also contained caliche substratum, but this caliche was not exposed (except where excavated by digging animals, such as prairie dogs black-tailed, *eynomys ludovicianus*) because the sandy soils had yet to be eroded. The abundant black grama (*Bouteloua eriopoda*) and absence of brush made RLS the most valuable forage land, as well as the most vulnerable to degradation. The third unit, Jornada Sand (RLS[W]), was described as the eroded phase of RLS in which sand of the originally smooth grama surface had been shifted by wind into low mesquite hummocks and ridges. In RLS[W]), sand buried caliche to depths of 6–10 feet, whereas in other places caliche was exposed due to wind scouring.

Veatch mapped four units in the gypsiferous playa area. The Lake Bed Clay (LC) unit was described as highly calcareous, chocolate red or grayish clay with scattered gypsum crystals overlying pure gypsum beds of lacustrine origin at depths up to 10 feet. The vegetation in LC was burrograss (*sehleropogon brevifolius)* and tobosa grass (*Pleuraphus mutica*) in 1918, with an entire absence of soapweed and shrubs present on neighboring sandy soils. The unit labeled Gypsum Soil (GY.S) described small areas where gypsum was at or very near the surface, covered only by a thin veneer of silt or very fine sand with only scant amounts of dropseed (*Sporobolus*) and Mormon tea (*Ephedra*). The Middle Well Sand (SG) was deep, loose sands that covered substrata of gypsum. This unit was then nearly barren except for some remaining threeawns (*Aristida*) and black grama. Jornada Gray Sand (GSL) was a second sand unit that occupied the bottoms and slopes of lake basins and, like SG, overlaid gypsum. This unit differed in color from other sands, which were prevailingly red. It also differed because its sand was derived from lakes rather than the Jornada Plain. The vegetation had a mixed character,

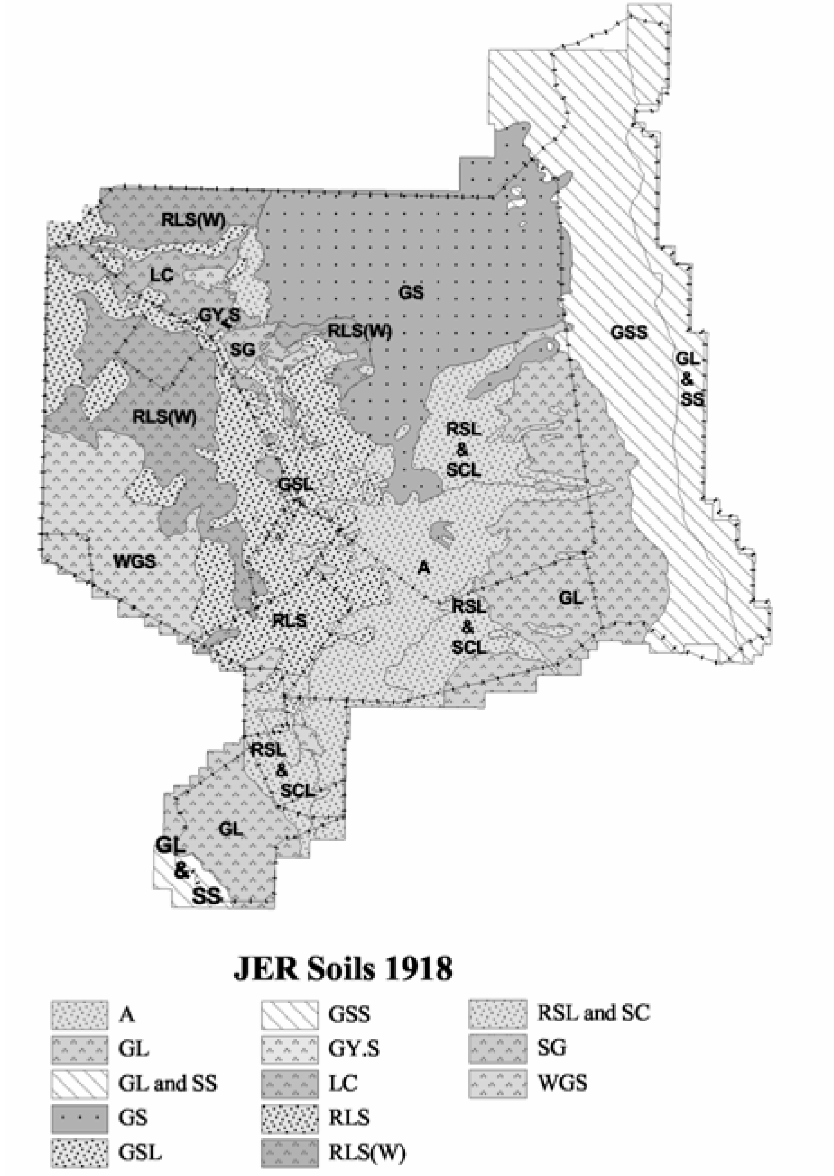


Fig. 4-1. The 1918 soil map of Jornada Experimental Range (JER) produced by J.O. Veatch under a cooperative agreement between the U.S. Bureau of Soils and the U.S. Forest Service (the agency that operated Jornada Experimental Range at that time). The 1918 soil survey contained 13 map units. Abbreviated descriptions of the map units are given in Table 4-1.

transitional from burrograss and tobosa grass of the lake bottoms to considerable black grama, threeawn, and soapweed (Yucca elata) on the slopes.

The piedmont slopes contained four units—the clay or adobe soil (A) that extended across the current boundary of the piedmont slope and basin floor. These clay flat soils were described as having some “lime cementation.” They ascended toward the foothills by broad, flat steps and scarplets on which numerous patches and low-winding ridges of loose, reddish, wind-laid sand resided. The vegetation was predominantly burrograss, tobosa grass, and tarbush (*Flourensia cernua*) on the flats with soaptree yucca, honey mesquite, Mormon tea, and creosotebush (*Larrea tridentata*) on the ridges. The Goldenburg Sands (GS) were wind-laid deposits overlying various alluvial strata that because of their less-developed caliche were recognized to be younger than similar duned soils of the Jornada Plain whose sands are essentially the same lithology. Vegetation of the GS unit was dominated by mesquite, with common amounts of sand sage and saltbush (*Atriplex*), and only sparse growth of dropseed and threeawn grass. The Jornada Clay Loam (RSL and SCL) was used to map various intermediate piedmont slope positions. The unit had a range of textures, degrees of lime carbonate, and vegetation, which consisted of brush (tarbush, creosotebush, and mesquite) and grasses (burro, tobosa, grama, and threeawn). Higher on the piedmont slopes, the alluvial fan and fan-piedmont landforms were mapped as the Middle Tank Gravelly Soils (GL). These soils contained coarse rock detritus that in places were cemented into conglomerates that restricted root penetration. Vegetation was described as a creosotebush-black brush (assumed to mean tarbush) association of low density, which attributed to the low moisture content of the soil.

Bedrock hills and mountains were mapped using two units. Foothills (GSS) were described as consisting of thin, silty, residual soils developed from underlying Paleozoic sedimentary rock. In places, sand of the Jornada Plain has been blown up on the hills and given rise to mesquite and soaptree yucca vegetation, in sharp contrast to the creosotebush and grass vegetation of the residual bedrock soils. Mountain Slope Soils (GL and SS) consisted of very thin, stony, yet dark soils that bear close relation to the underlying bedrock. From a distance, the mountain slopes were described as appearing nearly barren; however, mixed grasses, mountain mahogany, and other shrubs occurred on the slopes while piñon (*Pinyon)*, juniper *(Juniperus)*, and oak (*Quercus)* were in the more favorable situations.

**The 1963 Map**

The second soil map of the Jornada Basin (see figure 4-2) was completed by the SCS but was not published except in a slightly modified form in Buffington and Herbel (1965).

The 1963 map made several advances. It expanded the 13 units of the 1918 map to 20 units. These units provide added detail to gypsiferous units, subdivisions of basin floor soils, and slopes, such as the delineation of the fault scarp near the western JER boundary. One significant observation is represented by the western boundary of the O unit. This line delineates the boundary between indurated caliche (stage IV and V petrocalcic horizons) to the west and nonindurated caliche (stage II and III calcic horizons) to the east. Recently, this soil boundary was described by Gile (1999), who attributed it to an early middle Pleistocene lake, Lake Jornada (Gile 2002).

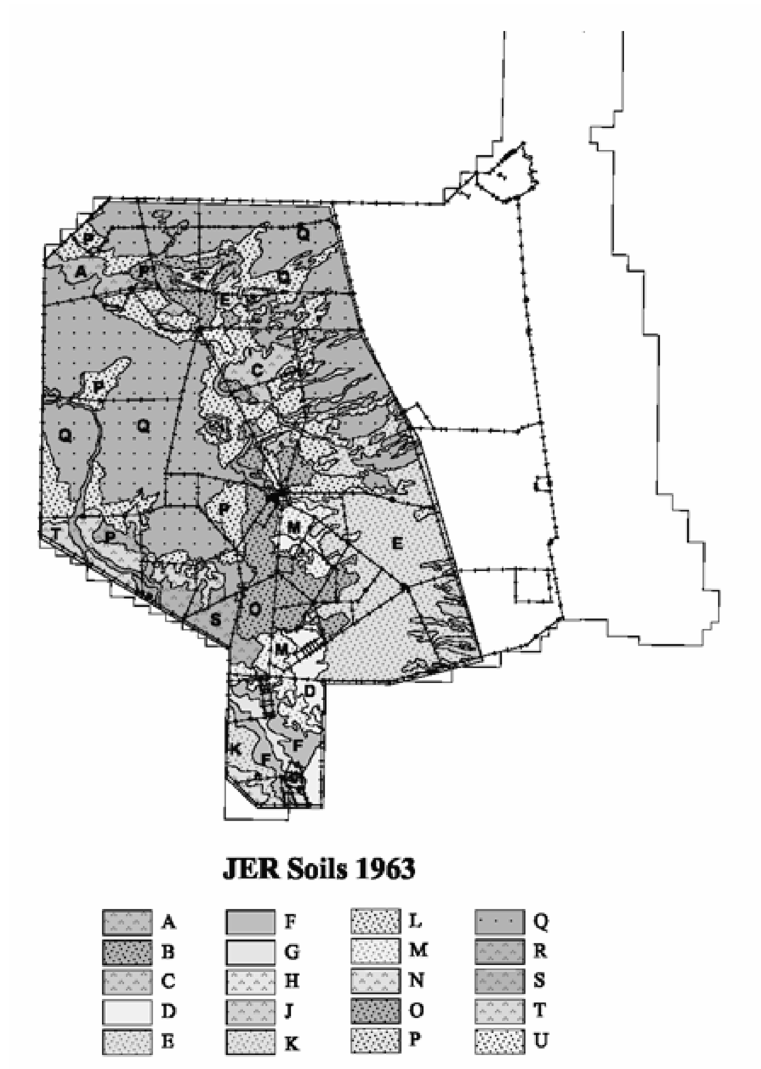


Fig. 4-2. Soil map of Jornada Experimental Range produced by the Soil Conservation Service (1963 unpublished). This soil survey was used, in a slightly modified form, to examine soil-vegetation relationships (Buffington and Herbel 1965). Abbreviated definitions of this map and their correlation to the 1918 map are given in Table 4-1.

The detail and accuracy of the 1963 map make it suitable for many landscape-scale ecological studies today (e.g., Buffington and Herbel 1965). However, it has limitations because it predated soil taxonomy (Soil Survey Staff 1975) and lacks quantitative soil characterization data. The map also carried the Q and P units onto the piedmont slope area of Veatch's Goldenburg Sands. Although these units mark the presence of coppice dunes Q and hummocky soils P on the piedmont slope, they do not convey the general absence of petrocalcic horizons. Nevertheless, the quality of the line work of this map make it the best soils map currently available for the Jornada Basin north of the Desert Project. The unit descriptions of the 1963 map and their correlation to the 1918 map are given in Table 4-1.

Table 4-1. Correlation of 1918 and 1963 soil maps of the Jornada Basin area, and abbreviated descriptions of 1963 mapping units

| 1918 Soil Map Units | 1963 Soil Map Unit Descriptions (Abbreviated from SCS 1963) |
|---|---|
| | Basin Floor *(Alluvial Plain)*[a] |
| West Gravelly Sand (WGS) | (T) Tencee (Simona-Palma complex)[b], gravelly loamy fine sand. Shallow to very shallow loamy sand underlain by caliche at 10 to 20 in. Occurs on bench-like surface higher than land to east. Similar to S except shallower, less B-horizon development, and more surface litter of caliche and blowouts. 0-3% slope. |
| | (S) Cacique loamy fine sand. Weakly developed textural B [argillic] horizons overlying semi-indurated to indurated caliche at 11 to 48 inches. Surface littered with caliche fragments. Rodent action has mixed caliche. More sloping than T. 1-3% slope. |
| Jornada Sand (RLS(W)) | (Q) Continental loamy fine sand, severely eroded, coppice dunes. Severely altered by erosion. Sand hummocks 3 to 6 ft high, 12 to 20 ft long with interdune blowouts. Semi-indurated to indurated caliche at 3.5 to 5 ft. 0 to 3% slope. |
| | (P) Continental loamy fine sand, hummocky. Semi-indurated to indurated caliche at 30 to 60 in. Less eroded than Q, more eroded than O. On piedmont slope, weakly calcareous upper horizons and indurated caliche is absent. 0 to 2% slope. |
| Jornada Red Loamy Sand (RLS) | (O) Continental loamy fine sand. Deep, reddish brown sandy soils with moderately well developed textural B [argillic] horizons. Caliche is soft to only semi-indurated; in places it may be indurated. Less wind erosion than P and Q. Different from M by being less calcareous, lighter textured, deeper to caliche, and higher on landscape. 1-3% slope. |
| | (M) Turney sandy loam. Minor blowouts and sand accumulation of 6 to 12 inches. Weak textured B [argillic] horizon of sandy clay loam. Strong Cca [calcic] horizon that may be weakly indurated. Correlates to mapping unit 56 & 57 of Desert Project. 0-2% slope. |
| | (R) Palma loamy fine sand, sloping. Sand accumulations on sloping ridges and escarpments. Usually have moderate to strong Cca horizons between 30 & 60 inches. Gypsum at about 36 inches in areas of ancient lakes. 3 to 6% slope. |
| | Basin Floor *(Alluvial Flat)* |
| Clay and Adobe Soil (A) | (G) McNeal (Continental) silt loam, bottom (bolson) phase. Lowest position on landscpe. Well developed textural B [argillic] horizon and Cca [calcic] horizon. Subject to runoff water. Correlates with mapping unit 55 of Desert Project. Slope 0-1%. |

| | |
|---|---|
| | (F) McNeal (Continental) loam. Loam to silt loam surface textures. Well-developed textural B [argillic] horizons and strong Cca [calcic] horizons. Soils developed in alluvial parent material of mostly mixed igneous rock. Paleosols are common. Correlates with mapping unit 16V of Desert Project. 0-2% slopes. |
| | (D) Harvey (Hoban) silt loam. Soils formed in non-gravelly limestone alluvium. Soil do not have textural B [argillic] horizons, but do have moderate Cca [calcic] horizons. Differ from G & F by not having textural B [argillic] horizons. Also, slightly higher landscape position than F. Correlates with mapping unit 51 of Desert Project. 0-1% slopes. |
| Lake Bed Clay (LC) | (A) Skassi (Verhalen) clay. Reddish brown calcareous clay to silty clay loam developed from lake sediments containing some soluble salts and well-rounded, gravel-size gypsum crystals. Underlain by massive gypsum. 0-1% slope. |
| Lake Bed Clay (LC) | (B) Rustler (Russler) loam. Strongly calcareous loam to silty clay loam in older lake basins. Subsoils resemble lacustrine sediments containing gypsum. Associated with shallow gypsum soils on higher positions and very fine textured gypsiferous soils on lower landscapes. 0-1% slopes. |
| Gypsum Soil (GY.S) | (H) Eroded gypsum land (Cottonwood-Gypsum Outcrop complex). Strongly calcareous, medium-textured soils overlying gypsum beds at 1 to 12 inches. Highly eroded. 0-3% slope. |
| Middle Well Sand (SG) | (U) Cottonwood fine sand, overblown. Shallow sandy soils over gypsum at 4 to 24 inches. Lacustrine material overblown by aeolian sands with slight depressions & rolling ridges within an old lake basin. 0-3% slope. |
| Jornada Gray Sand (GSL) | (L) Gomez sandy loam. Weakly developed, strongly calcareous soil with 24 to 40 inch depth to gypsum beds. Soil developed from strongly calcareous lacustrine material deposited by strong winds from adjacent playas or shorelines of ancient lakes. 0-7% slope. |
| | (C) Cottonwood soils (Cottonwood-Reeves-Hoban complex). Complex of calcareous-gypsiferous soils on a shelf midway between sandy soils higher on landscape and finer soils lower on landscape. Gypsum ranges from soft powder to coarse crystals. Textures range from clay loam to sand. 0-3% slope. |
| Piedmont Slope *(of San Andres Mountains)* | |
| Goldenburg Sand (GS) | (Q) Continental loamy fine sand, severely eroded, coppice dunes. (Q also used for RLS(W)). Severely altered by erosion. Sand hummocks 3 to 6 ft high, 12 to 20 ft long with interdune blowouts. Semi-indurated to indurated caliche at 3.5 to 5 ft. 0 to 3% slope. |
| | (P) Continental loamy fine sand, hummocky. (P also used for RLS(W)). Semi-indurated to indurated caliche at 30 to 60 in. Less eroded than Q, more eroded than O. On piedmont slope, weakly calcareous upper horizons and indurated caliche is absent. 0 to 2 % slope. |
| Clay and Adobe Soil (A) | (E) Target-Isacks soils (Dona Ana Complex). Weakly developed, yet strongly calcareous soils on alluvial fans of limestone and calcareous sandstone that extend from the bottom of the Jornada basin eastward to the foothills of the San Andres Mountains. Erosion escarpments range from 6 inches to 7 feet high with narrow sandy ridges parallel to scarps. Surface soils range from silt loam to loamy sand. 0-3% slope. |
| Jornada Clay Loam (RSL & SCL) | (E) Target-Isaacks soils (Dona Ana Complex). (E also used for Clay and Adobe Soil (A)). Weakly developed, yet strongly calcareous soils on alluvial fans of limestone and calcareous sandstone that extend from the bottom of the Jornada basin eastward to the foothills of the San Andres mountains. Erosion escarpments range from 6 inches to 7 feet high with narrow sandy ridges parallel to scarps. Surface soils range from silt loam to loamy sand. 0-3% slope. |
| Middle Tank Gravelly Soil (GL) | (J) Solidad (Cave) gravelly sandy loam. Shallow, violently calcareous soils with weak Cca horizon underlain by weakly cemented limestone cobbles or indurated caliche. Soils developed in alluvial fans consisting mostly of limestone with some calcareous sandstone on long ridges that slope to west. Water erosion is shown by gullies to indurated caliche (calcrete). Surface |

| | |
|---|---|
| | covered with up to 35% gravels. 2-5% slope. |
| Piedmont Slope *(of Dona Ana Mountains)* | |
| Jornada Clay Loam (RSL & SCL) | (K) Daggett gravelly sandy loam. Gravelly, weakly developed regosols. Parent material contains caliche mixed with monzonite and rhyolite gravel. Soils have very weak Cca horizons overlying paleosols with textured B [argillic] and Cca [calcic] horizons. Moderate gully and sheet erosion. Surface covered with gravel more concentrated than in profile. Correlates with mapping unit 13V of Desert Project. 1-3% slopes. |
| | (F) McNeal (Continental) loam. (F also used for A). Loam to silt loam surface textures. Well-developed textural B [argillic] horizons and strong Cca [calcic] horizons. Lower lying soils developed in alluvial parent material of mostly mixed igneous rock. Paleosols are common. Correlates with mapping unit 16V of Desert Project. 0-2% slopes. |
| Middle Tank Gravelly Soil (GL) | (N) Solidad (Cavot) very gravelly sandy loam. Soil 10 to 32 inches over either semi-indurated or indurated caliche. Soil paved with gravel and fine cobbles. Soil developed in outwash alluvial deposits of mixed igneous rocks. Profiles free of toxic salts and alkali. Active sheet and gully erosion. 2-5% slope. |
| Bedrock Hills and Mountains (San Andres Mountains) | |
| Foothills (GSS) | (V)[c] Rock outcrops. Much of the surface is bare rock. In some areas, sand has accumulated quite high on the slopes and covers, or partially covers, the rock. |

## The Doña Ana County and White Sands Missile Range Soil Surveys

In 1980, the Doña Ana County Soil Survey (Bulloch and Neher 1980) was published (figure 4-3). It provides a general description of Jornada soils and made the advancement of classifying soils according to the soil taxonomy system (Soil Survey Staff 1975, 1999). This survey also covers both the JER and CDRRC. However, because it was designed to be a general survey, it has limitations for scientific studies requiring detailed soils information.

In 1976, the White Sands Soil Survey was published by the SCS at a scale of 1:100,000 (Neher and Bailey 1976). This survey covers the eastern part of the JER in the area that is jointly administered by White Sands Missile Range and the USDA. This survey also classifies soils using the soil taxonomy system. Unlike most SCS soil surveys, however, this one is unique because the maps do not have an aerial photographic base (because of missile range security).

**The Desert Soil-Geomorphology Project**

The Desert Soil-Geomorphology Project provides uniquely detailed and quantitative soil information. In August 1957, R. V Ruhe and L. H. Gile moved to Las Cruces to begin the

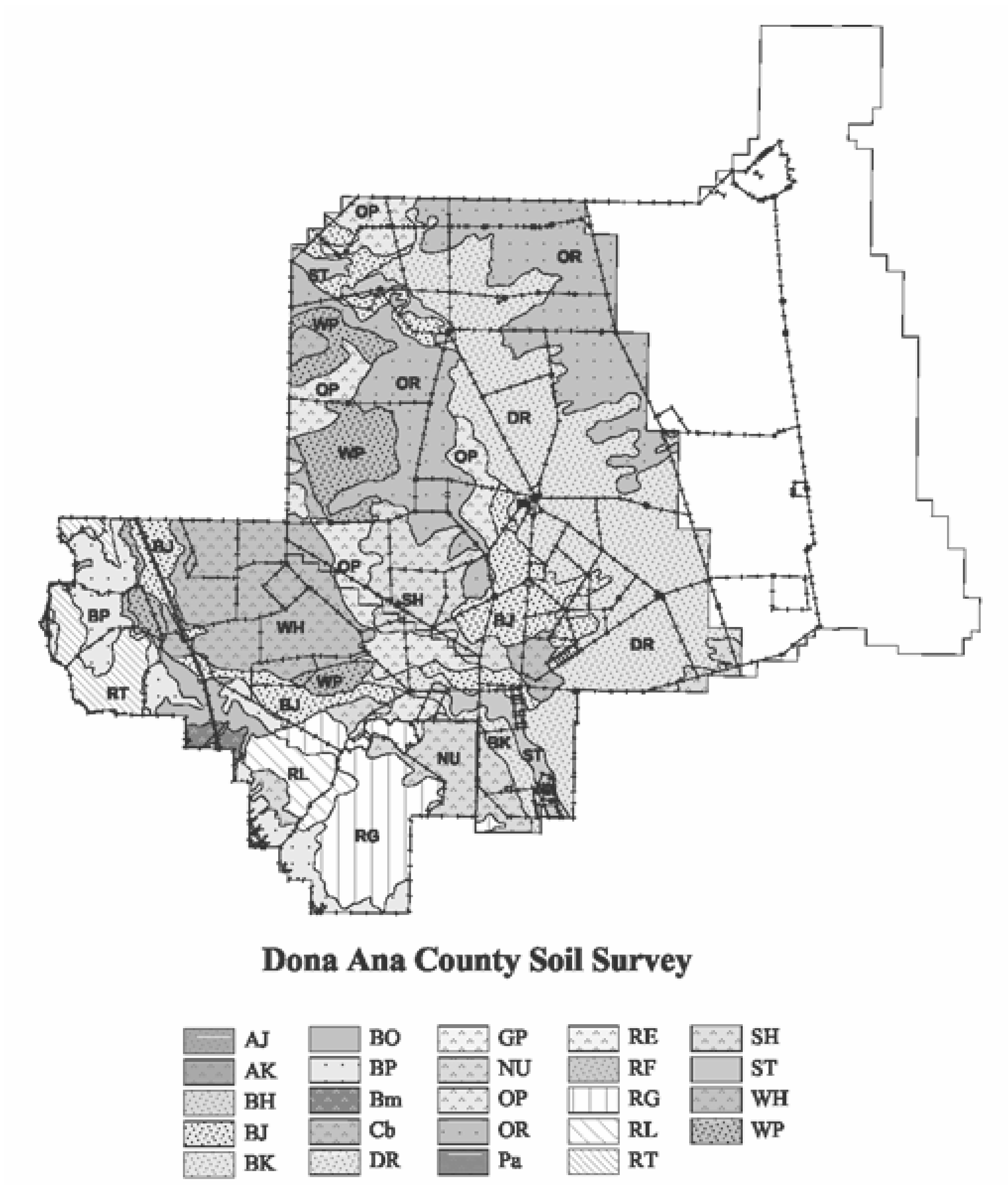


Fig. 4-3. The Dona Ana Soil Survey (Bulloch and Neher 1980). This survey provides a general survey of soils at both Jornada Experimental Range and the Chihuahuan Desert Rangeland Research Center (CDRRC). Soil series and classification based on the Soil Taxonomy system are given in Table 4-2.

Desert Soil-Geomorphology Project, which was one of a few regional soil-geomorphic projects established by SCS in the 1950s. At that time, little was known about soils in arid and semiarid regions of the American Southwest away from alluvial valley floors. This study was undertaken to learn more about the morphology, classification, and genesis of desert soils and their relation to late-Cenozoic landscape evolution, as well as to establish principles that could be used to improve the quality of soil survey in similar settings (Ruhe 1967; Hawley 1975b). The study area of the Desert Soil-Geomorphology Project (informally called the Desert Project) originally encompassed the JER, but it was later reduced to its 400-mi$^2$ area to focus more effort on a smaller area (Gile personal communication).

The Desert Project made several contributions to the understanding of soil-geomorphic relationships in arid and semiarid climates. In addition to the work on the local Cenozoic stratigraphy (Ruhe 1962; Hawley 1975a), hydrogeology (Hawley and Lozinsky 1992), geomorphic surfaces (Ruhe 1964; Gile et al. 1981), and paleoclimate (Gile 1975c; Hawley et al. 1976), general principles were established that dealt with (1) pedogenic-illuvial origin of carbonate ($CaCO_3$) horizons, (2) atmospheric additions, (3) soil chronology, (4) silicate clay accumulation, and (5) causal factors for soil boundaries.

**Pedogenic-Illuvial Origin of Carbonate Horizons**

Several hypotheses for the origin of calcium carbonate in soils had been proposed by the late 1950s when the Desert Project began, including lacustrine, fluvial, ascending groundwater, and pedologic origins (e.g., Bretz and Horberg 1949; Brown 1956; see Gile and Grossman 1979 for further discussion). However, except for small outcrops of groundwater carbonate, the following field evidence argued for a pedogenic-illuvial origin of carbonate in Desert Project soils: (1) Carbonate horizons are parallel to the land surface. (2) Carbonate horizons have upper boundaries within several inches to about 2 feet of the soil surface. (3) Carbonate horizons have distinctive morphologies that show lateral continuity and differ markedly from morphologies of overlying and underlying horizons. (4) Carbonate horizons occur between horizons containing little or no carbonate. (5) Carbonate horizons occur across sediments of various compositions and textures. And (6) carbonate horizons form in a developmental sequence related to time (Gile et al. 1965). This evidence has been useful for understanding the origin of carbonate in other desert sites, such as the proposed Yucca Mountain nuclear waste repository in Nevada (e.g., Kerr 1992; Hill et al. 1995; Monger and Adams 1996).

**Atmospheric Additions**

Although there were multiple lines of evidence that suggested a pedogenic-illuvial origin for most carbonate horizons in the Desert Project, the source of Ca was an enigma. First, soils with igneous parent materials, especially rhyolite, were only slightly weathered, and second, these sediments contained only small amounts of Ca (Gile et al. 1966; Ruhe 1967). Therefore, an analysis of dust ensued. Dust traps were set out across the Desert Project. Ten years of dust measurements revealed that calcareous dust fell ubiquitously on the landscape, ranging from 0.2 $g/m^2/yr$ in a grassy basin floor area to 1.1 $g/m^2/yr$ in a sandy bare-ground area (Gile and Grossman 1979). Meanwhile, rain as a source of Ca became recognized as a more important source of Ca than dust. Chemical analysis of rain by Junge and Werby (1958) and Lodge et al. (1968) revealed that Ca from rainwater could produce an estimated 1.5 g $CaCO_3/m^2/yr$, assuming 200 mm annual rainfall. Therefore, if ample bicarbonate is generated by roots and microbes, carbonate resulting from Ca in rain could be roughly two to three times greater than carbonate resulting from calcareous dustfall (Gile et al. 1981).

**Soil Chronology**

Measurements of soil age, which ranges from Pliocene to Holocene in the Jornada region, were made using several techniques. For soils of historical age, land survey notes were used. These notes made it possible to determine which coppice dunes (Gile 1966a) and arroyo sediments were deposited between 1858 and 1922 (Gile and Hawley 1968). For soils of prehistorical age, radiocarbon dates of buried charcoal, which ranged from less than 200 to 9,360 yr B.P., provide the most authoritative dates (Hawley and Kottlowski 1969; Gile et al. 1981). Radiocarbon dates of $CaCO_3$ carbon were also used to help determine soil ages, but calcium carbonate is subject to inputs of modern carbon and is of little value in distinguishing between late Pleistocene and older soil horizons (Gile et al. 1981). For soils of middle Pleistocene age and greater, the Lava Creek B (0.61 to 0.67 Ma) and Bishop (0.76 Ma) volcanic ashes have been important for bracketing soil ages (Hawley et al. 1976; Izett et al. 1992; Sarna-Wojcicki and Pringle 1992). Paleontological remains provided some of the earliest clues to the ages of soils. For example, horses (*Equus*), short-jawed mastodons (*Cuvieronius*), mammoths (*Mammuthus*), and stegomastodons (*Morrilla*) provided evidence that basin-floor soils formed in Camp Rice fluvial sediments were at least Kansan in age (Ruhe 1962; Hawley et al. 1969).

Subsequent work refined the age of this faunal assemblage to be early Pleistocene (Tedford 1981).

Tracing soil horizons and geomorphic surfaces laterally provided some of the most conclusive evidence about relative ages of soils. For example, a soil can be determined to be younger than a neighboring soil if its geomorphic surface buries, cuts, or is inset against the neighboring surface. Another indicator of relative soil age is the degree of profile development, such as solum thickness (i.e., depth to the bottom of B horizons) and the expression of carbonate horizons (Gile 1970).

**Silicate Clay Accumulation**

Like the accumulation of carbonate and formation of calcic and petrocalcic horizons, the accumulation of silicate clay and formation of argillic horizons is an important diagnostic criterion for soil classification. For a horizon to qualify as argillic, clay must be illuvial and have more clay than the overlying eluvial horizon (Soil Survey Staff 1999). Clay accumulation in arid soils, however, was formerly thought to be due to in-place weathering rather than illuviation (Nikiforoff 1937; Brown and Drosdoff 1940). Yet clay in soils of the Desert Project showed coated particles in the B horizon and evidence of having an illuvial origin and meeting the criteria of an argillic horizon (Gile and Grossman 1968).

Other studies focused on the affect of parent material on argillic horizons and on factors that obliterate argillic horizons. Parent material was found to have an important control on clay illuviation because argillic horizons typically do not exist in parent material that contains abundant limestone rocks (Gile et al. 1981).

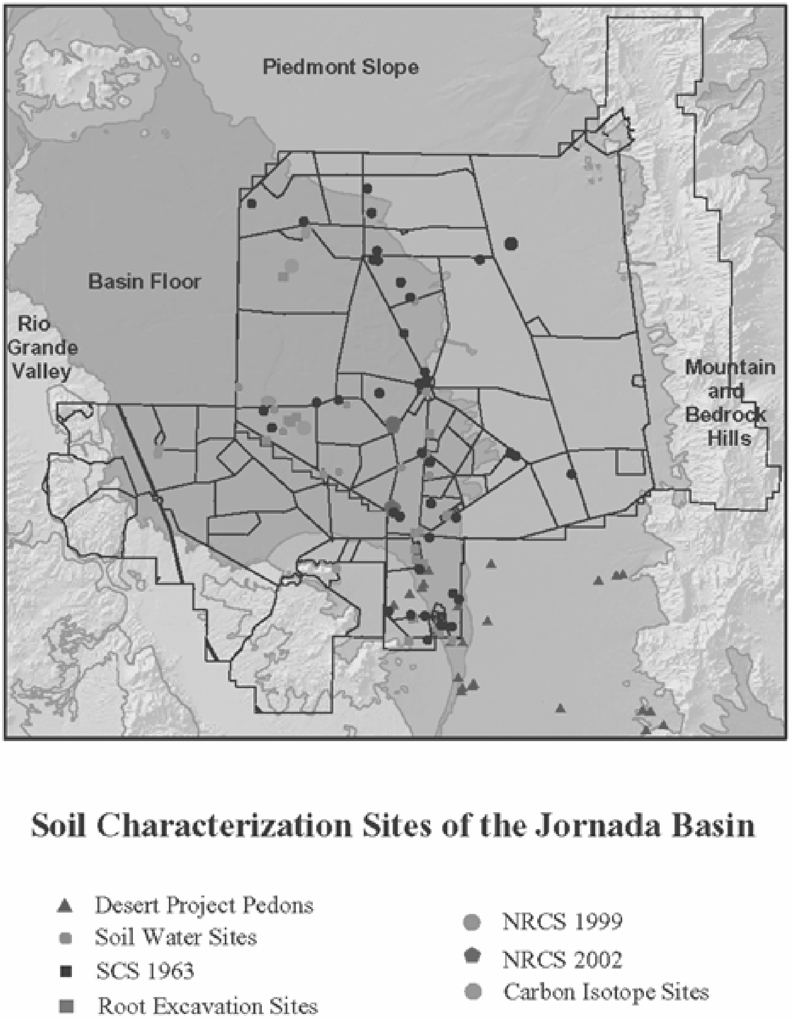


Fig. 4-4. Map of physiographic units and locations of sites where soil characterization data have been generated. Publications and websites where data are located are in Gile and Grossman (1979), Herbel et al. (1994), NRCS (2005) web site (http://soils.usda.gov), Gibbens and Lenz (2001), and Connin et al. (1997a; 1997b).

The explanation apparently lies in the flocculating effect that carbonate has on clay movement. Factors that obliterate argillic horizons include (1) landscape dissection and erosional truncation of argillic horizons, (2) engulfment of argillic horizons by pedogenic carbonate, and (3) faunal mixing in which tunnels and mounds made by kangaroo rats (*Dipodomys)*, badgers *(Taxidea)*, and termites (primarily *Gnathamitermes)* destroy the fabric of argillic horizons (Gile 1975a).

**Characterization Data of Jornada Basin Soils**

Sites where soil characterization has been conducted are shown in figure 4-4. The sites marked Desert Project Pedons contain physical and chemical lab analyses performed by the SCS (now the Natural Resources Conservations Service, NRCS). These include analysis of particle size, organic carbon, nitrogen, carbonate, extractable iron, bulk density, shrink-swell potential, water-holding properties, extractable ions, clay mineralogy, pH, and electrical conductivity, among others (Gile and Grossman 1979).

Other sites with NRCS laboratory data are (1) the soil water sites, (2) the NRCS 1999 sites, and (3) the NRCS 2002 sites. Data from the NRCS 1999 and 2002 sites are on the NRCS Web site (http://soils.usda.gov). Data from the soil water sites are in Herbel et al. (1994). Other soil data were gathered at the root excavation sites (Gibbens and Lenz 2001) and carbon isotope sites (Connin et al. 1997a, b).

**Processes of Soil Development in the Jornada Basin**

When Veatch made the 1918 soil map of the Jornada Basin, Curtis Marbut (1863–1935) was chief of the U.S. National Soil Survey. During that time, Marbut read a German translation of K. D. Glinkas's monograph on the nature of soil science and pedology in Russia (Gardner 1957). This introduced Marbut to V. V. Dokuchaiev (1846–1903) and the Russian concepts of soil development. Of primary importance was the concept that soils are the evolutionary product of five factors—topography, climate, parent material, biota, and time. Since that time, the understanding of soil development in any region has been enhanced by knowledge of the five factors of soil formation (Jenny 1941).

The five soil-forming factors establish a context and provide the external forces for soil development in the Jornada Basin. Within that context, several physical, chemical, and biological processes are active. Soil-forming processes (as contrasted with factors) were grouped into four categories by Simonson (1959): additions, transfers, transformations, and removals (figure 4-5).

The cumulative result of these pedogenic processes is the transformation of bedrock or sedimentary deposits into soil with pedogenic horizons. Pedogenic horizons (e.g., A, E, B horizons) are produced by the four soil-forming processes. The C horizon, in contrast, is typically a sedimentary layer little affected by pedogenesis (that is, only slightly modified by the four soil-forming processes). All the processes illustrated in figure 4-5 occur in soils of the Jornada Basin, but they occur at different rates. A few of the more notable results of these processes are described shortly (organic matter accumulation, pedogenic carbonate accumulation, desert pavement and the formation of eluvial horizons, and clay accumulation).

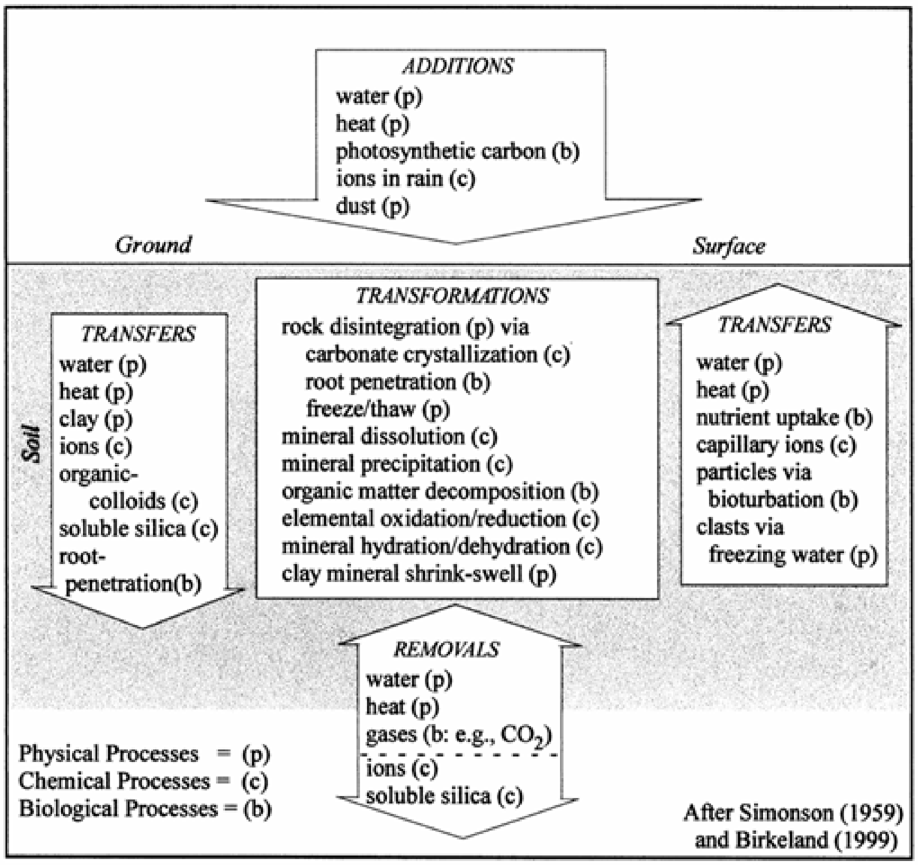


Fig. 4-5. Physical, chemical, and biological processes that operate interactively to produce soil horizons. These processes are grouped into four categories: additions, transfers, transformations, and removals (Simonson 1959). All of these processes are active in Jornada soils, though some, like freeze-thaw, are less active than processes such as heat transfer or organic matter decomposition.

### Organic Matter Accumulation

Organic matter plays an important role in nutrient cycling and aggregate stability (chapter 6). Desert soils in the Jornada Basin have low concentrations of soil organic matter. Even in A horizons most concentrations are only 0.1–0.3% organic carbon. On the high end, soils above elevations of about 1,524 m (5,000 ft) can have up to 1.3% organic carbon in A horizons (Gile et al. 1981). These soils have enough organic matter to classify as Mollisols, rather than Aridisols or Entisols. Downslope, these soils change from Mollisols to Aridisols. Where soils form in alluvium derived from bedrock with granitic texture, such as the sorts around Summerford Mountain. A horizons retain a dark color (giving a false impression of high organic content) as a consequence of thin organic coatings on sand and fine gravel (Encina-Rojas 1995).

Other soils containing relatively high levels of organic matter are located in topographically low areas that receive water from hill slope runoff. In these soils, organic carbon can be as high as 2.21% (Herbel et al. 1994). This is the result of greater plant densities supported by increased water supply and an increased clay content that curtails organic matter decomposition (Deng and Dixon 2002). In addition, soils developed in limestone alluvium have a tendency to contain higher amounts of organic matter than neighboring soils formed in igneous alluvium (Grossman et al. 1995).

On the low end, some sandy soils barren of vegetation in the Jornada Basin contain as little as 0.1% organic carbon. In areas where black grama grass has converted to mesquite coppice dunes over the past 150 years, losses of soil organic matter have occurred, although carbon storage of the ecosystem as a whole has changed little (Schlesinger and Pilmanis 1998). In bare interdune areas, the loss of organic matter is the result of not only decreased organic inputs but also the loss of organic matter by wind and water erosion (Schlesinger et al. 1990).

**Pedogenic Carbonate Accumulation**

Unlike organic carbon, which reaches an equilibrium concentration within an ecosystem within decades to centuries, pedogenic carbonate accumulates over millennia to progressively higher concentrations. Consequently, carbonate is one of the prominent (if not *the* prominent) pedogenic feature in the Jornada Basin. For example, soils of the southeastern region of the JER, which are of early Pleistocene age (Mack et al. 1996), have pedogenic carbonate amounts that reach 223 kg C/m$^2$, a value that equals some of the highest concentrations of organic carbon in peat-bog Histosols (NRCS Web site 2005). As in the Mojave Desert (Schlesinger 1985), roots (Gallegos 1999) and microorganisms (Monger et al. 1991a) play a role in precipitating pedogenic carbonate, which in the Jornada Basin has been studied from both soil-geomorphic and ecological aspects.

**Soil-Geomorphic Aspects of Pedogenic Carbonate**

Several names have been used to describe soil carbonate in arid and semiarid soils: caliche, calcrete, croute calcaire, tosca, caprock, crust, calcic horizons, and petrocalcic horizons (Gile 1961; Goudie 1973; Dregne 1976; Soil Survey Staff 1999). Forms of carbonate accumulation have been described as filamentary, concretionary, cylindroidal, nodular, plugged horizons, and laminar horizons (Gile 1961; Gile et al. 1966). These carbonate accumulations range from nonindurated, which slake when placed in water, to very strongly indurated, which do not slake in water and cannot be scored with a knife. On the low end, soil horizons with carbonate filaments can contain as little as 1% $CaCO_3$ and, depending on texture, have a bulk density of about 1.68 g/cm$^3$ and an infiltration rate of 12.4 cm/h (Gile 1961). On the high end, laminar horizons contain as much as 93% $CaCO_3$, have a bulk density of 2.22 g/cm$^3$, and have an infiltration rate of 0.1 cm/h.

Carbonate is an important indicator of soil age because progressively older geomorphic surfaces contain progressively greater amounts of carbonate. Over time, four diagnostic morphogenetic stages of carbonate are formed (Gile et al. 1966). For example, soils formed in sediment deposited by the Rio Grande progress from having no display of carbonate to having stage I filaments, then stage II nodules, a stage III plugged horizon, and eventually a stage IV laminar horizon atop the plugged horizon. Researchers applying this classification to desert soils elsewhere have added two more stages of carbonate accumulation: stage V and stage VI (Machette 1985). Stage V contains diagnostically thick laminae (> 1 cm) and pisolites; stage VI contains multiple generations of laminae, breccia, and pisolites. All six stages are found in the Jornada region of south-central New Mexico (Gile et al. 1996). The time required to reach a certain morphogenic stage depends on the texture of the soil. Gravelly soils pass through the stages more quickly than fine-textured soils because gravelly soils have lower surface area and less poor space.

Until about 1965, horizons with carbonate accumulation were designated as C horizons with a “ca” suffix or “cam” suffix if indurated, following the procedure of the *Soil Survey Manual* (Soil Survey Staff 1951). Subsequent work in the Desert Project showed that carbonate accumulation was a pedogenic process. Therefore, horizons with significant amounts of carbonate should be designated B horizons. The prominence of carbonate horizons in arid and semiarid regions led Gile et al. (1965) to propose the K horizon as a master horizon (i.e., horizons such as the O, E, A, B, C, and R horizons). The K horizon is based on the presence of K-fabric, which is defined as “fine-grained authigenic carbonate that coats or engulfs skeletal pebbles, sand, and silt grains as an essentially continuous medium” (Gile et al. 1965). The K horizon, by definition, contains 90% or more K-fabric. Although not formally accepted by the NRCS, except that the suffix “k” has replaced the “ca” suffix, the K horizon has been used extensively in quaternary geology studies of the Southwestern United States (e.g., Machette 1985; Birkeland 1999).

**Ecological Aspects of Pedogenic Carbonate**

Mineralogically, pedogenic carbonate in the Jornada Basin is calcium carbonate in the form of calcite, regardless of whether it formed in igneous or limestone parent material (Kraimer 2003). Calcium carbonate is known to have important chemical influences on plant growth by its control on pH, phosphorous, and micronutrient availability (chapter 6). For rangeland ecosystems, carbonate accumulation also has an important physical influence on plant growth by its influence on water storage via its affect on soil texture. Carbonate crystals are generally in the size range of coarse clay to fine silt, approximately 1-10 microns (Monger et al. 1991b), which increases surface area and microporosity of the horizon impregnated with carbonate. For example, soil-water release curves for carbonate nodules revealed that the nodules store about twice the water as adjacent soil not impregnated with carbonate (Monger 1990). Hennessy et al. (1983b) measured water properties of caliche in the Jornada Basin and found that caliche absorbed appreciable quantities of water and retained it for extended periods, which may have contributed to certain areas of black grama grass underlain by caliche surviving the 1950s drought (Herbel et al. 1972). Moreover, creosotebush on sites underlain by caliche showed less water stress when rainfall was low than sites without caliche (Cunningham and Burk1973).

**Desert Pavement and the Formation of Eluvial Horizons**

Gravelly soils of Pleistocene age in the Jornada Basin commonly develop desert pavements. Depending on local circumstances, these gravelly pavements can form as the result of erosion removing smaller particles (Cooke et al. 1993), eolian materials accumulating beneath and lifting gravels (McFadden et al. 1987), or a combination of both processes. Many desert pavements in the Jornada Basin region, especially those of stable geomorphic surfaces, are blackened and reddened by desert varnish on coarse fragments other than limestone (Gile and Grossman 1979).

Thin vesicular A horizons, Av (Birkeland 1999), characterized by having spherical voids disseminated through the horizon, occur just beneath many desert pavements. These apparently form by the entrapment of air that is displaced upward by infiltrating water (Springer 1958). The rate at which vesicular A horizons form can be quite rapid based on the observation that well-developed vesicular horizon formed in tire tracks known to be less than two years old (Gile and Grossman 1979).

The vesicular A horizon is one form of an eluvial zone (i.e., a soil zone from which clay and chemical compounds have been removed by percolating water). Eluvial horizons are designated by the letter E (formerly A2) when eluviation dominates other properties of the A or B horizons (Soil Survey Staff 1999). E horizons are not widespread across the Jornada Basin but do occur where leaching and eluviation have taken place and the horizon has not been truncated by erosion (e.g., Gile et al. 1981), such as the stellar series on the lower piedmont slope of the Doña Ana Mountains.

## Clay Accumulation and Mineralogy

The amount of clay in soil affects vegetation by its control on water storage, air and water permeability, nutrient storage, shrink-swell properties, soil hardness, and erodibility. As clay content increases, water storage, nutrient storage, shrink-swell, and hardness generally increase, whereas erodibility and air permeability generally decrease. In the Jornada Basin, soils with the highest clay content occur in playas. The Red Lake Playa site, for example, contains soils that have up to 69% clay (largely smectite). Its water content is as high as 32% at 1/3 bar and 20% at 15 bar tension, and it has a cation exchange capacity of up to 30 cmol/kg (table 4-2).

For comparison, a coppice dune along the Camino Real has as little as 5% clay, a water content of 5% at 1/3 bar and 3% at 15 bar tension, and a cation exchange capacity of 5.8 cmol/kg.

Mineralogically, the clay fraction (< 2 microns) in soils of the Jornada Basin contains smectite, illite (mica), kaolinite, vermiculite, mixed-layer clays, palygorskite, sepiolite, quartz, feldspars, and calcite (Vanden Heuvel 1966; Gile and Grossman 1979; Monger and Lynn 1996). These occur in various proportions depending on parent material and age. For example, palygorskite and sepiolite only occur in petrocalcic horizons (Monger and Daugherty 1991a), in contrast to smectite, illite, and kaolinite, which are nearly ubiquitous.

Chemical weathering of monzonite alluvium of the Jornada Basin area has produced kaolinite (Monger and Lynn 1996). Another example of chemical weathering can be found in soils of the basin floors that formed in ancestral Rio Grande alluvium. The sand mineralogy in these soils show the highest degree of chemical weathering in the

Table 4-2. Classification of soil series mapped for Jornada Experimental Range and Chihuahuan Desert Rangeland Research Center by the1980 Dona Ana Soil Survey (Fig. 4-3). The 1975 classification system (Soil Survey Staff 1975) was used in the Dona Ana Soil Survey. Subgroups of Aridisols have since been revised (Soil Survey Staff 1999). Particle-size classes, mineralogy classes, and temperature regimes are the same for both the 1975 and 1999 classification systems.

| Series[a] | Family Classification (1975 system) | Revised Subgroup Classification (1999) |
|---|---|---|
| Agua | c-l/s or s-k[b], mixed (calcareous), thermic Typic Torrifluvents | ...no revision |
| Arizo | sandy-skeletal, mixed, thermic Typic Torriorthents | ...no revision |
| Belen | cl/l, montmorillonitic (calcareous), thermic Vertic Torrifluvents | ...no revision |
| Berino | Fine-loamy, mixed, thermic Typic Haplargids | ...Typic Calciargids |
| Bluepoint | Mixed, thermic Typic Torripsamments | ...no revision |
| Bucklebar | Fine-loamy, mixed, thermic Typic Haplargids | ...no revision |
| Caliza | Sandy-skeletal, mixed, thermic Typic Calciorthids | ...Typic Haplocalcids |
| Canutio | l-sk, mixed (calcareous), thermic Typic Torriorthents | ...no revision |
| Dona Ana | Fine-loamy, mixed thermic Typic Haplargids | ...Typic Calciargids |
| Harrisburg | Coarse-loamy, mixed, thermic Typic Paleorthids | ...Typic Petrocalcids |
| Lozier | Loamy-skeletal, carbonatic, thermic Lithic Calciorthids | ...Lithic Haplocalcids |
| Nickel | Loamy-skeletal, mixed, thermic Typic Calciorthids | ...Typic Haplocalcids |
| Onite | Coarse-loamy, mixed, thermic Typic Haplargids | ...Typic Calciargids |
| Pajarito | Coarse-loamy, mixed, thermic Typic Camborthids | ...Typic Haplocambids |
| Pintura | Mixed, thermic, Typic Torripsamments | ...no revision |
| Reagan | Fine-silty, mixed, thermic Ustollic Calciorthids | ...Ustic Haplocalcids |
| Simona | Loamy, mixed, thermic, shallow Typic Paleorthids | ...Typic Petrocalcids |
| Stellar | Fine, mixed, thermic Ustollic Haplargids | ...Ustic Calciargids |
| Upton | Loamy, carbonatic, thermic, shallow Typic Paleorthids | ...Calcic Petrocalcids |
| Wink | Coarse-loamy, mixed, thermic Typic Calciorthids | ...Petronodic Haplocalcids |
| Yturbide | Mixed, thermic Typic Torripsamments | ...no revision |

[a]Symbols and Mapping-Unit Names for the Dona Ana Soil Survey are listed below.
[b]Abbreviations of particle size classes; c = coarse, f = fine, l = loamy, s = sandy, sk = skeletal

| | |
|---|---|
| AJ - Agua Variant soils, moderately wet | OR - Onite-Pintura association |
| AK - Agua Variant and Belen Variant soils | Pa - Pajarito fine sandy loam |
| BH- Belen Variant soils | RE - riverwash |
| BJ - Berino-Bucklebar association | RF - riverwash-Arizo complex |
| BK - Berino-Dona Ana association | RG - Rock outcrop-Argid complex |
| BP - Bluepoint-Caliza-Yturbide complex | RL - Rock outcrop-Lozier complex |
| BO - Bluepoint loamy-sand, 1-15 % slopes | RT - Rock outcrop-Torriorthents association |
| Bm - Bluepoint loamy-sand, 1-5 % slopes | SH - Simona-Harrisburg association |
| Cb - Canutio-Arizo gravelly sandy loam | ST - Stellar association |
| DR - Dona Ana-Reagan association | WH - Wink-Harrisburg association |
| NU - Nickel-Upton association | WP - Wink-Pintura complex |
| OP - Onite-Pajarito association | |

A and B horizons and lowest degree of chemical weathering in C horizons (e.g., Monger 1990). In petrocalcic horizons, pressure solution resulting from carbonate precipitation is an additional process that hastens the dissolution of sand grains and promotes the neoformation of palygorskite (Monger and Daugherty 1991b).

**Processes that Obliterate Soil Development**

**Alluvial Activity**

Alluvial activity in the Jornada Basin consists of two processes: erosion and sedimentation. Water erosion is prominent on the piedmont slopes (chapter 7) but is also important in interdune areas on the basin floor where short-distance (on the order of meters to tens of meters) erosion and sedimentation occur. Erosion obliterates soil development by truncating pedogenic horizons, as exemplified along the Rio Grande, where lowering base levels have initiated landscape dissection (Gile et al. 1969). Figure 4-6 illustrates how progressive erosion and truncation removes pedogenic soil horizons, which, in turn, changes the soil classification from Aridisols having argillic and calcic horizons (Calciargids) to Entisols having no subsurface diagnostic horizons (e.g., Torriorthents). <<COMP: Insert figure 4-6 about here>>

On piedmont slopes, erosion upslope supplies sediment downslope that progressively fills broad swales and interfan valleys until these landforms are no longer the topographic lows. Subsequently, the locus for further deposition is shifted laterally across the piedmont slope into new topographic lows (Peterson 1981). As a result, alluvial fans and coalescent fan piedmonts (bajadas) are built. In general, erosion in the Jornada Basin produces sediments that are not removed by water from the basin. The exception is the Rio Grande Valley, where the drainage system is integrated with the river.

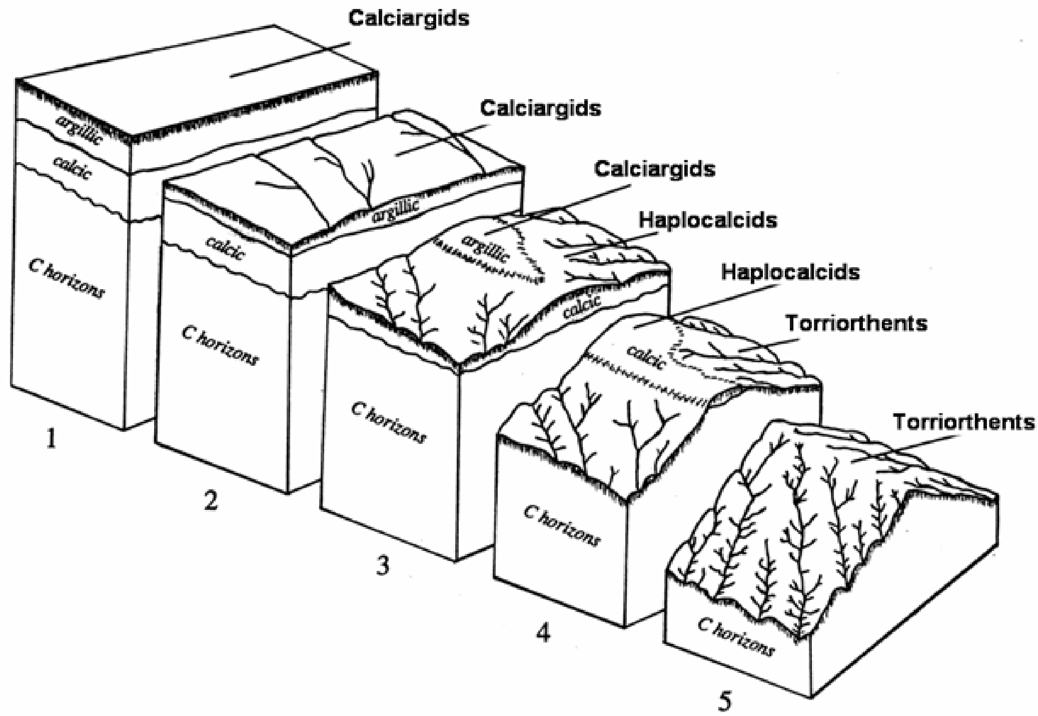


Fig. 4-6. Illustration of the effects of erosional dissection on argillic and calcic horizons. Block diagram 1 shows a stable, non-dissected landscape with an argillic and calcic horizon overlying C horizons, which classifies as Calciargids at the Great Group level (Soil Survey Staff 1999). With progressive dissection and truncation of these horizons, soils become Torriorthents, as illustrated in block diagram 5 (Modified from Gile et al. 1981).

Small lakes were sites of additional alluvial (lacustrine) deposition in the Jornada Basin. Evidence that these deposits are lacustrine in origin includes the terraces, thick clay deposits, and large gypsum crystals (selenite) found there. Lakes of the Jornada Basin have probably been dry since the end of early Holocene (~ 8,000 years ago) when similar lakes in the northern Chihuahuan Desert became extinct (Hawley 1993).

**Eolian Activity**

Like alluvial activity, eolian activity consists of two categories: erosion and sedimentation. However, unlike alluvial activity in the Jornada Basin, wind erosion can completely remove particles from the basin ecosystem (chapter 9). During high winds, much of the sand fraction saltates and creeps laterally. If mesquite shrubs are present, a portion of this material is trapped and coppice dunes form (Gile 1966b). Huge amounts of sand have been carried across the basin floor in an east-northeasterly direction by the prevailing wind and blown up the piedmont slope of the San Andres Mountains, over the bedrock outcrops, and into the intermountain valleys. The timing of this process, based on the degree of argillic and calcic horizon development in many of the intermountain sand deposits, predates the arrival of cattle in the late 1800s. However, the precise timing of the eolian deposition and the magnitude of present-day eolian deposition in relation to natural cycles of prehistoric deposition remain to be determined.

Erosion by wind (deflation) is a critically important process in the Jornada Basin. As with landscape dissection, deflation truncates soil horizons and changes soil classification. Large, linear deflational streaks are oriented to the east-northeast in the western portion of the Jornada Basin. In these areas, the soil profile is truncated and petrocalcic horizons are very near the surface (Gile 1999). Some of these features, called streets (Okin and Gillette 2001), occupy areas between coppice dunes, which in some cases are also linear and oriented in the prevailing wind direction.

**Faunal Activity**

Fauna, such as small mammals, reptiles, and insects, play a major role in obliterating soil horizons by their burrowing activity (chapter 12). For example, faunal burrowing obliterated argillic horizons in soils of the southern Jornada Basin (Gile 1975b). Kangaroo rats can penetrate into carbonate horizons and bring carbonate fragments to the surface (Anderson and Kay 1999), where they are apparent in aerial photographs. In some cases, termites are agents of carbonate movement. In the Jornada Basin, it is common to find termite sheaths that are calcareous in contrast to the noncalcareous soil surface on which they reside. Thin sections of such galleries and of the termites themselves revealed an arrangement of carbonate crystals that led to the hypothesis that termites biomineralize carbonate for use as cement for gallery construction (Monger and Gallegos 2000). However, in other areas of the Jornada Basin, especially where the underlying soils contain argillic horizons, the sheaths are cemented with silicate clays. This evidence, combined with isotopic, mineralogic, and electron microscopy, now indicates that termites transport carbonate from subsoil rather than biomineralizing it for gallery construction (Liu 2002).

**Links to Past Climates**

Regions that have undergone bioclimate change, such as the Jornada Basin, often contain soil profiles with relict mineralogical and morphological properties generated during climates of the past. These properties can provide evidence about past climates and vegetation, provided other soil-forming factors can be held relatively constant. Although properties like clay mineralogy and elemental composition have been useful for deriving paleoclimatic information (e.g., Birkeland 1999), pedogenic carbonate is particularly valuable because it contains evidence about past climates in at least three forms: the presence of carbonate, carbonate depth, and carbon and oxygen isotopes in carbonate. In addition to carbonates, landscape stability and soil formation provide clues about past climates.

**Presence of Carbonate**

Presence of pedogenic carbonate is a common feature of arid and semiarid soils. Although pedogenic carbonate can exist in humid climates under certain circumstances of high water tables and calcareous parent materials (Sobecki and Wilding 1983), an analysis of 1,168 soil profiles with carbonate showed that 95% of them exist in climates where the annual precipitation is less than 760 mm (Royer 1999). A typical value of 500 mm (20 inches) has been used as the general boundary between soils with carbonate and soils without carbonate (Birkeland 1999). Therefore, inferences can be made about past climates based on the premise that soils formed in humid climates do not have carbonate. For example, the sequence of paleosols (i.e., multiple buried soil profiles) shown in figure 4-7a–c provide evidence that the climate has not been humid enough to remove carbonate from the modern soil or any of the buried soils when they were at the land surface. <<COMP: Insert figure 4-7 about here>>In other words, the climate in the Jornada Basin has probably been arid, semiarid, or at most subhumid for at least the past 500,000 years, which is the estimated age of the stratigraphic section based on correlation to the Jornada I surface at other sites in the region that are dated by K/Ar and paleomagnetic methods (Hawley 1975a; Seager et al. 1984; Gile 1990, 1999; Mack et al. 1993).

**Carbonate Depth**

Within the confines of dry climates, it has been observed that the depth of pedogenic carbonate is proportional to annual rainfall, that is, greater precipitation corresponds to greater depths to the top of the carbonate horizons (Jenny and Leonard 1934; Arkely 1963; Gile 1975c). However, erosion, runoff, and run-in can confound this general

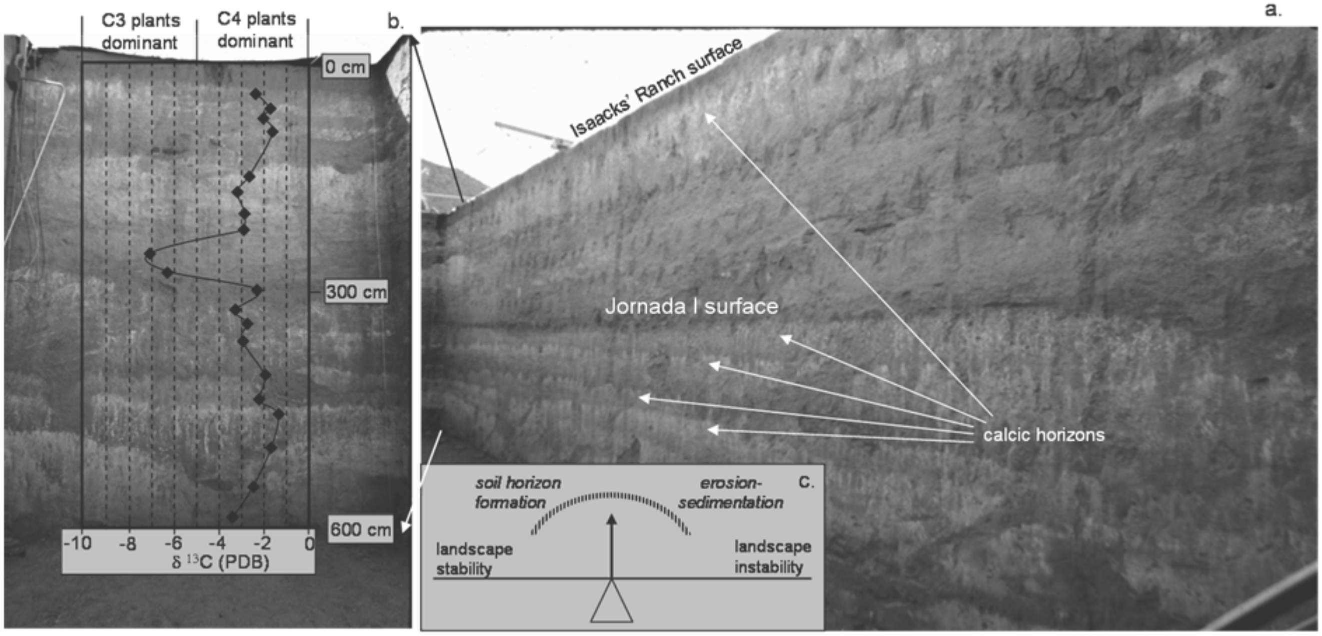


Fig. 4-7. (a) North face of a 6-m-deep trench on the piedmont slope northeast of Summerford Mountain along the LTER I transect (Wierenga et al. 1991). The stratigraphic record extends from the current land surface and the Isaacks' Ranch geomorphic surface to below the Jornada I surface, which has an estimated age as old as 500,000 years (Table 2-1). White arrows locate some of the calcic horizons, which are overlain by red argillic horizons unless truncated. (b) West face of the trench showing depths and a graph of the $\delta^{13}C$ values of carbonate. Values of $\delta^{13}C$ greater than -5 percent are thought to represent vegetation dominated by $C_4$ plants (Cerling 1984). (c) Illustration of a landscape stability model in which increased landscape stability gives rise to increased soil horizon formation, in contrast to progressive instability that is characterized by progressive erosion and sedimentation.

relationship, and it has recently been shown that a statistically significant correlation does not exist between carbonate depth and rainfall, especially for shallow carbonate in arid and semiarid climates (Royer 1999). Nevertheless, within a small region and especially within a single soil profile, carbonate depth is likely to be a function of long-term depth of soil wetting. For example, the vertical, karst-like pipes that cross-cut petrocalcic horizon in middle Pleistocene soils of the Jornada Basin are probably the result of deep water penetration during wetter climates (pluvials) in the Pleistocene (Gile et al. 1981). Similarly, horizons of carbonate filaments that occupy shallow depths in the same middle

Pleistocene soils provide evidence of an upward shift in the depth of wetting during subsequent drier climates (Gile et al. 1981; Monger 2003).

In addition to field observations of carbonate depths, models have been useful for understanding the relationship of carbonate depth and climate. McFadden and Tinsley (1985) developed a model that defined soil as a vertical sequence of compartments, each with a specified texture, bulk density, water-holding capacity, mineralogy, $pCO_2$ content, ionic strength, and temperature. Similarly, the model by Marion et al. (1985) and a later model by Marion and Schlesinger (1994) used stochastic precipitation, evapotranspiration, chemical thermodynamics, soil parameterization, and soil water movement to simulate carbonate and gypsum deposition. For soils in the Jornada Basin, the depth of carbonate was modeled as being about 15 cm deeper during wetter Pleistocene climates than during current arid conditions (Marion et al. 1985).

**Carbon and Oxygen Isotopes in Carbonate**

Carbon and oxygen isotopes in pedogenic carbonate contain climatic information by recording the relative abundance of $C_3$ to $C_4$ plants and the isotopic signatures of meteoritic water (Cerling 1984). In the Jornada Basin and Desert Project, early isotope studies were conducted by Gardner (1984), who showed that soils in different landscape positions contained different isotopic signatures and that repeated dissolution and reprecipitation tended to homogenize isotopic signatures in older soils. Later studies found isotopic shifts across stratigraphic boundaries of middle Holocene age in both alluvial (Cole and Monger 1994; Monger et al. 1998) and eolian paleosols (Buck and Monger 1999). In both cases, shifts in $^{13}C/^{12}C$ ratios indicated a change from $C_4$ (grass) to

$C_3$ (shrub), which slightly predated sedimentation, and an upward shift in the depth of carbonate deposition. Though relative amounts vary, carbon isotopes suggest that $C_4$ plants have been dominant during the late quaternary in the Jornada Basin (figure 4-7b). Much younger isotopic shifts in carbonate and organic matter have also recorded the replacement of grass by mesquite within historical sediment (Connin et al. 1997a, b).

**Landscape Stability**

Landscape stability (i.e., periods when land surfaces are not being rapidly dissected by erosion or rapidly buried by sedimentation) is prerequisite for pedogenic carbonate to develop to a substantial degree. For example, stage I carbonate filaments can develop within 100 years, whereas stage II nodules take about 8,000 years to form (Gile et al. 1981). Stage III and IV petrocalcic horizons might take 75,000 years to form depending on texture. Carbonate horizons are therefore important indicators of sustained soil formation on relatively stable surfaces. Argillic horizons (which typically form above carbonate horizons) also provide important clues that soil formation has proceeded for lengthy time periods. For example, argillic horizons are common in soils of the Isaac's Ranch geomorphic surface just south of the JER, which are about 8,000–15,000 years old (Gile et al. 1981), but are less common in younger soils.

The presence of carbonate and argillic horizons in stacked sequences of paleosols has been interpreted as evidence for alternating periods of landscape stability and instability in the Jornada Basin and across the Desert Project area (Gile and Hawley 1966). For example, paleosols with calcic horizons shown in figure 4-7a could be interpreted using the stability-instability model to be a record of intervals of landscape instability (when erosion upslope deposited sediments downslope) which alternated with periods of landscape stability (when sedimentation ceased and calcic and argillic horizons formed).

However, there are caveats that need to be applied to this model. First, instead of landscapes oscillating between the two stability-instability end members (as illustrated in figure 4-7c), the pointer may spend a lot of time at various places between the extremes. That is, there is probably much time during which erosion rates and sedimentation rates occur slowly enough to allow some carbonate and clay accumulation. A second complication involves the shifting of a main depositional channel, which would have caused a cessation of sediment deposition. Therefore, the hiatus would not be the result of a change from landscape instability to stability but rather to moving loci of deposition.

**Conclusions**

The 1918 soil map and report of the JER (Veatch 1918) captures the essence of the physical landscape of the Jornada Basin and provides a valuable account of the native vegetation, soil-vegetation associations, and the effects of overgrazing in 1918. The second soil map (SCS 1963) provides accurate delineations but lacks quantitative soil classification because it predated soil taxonomy by about a decade. The most detailed soil map of the Jornada Basin was produced by the Desert Soil-Geomorphology Project (Gile et al. 1981), which covers a 400-mi$^2$ area around Las Cruces, including the southern portions of the JER and the CDRRC. This map and associated investigations provide large databases of soil properties, detailed geomorphic mapping, and thorough studies of Cenozoic geology, the origin of soil carbonate, the importance of atmospheric additions of $CaCO_3$ dust and $Ca^{2+}$, soil chronology, the accumulation of silicate clay by illuviation, and factors that cause soil boundaries.

Notable consequences of soil development in the Jornada Basin include the accumulation of organic matter, pedogenic carbonate, and silicate clay. Organic carbon, which has important influences on nutrient cycling and aggregate stability, ranges from 0.1% weight in sand dunes to 2.2% weight in soils in depressions that receive run-in water. Pedogenic carbonate, which has influences on water storage and is an important indicator of landscape evolution, ranges from less than 1% weight in soils of historical age to 90% weight in soils of Pliocene age (Gile et al. 1981, 1996). Silicate clay, which affects both water and nutrient storage as well as permeability and erodibility, ranges from less than 5% weight in coppice dunes to as much as 69% in playas.

Erosion by water and wind are the main processes that truncate soil horizons. Sediments from water erosion are moved laterally downslope but remain within the Jornada Basin. Sediments from wind erosion, though also moved laterally across the landscape, can be removed entirely from the Jornada Basin, especially particles of very fine sand and smaller. Erosion and sedimentation working in concert with Cenozoic tectonic extension has produced the modern terrain of the Jornada Basin.

Jornada soils of Pleistocene age have existed through multiple cycles of bioclimatic change. The presence of carbonate in buried paleosols indicates that the Jornada Basin has had a climate drier than 760 mm of annual precipitation for at least the past 500,000 years. However, dissolution pipes through carbonate horizons, combined with regional paleolake, paleoecology, and isotope studies, indicate that there have been multiple swings between relatively wet and dry climates in the Jornada Basin.