Characterizing the Distribution of Pedogenic Carbonates
Using a Geographic Information System and a Carbonate Accumulation Program
Amargosa Desert, Nevada

by
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ABSTRACT

The purpose of this study is to characterize the distribution of pedogenic carbonates in the Amargosa Desert, Nevada, as related to geomorphologic deposits and climate. The objective of this study is to characterize the distribution of pedogenic carbonates using both field methods and a model simulation managed by a Geographic Information System (GIS). A public-domain computer simulation model on carbonate development, CALSOIL, was integrated with several GIS’s to accomplish this study efficiently.

The method used in the study was to compile the maps and necessary information. These maps were then scanned into digital format and edited. The digital maps were then labeled with the parameters necessary to calculate pedogenic carbonate development. Carbonate solubility and water movement in soils are the basis for the calculations. The parameters utilized in the model include leaching index, calcic dust influx, partial pressure of carbon dioxide, permanent wilting point, available water holding capacity, initial water content, age, soil texture, and soil temperature. The pedogenic carbonate distribution for the area was then simulated using five different climatic variations. A GIS was used to manage these inputs and analyze and display the results of the
calculations.

In the area, pedogenic carbonate ranges from no development to Stage V. The age, texture, atmospheric inputs, and climate all affect the distribution of the pedogenic carbonates. The on-site and published distribution of carbonate stages were compared with the model simulations. The model showed that simulating a pluvial climate for the period before 10,000 years ago and then a jump to the present day climate at 10,000 years was the most accurate. Finally, the GIS was an effective means of managing and manipulating such a large technical and spatial data base.
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Chapter 1
INTRODUCTION

A high-level nuclear waste repository has been proposed for Yucca Mountain on the Nevada Test Site in southwestern Nevada (Figure 1). Long-term environmental stability and the impact of future climatic and framework changes need to be considered to assure integrity of any nuclear-waste site. The United States Geological Survey (USGS) is evaluating these long-term changes as part of the Paleohydrology Program, Yucca Mountain Project. This study is a part of the paleohydrologic evaluation of the region near Yucca Mountain.

1.1 Purpose

The purpose of this study is to characterize the distribution of pedogenic carbonates as related to geomorphic deposits and climate. A published model on carbonate distribution was integrated with a Geographic Information System (GIS) for this study. A model was used so that future climatic changes could be simulated to predict distributions under different conditions. The results of this study will be applied to other infiltration and paleohydrology studies in the southern Nevada region. Pedogenic carbonates are useful in assessing infiltration rates and paleoclimate conditions.
Figure 1. Index map of study area and vicinity (modified from Winograd and Thordarson, 1975).
1.2 Objective

The objective of this study is to characterize the distribution of pedogenic carbonates using both field methods and a model simulation managed by a GIS. The method could then be used to predict pedogenic carbonate distributions in other areas or other times with similar climatic regimes.

1.3 Location

The Amargosa Desert study area (Figure 1), located in southwestern Nevada, includes Ash Meadows, Crater Flat, Amargosa Valley, and part of Yucca Mountain, the site of the proposed nuclear-waste repository. The semi-arid to arid area is located within the southern Great Basin, a subprovince of the Basin and Range physiographic province. Pyramid Peak (2043 meters or 6703 feet) in the Funeral Mountains, the highest point in the immediate area, is about 1400 meters (4,700 feet) above Alkali Flat, the lowest elevation (610 meters or 2000 feet). Local relief on the desert floor is rarely more than 15 meters (50 feet). The Amargosa River flows southward through the Amargosa Desert approximately parallel to and about 40 kilometers (25 miles) east of Death Valley, California, and has an average gradient of about 2.7 meters per kilometer (14 feet per mile) (Denny and Drewes, 1965).
Chapter 2
PREVIOUS WORK

2.1 Geological Investigations

Many investigations have been conducted regarding the geology, tectonics, hydrogeology, and geochemistry of the Amargosa Desert region. The first detailed study of geology and tectonics within the area was done by Longwell (1960), Ross and Longwell (1964), Denny and Drewes (1965), Lipman and others (1966), and Orkild and others (1968). These studies were followed by the more specialized studies of Stewart (1971, 1978), Reynolds (1974), Byers and others (1976a, 1976b), Dickinson and Snyder (1979), Carr (1982), Scott and Bonk (1984), Grose and Smith (1984), and Troxel and Wright (1987).

The surficial geology and soils have likewise been the subject of careful study. The surficial geology has been compiled on a series of 1:48,000 scale maps for the special needs of the Yucca Mountain Project by Swadley (1983), Pexton (1984), Swadley and Carr (1987), and Swadley and Parrish (1988). Earlier surficial mapping in the Amargosa desert was done by Denny and Drewes (1965) at a scale of 1:62,500. The Soils Conservation Service (SCS) of the U.S. Department of Agriculture (USDA) is currently completing a soil survey for Nye County, Nevada, the county containing the field area
(USDA, 1990).


Geochemical investigations have been conducted for the carbonate and tuffaceous aquifers by Winograd and Thordarson (1975). Water quality studies have been conducted on a regional scale by White (1979), Claassen (1973, 1983), Benson and others (1983), and Benson and McKinley (1985).
2.2 Pedological Investigations

Many investigations on carbonate distribution in soils have been conducted in arid and semi-arid areas. The general accumulation of carbonate in the soils was first described by Price (1933), Bryan (1943), Bretz and Horberg (1949), and Brown (1956). Later, Gile and others (1966), Reeves (1970 and 1976), Goudie (1973), Lattman (1973), Bachman and Machette (1977), Goudie and Pye (1983), and Marion and others, (1985) studied pedogenic carbonates.

The modeling of carbonate accumulation in soils has been conducted by Marion and others (1985), Mayer (1986), and Mayer and others (1988). The stages of carbonate accumulation have been summarized by Gile and others (1966), Bachman and Machette (1977), and Machette (1986). The results of these studies are summarized in Appendix A.

Taylor (1986) has studied extensively the pedogenic carbonate distribution on the flanks of Yucca Mountain. Additionally, she used pedogenic carbonate distribution and other soil profile characteristics to determine the paleoclimate in the area.

2.3 CALSOIL

Computer models have been developed to approximate CaCO₃ accumulation in the soils of semi-arid to arid areas (Mayer,
These programs are generally written for young soils (Pleistocene and younger), but older soils can also be investigated to a limited extent. The limited knowledge of Pre-Pleistocene climates may cause problems.

CALSOIL is a computer program designed to simulate the development of calcic soil horizons in the southwestern United States (Mayer, 1986). The program was used since it is public-domain and was developed for use in the southwestern United States. Carbonate solubility and water movement in soils are the basis for CALSOIL calculations (program listing in Appendix B).

Water movement is calculated based on water-holding capacities of the deposit and climate. Likewise, carbonate movement is modeled as a function of calcite equilibria. Calcite equilibria depend on temperature and the partial pressure of carbon dioxide in the soil. The program uses Ca\(^{++}\) molality as given by Drever (1982):

\[
m^{3}\text{Ca}^{++} = \frac{(pCO_2 \cdot K_1 \cdot K_{cal} \cdot K_{CO2})}{(4 \cdot K_2)}
\]

where \(m\) is the molality of \(\text{Ca}^{++}\), \(pCO_2\) is the partial pressure of carbon dioxide in the soil environment, and \(K_1\), \(K_2\), \(K_{cal}\), and \(K_{CO2}\) are the temperature dependent dissociation constants that describe this carbonate system. Equation (1) assumes that the
activities of Ca\(^{++}\) and HCO\(_3^-\) are both unity, there are no other ions in solution, and the parent material is chemically inert.

Desert soils commonly do have other salts present, such as gypsum and halite, so that equation (1) may be inaccurate. The extent of this inaccuracy has not been measured directly since it would vary directly with relative amounts of ions present.

The temperature dependencies of the dissociation constants are given by:

\[-\log(K_1) = 6.53 - 0.0058T \quad r^2 = 0.89\]
\[-\log(K_2) = 10.59 - 0.0091T \quad r^2 = 0.97\]
\[-\log(K_{CO_2}) = 1.21 + 0.01T \quad r^2 = 0.82\]
\[-\log(K_{cal}) = 8.03 + 0.0122T \quad r^2 = 1.00\]

where T is the temperature of the system in degrees Celsius and \(r^2\) is the coefficient of determination. These equations are based on linear regression of the dissociation constants with temperature from data given in Drever (1982).

The model simulates "synthetic" distributions showing the translocation of CaCO\(_3\), as a function of soil depth, time, and climate. The parameters in the model include leaching index value, calcic dust influx, parent material CaCO\(_3\) content, partial pressure of soil carbon dioxide, texture, initial water content, and soil temperature (Mayer, 1986). These parameters are described in greater detail in Chapter 5.
2.4 GIS Description

A geographical information system (GIS) is a computerized database management and modeling tool for the capture, storage, retrieval, analysis, transformation, manipulation, and display of spatial, or locationally defined, data. Spatial data describe the real world in terms of position with respect to a known coordinate system, attributes that are related to position, and spatial interrelations with each other (Burrough, 1986). GIS’s are not simply database managers. They are modeling systems capable of assisting in analysis and interpretation of complex phenomena. A GIS is composed of four basic parts: data input, data base management, data analysis, and data display.

2.4.1 Data Input

Data input includes all methods of transforming existing geographical or spatial data into digital form. This process includes hand-digitizing of maps at different scales, automated digital scanning of maps and lists of data, hand entry of data into a digital data file, or access of pre-existing digital data including remotely sensed images (Burrough, 1986). Each point, line, or area element in a GIS is given non-graphic information. This information is referred to as an attribute. Once data have been input and
referenced to a common coordinate system, the data exist as a library of information concerning the particular study.

2.4.2 Data Base Management

Data base management involves data storage, retrieval, manipulation and editing of existing digital data. Data storage, or database management, involves the way in which input data is structured and organized. This involves how point, line, and areal data is to be handled by the computer system and interpreted by the user (Burrough, 1986).

Data manipulation and editing refers to changes made in data to remove errors, to bring data up to date, or to match the data to other data sets. This transformation of data can be carried out on either the spatial or non-spatial aspects of the data, either separately or in combination. Many of these manipulation functions, such as scale-changing, fitting data to new projections, arc/node alignment, polygon closing, logical retrieval of data, and attribute labeling are quite time-consuming and often require more time than actual data analysis (Burrough, 1986).

Spatial data of a GIS can be represented as triangular meshes, vectors, and rasters (including quadtrees). Triangular meshes (TIN) are models that use a sheet of continuous, connected angular facets based on triangulation of
irregularly spaced points (Burrough, 1986). TIN's are suitable when dealing with precise observations of a continuous variable.

Vector data can be stored in three different forms. First, it can be stored as point data in which the spatial relationship of the information has no dimension. These points are often referred to as nodes. Second, data can be stored as a series of connected points, or lines, in which the spatial relationship is one-dimensional. These lines are often referred to as arcs. The data can be stored as area entities, or polygons, in which the spatial relationship of the stored information is two-dimensional (Burrough, 1986). One example of a vector based GIS is the Environmental Systems Research Institute (ESRI) ARCINFO system.

Vector systems have a number of advantages and disadvantages. Vectors are an approximation, but they are considered to be the most precise data capture method. Although vector systems have no constraints on overlaying files of different resolution, the many formats make data exchange difficult. Finally, vector data bases tend to be large and overlays and other boolean operations are complex and time consuming.

Raster data structures consist of an array of grid cells (or pixels) which are referenced by a row and a column number.
Each pixel then contains an attribute number, or set of numbers, corresponding to the characteristic being mapped (Burrough, 1986).

Raster systems also have advantages and disadvantages. Rasters are an approximation that is usually much coarser than vectors. As the resolution increases, the size of data bases increase geometrically. Despite these problems, the fewer formats make data exchange easier. Overlays and other boolean operations are simple. Finally, rasters force the same level of resolution for any analysis.

Quadtrees are data structures in a raster database that seek to minimize data storage. Quadtrees are also an approximation, but can approach accuracy tolerances of vectors. As the resolution increases, the size of data bases only increases linearly. Overlays and other boolean operations are more complex than raster, but not as complex as vector. Quadtrees have no constrains on overlaying files of different resolution. Finally, quadtrees have no standard formats, but they convert to raster easily. Tydac Technologies GIS Spatial Analysis System (SPANS) works with quadtree structures.
2.4.3 Data Analysis

Data analysis is that function of GIS which has made it acceptable to geographers, scientists, land managers and engineers. As a result of being able to carry out large, often tedious, mathematical operations, the GIS becomes an efficient and practical tool for conducting integrated resource surveys. The main problem with integrated surveys pre-GIS was that for many purposes they were too general. Retrieval of evaluated information directly from a hand-drafted map was impossible if the map author did not create a detailed explanation. Also, single-factor maps were evaluated by overlaying transparent copies and looking for the places where the boundaries on the maps coincide. This process often involved the discretion of the evaluator conducting the survey and lacked accuracy. However, with a GIS, computer-aided map overlaying using Boolean logic and other operations allows for the universal application of all evaluation criteria. As a result, the often biased process becomes standardized and quality controlled.

2.4.4 Data Output/Display

Data output or display involves that way in which analyses are represented. This representation can be in the form of maps, tables, and figures (graphs and charts). This
aspect of GIS technology is, perhaps, the most significant because it allows the user to demonstrate analyses in a clear manner.
Chapter 3

GENERAL BACKGROUND

3.1 Geography

The Amargosa Desert is a large valley in the Basin and Range physiographic province. The valley is bounded by mountain blocks on all sides. On the west, the Funeral Mountains form a long continuous ridge. The northern part of the area is blocked by a number of hills and mountains including Bare Mountain, Bull Frog Hills, and Yucca Mountain. The Specter Range and the Spring range form boundaries on the east. The southern part of the desert is partially blocked by the Resting Spring Range. The Amargosa River flows south through the desert on the west side of the valley (Figure 1).

3.2 Geology

3.2.1 Clastic Sources

The Funeral Mountains, Bare Mountain, Yucca Mountain, Bull Frog Hills, and the Resting Spring Range are the mountain ranges that provide most of the source material for the three to five thousand feet of deposits in the Amargosa Desert (Denny and Drewes, 1966), (Figure 2). In general, the Funeral Mountains and part of Bare Mountain are composed of about 5,000 feet of Silurian to Mississippian limestone and dolomite. The Funeral mountains, which form the western
boundary of the valley, are an eastward-dipping fault block bounded on the south by the Furnace Creek fault zone and on the east and west by normal faults characteristic of the Basin and Range province (Denny and Drewes, 1966). The Funeral mountains and Bare Mountain provide carbonate and metamorphic clastics to the basin.

Volcanic rocks, including those of Yucca Mountain, the Bull Frog Hills, and northern Bare Mountain, form ridges in the northern part of the study area. Pliocene and Quaternary extrusive volcanic rocks also form cones and lava flows in Crater Flat. These features are composed mostly of ashes and tuffs of rhyolitic composition and are a major source of volcanoclastics in the basin (Swadley and Carr, 1987).

The Resting Spring Range, on the east side of the Amargosa Desert, is composed of about 5,000 feet of gently dipping Cambrian rocks. These rocks are dominantly quartzite, limestone, and dolomite, and are broken by numerous steep faults of small displacement (Denny and Drewes, 1986). This range provides carbonate clastics to the southeast part of the study area.
Figure 2. Field area from Yucca Mountain looking south across the Amargosa Desert toward the Funeral Mountains, with the Panamint Range in the distance. Big Dune and some lava flows can be seen on the desert floor.
3.2.2 Valley Deposits

3.2.2.1 Pliocene Stratigraphy

Varied fluvial, paludal, pond, and playa sedimentary rocks, QT1l and QT1d, (combined as QT1 on Figure 3) were deposited, during the Pliocene between 4 and 1.5 Ma (Pexton, 1990). An age of 2.95 Ma is reported by Swadley (1990) for these marsh deposits. Precipitation during this time was probably five times or more greater than the present and temperatures were about the same as the present (Hoover, 1985). The existence of a large lake in the Amargosa Desert is still being contested (Pexton, 1990; Hoover, 1985). These deposits are exposed in the southeastern part of the area at Fairbank Buttes and nearby localities (Figure 4). Numerous clay pits and prospects have been dug where the marsh deposits are observed near or at the surface.

3.2.2.2 Pliocene and Pleistocene Stratigraphy

A widespread erosional disconformity separates the Pliocene units from Pliocene-Pleistocene fluvial units (QTg and QTa) (Pexton, 1990). A drier climate than that of the previous occurred during the late Pliocene and Quaternary time (Hoover, 1985). As a result, weathered material on hillslopes was released as debris flows and avalanches, colluvium, and alluvium. These Pliocene and Quaternary fans consist of thin-
Figure 3. Hypothetical cross section and correlation of surficial units (modified from Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; and Denny and Drewes, 1965).
Figure 4. Marsh deposits (QT1) at Fairbank Butte.
bedded gravel deposits that filled the shallow valleys (QTg) and fluvial gravels (QTa) (Figures 3 and 5) (Hoover, 1985). Unit QTg was deposited under moderate to high-energy conditions by rivers that cut channels into soft deposits of unit QTld (Pexton, 1990). Unit QTa was deposited from about 1.3 to 0.9 Ma (Hoover, 1985). The minimum age of unit QTa and QTg is estimated to be about 740 Ka (Hoover, 1985). The gravels of unit QTa have a steeper gradient and are topographically higher than younger deposits in the study area (Pexton, 1990). Both unit QTa and QTg consist chiefly of pebbles, cobbles, and boulders that are poorly sorted and poorly indurated. They also contain subordinate sand and finer grained material. A very dense desert pavement has formed on QTa and QTg (Pexton, 1990).

3.2.2.3 Quaternary Stratigraphy

Quaternary deposits comprise the uppermost surficial deposits in the study area. Deposits younger than unit QTa are noted by a number (Holocene unit Q1 or Pleistocene unit Q2) indicating the major time-stratigraphic unit and a letter indicating the lithology of the subunit. The letters a, b, and c indicate relative age of a fluvial unit with a being the youngest and c the oldest. Regional unconformities separate unit Q2 from unit QTa and unit Q1 from unit Q2. Where
Figure 5. Older fluvial gravel (QTa) well cemented with pedogenic carbonate.
subunits occur together on a scale too small to be mapped separately, they are combined, such as Q1ab (Pexton, 1990).

The older Quaternary surficial deposits consist of alluvial deposits and debris flows observed in all the valleys and washes (Q2c, Q2b, and Q2a) (Figures 3 and 6), eolian dunes and sand sheets deposited as ramp-like accumulations (Q2e) (Figures 3 and 7), and alluvial sand sheets (Q2s) (Figures 3 and 8). Pleistocene alluvial fan deposits are smooth surfaced deposits that overlie unit QTa. Units Q2c, Q2b, Q2a, and Q2s consist of gravel, sand, and silt. Desert pavements on these deposits (Q2) are the boundary of a regional unconformity separating the older deposits from the youngest deposits (Pexton, 1990). Hoover (1985) estimates the minimum age of Q2 units to be about 200 Ka (Figure 3).

The youngest surficial units were deposited in the washes, on lower slopes below the washes, and on the valley floor of the Amargosa Desert (Figures 2 and 3). These deposits consist of predominantly alluvial deposits (Q1c and Q1a), debris flows (Q1b), alluvial sand sheets (Q1s), and dunes and sand sheets (Q1e). Quaternary fluvial sheet sand deposits, unit Q1s, overlies older Pliocene and Quaternary units in much of the plains area of the Amargosa Desert (Figure 9). Holocene fluvial deposits, unit Q1ab, occur in present drainages. Unit Q1ab is a combination of unit Q1a,
Figure 6. Deposit of middle aged alluvium (Q2bc).
Figure 7. Deposit of older eolian sand (Q2e).
Figure 8. Deposit of older cemented fluvial sheet sand (Q2s).
Figure 9. Fluvial sheet sand and gravel (Qls) over marsh deposits.
modern channel deposits, and unit Q1b, which forms low terraces along active drainages (Figure 10). Holocene fluvial deposits, unit Qlc, occur as remnants of terraces along many washes. All of these deposits have intermixed gravel (Pexton, 1990).

Holocene eolian dunes and sheets, unit Qle, occur as isolated deposits associated with stabilizing vegetation and as dunes and sand ramps (Figure 11). The dunes result from prevailing southerly winds in the Amargosa Desert. The eolian deposits consist of moderately well sorted sand-size particles (Pexton, 1990).

Holocene Q1 sediments were deposited during the last 8,300 years (Hoover, 1985). These youngest deposits have been modified only slightly since deposition. Therefore, soils are weakly developed, desert pavements are not present, and only the oldest surfaces have been smoothed by creep and sheetwash (Hoover, 1985).

Carbonate and opaline (SiO₂) eolian dust have been added to all the deposits over time (Taylor, 1986). Thus, repeated cycles of deposition, nondeposition, and soil development characterize the Tertiary and Quaternary history of the area.
Figure 10. Young fluvial gravel, sand, and silt (Qlab) in channel.
Figure 11. Young eolian deposits (Qle) anchored by mesquite.
3.2.2.4 Spring Deposits

The Ash Meadows area has been the site of spring discharges since at least the middle Pliocene (Pexton, 1990). Spring deposits that consist of tufas and calcite veins and vents occur in surficial materials that range in age from pre-QTa to the present (Pexton, 1990). These spring deposits occur in the Amargosa Desert and near outcrops of Paleozoic carbonate rocks (Hoover, 1985; Dudley and Larson, 1974). The tufas occur as single outcrops or a few scattered outcrops that range from a few meters to 50 meters in their maximum lateral dimension. At Point of Rock Springs in the Ash Meadows area, tufas form a spring mound that has an area of at least 10,000 m² (100,000 ft²) (Pexton, 1990). This is the only spring mound mapped in the area (Figure 12). Tufas are not currently forming in the Amargosa Desert, because the area is being eroded and spring water drains rapidly away in channels or sinks into the ground (Pexton, 1990). Springs probably discharged more water and were more widespread during pluvial periods (Pexton, 1990).

3.3 Climate

3.3.1 Paleoclimates

Observations gathered from packrat midden investigations, areal extent of Quaternary lakes, landform development,
Figure 12. Spring mound (Qsd) in Ash Meadows.
depositional processes, and weathering processes indicate that the climate during the past 1.1 million years or more has been semiarid to arid and warm, with maximum annual precipitation from two to four times the present (Hoover, 1985). Spaulding's (1983) work on packrat middens in the southern Great Basin has provided a climatic history of the past 45 thousand years. His work is supported by pollen data for the southwestern US (Spaulding and others, 1983). Mifflin and Wheat (1979) have provided a basis for determining precipitation and temperature from the size of late Wisconsin lakes and their tributary basins.

Based on these studies, climatic conditions during the glacial maximum (18 Ka), compared to the present climate, probably had a mean annual temperature 6-7°C lower, drier summers, winter precipitation up to 70 percent greater, and mean annual precipitation was not more than 40 percent greater (Table 1) (Spaulding, 1983; Spaulding and others, 1983).

Mifflin and Wheat (1976) propose that the mean annual temperature was 5°C lower and the mean annual precipitation was 69 percent greater. Therefore, precipitation during the deposition of surficial deposits in the area was probably much less than the maximum of 50 to 75 cm (20 to 30 in) that will allow development of a calcic horizon (Hoover, 1985).
Table 1

Estimates of late Quaternary climates in the Nevada Test Site area (after Spaulding, 1983).
The present climate ranges are (USDA, 1990):
- Precipitation of 10–20 cm (4–8 in.)
- Temperature of 11–19°C (53–66°F).

<table>
<thead>
<tr>
<th>Period (10^3 years ago)</th>
<th>Differences from present</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>45–35</td>
<td>-1 to -3</td>
</tr>
<tr>
<td>35–23</td>
<td>-3 to -6</td>
</tr>
<tr>
<td>23–12</td>
<td>-3 to -7</td>
</tr>
<tr>
<td>18</td>
<td>-6 to -7</td>
</tr>
<tr>
<td>12–8</td>
<td>0</td>
</tr>
<tr>
<td>8 to present</td>
<td>0 to +2</td>
</tr>
</tbody>
</table>

3.3.2 Modern Climate
3.3.2.1 Precipitation

The present climate in southern Nevada is arid to semiarid. The areal distribution of precipitation is related to orographic effects and a large range in elevations. Precipitation in the southern Great Basin is affected by the rainshadow of the Transverse ranges and the Sierra Nevada (Hoover, 1985).

In addition to orographic influences, two basic storm types occur in the area. The storm types result in precipitation derived from winter cyclonic activity and intense summer convection (Houghton and others, 1975). Precipitation is greater during the November–March period and less during the April–October period. The annual cycle with
a winter maximum, a secondary maximum in summer, and minima during the transition seasons, is well established (Quiring, 1985). The maximum monthly precipitation, which occurs in winter, ranges from 13 to 23 percent (averaging 16%) of the average annual precipitation (Quiring, 1985).

The seasonality of precipitation influences some of the soil properties, including carbonate distribution. Soil moisture temperatures during the winter months result in CaCO₃ being more soluble. Strong winds with accompanying violent dust storms are common when precipitation is slight. The individual stations show variations from the average annual cycle. Variations in the winter precipitation maximum is common in the area. Wide variation in annual precipitation and concentration of rainfall in a few storms is characteristic (Quiring, 1985). Cumulative averages, however, demonstrate that the mean annual precipitation after 10 years differed by less than 10 percent from the 20- to 30- year means (Hoover, 1985).

The precipitation/elevation ratio is approximately 15 centimeters per kilometer of elevation (1.8 in./1000 ft.) (Quiring, 1985). This ratio is based on vegetation change and precipitation data from stations in southern and south-central Nevada that are at similar elevations and latitudes to the study area. The ratio indicates that the mean annual
precipitation ranges from 9 centimeters (4 in.) in the valley to approximately 30 centimeters (12 in.) on Pyramid Peak (Quiring, 1983). These ranges coincide with the USDA Soil Survey's (1990) estimate of mean annual precipitation (Figure 13).

3.3.2.2 Temperature

Temperature is an important factor for pedogenic carbonate development. If precipitation were constant, CaCO₃ could be translocated by simply decreasing the temperature of available moisture and, thus, increasing the solubility of CaCO₃ (Taylor, 1986; Drever, 1982).

Mean annual temperature is a function of latitude, elevation, cloud cover, surface reflectivity, and topographic aspect. Long term temperature data are lacking for the Amargosa Desert. Hoover (1985), however, estimates that there is a 0.74°C/100 m (4.08°F/1000 ft) gradient in the Amargosa Desert. Hence, mean annual temperature ranges from 19.1°C (66.3°F) at 610 m (2000 ft) to 8.4°C (47.1°F) at 2043 m (6703 ft) elevation. These numbers correspond with estimates of mean annual temperature (Figure 14) published in the USDA Soil Survey (1990). On the valley floor, the average maximum monthly temperature for July is more than 42.5°C (100°F); minimum winter temperatures are below freezing in December and January. A high of 81°C (162°F) was observed on a thermometer.
Figure 13. Map showing the distribution of precipitation indicated by the USDA Soil Survey (1990) in the study area.
Figure 14. Map showing the distribution of temperatures indicated by the USDA Soil Survey (1990) in the study area.
placed on a desert pavement with the bulb covered by a layer of fine sand (Denny and Drewes, 1965).

3.4 Vegetation

The field area is located on the boundary of the Mojave Desert to the south and the Great Basin Desert to the north (Cronquist and others, 1972). Vegetation covers only 3 to 36 percent of the surface at elevations of 1000 to 1500 meters (3281 ft to 4922 ft) (Romney and others, 1973). The vegetation types include xerophytes in the upland and well drained areas and phreatophytes in the areas of surface or ground-water availability. The roots of these plants affect the pedogenic carbonate by changing the partial pressure of carbon dioxide, which affects the solubility of calcium carbonate. The partial pressure increases to the maximum rooting depth of the plants and then decreases with depth.

3.5 Soils
3.5.1 Texture

The Quaternary and Tertiary alluvium and colluvium are gravelly units that are well drained and do not, at present, have shallow water tables unless located in a regional ground-water discharge area. The relative gravel content, as described by the Soil Survey (USDA, 1990), is shown in Figure
15. This gravel content is a relative number with those soils described as "gravelly" given a high gravel content and those without such a descriptor given a low gravel content (USDA, 1990). Bretz and Horberg (1966) hypothesized that most of these gravelly soils were not affected significantly by capillary rise from a shallow water table. The soils occur on dissected land surfaces, therefore, the shallow water table would decline with each erosion cycle. The water table at Ash Meadows and along parts of the Amargosa River is at or near the surface. At these locations, ground-water could be contributing a significant source of CaCO₃. As a result, these soils were not simulated by a numerical model, but were located on the simulations as lakes or swamps.

3.5.2 Calcium Carbonate Sources

There are several sources for the CaCO₃ in soils. One source is from weathering and/or translocation of a constituent in place from the alluvial, colluvial, lacustrine, or discharge deposits. A second source is atmospheric addition, either as ions or ion complexes in solution (Ca⁺⁺, HCO₃⁻) or as solid dust particles of CaCO₃ or other carbonate salts (Gile and others, 1979).

Some parent sediments are noncalcareous, whereas others are derived primarily from limestone. Analyses of dust fall,
Figure 15. Map showing the distribution of gravel indicated by the USDA Soil Survey (1990) in the study area.
however, indicate that calcareous dust has been deposited on the sediments. The dust is deposited by one storm, wetted, and is then largely blown on by the next windstorm (Gile and others, 1966). On each wetting cycle, a small part of the carbonate in the dust is dissolved, moved into the soil, and precipitated as the water evaporates. Thus, regardless of the composition of the parent sediment, all soils are considered to have an source of carbonates.

The development of calcic horizons is dependent on dust supply and the amount of CaCO₃ in precipitation in soils where CaCO₃ is a minor constituent of the parent materials of alluvium (Gile and others, 1966). A calcareous dust source for the carbonate (at a rate greater than the rate of dissolution) provides an explanation for the occurrence of equally prominent carbonate horizons in calcareous and noncalcareous sediments of the same age.

3.5.3 Effect of Climate

A generalized model for CaCO₃ accumulation rates is that the rates vary with climate (Bachman and Machette, 1977). During interglacial times, increased aridity, decreased vegetation cover, and exposed playa surfaces increase accumulation rates. Conversely, increased vegetation and more precipitation associated with glacial climates result in
relatively slow rates of \( \text{CaCO}_3 \) accumulation.

Sufficient precipitation, however, is necessary to transport the atmospheric materials into the soil (Machette, 1986). If the supply of carbonate in dust or parent material exceeds the amount that can be leached from the soil by precipitation, then the rate of development of the calcic horizon is dependent on the rate of precipitation (Machette, 1986). Therefore, pedogenic carbonate may be precipitation-limited. As a result, soils may be accumulating material more slowly during dryer times, such as the Holocene, than in the late Pleistocene because of the lack of water to move the material into the soil.

During glacial climates there is more precipitation to move the material, while during interglacial times there appears to be insufficient precipitation to move all the available dust into the soil. Because of these conflicting factors for accumulation, Taylor (1986) suggests that the climatic change and the contribution of all factors was not enough to significantly change rates of \( \text{CaCO}_3 \) accumulation. This study will further examine the effect that precipitation changes have on carbonate distribution.
3.5.4 Carbonate Stages

Carbonate accumulation in soils can be characterized by stages of development (Gile and others, 1966; Bachman and Machette, 1977; Machette, 1986) (Table 2). These morphologies can be used to indicate the maximum amount of CaCO₃ content. Some authors indicate four or five stages, and others indicate five or six. The fifth and sixth stages are a more developed fourth stage, with only a subjective separation. During field mapping five stages were used to characterize the pedogenic carbonate.

3.6 Hydrogeology

The Amargosa Desert is conceptualized as having one intermontane, shallow ground-water basin that is vertically connected to a deep, regional ground-water flow system (Downey and others, 1990). The intermontane, shallow ground-water basin includes unconsolidated sediments interbedded with layered volcanic rocks in the Amargosa Desert (Downey and others, 1990). This shallow ground-water basin may range from unconfined to semi-confined and is quite variable in lithology. The units include fine-grained playa and lake beds with salts, boulder-cobble-pebble debris flow-fan deposits, and consolidated volcanic tuffs. Accordingly, they can exhibit matrix flow in the unconsolidated materials, and fault
Table 2

Stages of calcium carbonate morphology observed in pedogenic carbonates developed under arid and semiarid climates of the American Southwest (Modified from Gile and others (1966), Bachman and Machette (1977), and Machette (1982))

<table>
<thead>
<tr>
<th>Stage</th>
<th>Gravel Content</th>
<th>Diagnostic morphologic characteristics</th>
<th>CaCO$_3$ distribution</th>
<th>CaCO$_3$ content</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>High</td>
<td>Thin, discontinuous coatings on pebbles, usually on undersides.</td>
<td>Coatings are sparse to common.</td>
<td>Tr-2%</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>A few filaments in soil or faint coatings on ped faces.</td>
<td>Filaments are sparse to common.</td>
<td>Tr-4%</td>
</tr>
<tr>
<td>II</td>
<td>High</td>
<td>Continuous, thin to thick coatings on tops and undersides of pebbles.</td>
<td>Coatings are common, and matrix is loose.</td>
<td>2%-10%</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Small soft nodules.</td>
<td>Nodules are common, and matrix is loose.</td>
<td>4%-20%</td>
</tr>
<tr>
<td>III</td>
<td>High</td>
<td>Massive accumulations between clasts.</td>
<td>Essentially continuous dispersion in matrix.</td>
<td>10%-25%</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Many coalesced nodules, matrix is cemented.</td>
<td>Essentially continuous dispersion in matrix.</td>
<td>20%-60%</td>
</tr>
<tr>
<td>IV</td>
<td>High</td>
<td>Thin (&lt; 1 cm) laminae in upper part of horizon.</td>
<td>Cemented platy to weak tabular structure and indurated laminae. Horizon is 0.5 to 1 meter thick.</td>
<td>&gt;25%</td>
</tr>
</tbody>
</table>

(continued)
Table 2 (continued)

<table>
<thead>
<tr>
<th>Gravel Stage</th>
<th>Content Characteristics</th>
<th>CaCO$_3$ Distribution Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Thin (&lt; 1 cm) laminae in upper part of horizon.</td>
<td>Cemented platy &gt;60% to weak tabular structure and indurated laminae. Horizon is 0.5 to 1 meter thick.</td>
</tr>
<tr>
<td>V High</td>
<td>Thick (&gt;1 cm) laminae and pisolites. Fractures are coated with laminated CaCO$_3$.</td>
<td>Indurated, dense, &gt;50% strong platy to tabular structure. Horizon is 1 to 2 meters thick.</td>
</tr>
<tr>
<td>Low</td>
<td>Thick (&gt;1 cm) laminae and pisolites. Fractures are coated with laminated CaCO$_3$.</td>
<td>Indurated, dense, &gt;75% strong platy to tabular structure. Horizon is 1 to 2 meters thick.</td>
</tr>
</tbody>
</table>
and fracture-controlled flow in more indurated materials (Downey and others, 1990). The dominant flow direction is from the north, northeast, and east to the south.

The regional, deep ground-water flow system may include all of the aquifers in the Paleozoic sedimentary rocks and the Tertiary volcanic rocks. This deeper system contains multiple, confined aquifers that are either carbonates or tuffs (Waddel, 1982; Downey and others, 1990). The flow system may be characterized as fault- and fracture-controlled. The dominant flow direction is from the north, northeast, and east to the south and southwest, and may show transbasinal flow (Sinton, 1987, Downey and others, 1990).

The study area has several major local and regional ground-water discharge areas, such as the Ash Meadows springs, Carson Slough, Alkali Flat and the Amargosa River near Amargosa Farms (Winograd and Thordarson, 1975). The spring waters are high in dissolved solids. These dissolved solids are composed predominantly of carbonate salts (Winograd and Thordarson, 1975). These salts may be a dust source that contributes to the accumulation of pedogenic carbonate.
Chapter 4

FIELD OBSERVATIONS OF PEDOGENIC CARBONATES

4.1 Development of Conceptual Model

A literature search and field reconnaissance was conducted. Hypotheses were formulated on the distribution and types of carbonate deposits utilizing the information gathered:

1) Carbonates form in the surficial units and not, to any significant extent, on the relatively impermeable competent bedrock. This bedrock, in general, lacks a soil profile.

2) The large influx of atmospheric CaCO$_3$ into the area overcomes any change in CaCO$_3$ found in the parent material.

3) Higher stages of carbonate development occur in older deposits.

4) Higher carbonate stages occur in finer grained deposits.

Using these hypotheses, a preliminary map of pedogenic carbonate distribution was constructed using surficial geologic maps, geologic maps, soil surveys, and geomorphic relationships. A number of simplifying assumptions were made:

1) climate change occurred 10,000 years ago from a wetter, cooler climate to the present climate;
2) climate was essentially the same for the period between 10 Ka and 2.95 Ma;
3) carbonate parent material did not affect pedogenic accumulation;
4) the influx of carbonate (dust and precipitation) was constant over the area;
5) and ages of deposits could be obtained from the surficial geology maps (Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; Denny and Drewes, 1965; and Pexton, 1990).

4.2 On-Site Mapping

On-site mapping of the preliminary carbonate distribution was conducted. Gullies, road cuts, river channels, prospect pits, gravel pits, clay pits, and other types of soil exposure were investigated to determine the maximum carbonate stage. The thickness of the pedogenic carbonate was not determined because the stage varies, both laterally and with depth, and due to the limited exposures. The stage was determined using the characteristics described in Table 2. In summary, the deposits with greater than 25% gravel content were examined to observe the carbonate on clasts and the presence and thickness of laminations (Gile and others, 1966). Deposits with less than 25% gravel content were examined to determine the extent
of matrix carbonate. As a result, determining the stage in fine-grained deposits is a subjective process (Gile and others, 1966) (Figures 16, 17, 18, 19, and 20).

More than one hundred sites located throughout the area were examined, with at least two sites in each of the different types of surficial deposits. The distribution of the carbonate stages, as determined by on-site examination, is shown in Figure 21.

4.3 On-Site Mapping Results

In the Amargosa Desert area, soils accumulate secondary CaCO₃ in a distinctive trend with increasing age of the surficial deposit. Observed calcic horizons range from Stage I films and coatings on the bottoms of clasts in lower Holocene and upper Pleistocene deposits, to thick, plugged horizons that completely fill the voids in lower Pleistocene deposits.

Soils formed in gravelly alluvium less than 3 thousand years old (Qlab) contain little or no secondary CaCO₃. Soils formed in gravelly alluvium 8.3 Ka (Qlc) commonly have Stage I carbonate. Other soils formed in the sandier gravelly alluvium 8.3 Ka (Qls) commonly have Stage I and Stage II carbonate scattered throughout the area. As a result, this area was mapped with the higher stage. Soils formed in 160 Ka
Figure 16. Stage I pedogenic carbonate in upper half of photograph (thin discontinuous coatings on underside of pebbles).
Figure 17. Stage II carbonate (continuous, thin to thick coatings on tops and undersides of pebbles).
Figure 18. Stage III carbonate (massive carbonate accumulation between clasts).
Figure 19. Stage IV carbonate (thin laminae in upper part of horizon).
Figure 20. Stage V carbonate (thick laminae and pisolites, fractures coated with carbonate).
Figure 21. On-site map showing the distribution of different carbonate stages and sample sites.
gravelly alluvium (Q2b) contain a stage II-III carbonate horizon. Soils formed in gravelly alluvium about 160-740 Ka (Q2bc, Q2s) commonly have stage II-IV carbonate. Soils formed in the older eolian deposits about 160-740 Ka (Q2e) have stage III-V carbonate. The oldest alluvium, which is greater than 1 Ma (QTa), contains carbonate of stage III-V.

The finer-grained deposits accumulate carbonate faster than the coarse-grained deposits. Soils formed in the older eolian deposits (Q2e) have more advanced carbonate stages than the other deposits of similar age. Soils formed in the sandier gravelly alluvium 8.3 Ka (Q1s) commonly have Stage I and Stage II carbonate scattered throughout the area, whereas the more gravelly alluvium 8.3 Ka (Q1ab) has only Stage I development.

Carbonate accumulations are believed to be from pedogenic processes. It would be coincidental if capillary rise were responsible for the pattern of increasing carbonate accumulation in the soils on progressively higher and older surfaces along the valley (Figure 3). The carbonate morphological sequences indicate that the authigenic carbonate is illuvial, formed by vertical movement and accumulation.

The rate of carbonate accumulation may be affected by the amount of carbonate clastics. These clastics, however, do not appear to affect development of pedogenic carbonate to a great
extent. Instead, the ubiquity of atmospheric carbonate suggests that the authigenic carbonate was derived dominantly from the atmospheric contributions.

The marsh deposits (QT11 and QT1d) are fine-grained, therefore, further studies are necessary to determine the stage of the carbonate developed from pedogenic processes. The deposits also have a large amount of primary carbonate. Thus, these deposits need further study to determine primary versus secondary carbonate.

Discharge deposits are affected by an influx of carbonate from the ground-water. Furthermore, these deposits are much wetter than the surrounding areas; the deposits are also fine-grained and as a result were not analyzed. These deposits also need further study to determine primary versus secondary carbonate. On Figure 16, most of these deposits are indicated by swampy areas.
Chapter 5
APPLICATION OF THE GIS AND CALSOIL MODELS

5.1 CALSOIL Program

The first step in simulating the natural carbonate profile is to define relations between spatial variables. The relation used in this study is the model CALSOIL by Mayer (1986) (Appendix B). This model has been adapted for GIS use. Furthermore, the model has been expanded to find the maximum stage of carbonate in a soil profile using the relation between carbonate concentration and stage. The percent of carbonate for each stage (Table 2) was compared to the maximum percent of carbonate calculated by the model for each soil profile. The model calculates percent of carbonate by taking the grams of carbonate per volume and dividing this number by the soil density (Appendix B). A density of 2.16 g/cm³ (135 lb./ft³) was used for the development of Stage I to III carbonate, and a density of 2.68 g/cm³ (167 lb./ft³) was used for stages greater than or equal to Stage IV (Reeves, 1976). The change in density is due to the higher concentration of carbonate that cements and fills voids at higher carbonate stages.

The calculations in the CALSOIL model simulated a yearly change in variables. Soil thickness, moisture characteristics, precipitation, and temperature were input
from the soils map (USDA, 1990). The ages of deposits were input from the surficial geology map (Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; Denny and Drewes, 1965; and Pexton, 1990). The initial carbonate content and the carbonate influxes were assumed to be uniform over the entire area due to the lack of data. The partial pressure of CO₂ was calculated based on maximum rooting depth. Likewise, the leaching index was calculated based on the precipitation distribution (USDA, 1990). All the variables are held constant for each polygon, except for the leaching index. The leaching index was varied with climate change. The parameters used for each polygon are discussed in the following section.

5.2 CALSOIL Parameters

5.2.1 Thickness

Each polygon is given a soil thickness. This thickness is then subdivided into 20 sections that allow water movement. Thicknesses of each polygon analyzed were taken from the Soil Survey (USDA, 1990). The Soil Survey indicates that profiles have a maximum thickness of 152.4 cm (5 ft.) for each polygon. Therefore, this value was used in this study as the maximum thickness when a smaller thickness was not given.
5.2.2 Moisture Characteristics

Unweathered alluvium (or colluvium) is the parent material for each polygon. The average grain size distribution for each polygon was taken from the soil survey (USDA, 1990). Since the soil survey contains collective soil types in each mapping unit, the types composing each unit were averaged. Each of these units represent a polygon. Available water holding capacities, field capacities, and permanent wilting points were calculated by Salter and William's (1965) table based on the grain-size distribution. Initial moisture content was assumed to be between permanent wilting point and field capacity, and close to the available water holding capacity.

5.2.3 Carbonate Influx

A CaCO₃ dust flux of 10⁻⁴.³ g/cm²/year was reported as representative for the area by Mayer and others (1988). The amount of Ca⁺⁺ in precipitation produces approximately three times the amount of carbonate in dust (Birkeland, 1984). This gives a total annual carbonate influx of about 10⁻³.⁷ g/cm². These values are based on dust trap data and precipitation chemistries. Parent material carbonate was assumed to be insignificant relative to the large influx of carbonate.
5.2.4 Partial Pressure CO₂

The partial pressure of carbon dioxide was assigned as $10^{-3.5}$ at the surface, increasing to $10^{-2.5}$ at the maximum rooting depth, and decreasing with depth to $10^{-3.4}$ at the base of the soil (Birkeland, 1984). The maximum rooting depth in the area is approximately 50 cm (20 in.) (Taylor, 1986). These values were used for each polygon in the study area.

5.2.5 Temperature

The soil temperature varies based on mean annual air temperature. The data are based on actual soil temperature values from Rock Valley, just east of the field area. Romney and others (1973) show soil temperature decreasing about 0.7°C from the mean annual temperature for each 15 cm (6 in.) in depth.

5.2.6 Leaching Index

The calculation of soil water movement (Arkley, 1963, 1967) is based on the concept that net excess of precipitation above potential evapotranspiration, for those months in which precipitation exceeds potential evapotranspiration, represents the total moisture available to wet the soil. This value is the leaching index. It may be calculated in two ways:

1) the excess of precipitation above potential
evapotranspiration during the months in which precipitation exceeds potential evapotranspiration is summed; or
2) the average precipitation for the wettest month is used if the maximum precipitation for a given month is greater than the summed difference of precipitation greater than potential evapotranspiration.

For arid and semiarid regions the second method gives the larger leaching index (Taylor, 1986; Arkley, 1963; and Arkley, 1967). Both the present and past climates have leaching indices less than the average greatest monthly precipitation, so the second method is appropriate in these simulations.

5.2.7 Simulation Variables

The length of simulation assigned for each map unit was based on the age of the deposit determined by surficial maps (Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; Denny and Drewes, 1965; and Pexton, 1990). The present precipitation was used for the climate during the last 10,000 years, while paleoclimate data were obtained from estimates suggested by Mifflin and Wheat (1979) and Spaulding (1983). The climate during the last 10,000 years will be referred to as the Holocene climate, while the climate during the period before 10,000 years before present will be referred to as
pluvial climate. A factor of 1.69 times the present precipitation was used to determine the precipitation value for the pluvial climate. The model does not accept thickness, temperature, moisture characteristic, carbonate influx, or \( \text{pCO}_2 \) changes with time.

5.3 GIS for Data Management

5.3.1 Data Input

The parameters necessary to compute pedogenic carbonate formation were input to a geographic information system (GIS). Surficial geology maps (Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; Denny and Drewes, 1965; and Pexton, 1990) and the soil survey for Nye County, Nevada (USDA, 1990) were converted into digital form. The process of transforming the paper maps into a digital data base, defined as conversion, was completed using a Tektronix scanner.

5.3.2 Data Manipulation

Data manipulation is the second central function of a GIS. These manipulation operations includes data editing functions and attributing. The editing functions are used to alter and delete data, and to maintain and update the data base. This was done with the GIS package ARCINFO (ESRI,
1987). ARCINFO was used to remove scanning errors and clean maps to match the original version.

The digital maps were then transferred into another GIS, SPANS (Tydac Tech., Inc., 1988). SPANS is designed to use other familiar personal computer programs for attribute input. SPANS was used to attribute the maps with data from the given maps and information from the soil survey. Each of the polygons on the surficial maps were labeled with deposit age and lithology. The soil maps were labeled with unit number, field capacity (FC), initial water content (IWC), permanent wilting point (PWP), available water-holding capacity (AWC), mean annual precipitation, mean annual temperature, thickness, particulate carbonate flux, dissolved carbonate flux, and gravel content. Topographic information exists as a digital elevation model, however, because of technical problems could not be used. This is hypothesized to have minimal effects for this study area.

5.3.3 Data Analysis

A third class of functions in GIS systems is analysis functions. SPANS may be combined with other computer programs, such as CALSOIL, for analysis. Analysis functions are much more adept and powerful with SPANS than ARCINFO. SPANS is capable of modeling real-world phenomena that vary
both in time and in space.

5.3.4 Data Visualization

The final function of a GIS is the presentation of the spatial data in the form of maps, tables, and figures. These outputs can be displayed both as an image on the monitor for visualization and as printed material. Some of the figures included in this report are printed copies of the spatial data.
Chapter 6
SIMULATIONS OF PEDOGENIC CARBONATES

The model was used to simulate carbonate development under five different climate regimes. A random component of ten percent of the precipitation being modeled was used in each case to account for variations in climate.

6.1 Climate Simulations

To begin with, two constant climates were simulated. A constant climate is one in which the leaching index does not change over the duration of the simulation, except for the random variation from iteration to iteration. In the first simulation, the Holocene climate was simulated for the duration of all deposits, despite the age of the unit (Figure 22). This model is referred to as the Holocene simulation. Second, the Pluvial climate was modelled for the entire duration of all deposits, despite the age of the unit (Figure 23). This simulation is referred to as the Pluvial simulation.

Next, two types of trend changes in climate were simulated. A trend climate is one where the leaching index gradually changes from the Pluvial climate value to the Holocene climate value. The gradual change is applied for each iteration. In the Trend One simulation, the linear trend
Figure 22a. Map of pedogenic carbonate stage distribution predicted by the Holocene Simulation.
Figure 22b. Map showing the residuals of the Holocene Simulation as compared to the on-site map.
Figure 23a. Map of pedogenic carbonate stage distribution predicted by the Pluvial Simulation.
Figure 23b. Map showing the residuals of the Pluvial Simulation as compared to the on-site map.
starts at the maximum age of the unit and continues until the present (Figure 24). Second, a linear trend from Pluvial to Holocene climate for deposits older than 10,000 years old, and the Holocene climate for deposits younger than 10,000 years was simulated (Figure 25). This second type of trend is referred to as the Trend Two simulation.

Finally, a the carbonate development for a threshold climate was simulated. A threshold climate is one where the leaching index changes from the initial to the final value at a particular iteration. The threshold from pluvial to Holocene climate with the change 10,000 years before present was simulated (Figure 26) as the Threshold Simulation. For example, a deposit estimated to be 40,000 years old is simulated by the program to have 30,000 years of Pluvial climate, followed by 10,000 years of Holocene climate. Deposits younger than 10,000 years old were modelled with the Holocene climate. Hence, a deposit 8,300 years old is simulated with 8,300 years of Holocene climate.

Each of the carbonate distributions predicted by the five climate simulations was then compared to the on-site distribution (Figures 22b, 23b, 24b, 25d, and 26b). The area of each stage and the percent of the total area of each stage for each of the five climates is summarized in Appendix D.
Figure 24a. Map of pedogenic carbonate stage distribution predicted by the Trend One Simulation.
Figure 24b. Map showing the residuals of the Trend One Simulation as compared to the on-site map.
Figure 25a. Map of pedogenic carbonate stage distribution predicted by the Trend Two Simulation.
Figure 25b. Map showing the residuals of the Trend Two Simulation as compared to the on-site map.
Figure 26a. Map of pedogenic carbonate stage distribution predicted by the Threshold Simulation.
Figure 26b. Map showing the residuals of the Threshold Simulation as compared to the on-site map.
6.2 CALSOIL Results

Despite the simplicity of CALSOIL, the model simulations of pedogenic carbonate appear to relate to the on-site distributions. The distribution was predicted using five different climatic regimes. Appendix E shows each of the map units with the age and the pedogenic carbonate stage predicted by each model variation.

The age of a deposit appears to be the most sensitive parameter in the model. Grain size, related to moisture characteristics of a soil, also affects carbonate development in the model. Finer grained deposits develop carbonate stages much faster than coarse grained deposits of the same age under the same climatic regime (Figures 22-26 and Appendix E).

6.2.1 Holocene Simulation

The climate appears to affect the stage of the pedogenic carbonate. If the Holocene climate is simulated as a constant, the stages are generally bimodal. Deposits older than 10,000 years contain Stage V carbonate, while the Holocene deposits contain only Stage I or II (Figure 23, Appendix E). The residuals of the constant Holocene climate model compared to the on-site distribution (Figure 23b) show that the older deposits are not simulated accurately (Figure 22b).
6.2.2 Pluvial Simulation

A constant Pluvial climate model, however, also does not explain the carbonate distribution adequately (Figures 22b and 24b). The model simulates a large area of Stage I carbonate. Most of this area, however, actually varied from Stage I to Stage II in the field. Therefore, this area may be an adequate representation, despite the large error shown in the residual maps. In addition to this area, the residual distribution is very similar to the residual distribution given in Figure 22b. This is a result of the older areas in simulation one being simulated mostly as a Pluvial climate. Hence, the stage of these older deposits is dependent on Pluvial climate conditions.

If the constant Holocene climate model (Figure 23a and Figure 23b) is compared with the constant Pluvial climate model (Figure 24a and Figure 24b), some areas that develop Stage V carbonate under Holocene conditions develop only Stage III carbonate under Pluvial conditions. Hence, the greater leaching indices of wetter climates appear to reduce, if not terminate, the progression of carbonate development. If the climate is wetter than the pluvial climate, carbonate may be leached from the soils.
6.2.3 Trend One Simulation

The Trend One simulation represents a change from Pluvial climate to Holocene climate in a linear trend based on the age of the deposit. The distribution indicated by this simulation (Figures 25a and 25b and Appendix E) is very similar to the Pluvial simulation. The gradual change in climate results in lower carbonate stages for younger deposits. This is a result of a climate that is wetter than that of simulation one.

6.2.4 Trend Two Simulation

The Trend Two simulation represents a change from Pluvial climate to Holocene climate in a linear trend, except for deposits younger than 10,000 years. The deposits less than 10 Ka are then simulated with a Holocene climate. The distribution shown in this simulation (Figures 26a and 26b) is very similar to the Threshold simulation (Figures 22a and 22b). A few areas in Trend Two simulation have one stage less than the on-site distribution and the Threshold simulation's distribution. These areas are coarse gravels that are relatively older. The lower stage of carbonate observed in these areas may be a result of a longer Pluvial climate simulated in these regions.
6.2.5 Threshold Simulation

The last simulation's distribution appears to follow the on-site distribution (Figures 22a and 22b) better than the other models (Figures 23-24). Soils accumulate secondary CaCO$_3$ in a trend with increasing age of surficial deposits. The areas of dissimilarity for the Threshold simulation (Figure 22b) appear to be associated with the marsh deposits. These older deposits may have been simulated with a higher carbonate because of: (1) erroneous age; (2) climate with much wetter conditions than the climates simulated existed for at least part of the history of the deposit, and carbonate was not developed or even leached from the deposits during this time; (3) the deposits may not have been exposed at the surface for much of geologic time; or (4) the determination of stages in the field has uncertainty due to the relatively fine-grained texture.
Chapter 7
COMPARISONS WITH PUBLISHED MAPS

In addition to field comparisons, the carbonate distribution predicted by the Threshold Simulation was compared to carbonate distributions published in the soil survey (USDA, 1990), surficial maps (Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; Denny and Drewes, 1965; and Pexton, 1990), and Taylor’s (1986) thesis. The soil survey (USDA, 1990) reports carbonate accumulations in horizon nomenclature and does not indicate stage of development. The stage of development predicted by the Threshold simulation does seem to follow the more advanced carbonate horizons described by the soil survey. The surficial maps indicate more advanced carbonate stages in the older surficial deposits and less advanced carbonate development in the younger deposits. This is also what is predicted by the model. These maps do not discuss carbonate development on deposits older than QTa (740 Ka). Finally, Taylor (1986) suggests the same carbonate development or one stage less on the units she mapped (Q1ab, Q1c, Q2, and QTa). She did not, however, find any Stage V carbonate in her limited field area. The fine grained deposits (QT11 and QT1d) have not been studied as to their stage of carbonate development.
Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to characterize the pedogenic carbonate distribution in an area adjacent to the Nevada Test Site. A number of surficial deposits of different ages ranging from 2000 to 6000 feet (610 to 1830 meters) in elevation were studied with respect to pedogenic carbonate distribution.

Soils that formed in alluvium, colluvium, and eolian fine grained materials of Holocene, Pleistocene, and late Pliocene (?) age in the Amargosa Desert are characterized by distinctive trends in the accumulation of secondary carbonate. Initially, carbonate appears as coatings on the underside of clasts and as time continues, forms cemented and indurated horizons. The carbonate stages show a relation to the age of the deposit, climate, and grain size distribution.

The accumulation of pedogenic CaCO₃ is dependent upon the availability of eolian material on the soil surface and sufficient precipitation to transport the material into the soil. Translocation of dissolved and solid material within the soil may be attributed to precipitation events. When moisture is available for translocation, CaCO₃ moves downward in solution and precipitates.

Stages of carbonate were mapped in the field using the
characteristics described in Table 2. Pedogenic carbonate stages ranging from no development to Stage V were located in the field area in both fine and coarse grained deposits.

A computer model, CALSOIL, was used to simulate the CaCO$_3$ distribution in the soils of the Amargosa Desert. The model parameters describe the physical characteristics of the deposit, CaCO$_3$ influx rates, and climate. The simulations were conducted using paleoclimatic data from Spaulding (1985) and Mifflin and Wheat (1979).

A GIS was used to manage the data, analyze the results, and display the results. The use of a GIS greatly simplified and expedited the procedure.

The on-site map was compared with the pedogenic carbonate distribution predicted by five different climatic simulations. Furthermore, residuals from the models compared to the on-site distribution were calculated. The Threshold Simulation, a Pluvial climate for periods before 10,000 years ago and a Holocene climate for the last 10,000 years, appeared to fit the data best (Figures 22-26). The distribution of pedogenic carbonate stages depends on the age of the deposit, climate, and grain size distribution.

Recommendations for other work in this area include determining more accurate ages on the deposits, measure pCO$_2$ more accurately, measure temperature distribution in the soils
more accurately, and determine a more accurate distribution of precipitation and temperature for the area. Densities of soils should be examined to determine what values should be used for different soils. CALSOIL should be expanded to include changes in temperatures with climate and other salts in the chemical equilibria.
Chapter 9

REFERENCES CITED


Hoover, D.L., 1985, Quaternary history of the Yucca Mountain area Nye County, Nevada: unpublished manuscript, personal communication to J.S. Downey.


APPENDIX A

PEDOGENIC CARBONATE BACKGROUND INFORMATION

The term caliche, from the Latin calx, lime, is applied commonly in North America to calcareous caprocks, soil hardpans, and earthy or porous materials that occur at the surface or at shallow depths (Price, 1933; Bretz and Horberg, 1949). Caliche is a generic term for a calcareous formation of considerable volume and thickness found a few centimeters (inches) or meters (feet) beneath the surface, upon broad, dry, gravelly plains and mesas (Reeves, 1976). Impurities are present in variable amounts and may consist of siliceous and ferruginous materials.

The term caliche has been used to describe calcareous and noncalcareous deposits of varied origin (Brown, 1956). This summary will restrict the use of caliche to those mostly calcareous materials that are formed in the zone of weathering. Subaqueous deposits (water table) and spring deposits will be differentiated from the pedogenic deposits. Due to the confusion caused by the varied definitions of caliche, the term pedogenic carbonate will be used. Calcic horizons in this report include both the calcic and petrocalcic horizons of the Soil Conservation Service.

Thirty to forty percent of the world's continental areas probably contain pedogenic carbonate of variable thickness,
age, and induration (Reeves, 1976). Within the United States, soils that continually accumulate carbonate generally are restricted to areas of arid and semiarid climate within the low altitude basins of the southwest (Machette, 1985). The origin and distribution of pedogenic carbonate is not related simply to age of the parent material or climate; instead, it is determined by the complex interaction of several independent variables (McFadden and Tinsley, 1985). Many factors affect the distribution and origin of pedogenic carbonates; the local relationships between salt source, precipitation, temperature, runoff, topography, and parent material are critical for pedogenic carbonate formation (Reeves, 1970). The ideal environment is neither arid nor humid; too little water allows only surficial accumulations of carbonate, whereas too much water and relief causes regional leaching of the soil solubles. An ideal location for accumulation of saline and alkaline minerals is in closed basins, such as playas, where evaporation exceeds outflow, and calcium carbonate generally accumulates in the soil (Price, 1933). As a result, there are many implications for the presence or absence of pedogenic carbonate in arid and semiarid regions. Some of these have direct application in the deciphering of tectonic, erosional, and climatic history (Bachman and Machette, 1977).
Numerous theories have been proposed for the origin of carbonate materials at or near the surface (Bretz and Horberg, 1949, Goudie, 1973). First, a fluvial genesis, where gully-bed concentration occurs during surface runoff on limestone-rich alluvial sediments is proposed (Machette, 1985). Second, a lacustrine genesis from ancient lake beds is possible (Marion and others, 1985). Third, an in situ origin by the decomposition and accumulation of parent carbonate is proposed (Marion and others, 1985). As a result, soils formed on calcareous carbonate materials accumulate pedogenic CaCO₃ at higher rates than soils formed from non-calcareous parent materials (Marion and others, 1985). Fourth, a capillary rise of salt-rich soil water during dry periods resulting in pedogenic carbonate formation is suggested (Machette, 1985). However, this process does not appear to have contributed significant amounts of salt to most pedogenic carbonates of the southwest (Machette, 1985). Capillarity is probably a local adjunct process in the formation of some pedogenic carbonates (Bachman and Machette, 1977). Fifth, a detrital source origin of pedogenic carbonate formed by solution, reprecipitation, and cementation of CaCO₃ and CaSO₄ fragments is proposed (Lattman, 1973). Finally, pedogenic sources are suggested as the most common origin. Salt is leached from the surface and upper soil horizons and subsequently is
precipitated and accumulated in the lower soil horizons at a depth controlled by soil moisture and texture. The major source of salt in this origin is from wind-blown silt and sand and from rainwater. As a result, the best deposition sites are downwind of playas with substantial carbonates or sulfates (Lattman, 1973). All of these theories have been applied to pedogenic carbonates in the southwest (Bretz and Horberg, 1949).

Several methods of pedogenic carbonate classification have been developed based on genetic factors, mineralogy, and soil fabric changes (Reeves, 1976); the two main pedogenic carbonate types are indurated and friable. This division, however, is arbitrary; pedogenic carbonate grades in three stages from a soft, calcareous, earthy zone at the base of the soil into a semilithified friable form, and then into caprock (Brown, 1956). In the first stage, pedogenic carbonate is composed of grains, flakes, and aggregations. Pedogenic carbonate then evolves into continuous, but nonindurated beds of porous, earthy CaCO3 or CaSO4. Indurated limestone or calcretes result only in desert areas or in high mountains of semiarid areas (Price, 1933). Machette (1985) has proposed dividing the grades into five stages. These morphologic stages exhibit physical characteristics that may be used for correlation of soils and geomorphic surfaces. Because each
stage is dependent on many factors, such as climate, availability of carbonates, and texture of parent materials, stratigraphic correlations may be valid only for local areas (Bachman and Machette, 1977). The morphological forms are diagnostic of stages of carbonate accumulation, not the age of the accumulation. Hence, the occurrence of similar stages of carbonate accumulation in different soils and on different geomorphic surfaces does not demonstrate that the carbonate accumulations occurred at the same time, though they could have (Gile and others, 1966).

Because of their indurated character, pedogenic carbonates are often relatively resistant to erosion and tend to form positive relief features. They have a direct effect on slope hydrology, sediment transport processes and slope evolution. They often form sub-planar cappings to residual hills, and encourage the development of hillslopes by parallel retreat. Where duricrusts overlie relatively weak sediments undercutting and collapse of resistant carbonates may result in the formation of pseudo-karst topography. Where pedogenic carbonate formation has taken place in low-lying areas, over long periods relief and drainage inversion may take place. Induration of the near-surface layers of a sediment body also helps to preserve otherwise ephemeral forms such as aeolian dunes, fans, and river terrace deposits (Goudie and Pye,
Pedogenic carbonate affects the landscape not only by creating characteristic landforms, but also by affecting vegetation associations. Types and thicknesses of pedogenic carbonate have different effects on vegetation. For example, plants indicative of a high water table in an otherwise arid area may indirectly indicate the presence of pedogenic carbonate. Salt tolerant plants may represent pedogenic carbonate while other less tolerant species may represent ground-water discharge areas or spring deposits. Additionally, the permeability and infiltration capacity of the hardpan layer, the presence of very shallow soil layers, and the presence of large quantities of lime may result in distinctive vegetation patterns and types (Goudie, 1973).

The distribution of pedogenic carbonate also can be related to key parameters of climate (McFadden and Tinsley, 1985). Climatic implications of pedogenic carbonate as a polygenetic fossil soil have been noted by Bryan (1943), who considers successive pedogenic carbonate layers a record of relatively arid conditions and solution features a record of relatively humid conditions. Pedogenic carbonate and associated solution features provide a partial record of climatic changes. Investigations of complex pedogenic carbonate profiles, together with geomorphic studies, may
reveal a relatively complete record of climatic changes in the region (Bretz and Horberg, 1949). For instance, climate controls the depth of carbonate leaching; maximum depth is approximately proportional to the mean annual precipitation in areas where carbonate is not completely leached. Variations in dust flux, precipitation, evaporation, and other variables affecting calcite dissolution and water percolation must be studied if pedogenic carbonate is to be analyzed for paleoclimatic conditions. As a result, computer models of pedogenic carbonate development have been used to confirm paleoclimatic hypotheses (Mayer and others, 1988; Marion and others, 1985).

In summary, factors affecting pedogenic carbonate formation are: climate (precipitation, temperature, and evapotranspiration), parent material (water holding capacity, calcium carbonate content, partial pressure carbon dioxide, and temperature), calcium carbonate source (precipitation and wind-borne dust), time, topography, and vegetation. Vegetation and topography are both incorporated in the other factors.
APPENDIX B

CALSOIL PROGRAM LISTING
(modified from Mayer, 1986)

100 CLEAR
2700 DIM POROSITY(50), DENSITY(50), HIST$(50)
2800 DIM EFFECP(99), PET(99), TEMP(99), CSOLUBLE(50), CAPACITY!(50), AWC(50)
2900 DIM WCOMPT!(50), COR(13), MAX(100)
3000 DIM PETCOMP!(50), PETINDEX(50), INFIL!(50), WILTPOINT(50)
3100 DIM CPRESENT(50), PC02(50), STEMP(50)
3200 DIM CADDDED(50), CCREMOVED(50), WATER!(50)
3300 DIM PFACTOR(13), PFETFACTOR(13), EFFECPI(13), PETI(13), EFFECPF(13), PETI(13)
3400 '  
5400 'MAIN CONTROL SECTION  
5500 '  
5550 REM GOSUB 8000
6000 OPEN "I", #1, "SOIL.DAT"
6005 OPEN "O", #2, "SOIL9.0UT"
6010 INPUT #1, SOIL, FC, WCOMPT!, WILTPOINT, AWC, CPRESENT, STEMP, LI(2), LI(1), THICK, YEARS, GRV
6020 IF YEARS<1 THEN STAGE=12: GOTO 12080
6030 IF YEARS<10 THEN STAGE=YEARS: GOTO 12080
6050 'INITIALIZE SOME VARIABLES
6100 Y=0: THICK=(THICK/20)*2.54: LI(2)=2.54*LI(2):
LI(1)=2.54*LI(1)*0.16: LEACHINDEX=LI(1): STEMP=(STEMP-32)*5/9
6200 N%=20: PERIOD%=3: YRSINC=.01*YEARS: DUST=.00005:
RAINWATER=.00015: CPRESENT=0
6210 LIFACTOR=(LI(1)-LI(2))/YEARS: CLVARIANCE%=1:
LIVARFACTOR=.1*LI(2)
6220 FOR I%=1 TO N%
6230 AWC(I%)=AWC: WCOMPT!(I%)=WCOMPT!
WILTPOINT(I%)=WILTPOINT: CPRESENT(I%)=CPRESENT
6240 NEXT I%
6250 IF YEARS > 10000 THEN YR=YEARS-10000: CLMODEL% = ?
6260 IF YEARS < = 10000 THEN YR=10000: CLMODEL% = ?:
leachindex=?
6300 REM loop for PC02
6305 PC02(1)=3.16228*.0001
6310 FOR I%=2 TO N%
6315 T=THICK*I%
6320 IF T = 18*2.54 THEN
PC02(I%)=PC02(I%-1)+(.00006225*THICK)
6335 IF (18*2.54 < T) AND (T < 25*2.54) THEN
PC02(I%)=PC02(I%-1)+(-.00001555*THICK)
IF T >= 25*2.54 THEN PCO2(I%)=.000398
NEXT I%

REM loop for STEMP!
STEMP(I%)=.5*THICK*.05+STEMP
FOR I% = 2 TO N%
STEMP(I%)=STEMP(I%-1)+THICK*.05
NEXT I%

REM OPEN "I",#2,COMPFILE$
REM FOR I%=1 TO N%
REM INPUT #2,AWC(I%), WCOMPT(I%),WILTPOINT(I%),
CPRESENT(I%), PCO2(I%),STEMP(I%),PETINDEX(I%)
REM NEXT I%
REM CLOSE #2

REM OPEN "I",#3,CLIMFILE$
ON PERIOD% GOSUB 7700,7800,7900
GOTO 10000

BEEP: RETURN
REM INPUT #3,
REM INPUT #3,LEACHINDEX,LI(1),LI(2),LIFACTOR,CLMODEL%,
CLVARIANCE%,LIVARFACTOR,YR:CLOSE #3:RETURN
RETURN

START$=DATE$
'yearly climate
FOR YRS=YRSINC TO YEARS STEP YRSINC
IF PERIOD%=3 THEN M%=1:GOTO 11200
FOR M%=1 TO 12
GOTO 19800 'GET CLIMATE
GOTO 12200 'COMPUTE WATER BALANCE AND CARBONATE
REM GOTO 23800 'OUTPUT
'CONTINUE
IF PERIOD%=3 THEN 11800
NEXT M%
NEXT YRS

REM FIND LARGEST CPRESENT
MAX=0
FOR I%= 1 TO Y
IF MAX < MAX(I%) THEN MAX= MAX(I%)
NEXT I%

rem FOR I%=1 TO 3:BEEP:NEXT I%
PERMAX=100*MAX/(THICK*2.1627)
IF (GRV < 1) AND (PERMAX >= 25) THEN
PERMAX=100*MAX/(THICK*2.68)
ELSE IF (GRV > 0.5) AND (PERMAX >= 60) THEN
PERMAX=100*MAX/(THICK*2.68)
12003 IF GRV < 1 THEN GOTO 12011
12004 IF PERMAX = 0 THEN STAGE = 0
12005 IF PERMAX <= 2 THEN STAGE = 1
12006 IF (2 < PERMAX) AND (PERMAX <= 10) THEN STAGE = 2
12007 IF (10 < PERMAX) AND (PERMAX <= 25) THEN STAGE = 3
12008 IF (25 < PERMAX) AND (PERMAX <= 50) THEN STAGE = 4
12009 IF PERMAX > 50 THEN STAGE = 5
12100 END
12101 GOTO 12080
12102 IF PERMAX = 0 THEN STAGE = 0
12103 IF PERMAX <= 4 THEN STAGE = 1
12104 IF (4 < PERMAX) AND (PERMAX <= 20) THEN STAGE = 2
12105 IF (20 < PERMAX) AND (PERMAX <= 60) THEN STAGE = 3
12106 IF (60 < PERMAX) AND (PERMAX <= 75) THEN STAGE = 4
12107 IF PERMAX > 75 THEN STAGE = 5
12120 MAIN LOOP FOR SOIL WATER AND CARBONATE
12140 INFIL1(0)=EFFECP(M%)
12160 FOR I%=1 TO N%
12170 IF PERIOD%=3 THEN WCOMPT!(I%)=WILTPONT(I%)
12180 CAPACITY!(I%)=AWC(I%)-WCOMPT!(I%)
12190 IF PERIOD%<3 THEN
12200 PETCOMP J(1%) = (PET(M%)*PETINDEX(I%))
12210 INFIL!(I%)=INFIL!(I%-1)-CAPACITY!(I%)
12220 IF INFIL!(I%)<0 THEN INFIL!(I%)=INFIL!(I%)
12230 WATER!(I%)=WATER!(I%)+INFIL!(I%)
12240 WCOMPT!(I%)=WCOMPT!(I%)+INFIL!(I%-1)-INFIL!(I%)
12250 IF WCOMPT!(I%)<WILTPONT(I%) THEN
12260 WCOMPT!(I%)=WILTPONT(I%)
12270 SUMWAT!=(WCOMPT!(I%) - WILTPONT(I%)) + SUMWAT!
12280 CAPACITY!(I%)=ABS(AWC(I%)-WCOMPT!(I%))
12290 NEXT I%
12300 IF PET(M%)>SUMWAT! THEN AVALVEP!=SUMWAT! ELSE
12310 AVALVEP!=PET(M%)
12320 IF PERIOD%=3 THEN 14700
12330 WHILE (AVALVEP!-SUMPETCOMP!)> .01
12340 FOR I%=1 TO N%
12350 IF (WCOMPT!(I%)-PETCOMP!(I%))<=WILTPONT(I%) THEN
12360 WCOMPT!(I%)=
WCOMPT1(I%) - PETCOMP1(I%):
CAPACITY1(I%) = AWC(I%) - WCOMPT1(I%)
14300 SUMPETCOMP1 = SUMPETCOMP1 + PETCOMP1(I%)
14400 NEXT I%
14500 WEND
14600 SUMwat1 = 0: SUMPETCOMP1 = 0
14700 ' CARBONATE ACCOUNTING LOOP
14800 '  CARBONATE ACCOUNTING LOOP
14900 ' IF PERIOD% = 1 THEN GOTO 15200
15000 IF PERIOD% = 2 THEN DUSTFLUX = DUST/12 ELSE DUSTFLUX = DUST
15100 REM RAINWATER = RAIN * EFFECP(M%)
15200 GOSUB 22700 ' CARBONATE SOLUBILITY
15300 CADDED(1) = (DUSTFLUX + RAINWATER) * YRSINC
15400 CREMOVED(1) = CSOLUBLE(1) * INFIL1(1) * YRSINC
15500 IF CREMOVED(1) > (CPRESENT(1) + CADDED(1)) THEN
15600 CREMOVED(1) = CPRESENT(1) + CADDED(1)
15700 CPRESENT(1) = CPRESENT(1) + CADDED(1) - CREMOVED(1)
15800 FOR I% = 2 TO N%
15900 CADDED(I%) = CREMOVED(I% - 1)
16000 CREMOVED(I%) = CSOLUBLE(I%) * INFIL1(I%) * YRSINC
16100 IF CREMOVED(I%) > (CPRESENT(I%) + CADDED(I%)) THEN
16200 CREMOVED(I%) = CPRESENT(I%) + CADDED(I%)
16300 CPRESENT(I%) = CPRESENT(I%) + CADDED(I%)
16400 NEXT I%
16500 REM FIND LARGEST VALUE OF CPRESENT IN EACH YEAR
16600 Y = Y + 1
16700 MAX(Y) = 0
16800 FOR I% = 1 TO N%
16900 IF MAX(Y) < CPRESENT(I%) THEN MAX(Y) = CPRESENT(I%)
17000 NEXT I%
17100 GOTO 11400
17200 ' FOR YEARLY MODELING

ADD A RANDOM VARIANCE TO CLIMATE
18300 RANDOMIZE(TIMER/3)
18400 IF PERIOD% = 3 THEN 19400
18500 PVAR = (2 * PVARFACTOR * RND) - PFARFACTOR
18600 EVAR = (2 * EVARFACTOR * RND) - EVARFACTOR
18700 EFFECP(M%) = EFFECP(M%) + PVAR
18800 PET(M%) = PET(M%) + EVAR
18900 GOTO 11300
19000 ' FOR YEARLY MODELING
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19500 LIVAR=(2*LIVARFACTOR*RND)-LIVARFACTOR
19600 EFFECP(1)=EFFECP(1)+LIVAR
19700 GOTO 11300
19800 ' SIMULATE CLIMATES ACCORDING TO SELECTIONS
19900 ' 20000
20100 IF PERIOD%=3 THEN 21500
20200 ' FOR MONTHLY MODELING USING ETp AND EFFECP
20300 ON CLMODEL% GOTO 20400,20700,21100
20400 ' FOR CONSTANT CLIMATE
20500 ' USE VALUES CALCULATED IN ETp
20600 IF CLVARIANCE%=1 THEN GOTO 18400 ELSE GOTO 11300
20700 ' FOR THRESHOLD CLIMATE
20800 IF YRS<YR THEN EFFECP(M%)=EFFECPI(M%):PET(M%)=PETI(M%)
20900 IF YRS>=YR THEN
EFFECP(M%)=EFFECPF(M%):PET(M%)=PETF(M%)
21000 IF CLVARIANCE%=1 GOTO 18400 ELSE GOTO 11300
21100 ' FOR MONTHLY TREND
21200 EFFECP(M%)=PRFACTOR(M%)+EFFECPI(M%)
21300 PET(M%)=PETFACTOR(M%)+PETI(M%)
21400 IF CLVARIANCE%=1 THEN GOTO 18400 ELSE GOTO 11300
21500 ' FOR YEARLY MODELING USING LEACHING INDEX
21600 ON CLMODEL% GOTO 21700,22000,22400
21700 ' FOR CONSTANT CLIMATE
21800 EFFECP(1)=LEACHINDEX
21900 IF CLVARIANCE%=1 THEN GOTO 18400 ELSE GOTO 11300
22000 ' FOR THRESHOLD CLIMATE
22100 IF YRS<YR THEN EFFECP(1)=LI(1)
22200 IF YRS>=YR THEN EFFECP(1)=LI(2)
22300 IF CLVARIANCE%=1 THEN GOTO 18400 ELSE GOTO 11300
22400 ' FOR TREND CLIMATE
22500 EFFECP(1)=LIFACTOR+LI(1):IF EFFECP(1)<0 THEN EFFECP(1)=0
22600 IF CLVARIANCE%=1 THEN GOTO 18400 ELSE GOTO 11300
22700 ' SUBROUTINE TO COMPUTE CARBONATE SOLUBILITY
22800 '
22900 FOR Z%=1 TO N%
23100 K1=6.53-.0058*STEMP(Z%):K1=10^(-1*K1)
23200 K2=10.59-9.100001E-03*STEMP(Z%):K2=10^(-1*K2)
23300 KCO2=1.21+.0102*STEMP(Z%):KCO2=10^(-1*KCO2)
23400 KCAL=8.03+1.223*STEMP(Z%):KCAL=10^(-1*KCAL)
23500 MCUBED=PCO2(Z%)*K1*KCAL*KCO2/(4*K2)
23550 CSOLUBLE(Z%)=(MCUBED^(1/3))*1
23600 NEXT Z%
23700 RETURN
23800 '
28800 RETURN
30000 '
30300 RETURN
30400 GOTO 11500
APPENDIX C

PROGRAM PARAMETERS

<table>
<thead>
<tr>
<th>SOIL #</th>
<th>PWP</th>
<th>AWC</th>
<th>MAT</th>
<th>MAP</th>
<th>AGE</th>
<th>GRAV.</th>
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<td>0.066</td>
<td>0.079</td>
<td>57</td>
<td>6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2004</td>
<td>0.066</td>
<td>0.079</td>
<td>56</td>
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<td>PWP = Permanent Wilting Point.</td>
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<td>AWC = Available Water Holding Capacity.</td>
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<td>MAT = Mean Annual Temperature in degrees Fahrenheit.</td>
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<td>MAP = Mean Annual Precipitation in inches.</td>
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<td>AGE = Age of deposit in years. A &quot;0&quot; indicates bedrock older than 2.95 million years outcropping in the majority of the area. These numbers were determined from the surficial maps (Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley, 1983; and Pexton, 1984).</td>
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<td>GRAV. = Gravel content. &quot;0&quot; indicates gravel content &lt; 25%. &quot;1&quot; indicates gravel content &gt; 25%.</td>
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<td>These numbers were determined by averaging the values for each soil unit on the Soil Survey (USDA, 1990) which compose each soil mapping unit.</td>
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APPENDIX D

DISTRIBUTION OF PEDOGENIC CARBONATE STAGES

Holocene Simulation

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<th>Class</th>
<th>Legend</th>
<th>Area (%)</th>
<th>Cum Area</th>
<th>Area (km sq)</th>
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Total of 10 classes  100.00  1192.08

Residuals of Holocene Simulation

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Total of 4 classes  100.00  278.054
Pluvial Simulation

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Total of 12 classes 100.00 1192.08

Residuals of Pluvial Simulation

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Total of 3 classes 100.00 705.396
Trend One Simulation

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Total of 12 classes: 100.00 1192.08

**Residuals of Trend Two Simulation**

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Total of 3 classes: 100.00 232.519
Threshold Simulation

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Total of 12 classes 100.00 1192.08

Residuals of Threshold Simulation

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Total of 2 classes 100.00 217.068
### APPENDIX F
### RESULTS OF SIMULATIONS

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"0" indicates numerous rock outcrops of bedrock older than 2.95 million years.

"1-5" indicates stage of pedogenic carbonate development for each model.