THESIS

# SOIL EVOLUTION ON A TERRACE CHRONOSEQUENCE IN THE WIND RIVER BASIN, WYOMING

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY CHARLES R. PEACOCK ENTITLED SOIL EVOLUTION ON A TERRACE CHRONOSEQUENCE IN THE WIND RIVER BASIN, WYOMING BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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## ABSTRACT OF THESIS

# SOIL EVOLUTION ON A TERRACE CHRONOSEQUENCE IN THE WIND RIVER BASIN, WYOMING

A series of strath terraces overlain with alluvial deposits from glacial and inter-glacial periods were used to develop a chronosequence. The sequence of soils examined in this study illustrate the effects of time on soil formation. Clay and carbonate percentages showed significant increases over time. Other indicators of soil evolution were less useful in evaluating the relationship between time and soil properties. Mineralogy characterization shows a predominance of smectite throughout the clay size fractions at each site. Chlorite, vermiculite and palygorskite are also abundant as well as intergrades of chlorite-smectite and mica-smectite. Results of this study demonstrate the dominance of aeolian additions to soil vs. chemical weathering in these environments. This work provides a greater understanding of the relationship between soil properties and time and should prove useful to pedologists, geologists and other scientists interested in landscape evolution.

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# CHAPTER 1

# INTRODUCTION

## SOIL FORMATION

In pedological research Jenny's state factor approach (1941, 1961) provides the theoretical framework for studies of soil evolution. This is expressed mathematically with the following equation:

$$s = f(cl,o,p,r,t) \qquad (1)$$

Any soil property "s" will vary as a function of climate (cl), biota (o), relief (r), and soil age (t). In order to evaluate the influence of a single factor on soil formation the other four factors must remain constant or inactive. For example, in this research an evaluation of time would be expressed as follows:

$$s = f(t),_{cl,o,p,r,} \qquad (2)$$

This equation was labeled as a chronofunction by Jenny (1941,1980) and is the principle design that is adopted in this study to evaluate soil evolution in relation to time.

The term "soil" means different things to different people. A contemporary view of pedology (soil genesis) treats the soil as a natural "organism" in itself with a wide range of chemical and physical processes taking place within it. Soil is an integral part of the ecosystem and affects the characteristics of its natural system, i.e. plant species, water movement, etc., but can also reflect the multitude of processes that go on in an ecosystem and give the soil its distinguishing morphological, chemical, physical, and mineralogical characteristics.

Hans Jenny stated,

> "*Soil genesis (formation) integrates gains, losses, and transformations of energy and matter, hence it embraces build-up as well as break-down of the soil body.*" (Jenny, 1980)

The effects of time on soil-forming processes and resultant properties are quite different between humid environments and dry environments. The climatic factor is considered by many to be the most important factor in influencing soil properties (Birkeland, 1974) because water is involved in most of the physical, chemical and biochemical reactions that take place in the soil. In wet areas the driving force in soil formation is a high leaching potential which weathers soil minerals and displaces materials downward to horizons within the profile or completely eliminates them from the profile. In dry areas chemical and physical weathering and biochemical activity are highly dependent on effective moisture (excess precipitation vs. PET). Soil development is dependent upon moisture for the removal of material by leaching and redistribution within the profile. For example, the depth to which moisture penetrates the soil determines quantities and distribution of soluble salts of calcium carbonate and gypsum. Horizons of salt accumulations are prominent features of most arid zone soils. However, the total amount of salts is primarily a function of the duration of pedogenesis (Birkeland, 1974).

Rates of organic matter accumulation are generally lower in arid than in humid regions because of the lower plant biomass. Organic matter content is also usually higher in cold, dry regions than in hot, humid regions where it is oxidized more quickly (Jenny, 1941; Birkeland, 1974).

Clay content and rates of accumulation can be difficult to relate directly to climate because factors other than climate may contribute to clay production. For example, clay amounts in arid regions can be the result of dust inputs such as that reported by Gile and Grossman (1979) in the Rio Grande Valley of New Mexico. However, if all other factors besides climate are constant, then you would expect to see the lowest rates of clay accumulation in cold, dry areas and increasing rates as temperature and humidity rise (Birkeland, 1974).

Clay mineralogy in most climate transects correlates best with precipitation or leaching index. Areas of high precipitation generally have clay species that have less silica such as kaolinite, and dry areas have clay species of high silica content such as montmorillonite (Birkeland, 1974).

However, this is a general trend and other factors would have to be considered when evaluating soil mineralogy in relation to climate. As with total clay amounts, consideration of external sources for the clay minerals is important when evaluating rates of accumulation.

## RESEARCH OBJECTIVES

The objectives of this research were to:

1) characterize selected morphological, mineralogical, and chemical properties on a terrace chronosequence in the western Wind River Basin, Wyoming
2) evaluate soil evolution on these terraces by discussing the soil properties in terms of their relationship to time, to identify dominant pedogenic processes
3) evaluate the utility of using selected soil properties to quantify relative ages of landscapes in similar environments.

## EXPERIMENTAL DESIGN

A soil chronosequence provides a useful way to assess changes in soil properties over time in a quantitative manner. An ideal chronosequence would involve a series of soils where time is the only state factor that is variable (Jenny, 1941). The glacial terraces of Wind River Basin in west central Wyoming offer an excellent opportunity to evaluate the effect of time on soil properties in a cool desert environment. This locale is not cold enough to be a "typical" cold desert which usually exists in Arctic and alpine environments (Cameron, 1969) but it is considerably colder than the warm deserts of Las Cruces, New Mexico where Gile and Grossman (1979) and others conducted an extensive study of soil formation and geomorphology. There have been few studies of soil formation in the Wind River Basin, although geological work has been performed here, with the type localities for the Pinedale, Bull Lake, and Sacagawea Ridge glaciations being found on the northeast flank of the Wind River Range. Chronosequence studies have been performed on glacial moraines nearby in the Wind River Range. However, these studies present more humid and colder climatic conditions and the chronosequences themselves span only 10,000 years (Birkeland et al., 1989).

The terraces on the western side of the basin have been mapped by several workers (Morris et al. 1959; Richmond and Murphy, 1965; Chadwick et al., 1993). The nature of these terraces and the environmental setting provide a unique situation in which we can assess the influence of time because the other state factors are constant while terraces are of varying age.

Vreeken (1975) describes four principle kinds of chronosequences. These are: 1) Post-incisive where there is a sequence of soils whose parent material was deposited at different times and soil formation has been taking place from the time of deposition to the present, 2) Pre-incisive where a particular soil has been developing but subsequent burial of parts of the soil has taken place at different times, 3) Time-transgressive where there are a series of buried soils, each indicating a period of non-burial or soil formation (no time overlap in each soil), 4) Time-transgressive with historical overlap; this is the most complex chronosequence in that it incorporates aspects of the other three and is also therefore the most difficult to study.

A problem with the fourth type is that some soil properties may be related to post-burial diagenesis or slope position as well as time (Birkeland, 1984b), although there are limitations with all four types. All chronosequence studies embrace the assumption that each soil has developed identically and that soil-forming environments were the same throughout the chronoseqence timespan. Another inherent assumption of chronosequence studies is that date controls on surfaces are believed to be correct. Thus observed differences in soil properties are "in fact" the result of age differences. Other factors that have influenced soil formation through the period of development need to be evaluated to accurately assess the relationship between soil properties and time, and I have attempted to address these problems in this study.

The conventional method of using a post-incisive chronosequence to infer soil development is to plot the degree of development of a soil property against the age of the soil as shown in Figure 1. Post-incisive chronosequences are most frequently studied because they are the most commonly found in natural environments. Few pre-incisive chronosequences have been reported (Vreeken, 1975) and anthropogenic burial was responsible for the formation of most of these. In this study we are dealing with a post-incisive chronosequence.

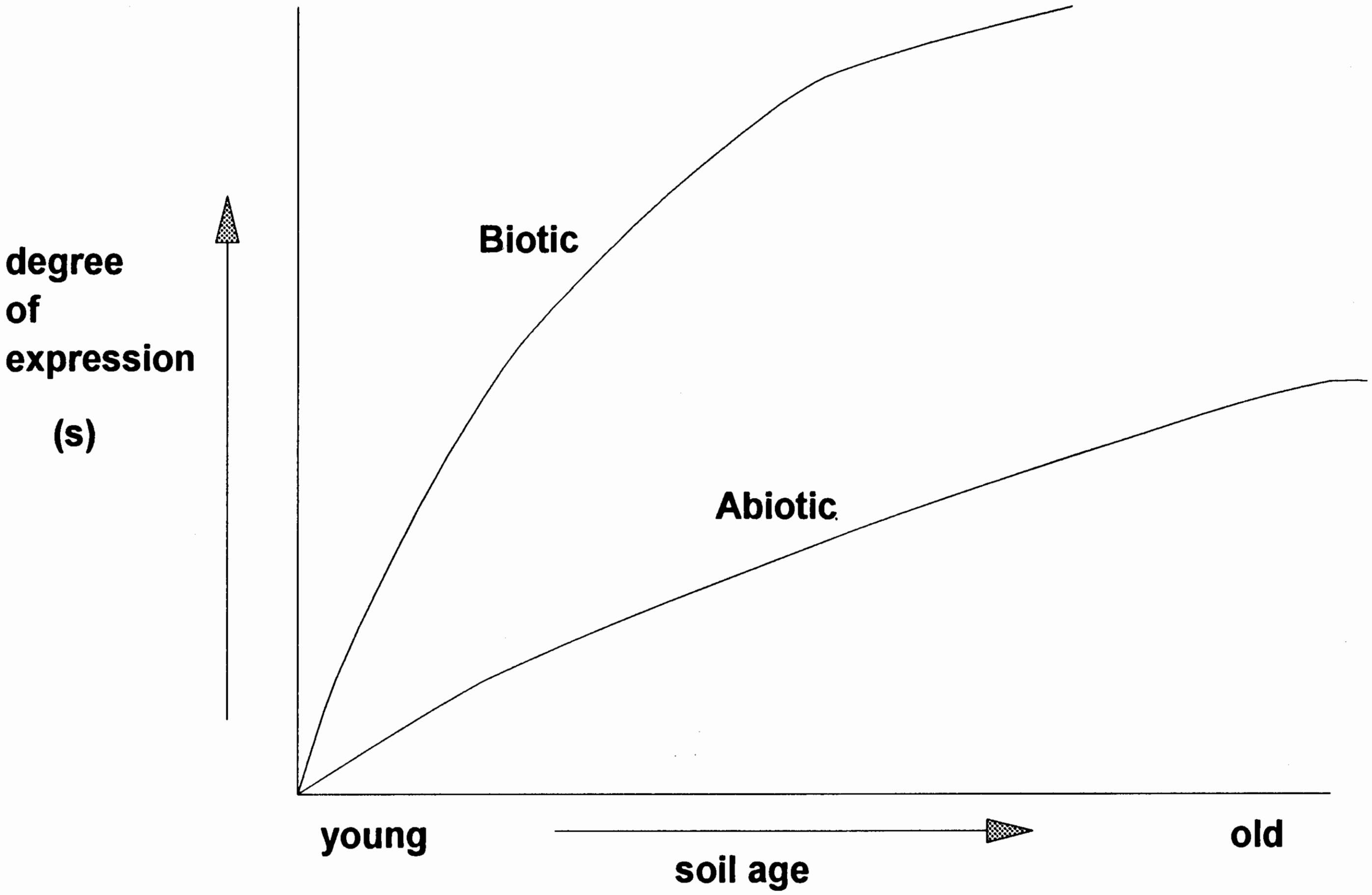


Figure 1. Relative rates of soil property development as influenced by abiotic vs. biotic processes.

## SOIL FORMATION AND TIME

Chronosequence studies have been used to determine soil resiliency (for disturbed soils), to assess regional paleoclimatic fluctuations, and for estimating the ages of geomorphic surfaces.

As stated in the objectives, this study aims to create "baseline" data for future soil and geomorphological studies in similar climates where surface ages are needed.

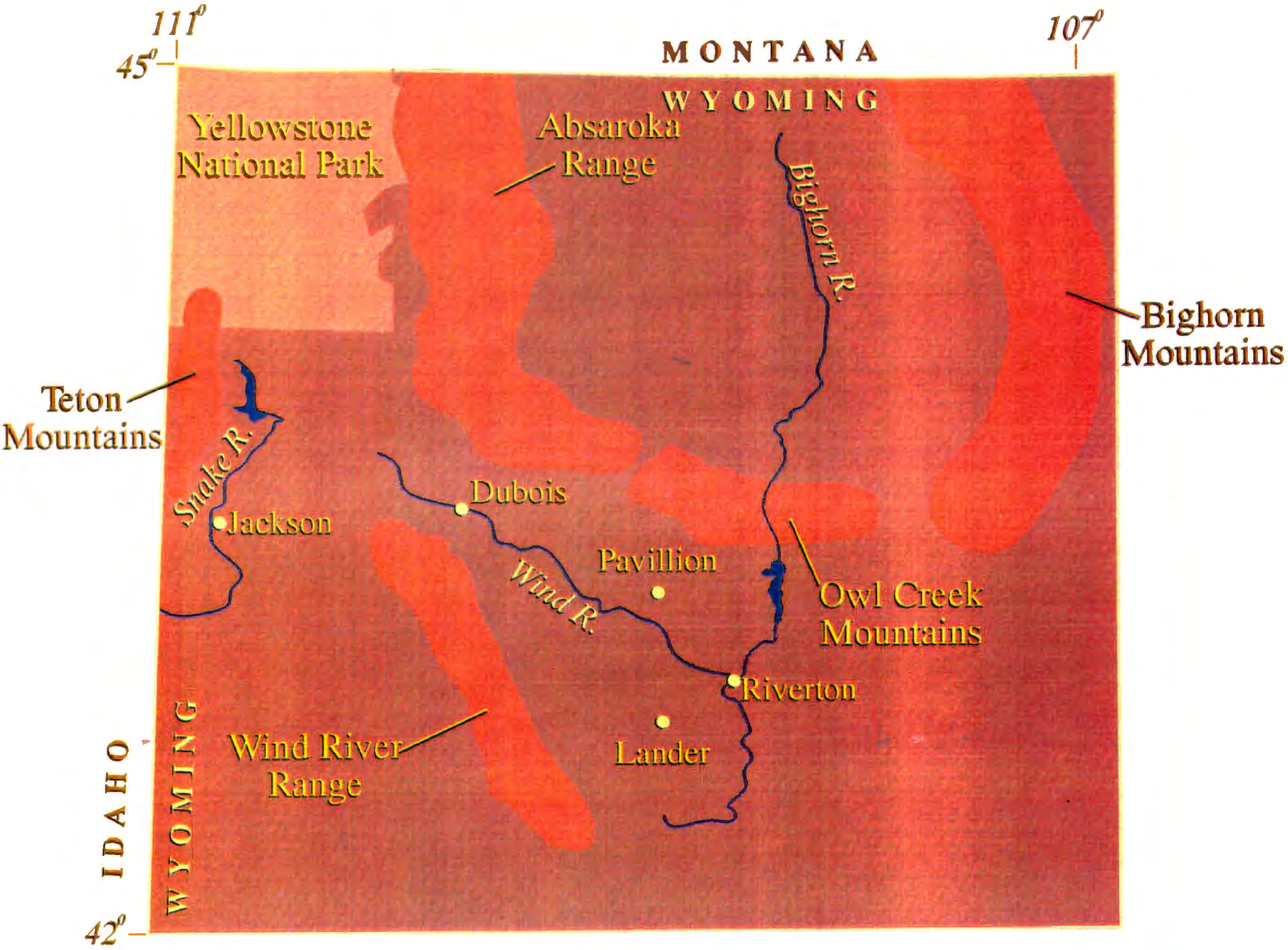
Properties that are biologically mediated, such as organic carbon percentage, may take only a few years to several hundred years to develop into a characteristic feature of that soil and are considered highly dynamic. Properties that are associated with the abiotic component (mineral weathering) such as the build up of iron oxides or other salts, may take much longer to develop strong characteristics, on the order of thousands of years. Figure 1 is a hypothetical representation of this concept showing the relative rates at which these properties change. As a soil ages the degree of expression of a specific property should strengthen. If you were to look at a series of soils that all differ only in age you may observe a similar rate function as that in Figure 1.

## DESCRIPTION OF THE STUDY AREA

The Wind River Basin is located in the west-central portion of Wyoming (Figure 2). It is bordered by the Wind River Range to the southwest, Absaroka Mountains to the north, and the Owl Creek Mountains to the northeast. Wind River heads in the northern Wind River and Absaroka Mountains and flows southeast through the basin and turns sharply northward through the Wind River Canyon and enters the Bighorn Basin where it is then called the Bighorn River. In this study we are primarily concerned with the northwest side of the basin from Dubois south to Lander and Pavillion (Figure 2).

The Wind River Range is approximately 160 km long and 64 km wide. The core of the range is composed of Precambrian rock (over 570 million years old) that was thrust over 21 km southwest over sedimentary deposits of the Green River Basin. This took place approximately 60 to 50 million years ago during the Laramide Orogeny which is responsible for most of the mountainous relief present in the Rocky Mountains (Lageson and Spearing, 1988). The Wind River Basin to the northeast of the range is a major sedimentary structural basin also formed during the Laramide Orogeny (Keefer, 1970; Jaworowski, 1992) and it encompasses 22,015 $km^2$ of Central Wyoming.

Figure 2. Map of northwest Wyoming and location of study area - Wind River Basin.


111°
107°
45°
42°
MONTANA
WYOMING
Yellowstone National Park
Absaroka Range
Bighorn R.
Bighorn Mountains
Teton Mountains
Snake R.
Jackson
Dubois
Pavillion
Wind R.
Owl Creek Mountains
Riverton
Lander
Wind River Range
IDAHO
WYOMING

Through Tertiary time (5-66 mybp) the Wind River Range and neighboring mountain Ranges were eroded and covered with resultant sedimentary deposits. There were also volcanic contributions to the burial during the Eocene (58 million ybp) that originated from fissures in northwest Wyoming. The Absaroka Range to the north of the basin was a result of this activity. Other volcanic activity through the Tertiary also contributed from Idaho, Oregon, Nevada and possibly Arizona and California. At the end of the Oligocene (24 million ybp) only 300 to 1200 m of the highest peaks were above the aggradational plain and the late Miocene (approx. 5-10 million ybp) marked the level of maximum fill. At the beginning of the Quaternary, approximately 2 million years ago, there was a regional uplift of the central portion of the continent and the buried basins were drastically exhumed in a relatively short period of time to expose the topography now visible in Wyoming and most other areas of the Rockies (McPhee, 1986, Lageson and Spearing, 1988). This long-term process is responsible for the superimposed rivers that are so predominant in the Rocky Mountain Region, especially Wyoming.

## TERRACE FORMATION

Blackwelder's explanation (1909) for the formation of the terraces is based on several interglacial erosion cycles which are recorded by the truncated surfaces or terraces.

These cycles of downcutting and lateral cutting were controlled by uplift of the mountains followed by tectonic stability. Although Blackwelder (1909) identified glacial deposits on or directly related to three of his six erosion cycles, he discounted a second hypothesis that climatic change played a major role in the cycles. However, Richmond and Murphy (1965; Murphy and Richmond, 1965) believed that the gravel veneers on the terraces were deposited as outwash during glaciations.

Morris et al. (1959) suggested several factors that could have contributed to the formation of the terraces; regional uplift or tilting, climatic change, changes in factors controlling the local base level and changes in the sizes of watersheds. They believed that the climatic change mechanism was compatible with the alternation of glacial and interglacial stages.

## TERRACE CHRONOLOGY

These terraces have formed at distinctly different time periods with the oldest terraces being the highest from the present stream channel and the youngest terraces being lower in elevation relative to the present stream. Morris et al. (1959) mapped 13 terraces along the Wind River and its tributaries north of Riverton (Fivemile, Muddy and Cottonwood creeks) in a study of ground water resources for the Riverton area conducted by the U.S.G.S. Several studies have contributed information needed to date the Quaternary terraces in the basin (Richmond and Murphy, 1965; Richmond and Murphy, 1976, 1989; Nettleton and Chadwick, 1991; Chadwick et al., 1993).

Chadwick et al. (1993) extended the previous mapping and correlation efforts of terraces by applying longitudinal profile analysis using U.S.G.S. 7.5 minute topographic maps, stereo air photos and field mapping. By doing so they were able to reconstruct paleo-river gradients and link terrace remnants. Discrepancies using terrace height for age correlation over long distances along the Wind River are evident because of the height relationship between specific terraces and the modern channel. Therefore, some of Conel and Chadwicks' date assignments differ from Morris et al. (1959).

Previous work reported three major glacial stages recorded by moraines; Sacagawea Ridge, Bull Lake and Pinedale (Richmond and Murphy, 1976, 1989; Nettleton and Chadwick, 1991; Chadwick et al. 1993). Many of the deposits from these glaciations correlate with specific river terraces. This provides a valuable tool in placing age constraints on the terraces.

At two sites in the study area are lenses of coarse volcanic ash (Lava Creek Ash) dated at 660 ky (Izzete et al., 1992) that are believed to correlate with the higher Sacagawea Ridge terrace. There are some critical discrepancies between previous and present mapping efforts concerning the ash, so the latest correlations by Chadwick et al. (1993) will be applied in this study. Chadwick et al. (1993) have constructed a multiple incision rate model for the estimation of terrace ages. The age constraints applied to this model include dated volcanic ash and C-14 and Cl-36 dating techniques. Table 1 shows the results of these calculations and a map of the correlated terraces is also included (Figure 3).

Dating of carbonate carbon by C-14 in the youngest terraces WR1 and WR2 yield dates of 12 to 7 ky and 20-26 ky, respectively. Dating by Cl-36 was also performed on boulders on terraces WR1 and WR3.

A terrace that Chadwick et al. (1993) have assigned to WR3 age is also clearly graded to outwash from the Bull Lake glacial deposits which are dated at 130 +/-10 ky in Yellowstone Park (Pierce and Morgan, 1992). This is another important date constraint for Chadwick's et al. model. The WR 7 terrace containing the ash establishes gravel deposition at approximately 660 ky and is used as one constraint in the model.

Dates for terraces based on C-14 and Cl-36 dates are indicative of the soil age, rather than the age of the actual bedrock terrace. In other words, it takes a period of time for the alluvium to be deposited and the soil to start forming after the terrace has been cut. But,

Table 1. Estimated terrace ages (Chadwick et al. 1993). Table does not include terraces that were not used in this study.

| TERRACE | PEDON | MAP SITE for FIGURE 2 | ASSIGNED AGE (ky) | ESTIMATED ERROR (ky) |
|---|---|---|---|---|
| WR0 | LN2 | 0 | FLOOD PLAIN | |
| WR1 | LN1<br>LN4 | 1a<br>1b | 10 | +/-2 |
| WR2 | | | 32 | |
| WR3 | BLN13<br>BLN14 | 3a<br>3b | 100 | +/-20 |
| WR4 | PB1 | 4 | 130 | +/-26 |
| WR7 | | | 660<br>(lava creek ash) | +/-60 |
| WR8 | BLS3 | 8 | 870 | +/-170 |
| WR9 | CR3<br>CR4 | 9a<br>9b | 950 | +/-190 |
| WR11 | CR5 | 11 | 1090 | +/-220 |
| WR12 | CR1<br>CR6 | 12a<br>12b | 1110 | +/-220 |
| WR13 | CR2<br>BLS2 | 13a<br>13b | 1320 | +/-260 |
| WR15 | BLS1 | 15 | 1740 | +/-250 |

Figure 3. Aerial photo with terrace map overlay depicting terraces and assigned ages (Chadwick et al., 1993).


10 kilometers
10 miles
TERRACE
OUTWASH
WR
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
N
RIVERTON
OCEAN LAKE
BULL LAKE
DINWOODY LAKES
WIND RIVER MOUNTAINS
109°00'00"
43°00'00"

considering the time span of the chronosequence, this kind of resolution between terrace formation and incipient soil formation is negligible.

Climate in the Wind River Basin during the Pleistocene has been variable with glaciations in the Wind River and Absaroka Ranges (Reheis et al., 1991). Because climatic change is coupled to the formation of the terraces it could interfere with the interpretation of the effects of time on soil formation. However, in this study I am treating climate as a subordinate factor (Jenny, 1980). The climatic conditions and changes that caused terrace formation are considered "small variations" relative to the dominant desert-steppe environment throughout the chronosequence timespan. The climate during the last glaciation was much colder than at present; effective moisture was probably higher which could have caused variations in vegetation density and depths of carbonate and clay translocation (Reheis et al., 1991).

## STATE FACTORS

Table 2 contains a summary of the state factors of the area. The **climate** is continental "steppe" (Martner, 1986) thus humidity is low and a wide range of temperatures can occur seasonally. The mean annual temperature in this area ranges from 4.8 degrees C at Dubois to 7.3 degrees C at Pavilion while the mean annual precipitation ranges from

29.72 cm at Ft. Washaki to 21.84 cm at DuBois. The largest percentage of precipitation in the basin falls as wet, heavy snow with moisture from the Gulf of Mexico in the months of March and April (Martner, 1986). The predominant **vegetation** (biota) consists primarily of sagebrush (*Artemesia* spp.), wheat grass (*Agropyron* spp.), cactus (*Opuntia* spp.), and needle and thread grass (*Stipa comata*). The **topographic** (relief) positions of the study sites are all on flat terrace surfaces.

Most of the surface bedrock in the basin is Eocene age Wind River Formation which is composed of brightly colored claystone and sandstone with some interbedded lenses of conglomerate (Lageson and Spearing, 1988). The landscape of the western side of the basin was carved by the Wind River and its tributaries. Recent alluvium covers the present floodplains while the flat-lying Quaternary strath terrace remnants (Wind River Formation) rise in elevation in a stair-step fashion above the present river. The **parent material** consists of fluvial deposits that cap the terraces (2-3 meters thick) which are derived from the Wind River and Absaroka Ranges and are dominated by non-calcareous, mixed but uniform (from site to site) volcanic and crystalline rocks (Jawoworski, 1992). **Time** was discussed in depth in the previous section.

TABLE 2. State factors of the research area

CLIMATE:

| | Pavillion | Ft. Washaki | Dubois |
|---|---|---|---|
| MAT deg.C | 7.3 | 6.7 | 4.8 |
| MAP cm. | 22.1 | 29.72 | 21.84 |

| | |
|---|---|
| BIOTA: | Sagebrush<br>(*Artemesia* spp.)<br>Wheat grass<br>(*Agropyron* spp.)<br>Cactus<br>(*Opuntia* spp.)<br>Needle and Thread Grass<br>(*Stipa comata*) |
| RELIEF: | Level, 0 to 2 percent slopes |
| PARENT MATERIAL: | Mixed volcanic and crystalline alluvium |

# LITERATURE REVIEW

## SOIL MORPHOLOGY

Surface A horizons in arid and semi-arid environments can show considerable variability in thickness and color (Gile and Grossman, 1979). Generally A horizons are thin in arid regions because of low effective moisture for plant growth for organic additions coupled with high oxidation rates of organic carbon (a major distinguishing property of A horizons). In most chronosequence studies in arid and semi-arid regions A horizon morphology is not focused upon heavily as a time-dependent characteristic (Reheis, 1987a and b; Harden et al., 1991; Gile and Grossman, 1979).

In contrast, chronosequence studies in more humid climates tend to show increased A horizon thickness. In general, organic carbon amounts are considered highly variable and thus unreliable as a time dependent soil property especially after 10,000 years. For example, McFadden and Hendricks (1985) observed thick, dark A horizons developing during the Holocene in a humid Mediterranean climate. But in successively older soils (to > 700,000 years) the A horizon declines in thickness and prominence until it is nearly eliminated. They attribute this to the progressive development of the clay-rich B horizon, in which soil permeability decreases.

Organic carbon accumulates in the upper few cm and is more readily oxidized. Eventually a threshold is reached where depletion exceeds addition.

The progressive development of B horizons is reported in virtually all chronosequence studies (Gile and Grossman, 1979; Dethier, 1988; Birkeland et al., 1987, to name just a few). The development of specific types of B horizons with characteristic accumulations of materials, such as Bt's (clay) or Bk's (calcium carbonate), are dependent on the other state factors that are dominant in the study area of the chronosequence in question.

The formation of calcium carbonate horizons in soils, a dominant feature of arid/semi-arid regions, has been attributed to several mechanisms ranging from lacustrine deposition (Elias, 1931; Frye, 1945) to capillary rise from ground water (Udden, 1923). Bretz and Horberg (1949) and Brown (1956) pointed out difficulties with the lacustrine process because of physiographic problems with the large lakes on the sloping High Plains surfaces and physical problems of the capillary rise from water tables that correlate with the carbonate in various areas (Gile and Grossman, 1979). Yet another idea is that carbonate was deposited from moisture that moved from the surface downward, and some laterally at the maximum depth of penetration.

Studies in arid regions present evidence that the later theory is the most probable process for carbonate accumulation (Hawker, 1927; Brown, 1956; Swineford et al., 1958; Stuart et al., 1961; Gile et al., 1966; Reeves, 1970; Gardner, 1972).

The form in which carbonate occurs in the soil is closely related to the total amounts of authigenic carbonate and can also indicate its relative age. For example Gile et al. (1966) presented four stages of carbonate accumulation in soils of the desert southwest. Table 3 gives a summary of the morphologies described for the two morphogenetic sequences, gravelly and non-gravelly, that were devised by Gile et al. (1966). As the stages progress I through IV the soil age is also progressively older.

Gile and Grossman (1979) determined a rate of carbonate accumulation for some New Mexico desert soils ranging between 1 and 10 $kg/m^2/Kyr$. No significance level was assigned because of many uncertainties but the current atmospheric addition was calculated at 2 $kg/m^2/Kyr$.

Depth to carbonate horizons and carbonate horizon thicknesses are closely related to precipitation (Gile and Grossman, 1979; Amundson et al. 1989). Higher precipitation regimes will decrease both the depth to carbonate and the thickness of carbonate horizons. Reheis (1987b) used the upper horizon boundary (wavy and irregular as opposed to smooth) as evidence for climatic fluctuation.

Table 3. Carbonate morphology based on relative soil age (Gile and Grossman, 1979)

| Stage & general character | Diagnostic carbonate morphology | |
|---|---|---|
| | Gravelly Soils | Nongravelly Soils |
| I (youngest)<br>weakest expression of macroscopic carbonate | thin, discontinuous pebble coatings | Few filaments or faint coatings |
| II<br>carbonate segregations separated by low-carbonate material | continuous pebble coatings some interpebble fillings | Few to common nodules |
| III<br>carbonate essentially continuous; plugged horizon forms in latter part | many interpebble fillings | Many nodules and internodular fillings |
| IV (oldest)<br>laminar horizon develops | laminar horizon overlying plugged horizon | Laminar horizon overlying plugged |

Clay-rich (Bt) horizons are reported in a variety of situations and can form in relatively short periods of time (Birkeland et al., 1987; 10-12 ky). The accumulation of clay is considered to be an accurate indicator of soil age if climate and clay sources can be accounted for. Most chronosequence studies show a strong relationship of clay accumulation to time (for example, McFadden and Hendricks, 1985; Reheis, 1987b; Gile and Grossman, 1979) but rates of accumulation can be highly variable depending on the source of clay, whether it is from in situ mineral weathering, illuviation, from dust inputs or a combination of sources. In some cases clay accumulation may be affected or even halted by other soil processes. Reheis (1987a) proposed that gypsum accumulation on soils in Wyoming suppressed the accumulation of clays in soils older than 300 ky.

## SOIL CHEMISTRY

Organic C is closely related to A horizon properties discussed in the morphology section. It is likely that A horizon properties such as organic C are in a "steady state" with prevailing conditions and are of limited use in stratigraphic studies (Birkeland, 1984b) and for chronosequence studies with the exception of relatively young deposits or sequences.

Jenny (1980) developed a hypothetical graph depicting a chronosequence of soils over a million years. He shows that humus content rises rapidly for about 4,000 years then a gradual reversal in the rate as the soil ages. He attributes this decline to the deterioration of the natural ecosystem caused by long-time soil leaching.

Syers et al. (1970) and Goh et al. (1976) reported on a variety of organic soil properties changing with time on a chronosequence of eolian dunes in New Zealand. Both show that organic C accumulation rates are high in the first 3000 years. After this, organic C is still accumulating but at a slower rate up to 10,000 years. It is important to note that in these specific studies organic C may still be accumulating at 10,000 years but at a much slower rate.

## SOIL MINERALOGY

Soil reddening or "rubification" increases with increasing soil age in complimentary environments. This occurs as pedogenic iron oxides are derived from Fe-bearing minerals in the parent material and accumulate in well drained soils under oxidized conditions (wet but not waterlogged) (Birkeland, 1974). McFadden and Hendricks (1985) have shown that total pedogenic Fe oxides in the soil profile, and Fe oxide crystallinity, increase with increasing soil age. They indicated that this is a result of unstable Fe-bearing minerals weathering to paracrystalline ferrihydrite which is a precursor to more crystalline goethite or hematite which will form as ferrihydrite is depleted. Crystallinity is measured by the ratio of oxalate extractable Fe (paracrystalline Fe) to dithionite extractable Fe (total Fe), with low values depicting high crystallinity (Schwertmann and Fischer, 1973; Singer, 1977). Several other studies have shown that Fe oxide content and crystallinity will also change with depth in the profile (Stonehouse and St. Arnaud, 1971; Moore, 1973; Singer, 1977).

Birkeland and others (1989) ranked pedogenic development by Fe accumulation and Al depletion according to climate (using several different chronosequences) showing that the greatest accumulation/depletion occurs in the warmest and wettest environment and only slight accumulations in the coldest and driest environments (Baffin Island). In the eastern Mojave Desert, Amundson et al. (1989) found that iron oxides increased with age in a semi-arid climate.

Most studies focus on the products of silicate weathering rather than on transformation rates of these minerals. Fewer studies have evaluated the rates of silicate transformations in chronosequences. Harris et al. (1980) evaluated the whole soil mineralogy (sand, silt and clay) of a chronosequence of the New River in Virginia. They found that quartz, feldspar, mica and amphibole predominate in the sand fraction in younger alluvial soils. Quartz and resistant heavy minerals are predominant in older soils. Silt mineralogy closely paralleled that of the sand. The clay mineralogy showed an age progression from mica and vermiculite to hydroxy interlayered vermiculite to kaolinite. The depletion of kaolinite from the surface of the younger soils is interpreted to be a result of eluviation. The main rate function that was interpreted was the apparent slow formation of kaolinite from other layer silicates, but on a whole soil basis, kaolinite may form relatively rapidly from sand and silt-sized feldspar. An increasing kaolinite depth trend was also observed and was attributed to illuviation. It was also suggested that stability was reached sooner in coarser than finer size fractions.

Other similar trends of silicate mineral transformations have been reported. Novak et al. (1971) reported a time sequence of mica weathering to vermiculite and mixed-layer mica-vermiculite to kaolinite. Mokma et al. (1973b) noted a similar trend, but no increase in kaolinite was detected with age up to 22,000 years. Brewer and Walker (1969) and Mokma et al. (1973a) confirmed the tendency for kaolinite to become dominant given adequate time with consideration that there may be some paleoclimatic influence. Because pedogenic kaolinite is associated with intense leaching (Jackson, 1965; Mankin, 1970), it may not be a significant soil constituent in arid climates (Ahmad et al., 1977). McFadden and Hendricks (1982, 1985) show an increase in kaolinite as Pleistocene soil age increases in a Mediterranean (humid) environment. They attribute this to the depletion of easily and more rapidly weathered mafic minerals relative to feldspar. The former weathers to vermiculite and Fe oxides whereas feldspar weathers directly to kaolinite.

The contents of chapter 2 summarize the methods used in this research. Chapter 3 is a detailed description of the results and an in-depth discussion of the soil property and time relationships for this environment. Chapter 4 outlines and summarizes the conclusions and evaluation of objective goals for this research.

# CHAPTER 2

# METHODS

## FIELD METHODS

Soil pits were excavated by backhoe to a minimum depth of 2 m at 15 locations (Figure 4). A total of 15 terraces were mapped by Chadwick and others (1993). Terraces 5 and 6 were not sampled because access was limited to these specific remnants. Terraces 10 and 14 were not sampled because the remnants were degraded and poorly preserved and therefore were not representative of the actual terraces. Selected horizons from five sites; 1b, 3b, 4, 9a, and 12b (site number indicates terrace number), were used for mineralogical analysis of iron oxides and X-Ray diffraction for silicate and aluminosilicate clays. These sites are also selected for illustrating and comparing soil properties in the results and discussion sections. Soils were morphologically described and classified according to Soil Survey Staff (1994, Table 4).

Figure 4. Aerial photo with terrace map overlay (Chadwick et al., 1993) depicting terraces and site locations, site no. corresponds to terrace no.

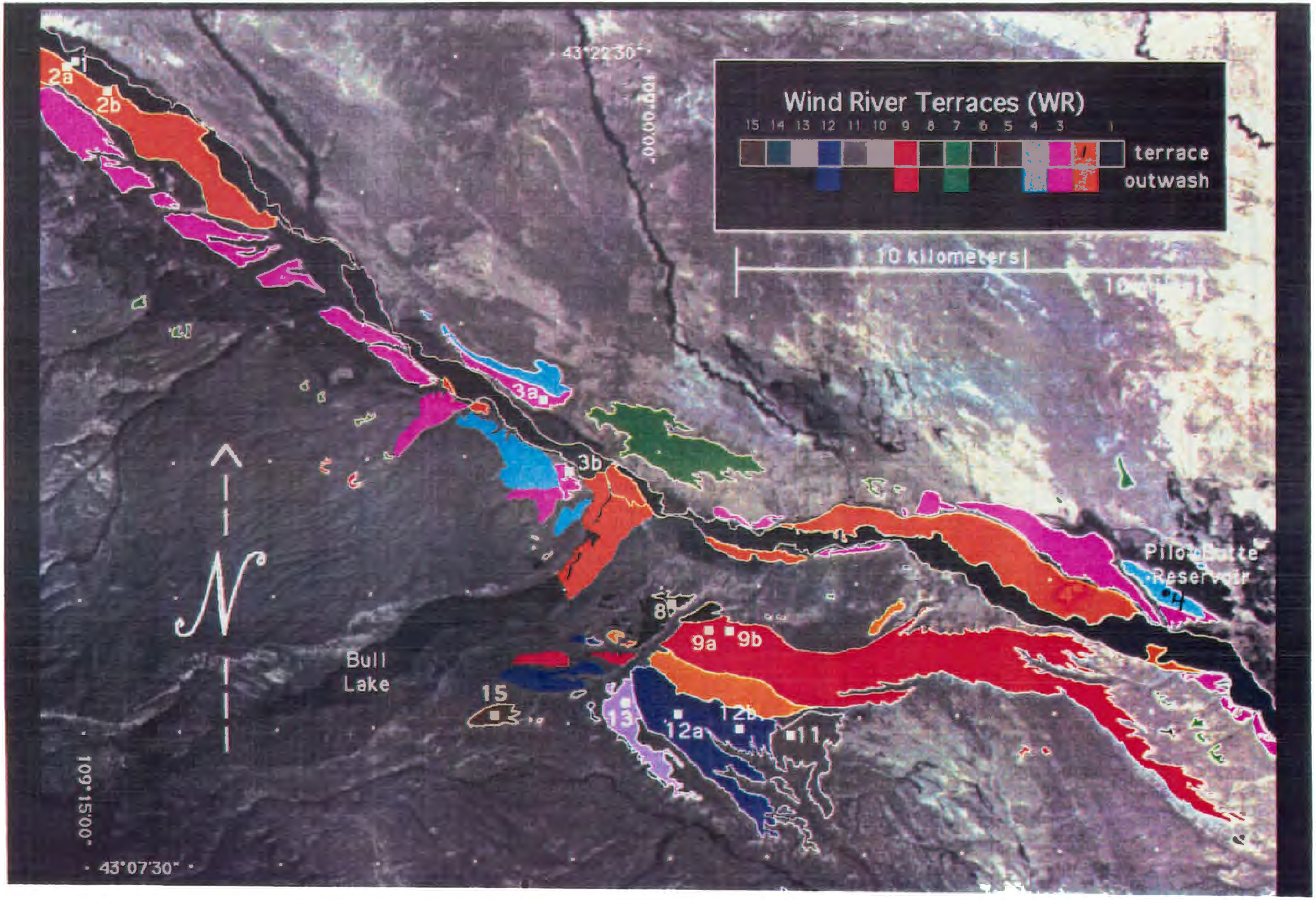

Wind River Terraces (WR)
15 14 13 12 11 10 9 8 7 6 5 4 3 1
terrace
outwash
10 kilometers
10
43°22'30"
109°00'00"
2a
2b
1
3a
3b
8
9a
9b
11
12a
12b
13
15
4
Bull Lake
Pilot Butte Reservoir
N
109°15'00"
43°07'30"

Table 4. Soils classifications at each site.

| SITE | AGE(ky) | SOIL CLASSIFICATION |
|---|---|---|
| 0 | flood plain | Sandy-Skeletal, mixed, frigid Typic Camborthid |
| 1a | 18 | Sandy-Skeletal, mixed, frigid Typic Camborthid |
| 1b | 18 | Sandy-Skeletal, mixed, frigid Typic Camborthid |
| 3a | 100 | Loamy-Skeletal, mixed, frigid Typic Calciorthid |
| 3b | 100 | Loamy-Skeletal, mixed, frigid Typic Calciorthid |
| 4 | 130 | Fine-Loamy, mixed, frigid Typic Haplargid |
| 8 | 870 | Fine-loamy, mixed, frigid Typic Haplargid |
| 9a | 950 | Fine-Loamy, mixed, frigid Typic Haplargid |
| 9b | 950 | Fine-Loamy, mixed, frigid Typic Haplargid |
| 11 | 1090 | Fine-loamy, mixed, frigid Typic Haplargid |
| 12a | 1110 | Fine-loamy, mixed, frigid Typic Haplargid |
| 12b | 1110 | Coarse-Loamy, mixed, frigid Typic Haplargid |
| 13a | 1320 | Fine-loamy, mixed, frigid Typic Haplargid |
| 13b | 1320 | Fine-loamy, mixed, frigid Typic Haplargid |
| 15 | 1740 | Fine-loamy, mixed, frigid Typic Haplargid |

Bulk samples were taken by genetic horizon and stored in plastic bags. An estimate of the > 2 mm fraction was made on all profiles on a volume basis and an actual measurement was taken on a few selected sites. Complete soil descriptions can be found in Appendix A.

Carbonate morphology was noted and carbonate pendants on clasts were chipped off and added to the sample. If this was not done I would be under-estimating the total carbonate in the profile by leaving it out of the sample.

## LABORATORY METHODS

For chemical analysis the soils were ground with a mechanical soil grinder and passed through a 2 mm sieve and stored in sample bags. Subsamples of the < 2 mm fraction were then taken to perform the analysis. The results of the general laboratory analysis are shown in Appendix B.

The soil pH was taken from a saturated paste of the < 2 mm fraction. The paraffin covered clod method (Blake and Hartge, 1986) was used to determine bulk density on some samples and calculated by interpolation for a bulk density estimate of the rest (estimated values are shown to 0.1 g $cm^{-3}$ in Appendix B). Particle size analysis was performed by a pipette method adapted from Day (1965) and Green (1981). Total sand (>50um), silt sizes of 50-20 um, 20-5 um, 5-2 um and clay (< 2um) fractions were calculated.

An acid neutralization method was used to determine $CaCO_3$ percentage. A known amount of $H_2SO_4$ (approx. 0.4 N) was added to the sample to neutralize the carbonate and the excess acid was back titrated with standardized HCl (approx. 0.4 N)(Workman et al., 1988).

Percent gypsum was also determined in several sites also by a dilution method (U.S. Salinity Lab Staff, 1954).

Total free Fe oxides were determined by Dithionite Citrate (DC) extraction (Soil Surv. Lab Staff, 1992). Dithionite reduces the Fe in the oxides to $Fe^{2+}$. Citrate can then chelate the $Fe^{2+}$ to keep it in solution at which point it can be read by AA or ICP. I used an Inductively Coupled Plasma Spectrometer for all Iron analysis. Paracrystalline and partial organically bound iron was extracted by the Acid-Oxalate/dark method (Soil Surv. Lab Staff, 1992). Pyrophosphate extraction was used to extract the total organically bound iron fraction (Soil Surv. Lab Staff, 1992). Along with the selective extractions the Oxalate Fe : DC Fe ratio was calculated to estimate the degree of iron oxide crystallinity (McFadden and Hendricks, 1985).

Total organic carbon was analyzed by the wet digestion method (Snyder and Trofymow, 1984). In this method inorganic carbon is destroyed by the addition of 1 M $H_2SO_4$ and $FeSO_4$. The remaining organic sample is digested with $H_2SO_4$ and dichromate. The oxidized carbon in the form of $CO_2$ is trapped in a NaOH trap of known volume and concentration, the remaining NaOH is titrated with 0.1 M HCl and the total organic carbon is calculated.

Using total profile content of some soil constituents is a more realistic way to make comparative judgements (McFadden and Hendricks, 1985) and is calculated by multiplying the percentage by the bulk density (volume factor) and then by horizon thickness. The sum of the values for each horizon in the pedon to a common depth is then considered the total profile content. In most situations a backhoe was used for excavating pits so 2 m depths were used for greater accuracy in calculating total profile contents.

In preparation for silicate mineralogy samples were pretreated with HOAC/NaOAC at pH 5 to destroy carbonates (Rabenhorst and Wilding, 1984) and also with $NaClO_3$ at pH 9 to destroy organic material (Anderson, 1963). The > 0.05 mm fraction (sand) was separated with a sieve and the silt and clay fractions were separated using centrifugation with the application of Stokes law (Whittig, 1965).

Clay samples were saturated with K and duplicate samples were saturated with Mg by using a Buchner microfiltration apparatus with 0.45 um cellulose filters. The K or Mg saturated samples were then transferred to microscope slides for oriented clay analysis on a General Electric XRD-700 X-Ray diffractometer. Treatments for the K saturated slides included samples at 1-3% moisture and were scanned at 4° 2 theta to 14°, samples that were heated to 550° C were scanned in the same range. Magnesium saturated samples were equilibrated/solvated in three treatments including $Mg(NO_3)_2$, Ethylene Glycol and Glycerol. These were scanned at 3° 2 theta to 30° for $Mg(NO_3)_2$, and 3° to 14° for the later two treatments. Using a quartz standard, relative amounts of various clay species were determined from peak heights.

# CHAPTER 3

# RESULTS AND DISCUSSION

## RESULTS

### SOIL MORPHOLOGICAL PROPERTIES

All of the soil profiles contained at least 2 textural discontinuities (Table 5). The most significant discontinuity that was common to all sites was the decrease of finer particle sizes and increase in > 2 mm fraction at depths from 30 to 40 cm. Beds in the alluvium contained sorted, rounded gravels, cobbles and stones that ranged in size from 1 to 30 cm in all sites.

The thickness of the A horizon is quite variable relative to terrace age. There is consistency, however, between sites on terraces of the same age, except for terraces WR1 and WR12 where the A horizon thicknesses differ.

Thickness of B horizons is also variable (Table 6). Site 0 on the floodplain has the thinnest B horizon at 13 cm. All sites older than the floodplain have B horizons between 124 and 243 cm with a high degree of variability between sites.

Carbonate found in these soils has two distinct morphological forms. It is disseminated in the finer fractions of the soil matrix and as rinds on the undersides of larger clasts (gravels-stones). Rinds on clasts of younger (e.g. WR2 soils) soils are a few mm thick and those on clasts in older soils (e.g. WR9 soils) may reach several

Table 5a. Morphological properties of representative soil profiles.
Site 1b, 10 ky

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES (Carbonate Stage) |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-14 | 10YR 6/2 | 10YR 4/2 | SL | 1 f vf sbk/<br>1 vf gr | 5 G | ev | CS | |
| ABk | 14-26 | 10YR 6/2 | 10YR 4/2 | SL-L | 1 f vf sbk | 5 G | ev | CS | |
| Bk1 | 26-42 | 10YR 5/2 | 10YR 4/3 | L | 1 f vf sbk | 5G | ev | CS | |
| 2Bk2 | 42-56 | 10YR 5/3 | 10YR 4/3 | vgLS | M | 40G/5C | ev | CW | |
| 2Bk3 | 56-83 | 10YR 6/2 | 10YR 5/2 | vgS | M | 40G/10C | ev | CW | All clasts have continuous CaCO3 coats < 0.5 mm thick (II) |
| 3Bk4 | 83-119 | 10YR 6/2 | 10YR 4/2 | egS | SG | 60G/10C | es/ev | CW | " (II) |
| 4Bk5 | 119-147 | 10YR 6/2 | 10YR 3/2 | ecS | M | 40G/30C | ev | CW | 70% of clasts have thin patchy CaCO3 coatings on bottoms (I) |
| 4Bk6 | 147-190 | 10YR 6/2 | 10YR 4/2 | ecS | M | 40G/30C | e/es | | " (I) |

Table 5b. Site 3b, 100 ky

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES (Carbonate stage) |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-4 | 10YR 3/2 | 10YR 4/2 | fSL | 1 f vf sbk/gr | 5G | eo | CS | |
| BA | 4-12 | 10YR 5/3 | 10YR 4/3 | L | 1 m f sbk | 5G | eo | CS | |
| Bw | 12-19 | 10YR 3/3 | 10YR 4/3 | L | 1 m f sbk | 5G | eo | CW | |
| 2Bk1 | 19-27 | 10YR 4/3 | 10YR 5/3 | SL | 1 m f sbk | 5G/5C | es | CS | Disseminated carbonate throughout (II) |
| 2Bk2 | 27-42 | 10YR 4/3 | 10YR 5/3 | SL | 1 m f sbk | 10G/5C | es | CW | good K fabric (III) |
| 3Bkm | 42-58 | 10YR 6/2 | 10YR 7/2 | LS | M | 25G/10C | ev | CW | Clast coatings are 0.3-0.5 cm thick (III)<br>90% of matrix cemented |
| 3Bkq1 | 58-96 | 10YR 4/2 | 10YR 6/2 | S | M | 40G/30C/5S | ev | CW | All clasts coated w/ carbonate (III)<br>75% of matrix cemented |
| 3Bkq2 | 96-136 | 10YR 4/2 | 10YR 5/1 | S | M | 30G/50C/5S | e-es mat.<br>ev clast | CW | Clasts have discontinuous carbonate coats (II)<br>0.1-0.5 cm thick, little carb. in matrix |
| 3BCk | 136-210+ | 10YR 4/2 | 10YR 5/1 | S | M | 40G/40C/5S | eo-e mat.<br>ev clast | | |

Table 5c. Site 4, 130 ky

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-10 | -- | 10YR 4/3 | SL | 1 f sbk | 5g | e | CS | |
| ABtk | 10-22 | -- | 10YR 4/3 | SL | 2 m sbk | 5g | es | CS | |
| Btk1 | 22-38 | -- | 10YR 4/3 | SL | 2 m abk | 5g | es | CS | |
| 2Btk2 | 38-46 | -- | 10YR 4/3 | SL | 1 f sbk | 25g | ev | CW | disseminated carbonate (II) |
| 3Bkm | 46-80 | 10YR 6/2 | 10YR 4/2 | LS | M | 30G/30C | ev | CW | cementing in matrix (III) |
| 3Bk1 | 80-105 | 10YR 6/2 | 10YR 4/2 | S | M | 40G/30C | es | CW | All clasts coated with carbonate (III) |
| 4Bk2 | 105-164 | 10YR 6/2 | 10YR 4/2 | S | M | 50G/25C | e | CI | Partial coating of clasts (II) |
| 4BCk | 164-210 | 10YR 6/2 | 10YR 4/2 | S | M | 50G/25C | eo-es | | |

Table 5d. Site 9a, 950 ky

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES (Carbonate stage) |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-7 | 10YR 6/3 | 10YR 4/3 | vfSL | 1 f vf sbk<br>1 m gr | 5G/5C | eo | CS | |
| Bt1 | 7-15 | 10YR 4/4 | 10YR 3/4 | SCL | 2 mf abk | 5G/5C | eo | CW | |
| Bt2 | 15-29 | 10YR 4/4 | 10YR 3/4 | SCL | 2 m pr/<br>2 c m abk | 5G/5C | eo | CW | |
| 2Bk1 | 29-41 | 10YR 7/3 | 10YR 5/3 | SCL | 2 m f abk | 10G/10C | ev | CI | There is a stoneline between horizons 3 and 4 |
| 2Bkm | 41-69 | 10YR 8/2 | 10YR 7/3 | gSL | M | 15G/5C | ev | CW | |
| 3Bk2 | 69-112 | 10YR 8/2 | 10YR 7/3 | ecS | M | 30G/35C | ev | CW | Most clasts have carbonate pendants 5-10 cm thick, some dissemination in matrix (III) |
| 3Bk3 | 112-186 | 10YR 5/2 | 10YR 4/2 | ecS | SG | 30G/40C | eo mat.<br>ev clast | CW | Most clasts have carbonate pendants 2-5 cm thick (III) |
| 3C | 186-215 | 10YR 5/2 | 10YR 4/2 | vcS | SG | 25G/25C | eo mat.<br>ev clast | | Pendants less than 1 cm thick |

Table 5e. Site 12b, 1110 ky

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES (Carbonate Stage) |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-17 | 10YR 4/3 | 10YR 3/3 | SL | 1 f vf sbk/<br>1 f gr | 5G | e | CS | |
| Bt | 17-36 | 10YR 5/3 | 10YR 4/3 | SL | 2 m abk | 5G | es | CS | CLAY FILMS (I) |
| Btk | 36-49 | 10YR 5/3 | 10YR 4/3 | SL | 1 m f sbk | 10G | es | CS | CLAY FILMS (I) |
| Bkm | 49-85 | 10YR 7/3 | 10YR 6/3 | gSL | M/pl | 15G | ev | CS | K fabric but not indurated (III) |
| 2Bk1 | 85-125 | 10YR 6/3 | 10YR 4/3 | vcLS | M | 35G/25C | ev | CW | carbonate coatings on clasts (III) 0.25-2.0 cm thick |
| 2Bk2 | 125-152 | 10YR 6/2 | 10YR 4/2 | ecLS | M | 40G/35C | es-ev | CW | carbonate coatings on clasts (III) 0.1-0.5 cm thick |
| 2Bk3 | 152-205 | 10YR 6/2 | 10YR 4/2 | ecS | M | 50G/35C | eo-ev | CW | carbonate coatings on clasts (II) 0.1-0.5 cm thick |
| 2Bk4 | 205-260 | 10YR 6/2 | 10YR 4/2 | ecS | M | 45G/40C | eo-es | | |

Table 6. Comparison of horizon thicknesses and depths in cm.

| Site | Age | A Horizon thickness | Bk Horizon | Bt Horizon | Depth to max carbonate | Depth to induration |
|---|---|---|---|---|---|---|
| 0 | present | 7 | 13 | - | - | - |
| 1 | 10 | 9±2 | 155±12 | - | 32.5±9 | - |
| 3 | 100 | 4±0 | 174±70 | - | 28±5 | 39±4 |
| 4 | 130 | 10 | 142 | 24 | 38 | 46 |
| 8 | 870 | 5 | 128+ | 36 | 53 | 41 |
| 9 | 950 | 7±0 | 192±17 | 23±1 | 39±2 | 39±2 |
| 11 | 1090 | 6 | 219 | 28 | 34 | 34 |
| 12 | 1110 | 12±6 | 200±60 | 30±2 | 48±1 | 48±1 |
| 13 | 1320 | 7±0 | 175 | 47±1 | 54±1 | 77±31 |
| 15 | 1740 | 6 | 217 | 25 | 81 | 57 |

cm in thickness (table 5). The K horizon designation was formulated by Gile et al. (1965) and implies the presence of a strong "K fabric" in which authigenic carbonate occurs as an essentially continuous medium. Some macroscopic forms of the K fabric are laminar, nodular, cylindroidal, massive, blocky, and platy (Gile and Grossman, 1979), of which massive is the most widely exhibited form in soils of this study. Table 5 shows stage designations for each horizon of the five representative sites.

Depth to cemented horizons (Table 6) is variable. All sites fall between 36 and 57 cm. Carbonate is the primary cementing agent but silica is also responsible. In site 13b the depth to induration is at 100 cm which is roughly twice that of all other sites. Induration in the soils of this study is relatively slight compared to that found in the hot deserts by Gile and Grossman (1979). These soils have only thin cemented horizons that are not 100% cemented (Appendix A).

## SOIL CHEMICAL PROPERTIES

Soil pH at all sites is lowest in the upper horizons and increases with soil depth (Table 7). The A horizon of several sites and specifically the six oldest sites (1090-1740 ky) has pH values just below 7. This property is variable between sites (sites 3a and 8 also have pH below 7) but does show a decreasing trend with age, a decrease of pH in A horizons from around 7.0-7.5 to 6.7-7.0. The pH of all

Table 7a. Physical and chemical properties of representative soil profiles; bulk density is in grams per cubic centimeter

* 3 significant digits indicate lab values, second decimal place is not significant.

Site 1b, 10 ky

| | | | paste | | Sand | Silt | | | Clay | *Bulk |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | | 50-20u | 20-5um | 5-2um | <2.0um | Dens. |
| DEPTH (cm) | HORIZON | % | | % | % | | | | | |
| 0 - 14 | A | 0.91 | 7.7 | 7.9 | 58.6 | 15.6 | 8.1 | 3.6 | 14.0 | 1.2 |
| 14 - 26 | ABk | 0.62 | 7.7 | 7.7 | 50.9 | 17.5 | 10.5 | 4.8 | 16.3 | 1.3 |
| 26 - 42 | Bk1 | 0.48 | 7.9 | 8.0 | 47.0 | 16.9 | 12.6 | 6.0 | 17.5 | 1.3 |
| 42 - 56 | 2Bk2 | 0.36 | 8.0 | 4.1 | 89.0 | 2.8 | 2.6 | 0.4 | 5.2 | 1.4 |
| 56 - 83 | 2Bk3 | 0.29 | 7.9 | 4.6 | 93.0 | 1.6 | 1.8 | 0.3 | 3.3 | 1.5 |
| 83 - 119 | 3Bk4 | 0.18 | 7.8 | 3.2 | 96.1 | 1.4 | 0.6 | 0.3 | 1.5 | 1.6 |
| 119 - 147 | 4Bk5 | 0.21 | 8.3 | 4.1 | 95.3 | 2.5 | 0.5 | 0.3 | 1.4 | 1.6 |
| 147 - 190 | 4Bk6 | 0.4 | 8.5 | 4.2 | 95.8 | 2.4 | 0.5 | 0.2 | 1.1 | 1.6 |

Table 7b. Site 3b, 100 ky

| DEPTH (cm) | HORIZON | TOC<br>% | paste<br>pH | CaCO3<br>% | Sand | ----Silt----<br>50-20u | <br>20-5um | <br>5-2um | Clay<br><2.0um | *Bulk<br>Dens. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | ---- | ---- | ----%---- | ---- | ---- | |
| 0 - 4 | A | 0.21 | 7.1 | 0.2 | 52.0 | 18.3 | 8.6 | 4.8 | 16.4 | 1.2 |
| 4 - 12 | BA | 0.91 | 7.2 | 0.4 | 50.2 | 17.0 | 9.1 | 5.0 | 18.7 | 1.36 |
| 12 - 19 | Bw | 0.93 | 7.5 | 1.2 | 51.8 | 15.8 | 9.1 | 5.0 | 18.2 | 1.38 |
| 19 - 27 | 2Bk1 | 0.3 | 7.7 | 4.0 | 55.9 | 18.2 | 10.5 | 6.0 | 9.4 | 1.3 |
| 27 - 42 | 2Bk2 | 0.2 | 7.6 | 20.2 | 59.2 | 15.2 | 7.4 | 3.7 | 14.5 | 1.3 |
| 42 - 58 | 3Bkm | 0.13 | 8.2 | 30.6 | 86.6 | 4.8 | 2.7 | 0.2 | 5.6 | 1.29 |
| 58 - 96 | 3Bkq1 | 0.13 | 8.2 | 14.5 | 95.2 | 1.4 | 1.0 | 0.1 | 2.3 | 1.4 |
| 96 - 136 | 3Bkq2 | 0.1 | 8.5 | 6.7 | 94.8 | 2.1 | 1.1 | 0.2 | 1.8 | 1.6 |
| 136 - 210+ | 3BCk | 0.12 | 8.5 | 6.7 | 95.2 | 1.9 | 1.1 | 0.2 | 1.7 | 1.7 |

Table 7c. Site 4, 130 ky

| DEPTH (cm) | HORIZON | TOC % | paste pH | CaCO3 % | Sand | Silt | | | Clay | *Bulk |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 50-20um | 20-5um | 5-2um | <2.0um | Dens. |
| | | | | | % | % | % | % | % | |
| 0 - 10 | A | 0.77 | 7.5 | 2.9 | 51.9 | 11.0 | 8.8 | 5.4 | 22.8 | 1.36 |
| 10 - 22 | ABtk | 0.75 | 7.8 | 4.2 | 45.8 | 10.9 | 9.0 | 5.1 | 29.2 | 1.36 |
| 22 - 38 | Btk1 | 0.65 | 8.0 | 5.6 | 50.2 | 10.3 | 9.4 | 5.6 | 24.5 | 1.38 |
| 38 - 46 | 2Btk2 | 1.19 | 8.1 | 20.4 | 62.6 | 8.2 | 6.5 | 3.3 | 19.4 | 1.3 |
| 46 - 80 | 3Bkm | 0.86 | 8.1 | 21.1 | 82.7 | 5.8 | 3.6 | 0.8 | 7.1 | 1.29 |
| 80 - 105 | 3Bk1 | 0.92 | 8.0 | 12.2 | 91.9 | 3.7 | 1.2 | 0.8 | 2.4 | 1.4 |
| 105 - 164 | 4Bk2 | 0.14 | 8.3 | 3.9 | 96.3 | 2.5 | 0.4 | 0.4 | 0.4 | 1.5 |
| 164 - 210 | 4BCk | 0.18 | 7.9 | 5.9 | 96.9 | 2.5 | <0.1 | 0.6 | 0.1 | 1.6 |

Table 7d. Site 9a, 950 ky

| | | | paste | | | Sand | --------Silt-------- | | | Clay | *Bulk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | CaSO4 | | 50-20um | 20-5um | 5-2um | <2.0um | Dens. |
| DEPTH (cm) | HORIZON | % | | % | % | ----------------- | ----------------- | ----------------- | % | ----------------- | |
| 0 - 7 | A | 0.96 | 7.4 | 0.7 | 0.05 | 57.8 | 15.1 | 8.1 | 2.7 | 16.3 | 1.2 |
| 7 - 15 | Bt1 | 0.79 | 6.7 | 0.6 | 0.15 | 46.2 | 12.7 | 9.2 | 3.7 | 28.1 | 1.4 |
| 15 - 29 | Bt2 | 0.82 | 7.3 | 1.1 | 0.2 | 49.5 | 12.5 | 8.0 | 3.3 | 26.7 | 1.45 |
| 29 - 41 | 2Bk1 | 0.89 | 7.7 | 23.2 | 1.07 | 61.3 | 10.3 | 7.0 | 2.3 | 19.2 | 1.49 |
| 41 - 69 | 2Bkm | 0.97 | 8.0 | 48.2 | 0.12 | 72.8 | 7.2 | 7.6 | 1.3 | 11.1 | 1.29 |
| 69 - 112 | 3Bk2 | 0.45 | 8.3 | 12.3 | 0.27 | 90.5 | 2.5 | 2.6 | <0.1 | 4.5 | 1.6 |
| 112 - 186 | 3Bk3 | 0.05 | 8.4 | 8.4 | 0.13 | 95.4 | 1.1 | 0.8 | 0.2 | 2.5 | 1.7 |
| 186 - 215 | 3C | 0.17 | 8.4 | 5.2 | 0.15 | 93.4 | 1.9 | 1.5 | <0.1 | 3.2 | 1.7 |

Table 7e. Site 12b, 1110 ky

| DEPTH (cm) | HORIZON | TOC % | paste pH | CaCO3 % | Sand | Silt | | | Clay | *Bulk Dens. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 50-20um | 20-5um | 5-2um | <2.0um | |
| | | | | | % | | | | | |
| 0 - 17 | A | 1.16 | 6.9 | 0.9 | 55.4 | 13.5 | 8.2 | 3.7 | 19.3 | 1.34 |
| 17 - 36 | Bt | 0.95 | 7.3 | 1.7 | 53.2 | 10.8 | 6.7 | 2.9 | 26.4 | 1.41 |
| 36 - 49 | Btk | 1.25 | 7.5 | 11.7 | 56.3 | 7.4 | 6.4 | 2.9 | 27.0 | 1.64 |
| 49 - 85 | Bkm | 1.88 | 7.7 | 42.1 | 66.2 | 6.3 | 6.6 | 3.4 | 17.5 | 1.61 |
| 85 - 125 | 2Bk1 | 0.84 | 8.1 | 16.2 | 85.6 | 6.9 | 5.0 | 0.1 | 2.5 | 1.58 |
| 125 - 152 | 2Bk2 | 0.43 | 8.3 | 8.2 | 88.9 | 4.8 | 3.5 | 0.3 | 2.6 | 1.34 |
| 152 - 205 | 2Bk3 | 0.25 | 8.3 | 4.4 | 91.2 | 4.8 | 1.9 | 0.5 | 1.6 | 1.31 |
| 205 - 260 | 2Bk4 | 0.13 | 8.4 | 1.2 | 95.3 | 3.0 | 0.9 | 0.5 | 1.6 | 1.4 |

subhorizons ranges from 7.0 to 8.6 which is typical of soil solutions in equilibrium with calcium carbonate (Lindsay, 1979).

Calcium carbonate is present in the surface horizon of the younger soils (WR0-1, floodplain and 10 ky) and in site 4 (130 ky, thousands of years) and 12b (1110 ky). The younger soils, WR0 and WR1, also display a fairly even distribution of carbonate through the profile (Appendix A and B). Depth to maximum carbonate content shows a high degree of variability (Table 6), but a general increase in the depth with age is evident. Figure 5 illustrates the relationship between calcium carbonate content and soil depth as a function of age. An increase in depth to maximum carbonate concentration is evident here. Horizons in sites 9a and 12b reach close to 50 percent carbonate.

Total profile content of carbonate is plotted against soil age in Figure 6. There is a an increasing linear trend for total carbonate with soil age (carbonate enrichment) with a strong correlation ($r^2 = 0.72$). Accumulation rates for carbonate reveal a wide range with 1.1 $gm^{-2}yr^{-1}$ to 3.93 for the younger terraces (WR1, WR3 and WR4), dropping to 0.23 to 0.44 $gm^{-2}yr^{-1}$ in the older terraces (WR8 and older). Table 8 shows the rates of accumulation for carbonate, clay, and organic carbon in all sites.

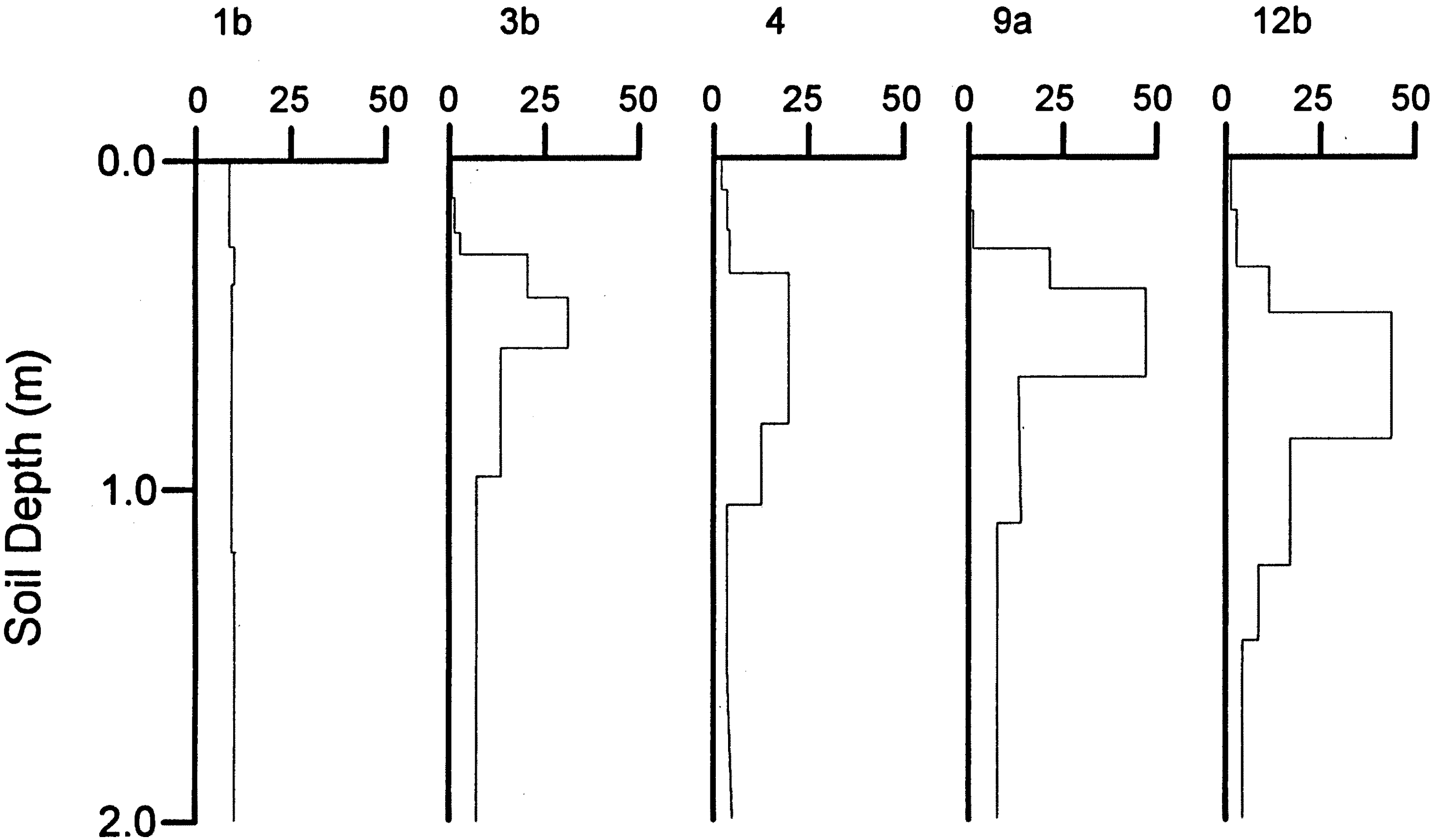


Figure 5. Carbonate percentage of < 2 mm fraction relative to soil depth and as a function of age, site 1b is 10 ky (thousands of years old), 3b is 100 ky, 4 is 130 ky, 9a is 950 ky and 12b is 1,110 ky.

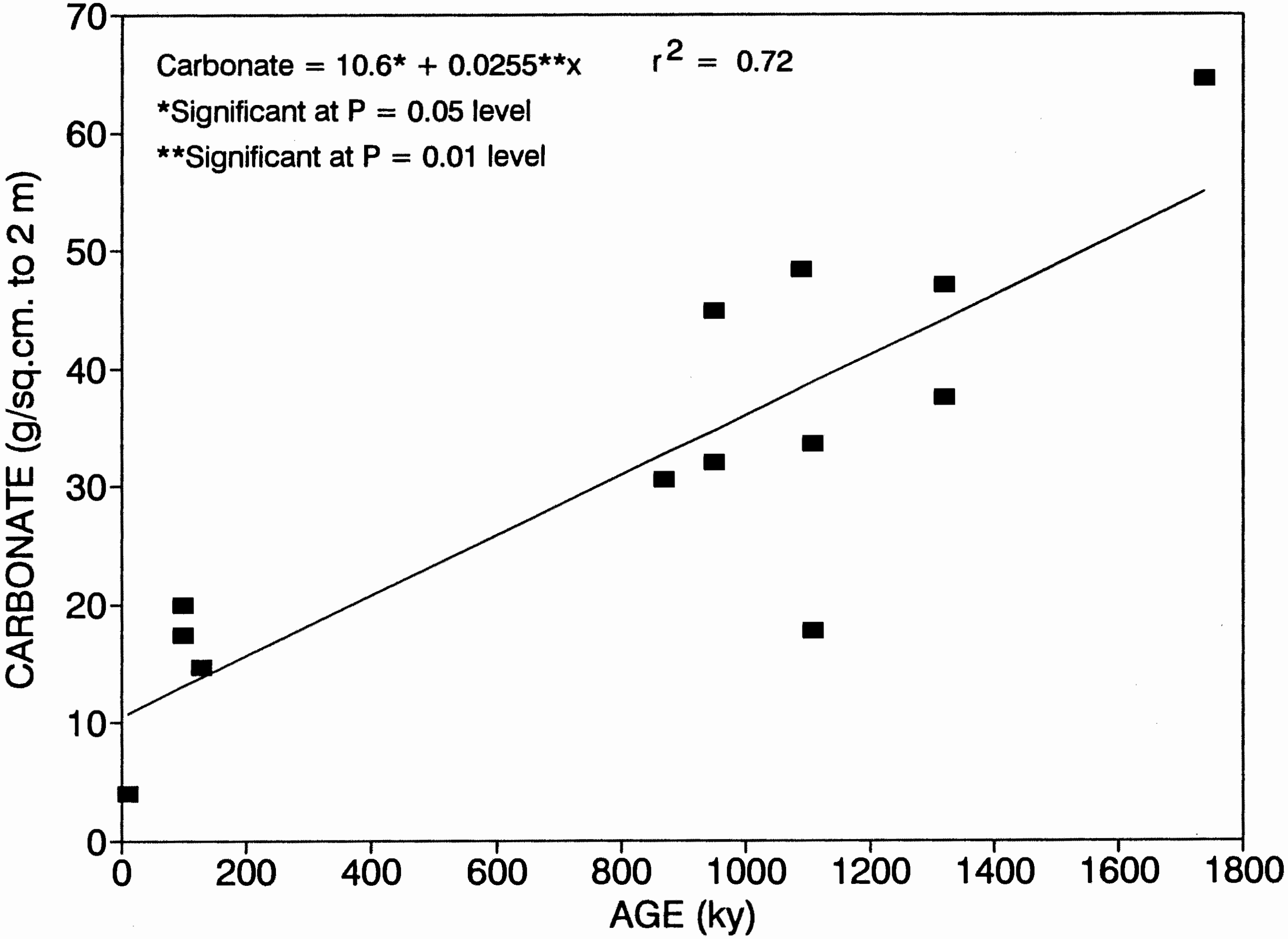


Figure 6. Relationship between total profile carbonate and soil age.

Organic carbon content increases with age in Figure 7. There is a noticeable trend with depth, with the highest amounts in the upper horizons and decreasing with depth as expected. Figure 8 shows the progression of total profile organic C through time. Relationships of soils to age are less clear with these organic C data due to high variability in total profile carbon on terraces of the same age, specifically sites 3a and 3b on WR3 and 12a and 12b on WR12. Accumulation rates for organic C range between 1.13 to 0.12 $gm^{-2}yr^{-1}$ for the younger terraces (WR1, 3, and 4) and average 0.01 in the older terraces.

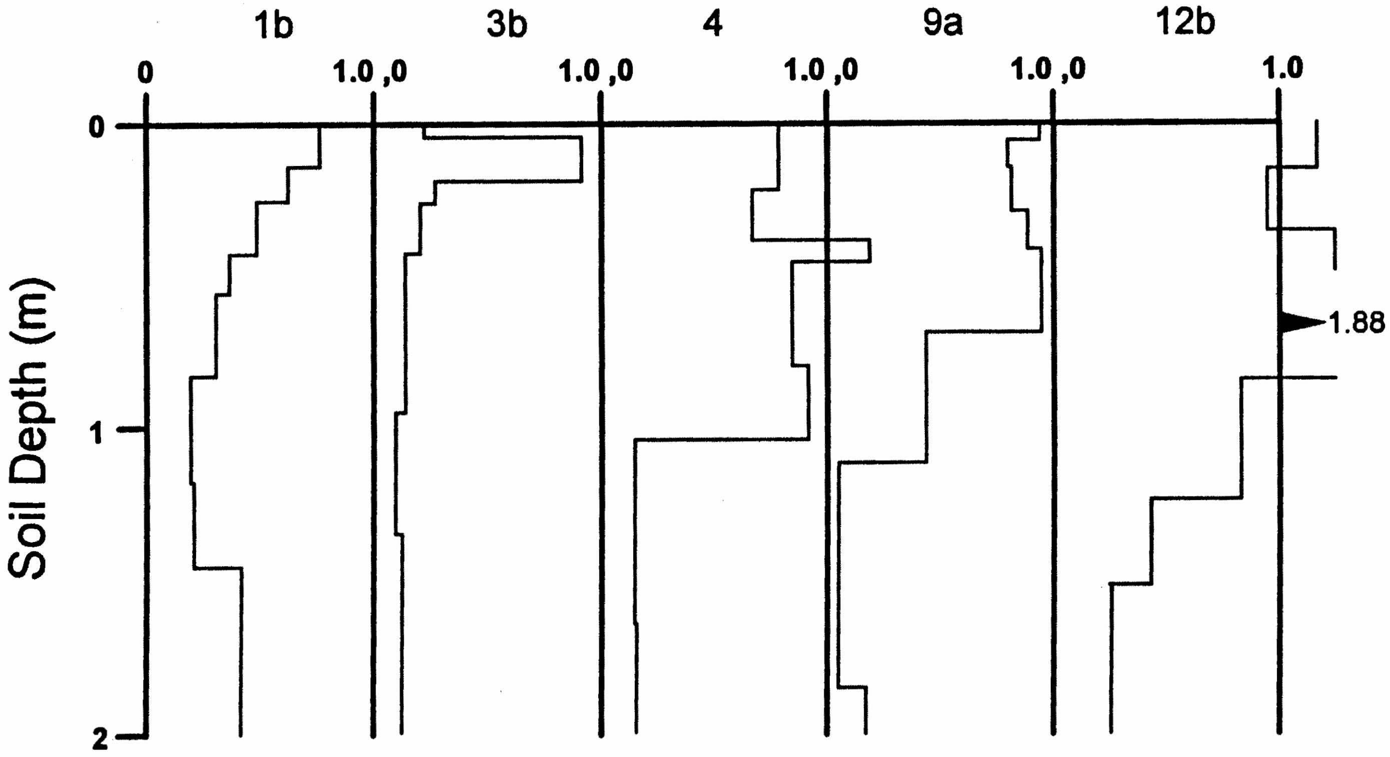


Figure 7. Organic carbon percentage of < 2 mm fraction relative to soil depth and as a function of time. Sites marked from 0 to 1 percent.

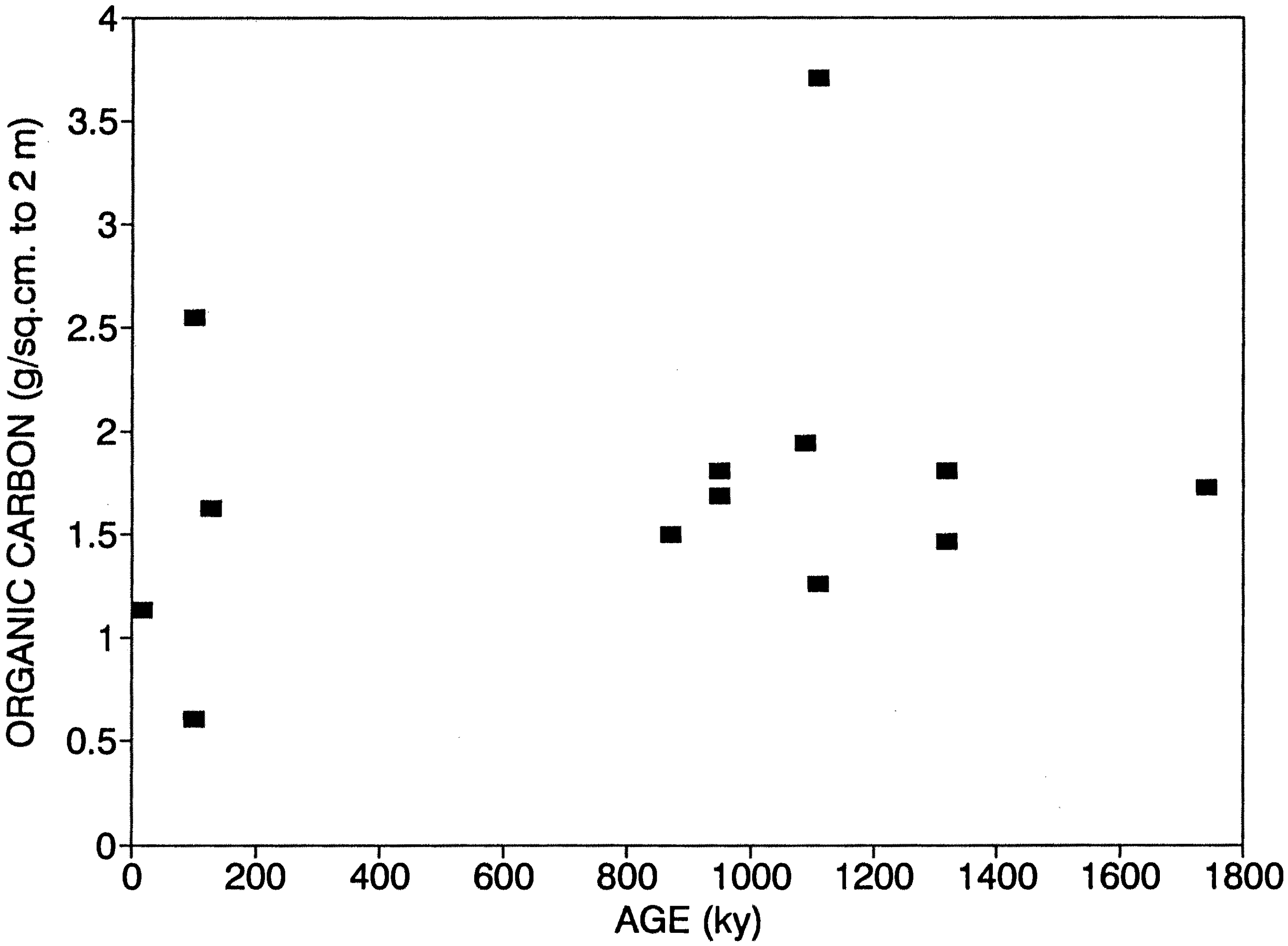


Figure 8. Relationship between total profile organic carbon and soil age.

Table 8. Accumulation rates for $CaCO_3$, organic C, and clay in g $m^{-2}$ $yr^{--1}$

| SITE | AGE (ky) | $CaCO_3$ | ORGANIC C | CLAY |
|---|---|---|---|---|
| 1b | 10 | 3.93 | 1.14 | 5.48 |
| 3a | 100 | 1.87 | 0.16 | 0.703 |
| 3b | 100 | 1.87 | 0.16 | 0.593 |
| 4 | 130 | 1.13 | 0.13 | 0.909 |
| 8 | 870 | 0.35 | 0.17 | 0.203 |
| 9a | 950 | 0.41 | 0.018 | 0.174 |
| 9b | 950 | 0.41 | 0.018 | 0.219 |
| 11 | 1090 | 0.44 | 0.018 | 0.176 |
| 12a | 1110 | 0.23 | 0.022 | 0.121 |
| 12b | 1110 | 0.23 | 0.022 | 0.211 |
| 13a | 1320 | 0.32 | 0.013 | 0.164 |
| 13b | 1320 | 0.32 | 0.013 | 0.178 |
| 15 | 1740 | 0.37 | 0.010 | 0.080 |

## SOIL MINERALOGICAL PROPERTIES

Clay distribution is significant in the upper 30-40 centimeters of all sites because of the drastic decrease in fine particle sizes at this depth (Table 7). Clay percent and distribution is uniform in the upper horizons of sites 0,1a,1b,3a and 3b (0 - 100 ky). Site 4 (130 ky) displays the first notable increase in clay percent and could likely meet the criteria for an argillic horizon.

Figure 9 shows clay content relative to soil depth as a function of time. Clay percentage increases from 17.5 percent in site 1b to 29.2 percent in the ABk of site 4. Clay percentage appears to reach a steady state in soils older than WR3 (inclusive) where argillic horizons are present.

Clay enrichment is obvious in Figure 10 where 12 sites are used to plot total profile content against age. Site 15 is an outlier where total profile clay content drops drastically. Clay accumulation rates range between 0.59 to 5.48 $gm^{-2}yr^{-1}$ in the younger terraces (WR1, 3 and 4) and between 0.12 and 0.22 for the older terraces (WR8 and older).

Only five sites were selected for mineralogical analysis of iron oxides and silicate mineralogy. Table 9 shows the results of the iron oxide analysis. Figure 11 shows the distribution of Fe(d) (total free iron oxides) with depth at five sites. There is an observable trend with depth in each site with higher amounts of Fe(d) in the upper 30 to 50 cm. This seems to correlate with the major discontinuity described previously where there is an increase in particle size at this depth. The only case in which this is not true is in site 12b where the Fe(d) decreases above the discontinuity in the Bkm (indurated) horizon.

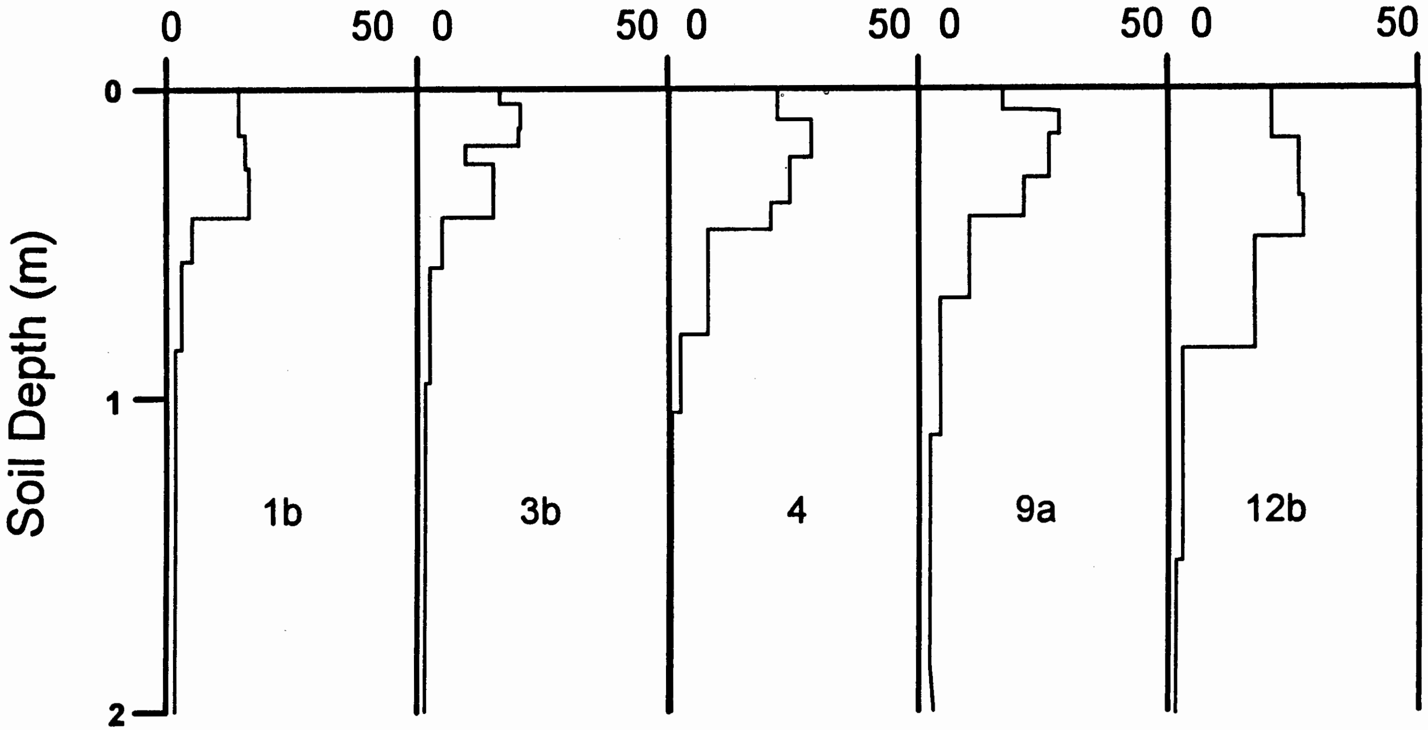


Figure 9. Clay percentage of < 2 mm fraction relative to soil depth and as a function of time. Sites marked from 0 to 50 percent.

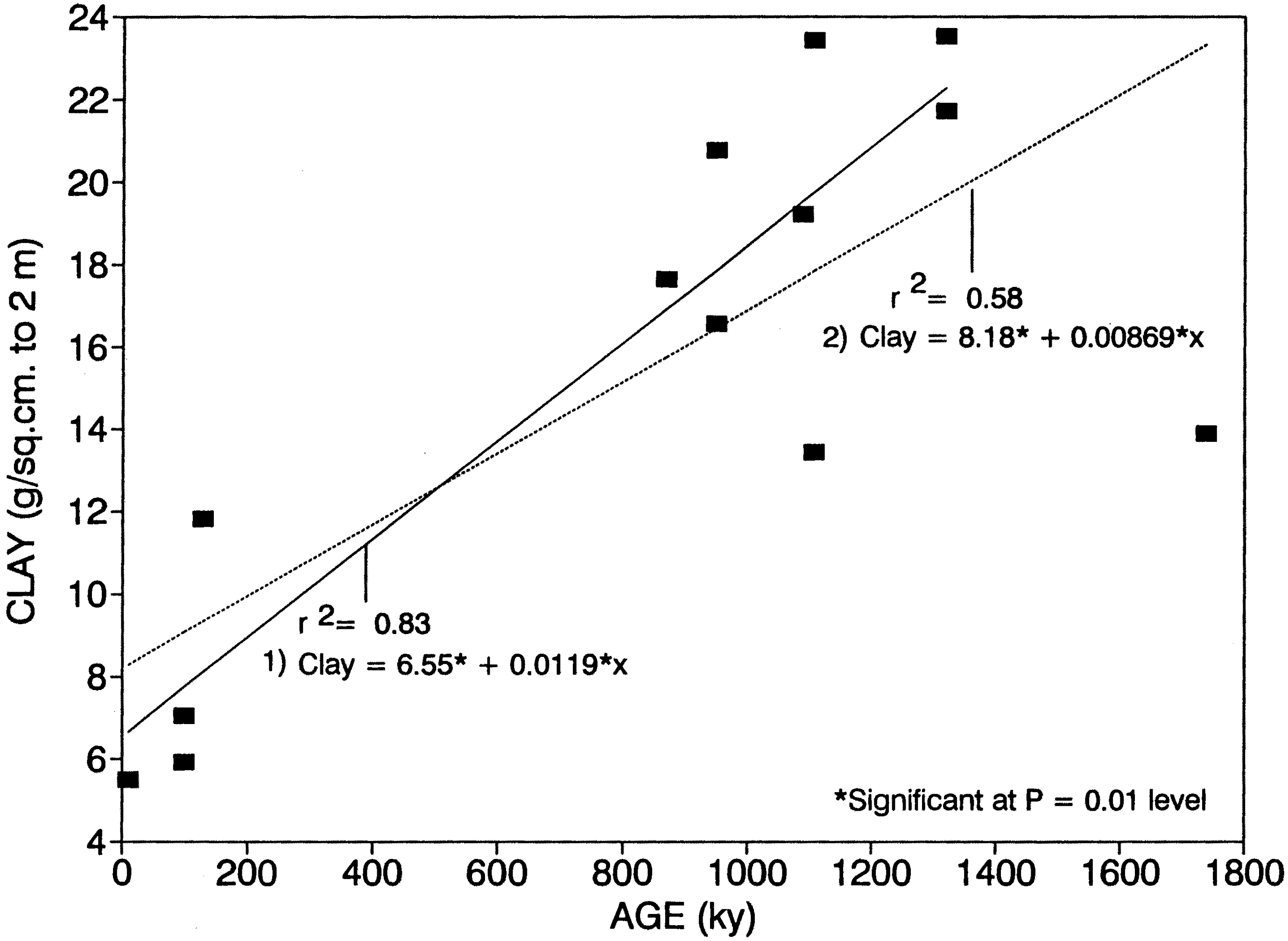


Figure 10. Relationship between total profile clay and soil age, equation 2 is calculated with site 15 outlier.

Table 9a. Selective extractions of iron oxides in five representative sites.

Site 1b, 10 ky

| DEPTH (cm) | HORIZON | DCB FE % | OXALATE Fe % | PYROPHOS. Fe % | Fe(o)/Fe(d) |
|---|---|---|---|---|---|
| 0 - 14 | A | 0.188 | 0.042 | 0.076 | 0.223 |
| 14 - 26 | ABk | 0.261 | 0.059 | 0.073 | 0.226 |
| 26 - 42 | Bk1 | 0.263 | 0.081 | 0.065 | 0.308 |
| 42 - 56 | 2Bk2 | 0.192 | 0.051 | 0.048 | 0.266 |
| 56 - 83 | 2Bk3 | 0.104 | - | - | - |
| 83 - 119 | 3Bk4 | 0.103 | 0.057 | 0.022 | 0.553 |
| 119 - 147 | 4Bk5 | 0.055 | - | - | - |
| 147 - 190 | 4Bk6 | 0.050 | 0.053 | 0.007 | 1.060 |

Table 9b. Site 3b, 100 ky

| DEPTH (cm) | HORIZON | DCB FE % | OXALATE Fe % | PYROPHOS. Fe % | Fe(o)/Fe(d) |
|---|---|---|---|---|---|
| 0 - 4 | A | 0.243 | 0.049 | 0.064 | 0.202 |
| 4 - 12 | BA | 0.234 | 0.061 | 0.100 | 0.261 |
| 12 - 19 | Bw | 0.283 | 0.053 | 0.109 | 0.188 |
| 19 - 27 | 2Bk1 | 0.238 | 0.038 | 0.087 | 0.160 |
| 27 - 42 | 2Bk2 | 0.218 | 0.022 | 0.071 | 0.101 |
| 42 - 58 | 3Bkm | 0.077 | 0.006 | 0.026 | 0.078 |
| 58 - 96 | 3Bkq1 | 0.091 | - | - | - |
| 96 - 136 | 3Bkq2 | 0.128 | 0.008 | 0.005 | 0.063 |
| 136 - 210+ | 3BCk | 0.080 | 0.013 | 0.001 | 0.163 |

Table 9c. Site 4, 130 ky

| DEPTH (cm) | HORIZON | DCB FE % | OXALATE Fe % | PYROPHOS. Fe % | Fe(o)/Fe(d) |
|---|---|---|---|---|---|
| 0 - 10 | A | 0.171 | 0.038 | 0.061 | 0.222 |
| 10 - 22 | ABk | 0.165 | 0.041 | 0.050 | 0.248 |
| 22 - 38 | Btk1 | 0.231 | 0.035 | 0.051 | 0.152 |
| 38 - 46 | 2Btk2 | 0.098 | 0.018 | 0.087 | 0.184 |
| 46 - 80 | 3Bkm | 0.048 | 0.009 | 0.038 | 0.187 |
| 80 - 105 | 3Bk1 | 0.064 | - | - | - |
| 105 - 164 | 4Bk2 | 0.095 | 0.007 | 0.009 | 0.074 |
| 164 - 210 | 4BCk | 0.107 | 0.008 | 0.006 | 0.075 |

Table 9d. Site 9a, 950 ky

| DEPTH (cm) | HORIZON | DCB FE % | OXALATE Fe % | PYROPHOS. Fe % | Fe(o)/Fe(d) |
|---|---|---|---|---|---|
| 0 - 7 | A | 0.202 | 0.039 | 0.047 | 0.193 |
| 7 - 15 | Bt1 | 0.311 | 0.073 | 0.132 | 0.235 |
| 15 - 29 | Bt2 | 0.288 | 0.058 | 0.153 | 0.201 |
| 29 - 41 | 2Bk1 | 0.116 | - | - | - |
| 41 - 69 | 2Bkm | 0.042 | 0.008 | 0.031 | 0.190 |
| 69 - 112 | 3Bk2 | 0.043 | - | - | - |
| 112 - 186 | 3Bk3 | 0.101 | 0.013 | 0.010 | 0.129 |
| 186 - 215 | 3C | 0.064 | 0.012 | 0.018 | 0.188 |

Table 9e. Site 12b, 1110 ky

| DEPTH (cm) | HORIZON | DCB FE % | OXALATE Fe % | PYROPHOS. Fe % | Fe(o)/Fe(d) |
|---|---|---|---|---|---|
| 0 - 17 | A | 0.254 | 0.048 | 0.146 | 0.189 |
| 17 - 36 | Bt | 0.304 | 0.042 | 0.184 | 0.138 |
| 36 - 49 | Bk1 | 0.207 | 0.027 | 0.113 | 0.130 |
| 49 - 85 | Bkm | 0.045 | 0.007 | 0.059 | 0.156 |
| 85 - 125 | 2Bk2 | 0.019 | 0.014 | 0.007 | 0.737 |
| 125 - 152 | 2Bk3 | 0.02 | - | - | - |
| 152 - 205 | 2Bk4 | 0.015 | 0.012 | 0.010 | 0.800 |
| 205 - 260 | 2Bk5 | 0.016 | - | - | - |

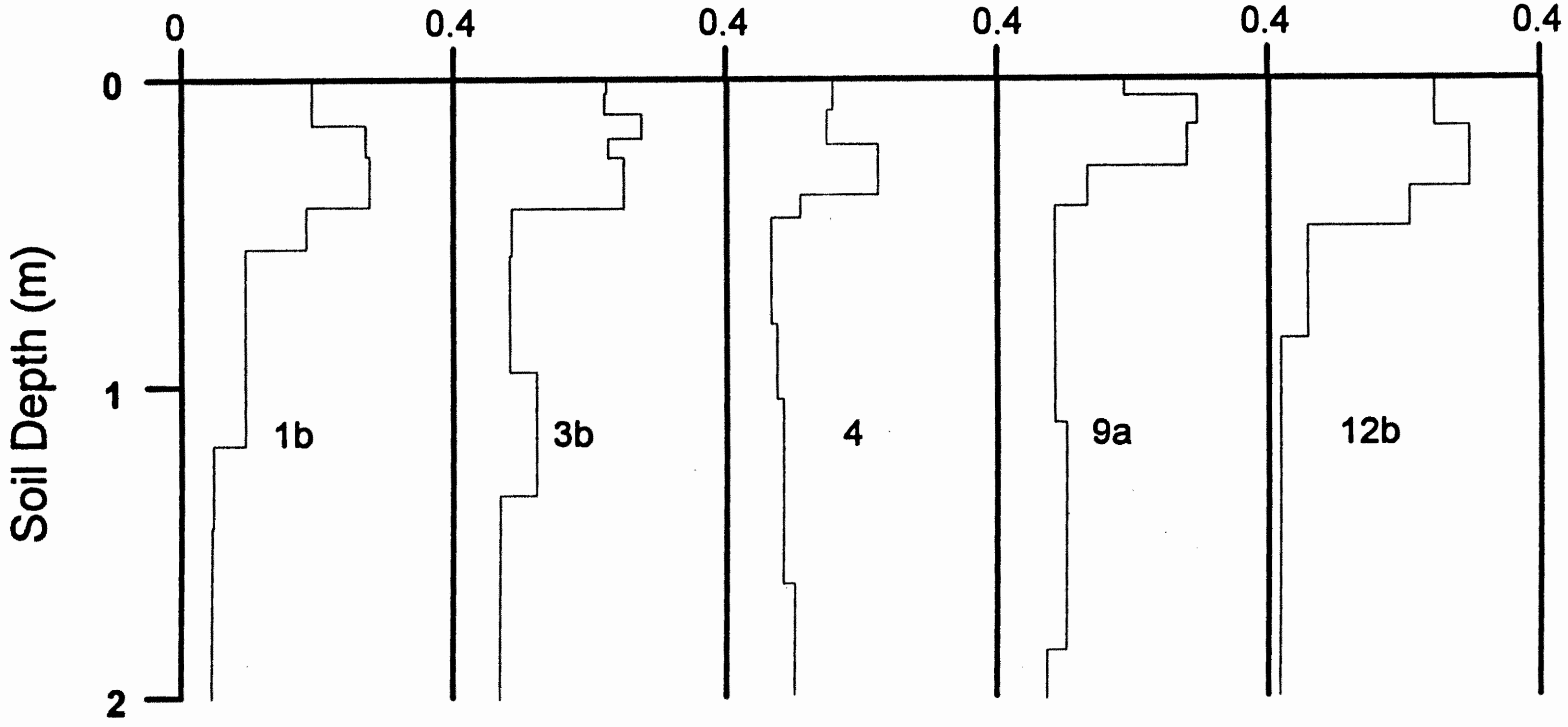


Figure 11. Dithionite Citrate extractable iron percentages of < 2 mm fraction relative to soil depth and as a function of time (carbonate free basis) . Sites marked from 0 to 0.4 percent.

Iron Oxide crystallinity is measured by the ratio Fe(o)/Fe(d) (para-crystalline/crystalline) where ratios close to 1 are relatively non-crystalline and ratios closer to 0 are more crystalline. Crystallinity values are variable within and among sites (table 9). Pyrophosphate extractable iron was also determined. This analysis is generally thought to extract only organically bound iron, however, many of the Fe(p) values were higher than the Fe(o) values which are supposed to be organic and non-crystalline iron. Our pyrophosphate extraction extracted more than just organically bound iron.

Mineralogical analysis of the clay fraction reveals a predominance of smectite in all sites (Table 10). In general, more smectite is found in the younger sites, 1b and 3b, than in the older sites but a strong trend is not observed. Mica and chlorite are both present in either small or trace amounts, however, mica shows a decreasing trend with depth in all sites. Mica-smectite and chlorite-smectite intergrades are present in small amounts in the youngest site but increase between sites 1b and 3b. Sites 3b to 12b are somewhat variable and show little change in mineralogical composition relative to the change between the 1b and 3b. Palygorskite is present in small to moderate amounts in all profiles but does not show a significant trend with time or depth. The highest amounts occur in the upper horizons of site 3b.

Table 10. Mineralogical characterization for representative sites.

| Clay mineralogy* | | | | | | | |
|---|---|---|---|---|---|---|---|
| Site | Horizon | Smectite | Mica | Chlorite | Mica-Smec. | Chlorite-Smec. | Palygorskite |
| 1b | A | XX | X | X | X | X | X |
| | ABk | XXX | X | X | X | X | X |
| | Bk1 | XXX | X | X | X | X | X |
| | 2Bk2 | XXX | tr | X | X | X | X |
| | 3Bk4 | XXX | tr | X | X | X | X |
| | 4Bk6 | XXX | tr | X | X | X | X |
| 3b | A | XX | X | X | XX | XX | XX |
| | BA | XX | X | X | XX | X | XX |
| | Bw | XXX | X | X | XX | XX | XX |
| | Bk1 | XXX | tr | X | XX | XX | XX |
| | Bk2 | XXX | tr | X | XX | XX | XX |
| | 2Bkm | XXX | tr | X | X | XX | X |
| | 2Bkq2 | XXX | tr | tr | X | X | X |
| | 2BCk | XXX | tr | tr | X | X | X |

Table 10. (cont.)

| Clay mineralogy* | | | | | | | |
|---|---|---|---|---|---|---|---|
| Site | Horizon | Smectite | Mica | Chlorite | Mica-Smec. | Chlorite-Smec. | Palygorskite |
| 4 | A | XX | X | tr | X | X | X |
| | ABtk | XX | X | * | X | X | X |
| | Btk1 | XX | X | X | XX | X | XX |
| | 2Btk2 | XX | tr | X | XX | XX | XX |
| | 3Bkm | XXX | tr | X | XX | XX | X |
| | 4Bk2 | XX | tr | X | X | X | X |
| | 4BCk | XX | tr | X | X | X | X |
| | | | | | | | |
| 9a | A | XX | X | tr | XX | XX | X |
| | Bt1 | XX | X | tr | XX | XX | XX |
| | Bt2 | XX | X | X | XX | XX | X |
| | 2Bkm | XX | tr | X | XX | XX | X |
| | 3Bk3 | XX | tr | X | X | X | X |
| | 3C | XX | tr | X | XX | XX | X |

Table 10. (cont.)

| Clay mineralogy* | | | | | | | |
|---|---|---|---|---|---|---|---|
| Site | Horizon | Smectite | Mica | Chlorite | Mica-Smec. | Chlorite-Smec. | Palygorskite |
| 12b | | | | | | | |
| | A | XX | X | X | XX | X | XX |
| | Bt | XX | tr | X | XX | XX | XX |
| | Btk | XXX | tr | X | XX | XX | X |
| | Bkm | XX | tr | X | X | X | X |
| | 2Bk1 | XX | tr | X | X | X | X |
| | 2BK3 | XX | tr | X | X | X | X |

***Designated by relative amount: *=no data, tr=trace, X=small, XX=moderate and XXX=large**
****Estimates of relative amounts of each mineral are based on the following criteria:**
**Smectite: peak at 1.53 and 1.69 nm on glycerol and glycol g2+ saturated treatment.**
**Mica: peak at 1.0 nm on Mg2+ saturated/54% R.H. treatment.**
**Chlorite: peak at 1.4 nm on K+ saturated/550 deg. C. treatment.**
**Mica-Smectite: peak at 1.94 nm on K+ saturated/1-3% R.H. treatment.**
**Chlorite-Smectite: peak at 1.2 nm on K+ saturated 1-3% R.H. treatment.**
**Palygorskite: peak at 1.04-1.05 nm on K+ saturated/1-3% R.H. treatment.**

## DISCUSSION

The experimental design of this research and the nature of the study area provide a scheme where the effects of time on soil properties can be evaluated. Dominant pedogenic and geomorphic processes and the rates of these processes can be assessed. Variations in other soil-forming factors may account for some of the variations within and among sites. Mineralogical analysis reveals a uniform alluvial and eolian parent material deposition from site to site. Climate and its resulting vegetation shows only a slight change with elevation above Wind River and should not influence the degree of weathering considerably between sites. Variations in the long term vegetation appear to have been greater within than among sites based on organic carbon data. The high degree of spatial variability in the younger sites is primarily related to differences in plant densities and distributions of plant material at the soil surface.

Many chronosequence studies are performed in areas where the weathering potential is high (high precipitation and/or temperature). Indeed, chronosequences in these climatic regimes reveal sharper and clearer trends for some soil properties than those in the opposite end of the regime such as this one. However, there are some soil properties that only chronosequences in dry and/or cool regions possess. In this study some soil properties show obvious trends with soil age while others do not.

Carbonate morphologies and amounts reveal the most noticeable trends in the series of soils used for this study. Carbonate accumulation is evident even in the youngest floodplain soil. Carbonate accumulation with soil age is consistent with results from other studies in arid regions (Gile and Grossman, 1979; Reheis, 1987b; Amundson et al., 1989). Carbonate morphologies follow the same typical development outlined by Gile and Grossman (1979) with well developed K horizons (horizons impregnated with carbonate) occurring in relatively young soils in the chronosequence. This indicates a readily available source for the necessary $Ca^{2+}$ in carbonate mineral formation which could be from two of three sources. The parent material (granitic and volcanic alluvium) is presumed to be non-calcareous. Thus the carbonate has originated from atmospheric inputs of calcium carbonate and subsequent dissolution and redistribution within the profile and/or from weathering of $Ca^{2+}$ bearing minerals and subsequent precipitation with carbonates in the soil profile. The exact contribution from each of these sources is not known and the source and quantity of dust to produce the extensive carbonate accumulations is not known either.

Gile et al. (1966) and Mcfadden and Tinsley (1985) both discount weathering of non-calcarious parent material as major sources for pedogenic calcium carbonate formation in soils. However, Boettinger and Southard (1991) suggest that most of the calcium carbonate in their study area in the Mojave Desert results from weathering of silicate minerals.

Capo and Chadwick (1993) developed a method using strontium isotopes to trace the source of calcium in soil carbonate in the New Mexico desert near Las Cruces. They found that approximately 95% of the calcium was derived from atmospheric inputs.

Although the older soils have a well developed K fabric they lack the cementation (petrocalcic horizons) found in warmer regions. Our field observations indicate that these soils possess periglacial features (Munn, 1987) and may have undergone a significant amount of freeze/thaw, inhibiting the weathering necessary to cause this extent of cementation or induration.

Stage progression develops more quickly in this area as opposed to Gile and Grossman's (1979) semi-arid area around Las Cruces. They show that soils at 25,000 to 75,000 years old have stage I, stage II in soils 200 - 400 ky and stage III in soil of mid-Pleistocene age. In this study soils of only 10,000 years have stage II carbonate and stage III at only 100 ky. Both of these areas are semi-arid and both have very gravelly soils and rates of addition are estimated to be higher in the youngest soils of the hot desert region so the reason for this difference is not known. Parent materials for these specific soils in Gile and Grossman's studyn (1979) were primarily monzonite alluvium whereas parent material in this study is igneous and volcanic alluvium.

The Bk horizons (total carbonate horizon) were extremely thick (most of the profile) and in some cases extended to the strath (e.g. site 12b). In most cases the bedrock was deeper than 2 m and we did not reach it at pit depths while carbonate was evident even at the bottom of the pit. Therefore, the actual Bk horizon thickness was not measured in these sites. When bedrock was reached at the bottom of the pit it could be assumed that carbonate horizon (Bk) depth is more a function of geologic rather than pedologic processes because it could be deeper if bedrock did not impede it.

The relationship of total profile carbonate and soil age (Figure 6) reveals a strong linear relationship, $r^2 = 0.72$, suggesting a constant addition over the chronosequence timespan. Chadwick and Davis (1990) found that soil development occurred during aeolian pulses (brought about by changing climatic conditions) in the Lahontan basin in northwestern Nevada. If the carbonate in the Wind River Basin results from dust inputs it would be possible that it could have been deposited in the same episodic manner. This could result in a "stair-step" effect on carbonate accumulation that could be revealed on a time vs. carbonate plot like the one in this study. Considering the rather "coarse resolution" of the chronosequence in this study it is difficult to reach a conclusion regarding this possibility. The idea of a stair step effect would indicate paleoclimatic variations that would make using soil properties for age determination a bit more complex for extrapolation to other areas.

Another possibility is a declining rate of calcium carbonate accumulation with soil age. Although carbonate accumulation rates are higher in the earlier part of the chronosequence than for the latter portion, I lack sufficient data for terraces between 130 ky and 950 ky. If this were the case (higher rates in younger soils), it would resemble a typical mineral weathering decreasing rate curve which would indicate the possibility that $Ca^{2+}$ originated from mineral weathering. However, considering the variability of carbonate content in older sites, it is not evident from these data.

The increase in clay content (Figure 10) can, like carbonate, be attributed to three sources: 1) formed as the result of primary mineral weathering, 2) deposited as or with the parent material, or 3) dust input on the soil surface and redistribution by illuviation.

Table 7 shows that only small amounts of clay are present in the lowest horizons which are more indicative of the original parent material. We can make the assumption that very little clay was deposited with the parent material. Evidence of illuviation is not common in this study, however, Nettleton and Chadwick (1991) found clay films in Haplargids of their study downriver near Riverton. Site 12b contained the only obvious clay films that would indicate illuviation.

A linear relationship between total profile content and soil age indicates that the addition of clay has been somewhat constant over the chronosequence. Site 15, the oldest study site, lies well off the curve. Considering the in-site variability at site 12 this is not surprising. Erosion of the soil surface could account for some of the variability. Several of the older sites; 9a, 11, 12a and 13 have stonelines most of which fall between 20 and 30 cm below the surface (Appendix A). Ruhe (1959) suggests that buried stonelines are evidence for erosion cycles where the soil surface was subjected to sheet erosion leaving a covering of coarse fragments on the surface. Subsequent periods of material deposition then buried the sheet of stones. If this concept is applied in this study then there has been at least one period of erosion and subsequent burial by dust fall on some terraces older than WR9 inclusive. The variability in clay amounts could possibly be attributed to surface erosion and subsequent depletion of clay sizes in some sites and/or to deposition of clay sizes from the result of erosional inputs in other sites. Although neither site 12b nor 15 (sites with high variability) have observable stonelines, site 12a does. Site 12a also contains the lower total profile clay of the two sites on WR12 (Appendix C) thus suggesting possible loss of clay due to surface erosion. Although site 15 (low clay content) does not have an obvious stoneline, this does not necessarily mean that erosion did not happen on this surface and it could still be responsible for the variability.

Although organic C is most dynamic in the first ten thousand years, I observed an increasing trend between site 1b and 3b (18 ky to 100 ky). On older terraces the organic carbon content is variable but there does seem to be a slight increasing trend with age. There is an obvious difference between Figure 7 which shows percentages increasing as soil age increases (using five sites) and Figure 8 showing total profile content change with age.

Other studies of long-term organic carbon reveal a decreasing trend with soil age. Jenny's (1980) theory for the decreasing C is based on the long term leaching of essential plant nutrients and thus a gradual decline in organic input. This is probably not applicable in this study because it is much too dry for leaching of any significance. A possible reason for organic carbon variability is also erosion. This would tend to strip organic C from A horizons on some pedons and deposit it on others. Erosion could also then be partly responsible for the variable A horizon thickness throughout the study area. Because of these variabilities organic C values should not be relied on heavily as an indicator of soil age in this area. The decline in addition rates of organic C in older terraces could be attributed to declines of productivity (below and above ground) due to changes in porosity and soil moisture dynamics associated with the massive accumulations of calcium carbonate in older soils.

Soil pH in subhorizons tends to be governed mostly by the presence of $CaCO_3$ which buffers the soil at a relatively high pH, usually 7.5 to 8.5. In surface horizons, specifically A horizons, carbonate has been removed in most sites and the pH is influenced by acids produced during organic matter decomposition.

Clay silicate mineralogy seems to support the assumption that mineral weathering did not contribute a significant amount of secondary materials to the soils as they aged. From a mineralogical perspective smectites would be expected to increase or at least remain stable in this environment because the leaching potential is low, leaving cations such as Mg, Fe, and Si in the soil solution. Conversely, kaolinite should not form in this environment because a high leaching regime is needed to remove basic cations from primary minerals and other clays for kaolinite synthesis (Allen and Hajek, 1989). Typically, if soils have significant mineral weathering you would expect to see decreases in relative amounts of primary minerals in the clay fraction such as mica (illite in clay fraction), feldspars and others and a relative increase in secondary minerals such as smectites, kaolinite, intergrades and others, particularly in the clay size fraction. I have not distinguished what minerals are present in the sand and silt fractions but smectites dominate the clay fraction while only trace amounts of kaolinite are present. Table 10 shows that the amounts of smectite do not change as soil age progresses, but when mounting the slides for analysis the clay amounts used were approximately equal and did not reflect actual change in clay percentage in each whole soil sample. With this semi-quantitative method relative amounts of minerals within each pedon are more reliable than relative amounts between progressively older soils. The fact that total profile clay increases with soil age (Figure 10) while all minerals listed in Table 11 stay the same relative to each other suggests that there is a proportional increase in all of these minerals as soils age.

The lack of a depleting or accumulating trend in relative amounts of minerals within the individual pedons, specifically illite and smectite, suggests that mineral weathering is not a large factor in clay accumulation. Illite is the only primary mineral of significance in the clay fraction and it shows no depletion relative to smectite, but it is in such small quantities it is unlikely that a detectable increase in smectite would be resultant from clay size illite transformations. The inability to make quantitative comparisons of clay mineralogy between sites, or by soil age, limits an interpretation of rates of specific mineral formation or addition.

Another interesting aspect of the clay mineralogy analysis is the presence of palygorskite in all sites. Palygorskite has been found to be a significant mineral in several soils of the arid western United States. Most recently Monger and Daugherty (1991) found that the palygorskite in some soils of the Desert Project (Gile and Grossman, 1979) was most likely pedogenic in origin. Amundson et. al. (1989) also reported palygorskite in some soils of the eastern Mojave Desert but did not suggest an origin. Others have also reported that palygorskite is resultant from pedogenesis (Singer and Norrish, 1974; Halitim et al., 1983) rather than from the previously thought exclusive sources of detritus from parent material and aerosolic dust inputs.

From Table 10 we can see that palygorskite is found in all sites in the study area and it is not specific to a certain depth or horizon but is present in somewhat uniform amounts throughout all the profiles. The upper portion of site 3b (100 ka) has the most palygorskite. Singer (1989) outlined several environmental factors that favor the formation and stability of palygorskite in soils. From an equilibrium standpoint, high concentrations of Mg and Si are needed along with alkaline pH conditions. These soils do have an alkaline pH (Appendix B) but Mg and Si concentrations are not known.

As a note, electron microscopy is a very useful tool in determining the origin of palygorskite. If it has formed in situ it will exhibit perpendicular fibers that grow into the soil matrix (Monger and Daugherty, 1991; Singer, 1989) and if it is not pedogenic these fibers will likely be broken and flattened. If the palygorskite is resultant from dust inputs then the dust source must have or have had a suitable environment for palygorskite stability.

The analysis of iron oxide mineralogy proved to be somewhat surprising. In most chronosequence studies there is an increase in total iron oxides even in dry climates. I did not find a change in total profile iron oxides (Table 9). Dithionite extractable (total) iron percentages are low throughout the study area (Table 9) which is also the case in the Wind River Range to the southwest where the soil parent materials are granitic and gneissic till and loess (Birkeland et al., 1989). The soils of Birkeland's et al. (1989) study revealed an increasing trend of iron oxides. The 100 cm of precipitation in the mountains is probably the most significant factor differentiating these two areas and is the likely cause for the difference because of the higher weathering potential. In another study by Birkeland et al. (1989), they found very low amounts of iron in soils from Baffin Island, Canada and only subtle increases with soil age based on an accumulation index. The climate at Baffin Island is considerably colder than in the Wind River Basin, -8 deg. C. MAT, but the precipitation was also higher at 34 cm MAP.

The climate of the Wind River Basin does not seem favorable to the formation of iron oxides which are predominantly synthesized from mineral weathering. Primary iron-bearing minerals are weathered, releasing iron into the soil solution which subsequently forms ferrihydrite, hematite, goethite, and other secondary iron minerals (Schwertmann and Fischer, 1973; Schwertmann and Taylor, 1977). It is also possible that iron oxides can be added to the soil in dust.

Iron oxide percentages (Figure 11) reveal a depth trend. The highest amounts of iron oxides are in the upper horizons of all sites and the possibility of erosion of the surfaces of the oldest soils could account for the appearance of iron depletion. Extractable iron seems to be closely associated with the finer particle sizes of the upper horizons while carbonate horizons develop in the coarser particle sizes beneath the discontinuity. It is possible that because the iron in these soils is closely associated with the finer particle sizes that it could be a result of minimal mineral weathering. Iron extractions were possibly "diluted" by the carbonate in the deeper horizons because it was not removed prior to analysis. Iron was recalculated on a carbonate-free basis (Figure 11) but it still reveals an obvious decrease at the depth of the discontinuity. Because removal of both carbonate and organic matter provide optimum conditions for Fe extraction (Jackson et al., 1986) it is possible that more iron could be retrieved from carbonate horizons if the carbonate was destroyed prior to analysis.

Iron oxide crystallinity does not indicate a significant trend with soil age. In most cases one would expect a probable decrease in crystallinity (an increasing Fe(o)/Fe(d) ratio) in the first ten thousand years of development because of the buildup of ferrihydrite (a paracrystalline mineral). One would also expect a gradual increase in crystallinity (decreasing ratio) as the ferrihydrite is converted to crystalline minerals such as hematite or goethite (McFadden and Hendricks, 1985). The crystallinity of iron seems to be somewhat variable between sites but seems to be fairly constant at a ratio of 0.2 to 0.3 in the upper horizons. The upper horizons of the oldest soil do not exceed 0.2 (Table 9), which could indicate a slight increase in crystallinity of the oldest soil. It was not possible to calculate a crystallinity value for the total profiles because we did not determine the oxalate extractable iron on all of the horizons. Extractable iron values were so low in the lower horizons that crystallinity values probably could not be trusted due to detection limits.

Although the data from the iron analysis do not directly support the dominance of either mineral weathering or dust inputs, they do imply that mineral weathering is a minimal influence on soil formation and that eolian processes, based on other data, may be a more important influence on soil formation.

# CHAPTER 4

# SUMMARY AND CONCLUSIONS

The potential application of using soils to determine soil age can be made clearer as research in wide ranges of climatic regimes is continued. The soil properties which can be used with confidence in different areas and regions of the world depend on how well we understand all of the environmental influences on the soil in the past and the present. Although the effect of time on soil properties has been extensively studied in arid regions, this study has shown that soils of cool desert environments respond differently with respect to duration of soil formation. The results of this study indicate that extrapolation of these relationships to areas outside of this region should be approached with caution.

Soils of the Wind River Basin exhibit soil properties typical of most semi-arid regions; some of these properties show increasing trends as soils age and others do not. The build up of salts, specifically calcium carbonate, is the most prominent property in these soils and reveals the strongest trend with increasing soil age. A strong linear trend suggests that the carbonate has been added to the soil at a steady rate from aerosolic additions to the soil surface. Carbonate stage progression occurs at a faster rate than in other areas (Gile and Grossman, 1979) but the lack of petrocalcic horizons suggests a possible freeze/thaw process within the soil. The possibility of input "pulses" of dust are not detectable in this study.

The accumulation of clay also reveals a linear trend supporting the steady addition concept. There is more variability than with carbonate which is attributed to erosion of some surfaces of WR9 age (950 ka) and older.

Soil organic carbon was also highly variable with soil age but did show a very general increasing trend with soil age. Variability is again attributed to erosion of WR9 surfaces and older, especially since organic C is so closely associated with the upper horizons of the profile. From this study it seems that organic C is a less reliable indicator of soil age because of its variability.

Analysis of iron oxide mineralogy indicates that it may not be a reliable indicator of soil age in this region even though it is useful in most other areas to differing extents. It seems when comparing results from this study to others that precipitation is the major influence on iron oxide mineralogy. Temperature does have an influence but to a much lesser extent. Most other chronosequence studies are in areas of higher precipitation and/or temperature while studies that have been done in lower temperatures have had higher precipitation such as Birkeland et al. (1989) in the Wind River Range and Baffin Island Canada. The decreasing trend for total profile iron with soil age may also be a result of erosion of older surfaces because the DC iron, like carbon, is at a maximum in the surface horizons. The lack of iron oxide accumulation suggested that chemical weathering was not a large contributor to soil development.

Mineralogical analysis of the clay fraction yielded data that indicated an overall chemical stability or lack of mineral transformation with time. Smectites were the dominant minerals in all sites and because all minerals stayed at the same relative amounts to each other within all sites of increasing age, we assume that all of these minerals increased as the soils aged and their most probable source was dust influx. Palygorskite was an interesting component of the clay mineralogy in that it may help in interpreting the source of other soil materials.

When applying these properties for extrapolation to other areas, calcium carbonate and clay content can be used with confidence. Organic C and Fe oxides should not be relied on heavily but can still be useful for comparisons to other studies. If erosional history is well understood iron may still possibly be a reliable age indicator in this kind of environment. This work can also provide a contrast to properties in studies in differing environments. Overall, a greater understanding of the relationships between soil properties and time in this environment should prove useful to pedologists, geologists and other scientists interested in landscape and ecosystem evolution.

Conclusions:

1. Soils on the alluvial terraces of the western Wind River Basin, Wyoming exhibit typical characteristics found in most soils of arid to semi-arid climates. A large accumulation of calcium carbonate is the most distinguishing property in all of these soils. Although precipitation is minimal in this area, clay has also accumulated in these soils. Soil pH is generally alkaline, which would be expected. Unlike some soils of warmer desert areas these soils do not exhibit evidence of iron oxide accumulations. Organic C seems to be relatively dynamic with variable amounts in the surfaces of soils throughout the study area. Clay mineralogy is dominated by smectites with smaller amounts of intergrades and palygorskite; again, typical of this environment.

2. Of the soil properties mentioned above, calcium carbonate and clay exhibit the best relationships to soil age, both with strong increasing trends. Organic carbon is difficult to relate to time in this area. Its variability between sites could be attributed to the effects of other soil-forming factors other than time, specifically climate which could have induced changes in vegetation densities or could also influence erosional processes. Iron oxides do not show any relation to time (no accumulation) in this area and thus could suggest a lack of chemical weathering. There were no depleting or accumulating trends regarding clay

mineralogy. The combination of strong linear accumulation trends for carbonate and clay and the lack of relationships for iron oxide and clay mineralogy suggest that chemical weathering has a minimal influence on the development of soils in this region. Aerosolic inputs (dust) are probably the most influential processes in soil development because dust is the most likely source of the carbonate and clay.

3. The somewhat linear trends for both calcium carbonate and clay accumulation over time indicate that these parameters may be useful in relating soil properties to time. These data could be used to quantify ages of surfaces in similar environments. The wide range in accumulation rates and in-site variability incite the need for caution when making comparisons. Overall the new understanding of the relationship between soil properties and time in this environment should prove useful for future work even if direct comparisons are difficult to draw to other areas.
It is not totally clear as to what other factors may have influenced iron oxide mineralogy in this area but it is still possible that iron oxides could be used in the same manner if all soil-forming processes are understood and accounted for.

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# APPENDIX A

## Soil Profile Descriptions

## Key to abbreviations in profile descriptions

Structure:

sbk = subangular blocky
M = massive
abk = angular blocky
gr = granular
SG = single grain
pr = prismatic
pl = platy

size:

vf = very fine
f = fine
m = medium
c = coarse
vc = very coarse

Texture:

S = sand, LS = loamy sand, L = loam, SL = sandy loam, Si = silt,
SiL = silt loam, SiC = silty clay, SCL = sandy clay loam,
SiCL = silty clay loam, SC = sandy clay

(in > 2 mm fraction):

G = gravel, C = cobble, S = stone

Eff. (effervescence):

eo = slight to no eff., e = moderate eff., es = strong eff.,
ev = very strong eff.

Bound (lower horizon boundary)

CS = clear smooth, CW = clear wavy, GW = gradual wavy,
Cl = clear irregular, GS = gradual smooth

Site 0, LN2

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-7 | 10YR 6/2 | 10YR 3/2 | fSL | 1 f sbk | 0 | e | CS | |
| Bw | 7-20 | 10YR 6/2 | 10YR 4/2 | vfSL | 1 f sbk | 0 | e | CS | |
| C1 | 20-34 | 2.5Y 6/2 | 10YR 4/2 | LS | 1 mf sbk | 0 | e | CS | |
| C2 | 34-40 | 10YR 6/2 | 10YR 4/2 | vfSL | M | 0 | e | CS | |
| C3 | 40-61 | 10YR 6/2 | 10YR 4/2 | vfSL | M | 0 | e | CW | |
| C4 | 61-71 | 2.5Y 6/2 | 10YR 4/2 | fSL | M | 10G | e | CW | very thin, patchy coats l |
| 2C5 | 71-88 | 2.5Y 6/2 | 2.5Y 4/2 | coS | M | 45G/25C | eo-e | CW | very thin, patchy coats l |
| 2C6 | 88-101 | 2.5Y 6/2 | 2.5Y 4/2 | coS | M | 45G/25C | eo-e | GW | very thin, patchy coats l |
| 2C7 | 101-150 | 2.5Y 6/2 | 2.5Y 4/2 | S | M | 30G/45C | eo | | very thin, patchy coats l |

Site 1a, Pedon LN1

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-7 | 10YR 6/3 | 10YR 4/3 | fSL | 1 m f gr | 0 | es | CS | |
| ABk | 7-16 | 10YR 5/3 | 10YR 4/3 | SiL | 1 m f sbk | 0 | ev | CS | |
| A' | 16-31 | 10YR 6/3 | 10YR 5/3 | SiL | 1 m f sbk | 0 | es | GS | |
| ABk' | 31-39 | 10YR 6/3 | 10YR 5/3 | SiL | 1 m f sbk | 10 | es | CS | |
| 2Bk1 | 39-59 | 10YR 8/2 | 10YR 6/3 | vgL | M | 30G/20C | ev | CW | Carbonate coating on top and bottom of clasts |
| 2Bk2 | 59-109 | 2.5Y 7/2 | 2.5Y 5/2 | egLS | M | 30G/40C | ev | GW | Carbonate coating on bottom |
| 2Bk3 | 109-183 | 10YR 6/2 | 10YR 4/3 | egLS | M | 40G/30C | es | GW | Thin, patchy coatings |
| 2Bk4 | 193-185 | 10YR 6/2 | 10YR 4/3 | egLS | M | 40G/30C | e | | Thin, patchy coatings |

Site 1b, Pedon LN4

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-14 | 10YR 6/2 | 10YR 4/2 | SL | 1 f vf sbk/ 1 vf gr | 5 G | ev | CS | |
| ABk | 14-26 | 10YR 6/2 | 10YR 4/2 | SL-L | 1 f vf sbk | 5 G | ev | CS | |
| Bk1 | 26-42 | 10YR 5/2 | 10YR 4/3 | L | 1 f vf sbk | 5G | ev | CS | |
| 2Bk2 | 42-56 | 10YR 5/3 | 10YR 4/3 | vgLS | M | 40G/5C | ev | CW | |
| 2Bk3 | 56-83 | 10YR 6/2 | 10YR 5/2 | vgS | M | 40G/10C | ev | CW | All clasts have continuous CaCO3 coats < 0.5 mm thick |
| 3Bk4 | 83-119 | 10YR 6/2 | 10YR 4/2 | egS | SG | 60G/10C | es/ev | CW | " |
| 4Bk5 | 119-147 | 10YR 6/2 | 10YR 3/2 | ecS | M | 40G/30C | ev | CW | 70% of clasts have thin patchy CaCO3 coatings on bottoms |
| 4Bk6 | 147-190 | 10YR 6/2 | 10YR 4/2 | ecS | M | 40G/30C | e/es | | " |

Site 3a, Pedon BLN13

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-4 | 10YR 4/2 | 10YR 3/2 | vfSL | v f sbk<br>1 vf gr | 5G | eo | CS | |
| BA | 4-16 | 10YR 4/3 | 10YR 3/3 | SL | 1 m f sbk | 5G | eo | CS | |
| Bk1 | 16-29 | 10YR 5/3 | 10YR 4/2 | SL | 1 m f sbk | 5G/5C | es | CW | |
| 2Bk1 | 29-36 | 10YR 6/2 | 10YR 4/2 | SL | 1 m vf sbk | 15G/10C | ev | CW | Disseminated carbonate throughout |
| 2Bkm | 36-68 | 10YR 7/1 | 10YR 5/2 | LS | 1 m sbk | 30G/35C/5S | ev | CW | 75% matrix cemented but K fabric weakly expressed |
| 3Bk2 | 68-92 | 10YR 5/1 | 10YR 4/1 | S | M | 40G/40C/5S | es | CI | 25% matrix cemented next to coated clasts |
| 3Bk3 | 92-150 | 10YR 5/1 | 10YR 4/1 | S | M | 30G/40C/15S | e matrix<br>ev clast | GW | 75% of clasts have 1mm-1cm thick pendants |
| 3Bk4 | 150-240 | 10YR 5/1 | 10YR 4/1 | S | M | 30G/40C/15S | es mat.<br>ev clast | CS | " |
| 4C | 240-260 | 10YR 5/2 | 10YR 3/2 | S | SG | 25G | eo mat.<br>ev clast | | 50% of clasts have thin discontinuous coatings |

Site 3b, Pedon BLN14

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-4 | 10YR 3/2 | 10YR 4/2 | fSL | 1 f vf sbk/gr | 5G | eo | CS | |
| BA | 4-12 | 10YR 5/3 | 10YR 4/3 | L | 1 m f sbk | 5G | eo | CS | |
| Bw | 12-19 | 10YR 3/3 | 10YR 4/3 | L | 1 m f sbk | 5G | eo | CW | |
| 2Bk1 | 19-27 | 10YR 4/3 | 10YR 5/3 | SL | 1 m f sbk | 5G/5C | es | CS | Disseminated carbonate throughout |
| 2Bk2 | 27-42 | 10YR 4/3 | 10YR 5/3 | SL | 1 m f sbk | 10G/5C | es | CW | good K fabric |
| 3Bkm | 42-58 | 10YR 6/2 | 10YR 7/2 | LS | M | 25G/10C | ev | CW | Clast coatings are 0.3-0.5 cm thick<br>90% of matrix cemented |
| 3Bkq1 | 58-96 | 10YR 4/2 | 10YR 6/2 | S | M | 40G/30C/5S | ev | CW | All clasts coated w/ carbonate<br>75% of matrix cemented |
| 3Bkq2 | 96-136 | 10YR 4/2 | 10YR 5/1 | S | M | 30G/50C/5S | e-es mat.<br>ev clast | CW | Clasts have discontinuous carbonate coats<br>0.1-0.5 cm thick, little carb. in matrix |
| 3BCk | 136-210+ | 10YR 4/2 | 10YR 5/1 | S | M | 40G/40C/5S | eo-e mat.<br>ev clast | | |

Site 4, Pedon PB1

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-10 | -- | 10YR 4/3 | SL | 1 f sbk | 5g | e | CS | |
| ABtk | 10-22 | -- | 10YR 4/3 | SL | 2 m sbk | 5g | es | CS | |
| Btk1 | 22-38 | -- | 10YR 4/3 | SL | 2 m abk | 5g | es | CS | |
| 2Btk2 | 38-46 | -- | 10YR 4/3 | SL | 1 f sbk | 25g | ev | CW | Disseminated carbonate (II) |
| 3Bkm | 46-80 | 10YR 6/2 | 10YR 4/2 | LS | M | 30G/30C | ev | CW | cementing in matrix (III) |
| 3Bk1 | 80-105 | 10YR 6/2 | 10YR 4/2 | S | M | 40G/30C | es | CW | all clasts coated with carbonate (II) |
| 4Bk2 | 105-164 | 10YR 6/2 | 10YR 4/2 | S | M | 50G/25C | e | CI | partial clast coatings (II) |
| 4BCk | 164-210 | 10YR 6/2 | 10YR 4/2 | S | M | 50G/25C | eo-es | | |

Site 8, Pedon BLS3

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-5 | 10YR 4/3 | 10YR 3/2 | SL | 1 f vf sbk | 5G | eo | CS | |
| BtA | 5-17 | 10YR 4/3 | 10YR 3/3 | SCL | 1 c m abk | 5G | eo | CS | |
| Btk1 | 17-27 | 10YR 4/3 | 10YR 3/3 | SCL | 2 m pr/ 2 c m abk | 5G | e-es | GS | |
| Btk2 | 27-41 | 10YR 5/2 | 10YR 4/2 | SCL | 2 m f sbk | 10G/5C | es | CW | |
| Bkm1 | 41-53 | 10YR 6/1 | 10YR 5/2 | SL | 2 m pl | 10G/5C | ev | CW | 80% matrix cemented by carbonate |
| 2Bkm2 | 53-80 | 10YR 8/1 | 10YR 7/2 | SL | M | 20G/10C | ev | CW | 70% cemented by carbonate and silica in K fabric |
| 2Bkg1 | 80-145 | 10YR 6/3 | 10YR 5/4 | S | M | 30G/25C/10S | es-ev | CI | 50% matrix cemented by carbonate and silica |
| 2Bkg2 | 145+ | 10YR 6/2 | 10YR 5/3 | S | M | 30G/30C/30S | eo-e matrix<br>es-ev clast | | Same as above |

Site 9a, Pedon CR3

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-7 | 10YR 6/3 | 10YR 4/3 | vfSL | 1 f vf sbk<br>1 m gr | 5G/5C | eo | CS | |
| Bt1 | 7-15 | 10YR 4/4 | 10YR 3/4 | SCL | 2 mf abk | 5G/5C | eo | CW | |
| Bt2 | 15-29 | 10YR 4/4 | 10YR 3/4 | SCL | 2 m pr/ 2 c m abk | 5G/5C | eo | CW | |
| 2Bk1 | 29-41 | 10YR 7/3 | 10YR 5/3 | SCL | 2 m f abk | 10G/10C | ev | CI | There is a stoneline between horizons 3 and 4 |
| 2Bkm | 41-69 | 10YR 8/2 | 10YR 7/3 | gSL | M | 15G/5C | ev | CW | |
| 3Bk2 | 69-112 | 10YR 8/2 | 10YR 7/3 | ecS | M | 30G/35C | ev | CW | Most clasts have carbonate pendants 5-10 cm thick, some dissemination in matrix |
| 3Bk3 | 112-186 | 10YR 5/2 | 10YR 4/2 | ecS | SG | 30G/40C | eo mat.<br>ev clast | CW | Most clasts have carbonate pendants 2-5 cm thick |
| 3C | 186-215 | 10YR 5/2 | 10YR 4/2 | vcS | SG | 25G/25C | eo mat.<br>ev clast | | Pendants less than 1 cm thick |

Site 9b. Pedon CR4

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-6 | 10YR 6/3 | 10YR 4/3 | L | 1 f vf sbk | 5G | eo | CS | |
| Bw | 6-13 | 10YR 4/4 | 10YR 3/4 | L | 1 m f abk | 5G | eo | CS | |
| Bt1 | 13-25 | 10YR 4/4 | 10YR 3/4 | L-SCL | 2 c m abk | 10G | eo | CS | |
| 2Bt2 | 25-37 | 10YR 7/3 | 10YR 5/3 | SL-SCL | 2 m f abk | 35G/10C | ev | CW | |
| 2Bkm1 | 37-56 | 10YR 8/2 | 10YR 7/3 | SL | M | | ev | CW | |
| 2Bk1 | 56-78 | 10YR 8/2 | 10YR 7/3 | LS | M | | ev | CW | |
| 3Bkm2 | 78-125 | 10YR 7/3 | 10YR 5/4 | LS | M | | ev | CW | Carbonate pendants form nearly continuous carbonate in matrix |
| 3Bk2 | 125-175 | 10YR 7/3 | 10YR 5/4 | S | M | | ev | CW | Pendants on clasts but no carbonate in matrix |
| 3Bk3 | 175-210 | 10YR 6/2 | 10YR 4/3 | S | SG | | eo matrix<br>ev clast | | Pendants on clasts but no carbonate in matrix |

Site 11, Pedon CR5

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-6 | 10YR 4/3 | 10YR 5/3 | L | 1 f vf sbk | 10G | eo | CW | |
| Bt1 | 6-12 | 10YR 4/4 | 10YR 3/4 | SCL | 2 m f abk | 10G | eo | CW | |
| Bt2 | 12-22 | 10YR 4/4 | 10YR 3/4 | SCL | 2 m pr/<br>2 m abk | 10G | eo | CW | |
| 2Btk | 22-34 | 10YR 7/3 | 10YR 6/4 | SL | 2 m f abk | 20G | ev | CI | Stone line at top of horizon |
| 2Bkm1 | 34-60 | 10YR 8/2 | 10YR 7/3 | SL | M | 15G/5C | ev | CW | |
| 2Bk1 | 60-95 | 10YR 8/2 | 10YR 7/3 | SL | M | 30G/5C | ev | CW | |
| 3Bkm2 | 95-140 | 10YR 7/2 | 10YR 5/2 | LS | M | 40G/40C | ev | CW | All clasts coated w/ carbonate<br>matrix cemented |
| 3Bk2 | 140-190 | 10YR 6/3 | 10YR 4/3 | S | M | 40G/40C/5S | es matrix<br>ev clast | CW | Discontinuous clast coatings |
| 3Bk3 | 190-225 | 10YR 6/2 | 10YR 4/2 | S | SG | 40G/40C/5S | eo matrix<br>ev clast | | Discontinuous clast coatings<br>matrix non calcarious |

Site 12a, Pedon CR1

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-8 | 10YR 6/3 | 10YR 4/3 | fSL | 1 f vf sbk<br>1 f vf gr | 5G | eo | CS | |
| ABt | 8-13 | 10YR 5/4 | 10YR 3/4 | SL-SCL | 2 c m abk<br>2 m f abk | 5G | eo | CW | |
| Bt | 13-27 | 7.5YR5/4 | 7.5YR4/4 | SCL | 2 m pr<br>2 c m abk | 5G | eo | CW | |
| 2Btk | 27-37 | 10YR 6/4 | 10YR 4/4 | SL | 3 m pr<br>3 c m abk | 10G | e/eo | CW | Stoneline at top of horizon |
| 2Bk1 | 37-48 | 10YR 7/2 | 10YR 6/3 | SL | M | 10G | ev | CI | Stoneline at top of horizon tonguing into underlying K fabric |
| 2Bkm1 | 48-62 | 10YR 8/2 | 10YR 7/3 | SL | M | 10G | ev | CW | Horizon composed almost entirely of K fabric, NOT indurated |
| 2Bkm2 | 62-90 | 10YR 8/2 | 10YR 7/3 | SL | M | 10G | ev | CW | Pendants 0.25-2.0 cm. thick |
| 3Bk2 | 90-120 | 10YR 7/2 | 10YR 6/3 | LS | SG | 40G/35C | ev | GW | Pendants 0.1-0.5 cm. thick |
| 3Bk3 | 120-170 | 10YR 5/3 | 10YR 4/3 | S | SG | 45G/30C | ev | | |

Site 12b, Pedon CR6

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-17 | 10YR 4/3 | 10YR 3/3 | SL | 1 f vf sbk/ 1 f gr | 5G | e | CS | |
| Bt | 17-36 | 10YR 5/3 | 10YR 4/3 | SL | 2 m abk | 5G | es | CS | 1 N PO PF -CLAY FILMS |
| Btk | 36-49 | 10YR 5/3 | 10YR 4/3 | SL | 1 m f sbk | 10G | es | CS | 1 N PO PF -CLAY FILMS |
| Bkm | 49-85 | 10YR 7/3 | 10YR 6/3 | gSL | M/pl | 15G | ev | CS | K fabric but not indurated |
| 2Bk1 | 85-125 | 10YR 6/3 | 10YR 4/3 | vcLS | M | 35G/25C | ev | CW | carbonate coatings on clasts 0.25-2.0 cm thick |
| 2Bk2 | 125-152 | 10YR 6/2 | 10YR 4/2 | ecLS | M | 40G/35C | es-ev | CW | carbonate coatings on clasts 0.1-0.5 cm thick |
| 2Bk3 | 152-205 | 10YR 6/2 | 10YR 4/2 | ecS | M | 50G/35C | eo-ev | CW | carbonate coatings on clasts 0.1-0.5 cm thick |
| 2Bk4 | 205-260 | 10YR 6/2 | 10YR 4/2 | ecS | M | 45G/40C | eo-es | | |

Site 13a, Pedon CR2

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF. | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-7 | 10YR 4/3 | 10YR 3/2 | fSL | 1 f vf sbk/ 1 f gr | 5G | eo | CS | |
| Bt1 | 7-16 | 10YR 5/4 | 10YR 4/4 | SCL | 2 c m abk | 5G | eo | CW | |
| 2Bt2 | 16-27 | 7.5YR6/4 | 7.5YR4/4 | SCL | 3 m pr/ 3 c m abk | 10G/5C | eo | CW | Stone line in horizon |
| 2Bt3 | 27-43 | 10YR 6/4 | 10YR 4/4 | SL | 3 c m abk | 5G/5C | eo | CW | |
| 3Btk | 43-55 | 10YR 6/3 | 10YR 5/3 | LS | 3 m abk/ 3 m pl | 5G/5C | ev | CI | Stone line in horizon |
| 3Bkm1 | 55-86 | 10YR 8/2 | 10YR 7/2 | SL | M | 15G/5C | ev | CW | Discontinuous laminations |
| 4Bkm2 | 86-110 | 10YR 8/2 | 10YR 7/2 | SL | M | 30G/25C | ev | CW | |
| 4Bk1 | 110-145 | 10YR 4/3 | 10YR 5/3 | S | M | 45G/40C | ev | CW | |
| 4Bk2 | 145-190 | 10YR 7/2 | 10YR 6/3 | S | M | 45G/40C | ev | CW | Laminar cap at bottom, top of next horizon |
| 5C | 190-260 | 10YR 6/3 | 10YR 4/3 | S | SG | -- | es-eo | | |

Site 13b, Pedon BLS2

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-7 | 10YR 4/2 | 10YR 3/3 | fSL | 1 vf sbk | 5G | eo | CS | |
| Bt1 | 7-17 | 10YR 4/2 | 10YR 3/2 | SCL | 2 m f abk/<br>2 m f sbk | 5G | eo | GS | |
| Bt2 | 17-29 | 10YR 4/3 | 10YR 3/3 | SL-SCL | 2 c m abk | 5G | eo | CW | Thin, patchy carbonate on bottom of gravels |
| 2Btk | 29-53 | 10YR 5/2 | 10YR 4/2 | SL | 2 m f abk | 20G/5C | es | CI | |
| 2Bk1 | 53-81 | 10YR 8/1 | 10YR 7/2 | cSL | M | 20G/10C | ev | CW | Impregnated K horizon<br>no evidence of laminations |
| 3Bk2 | 81-100 | 10YR 6/2 | 10YR 5/2 | cLS | M | 30G/5C/5S | ev | CW | |
| 4Bkm | 100-137 | 10YR 6/2 | 10YR 4/2 | LS | M | 40G/15C/10S | ev | CW | Matrix well cemented |
| 4Bk3 | 137-174 | 10YR 5/2 | 10YR 4/2 | LS | M | 50G/20C | e matrix<br>ev clast | CW | Clast coatings partially cement matrix |
| 4BCk | 174+ | 10YR 5/2 | 10YR 4/2 | LS | M | 50G/10C/10S | es matrix<br>ev clast | | Clast coatings slightly cement matrix |

Site 15, Pedon BLS1

| HORIZON | DEPTH (cm) | COLOR Dry | COLOR Moist | TEXTURE | STRUCTURE | >2mm (% Vol.) | EFF | BOUND | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| A | 0-6 | 10YR 4/3 | 10YR 3/2 | fSL | 1 f vf sbk/<br>1 vf vf gr | 5G | eo | CS | |
| AB | 6-13 | 10YR 4/4 | 10YR 3/3 | SL-SCL | 2 m f abk | 5G | eo | CS | |
| Bt1 | 13-24 | 10YR 4/4 | 10YR 4/4 | SCL | 2 m f sbk/<br>2 m f abk | 5G | eo matrix<br>es clast | CS | few filaments |
| Bt2 | 24-38 | 10YR 4/4 | 10YR 4/4 | SCL | 2 m pr/<br>2 c m abk | 5G | eo matrix<br>es clast | CW | Slightly redder clast bottoms<br>few filaments |
| 2Btk | 38-57 | 10YR 5/4 | 10YR 4/4 | LS | 2 f abk/<br>2 m pl | 15G/5C | ev | CI | Clasts completely coated<br>matrix partially impregnated |
| 2Bkm | 57-81 | 10YR 8/1 | 10YR 7/3 | LS | 2 m pl/<br>M | 15G/5C | ev | CW | Structural plates are micro lamina<br>full K fabric |
| 3Bk1 | 81-110 | 10YR 8/1 | 10YR 7/2 | LS | M | 25G/5C | ev | CW | Matrix entirely impregnated by carbonate<br>poor expression of K fabric |
| 3Bk2 | 110-153 | 10YR 8/2 | 10YR 5/3 | LS | M | 30G/10C/10S | ev | CW | (same as above) |
| 3Bk3 | 153-230 | 10YR 6/2 | 10YR 4/2 | S | M | 40G/35C/10S | e-es m.<br>ev clast | CW | Clast coatings grow into matrix |
| 3BCk | 230+ | 10YR 6/2 | 10YR 4/2 | S | M/SG | 40G/35C/10S | eo-es m.<br>ev clast | | Clast coatings do not grow into matrix |

# APPENDIX B

General Laboratory Analysis

Site 1b, Pedon LN4

| DEPTH (cm) | HORIZON | TOC % | paste pH | CaCO3 % | Sand | Silt | | | Clay | BULK DENS. g/cu.cm. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 50-20u | 20-5um | 5-2um | <2.0um | |
| | | | | | % | | | | | |
| 0 - 14 | A | 0.91 | 7.7 | 7.9 | 58.6 | 15.6 | 8.1 | 3.6 | 14.0 | 1.2 |
| 14 - 26 | ABk | 0.62 | 7.7 | 7.7 | 50.9 | 17.5 | 10.5 | 4.8 | 16.3 | 1.3 |
| 26 - 42 | Bk1 | 0.48 | 7.9 | 8.0 | 47.0 | 16.9 | 12.6 | 6.0 | 17.5 | 1.3 |
| 42 - 56 | 2Bk2 | 0.36 | 8.0 | 4.1 | 89.0 | 2.8 | 2.6 | 0.4 | 5.2 | 1.4 |
| 56 - 83 | 2Bk3 | 0.29 | 7.9 | 4.6 | 93.0 | 1.6 | 1.8 | 0.3 | 3.3 | 1.5 |
| 83 - 119 | 3Bk4 | 0.18 | 7.8 | 3.2 | 96.1 | 1.4 | 0.6 | 0.3 | 1.5 | 1.6 |
| 119 - 147 | 4Bk5 | 0.21 | 8.3 | 4.1 | 95.3 | 2.5 | 0.5 | 0.3 | 1.4 | 1.6 |
| 147 - 190 | 4Bk6 | 0.4 | 8.5 | 4.2 | 95.8 | 2.4 | 0.5 | 0.2 | 1.1 | 1.6 |

Site 3a, Pedon BLN13

| DEPTH (cm) | HORIZON | TOC % | paste pH | CaCO3 % | Sand % | Silt 50-20u % | Silt 20-5um % | Silt 5-2um % | Clay <2.0um % | BULK DENS. g/cu.cm. |
|---|---|---|---|---|---|---|---|---|---|---|
| 0-4 | A | 0.55 | 6.8 | 0.4 | 60.2 | 14.9 | 9.5 | 1.6 | 13.7 | 1.2 |
| 4-16 | BA | 0.22 | 7.6 | 1.1 | 60.8 | 13.2 | 6.7 | 3.9 | 15.4 | 1.37 |
| 16-29 | Bk | 0.15 | 7.6 | 7.5 | 61.8 | 15.4 | 7.1 | 4.2 | 11.5 | 1.36 |
| 29-36 | 2Bk1 | 0.16 | 7.6 | 23.9 | 62.5 | 9.7 | 6.6 | 2.5 | 18.7 | 1.29 |
| 36-68 | 2Bkm | 0.57 | 8.1 | 23.8 | 83.6 | 6.2 | 3.9 | <0.1 | 6.3 | 1.39 |
| 68-92 | 3Bk2 | 0.47 | 8.2 | 8.9 | 94.7 | 1.4 | 1.3 | 0.1 | 2.5 | 1.5 |
| 92-150 | 3Bk3 | 1.07 | 8.4 | 6.2 | 96.4 | 0.4 | 0.9 | 0.2 | 2.2 | 1.6 |
| 150-240 | 3Bk4 | 0.96 | 8.0 | 5.1 | 94.7 | 1.3 | 1.2 | 0.2 | 2.6 | 1.7 |
| 240-260 | 4C | 0.35 | 8.6 | 3.4 | 98.0 | <0.1 | <0.1 | 0.2 | 1.8 | 1.7 |

Site 3b, Pedon BLN14

| | | | paste | | Sand | Silt | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | | 50-20u | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | % | | | | | g/cu.cm. |
| 0 - 4 | A | 0.21 | 7.1 | 0.2 | 52.0 | 18.3 | 8.6 | 4.8 | 16.4 | 1.2 |
| 4 - 12 | BA | 0.91 | 7.2 | 0.4 | 50.2 | 17.0 | 9.1 | 5.0 | 18.7 | 1.36 |
| 12 - 19 | Bw | 0.93 | 7.5 | 1.2 | 51.8 | 15.8 | 9.1 | 5.0 | 18.2 | 1.38 |
| 19 - 27 | 2Bk1 | 0.3 | 7.7 | 4.0 | 55.9 | 18.2 | 10.5 | 6.0 | 9.4 | 1.3 |
| 27 - 42 | 2Bk2 | 0.2 | 7.6 | 20.2 | 59.2 | 15.2 | 7.4 | 3.7 | 14.5 | 1.3 |
| 42 - 58 | 3Bkm | 0.13 | 8.2 | 30.6 | 86.6 | 4.8 | 2.7 | 0.2 | 5.6 | 1.29 |
| 58 - 96 | 3Bkq1 | 0.13 | 8.2 | 14.5 | 95.2 | 1.4 | 1.0 | 0.1 | 2.3 | 1.4 |
| 96 - 136 | 3Bkq2 | 0.1 | 8.5 | 6.7 | 94.8 | 2.1 | 1.1 | 0.2 | 1.8 | 1.6 |
| 136 - 210+ | 3BCk | 0.12 | 8.5 | 6.7 | 95.2 | 1.9 | 1.1 | 0.2 | 1.7 | 1.7 |

Site 4, Pedon PB1

| DEPTH (cm) | HORIZON | TOC % | paste pH | CaCO3 % | Sand | Silt 50-20um | Silt 20-5um | Silt 5-2um | Clay <2.0um | BULK DENS. g/cu.cm. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | % | % | % | % | % | |
| 0 - 10 | A | 0.77 | 7.5 | 2.9 | 51.9 | 11.0 | 8.8 | 5.4 | 22.8 | 1.36 |
| 10 - 22 | ABtk | 0.75 | 7.8 | 4.2 | 45.8 | 10.9 | 9.0 | 5.1 | 29.2 | 1.36 |
| 22 - 38 | Btk1 | 0.65 | 8.0 | 5.6 | 50.2 | 10.3 | 9.4 | 5.6 | 24.5 | 1.38 |
| 38 - 46 | 2Btk2 | 1.19 | 8.1 | 20.4 | 62.6 | 8.2 | 6.5 | 3.3 | 19.4 | 1.3 |
| 46 - 80 | 3Bkm | 0.86 | 8.1 | 21.1 | 82.7 | 5.8 | 3.6 | 0.8 | 7.1 | 1.29 |
| 80 - 105 | 3Bk1 | 0.92 | 8.0 | 12.2 | 91.9 | 3.7 | 1.2 | 0.8 | 2.4 | 1.4 |
| 105 - 164 | 4Bk2 | 0.14 | 8.3 | 3.9 | 96.3 | 2.5 | 0.4 | 0.4 | 0.4 | 1.5 |
| 164 - 210 | 4BCk | 0.18 | 7.9 | 5.9 | 96.9 | 2.5 | <0.1 | 0.6 | 0.1 | 1.6 |

Site 8, Pedon BLS3

| | | | paste | | Sand | ----------------Silt---------------- | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | | 50-20u | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | ------------------------------%------------------------------ | | | | | g/cu.cm. |
| 0-5 | A | 0.78 | 6.9 | 0.2 | 58.8 | 13.6 | 8.1 | 3.0 | 16.5 | 1.2 |
| 5-17 | BtA | 0.99 | 7.1 | 0.6 | 54.2 | 12.4 | 6.8 | 3.1 | 23.5 | 1.36 |
| 17-27 | Btk1 | 0.78 | 7.7 | 2.6 | 54.2 | 11.5 | 7.3 | 3.4 | 23.6 | 1.35 |
| 27-41 | Btk2 | 0.81 | 7.9 | 15.0 | 56.6 | 13.3 | 7.1 | 2.4 | 20.7 | 1.41 |
| 41-53 | Bkm1 | 0.78 | 8.1 | 32.7 | 61.4 | 11.4 | 7.6 | 1.6 | 18.9 | 1.18 |
| 53-80 | 2Bkm2 | 0.64 | 8.3 | 39.4 | 73.9 | 6.2 | 8.3 | 0.3 | 11.2 | 1.17 |
| 80-145 | 2Bkq1 | 0.25 | 8.6 | 11.2 | 92.3 | 1.3 | 2.0 | 0.3 | 4.1 | 1.5 |
| 183-185 | 2Bkq2 | 0.22 | 8.6 | 10.6 | 92.0 | 2.3 | 1.8 | 0.3 | 3.6 | 1.6 |

Site 9a, Pedon CR3

| | | | paste | | | Sand | ----Silt---- | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | CaSO4 | | 50-20um | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | % | ----% | | | | ---- | g/cu.cm. |
| 0 - 7 | A | 0.96 | 7.4 | 0.7 | 0.05 | 57.8 | 15.1 | 8.1 | 2.7 | 16.3 | 1.2 |
| 7 - 15 | Bt1 | 0.79 | 6.7 | 0.6 | 0.15 | 46.2 | 12.7 | 9.2 | 3.7 | 28.1 | 1.4 |
| 15 - 29 | Bt2 | 0.82 | 7.3 | 1.1 | 0.2 | 49.5 | 12.5 | 8.0 | 3.3 | 26.7 | 1.45 |
| 29 - 41 | 2Bk1 | 0.89 | 7.7 | 23.2 | 1.07 | 61.3 | 10.3 | 7.0 | 2.3 | 19.2 | 1.49 |
| 41 - 69 | 2Bkm | 0.97 | 8.0 | 48.2 | 0.12 | 72.8 | 7.2 | 7.6 | 1.3 | 11.1 | 1.29 |
| 69 - 112 | 3Bk2 | 0.45 | 8.3 | 12.3 | 0.27 | 90.5 | 2.5 | 2.6 | <0.1 | 4.5 | 1.6 |
| 112 - 186 | 3Bk3 | 0.05 | 8.4 | 8.4 | 0.13 | 95.4 | 1.1 | 0.8 | 0.2 | 2.5 | 1.7 |
| 186 - 215 | 3C | 0.17 | 8.4 | 5.2 | 0.15 | 93.4 | 1.9 | 1.5 | <0.1 | 3.2 | 1.7 |

Site 9b, Pedon CR4

| | | | paste | | | Sand | Silt | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | CaSO4 | | 50-20um | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | % | % | | | | | g/cu.cm. |
| 0-6 | A | 0.71 | 7.1 | 0.2 | 0.04 | 50.1 | 15.4 | 9.9 | 3.4 | 20.7 | 1.2 |
| 6-13 | Bw | 0.94 | 7.2 | 0.4 | 0.12 | 48.4 | 12.8 | 9.2 | 4.3 | 25.3 | 1.29 |
| 13-25 | Bt1 | 0.89 | 7.4 | 0.7 | 0.20 | 50.7 | 11.1 | 8.9 | 4.6 | 24.7 | 1.35 |
| 25-37 | 2Bt2 | 1.04 | 7.6 | 16.9 | 0.58 | 57.7 | 11.4 | 7.8 | 3.5 | 19.6 | 1.45 |
| 37-56 | 2Bkm1 | 0.48 | 7.8 | 46.7 | 0.93 | 68.1 | 8.5 | 6.6 | 0.4 | 16.4 | 1.48 |
| 56-78 | 2Bk1 | 0.97 | 7.9 | 42.8 | 0.51 | 83.0 | 3.5 | 5.6 | 0.2 | 7.8 | 1.5 |
| 78-125 | 3Bkm2 | 0.37 | 8.4 | 19.0 | 0.15 | 86.4 | 2.4 | 3.6 | 0.8 | 6.8 | 1.78 |
| 125-175 | 3Bk2 | 0.21 | 8.5 | 12.2 | 0.21 | 89.3 | 2.7 | 2.9 | 0.2 | 4.9 | 1.7 |
| 175-210 | 3Bk3 | 0.02 | 8.5 | 2.4 | 0.04 | 97.1 | 0.1 | 0.3 | 0.5 | 2.0 | 1.7 |

Site 11, Pedon CR5

| | | | paste | | | Sand | Silt | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | $CaCO_3$ | $CaSO_4$ | | 50-20um | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | % | % | | | | | g/cu.cm. |
| 0-6 | A | 0.75 | 6.8 | 0.1 | 0.05 | 50.2 | 14.3 | 11.7 | 5.5 | 18.3 | 1.2 |
| 6-12 | Bt1 | 0.82 | 7.3 | 0.7 | 0.09 | 49.2 | 10.3 | 8.6 | 4.2 | 27.8 | 1.56 |
| 12-22 | Bt2 | 0.65 | 7.2 | 0.4 | 0.15 | 52.8 | 10.7 | 7.1 | 3.2 | 26.1 | 1.55 |
| 22-34 | 2Btk | 1.02 | 8.1 | 23.8 | 0.69 | 61.1 | 11.5 | 6.4 | 3.0 | 17.9 | 1.42 |
| 34-60 | 2Bkm1 | 0.71 | 7.8 | 51.6 | 1.32 | 66.5 | 9.2 | 7.0 | 0.6 | 16.6 | 1.44 |
| 60-95 | 2Bk1 | 0.68 | 8.1 | 38.9 | 0.67 | 74.4 | 5.9 | 7.7 | 2.6 | 9.5 | 1.3 |
| 95-140 | 3Bkm2 | 0.50 | 8.4 | 19.7 | 0.32 | 85.5 | 4.1 | 4.2 | 1.3 | 4.9 | 1.26 |
| 140-190 | 3Bk2 | 0.08 | 8.6 | 7.3 | 0.15 | 92.5 | 1.8 | 2.4 | <0.1 | 3.2 | 1.5 |
| 190-225 | 3Bk3 | 0.04 | 8.7 | 4.5 | 0.09 | 96.1 | 1.0 | 0.8 | 0.1 | 2.0 | 1.6 |

Site 12a, Pedon CR1

| | | | paste | | | Sand | ---Silt--- | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | CaSO4 | | 50-20um | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | % | --- | --- | % | --- | --- | g/cu.cm. |
| 0-8 | A | 0.68 | 6.8 | 0.1 | 0.06 | 57.4 | 15.7 | 9.7 | 4.5 | 12.8 | 1.34 |
| 8-13 | ABt | 0.81 | 7.0 | 0.2 | 0.13 | 58.3 | 10.3 | 7.7 | 3.4 | 20.4 | 1.37 |
| 13-27 | Bt | 0.47 | 7.1 | 0.6 | 0.15 | 58.3 | 9.0 | 6.7 | 2.6 | 23.4 | 1.49 |
| 27-37 | 2Btk | 0.43 | 7.7 | 2.3 | 0.32 | 70.4 | 6.2 | 4.9 | 1.4 | 17.1 | 1.55 |
| 37-48 | 2Bk1 | 0.41 | 8.2 | 12.7 | 0.83 | 77.8 | 5.0 | 4.4 | 1.1 | 11.6 | 1.47 |
| 48-62 | 2Bkm1 | 0.44 | 8.3 | 30.7 | 1.17 | 73.4 | 6.3 | 5.5 | 1.6 | 13.3 | 1.34 |
| 62-90 | 2Bkm2 | 0.35 | 8.5 | 10.1 | 0.27 | 84.5 | 5.0 | 5.9 | 1.3 | 3.3 | 1.6 |
| 90-120 | 3Bk2 | | | | | | | | | | |
| 120-170 | 3Bk3 | 0.28 | 8.3 | 7.5 | 2.27 | 90.9 | 2.5 | 3.2 | 0.7 | 2.6 | 1.7 |

* 2Bkm2 and 3Bk1 were analysed together

Site 12b, Pedon CR6

| | | | paste | | Sand | Silt | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | | 50-20um | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | % | | | | | g/cu.cm. |
| 0 - 17 | A | 1.16 | 6.9 | 0.9 | 55.4 | 13.5 | 8.2 | 3.7 | 19.3 | 1.34 |
| 17 - 36 | Bt | 0.95 | 7.3 | 1.7 | 53.2 | 10.8 | 6.7 | 2.9 | 26.4 | 1.41 |
| 36 - 49 | Btk | 1.25 | 7.5 | 11.7 | 56.3 | 7.4 | 6.4 | 2.9 | 27.0 | 1.64 |
| 49 - 85 | Bkm | 1.88 | 7.7 | 42.1 | 66.2 | 6.3 | 6.6 | 3.4 | 17.5 | 1.61 |
| 85 - 125 | 2Bk1 | 0.84 | 8.1 | 16.2 | 85.6 | 6.9 | 5.0 | 0.1 | 2.5 | 1.58 |
| 125 - 152 | 2Bk2 | 0.43 | 8.3 | 8.2 | 88.9 | 4.8 | 3.5 | 0.3 | 2.6 | 1.34 |
| 152 - 205 | 2Bk3 | 0.25 | 8.3 | 4.4 | 91.2 | 4.8 | 1.9 | 0.5 | 1.6 | 1.31 |
| 205 - 260 | 2Bk4 | 0.13 | 8.4 | 1.2 | 95.3 | 3.0 | 0.9 | 0.5 | 1.6 | 1.4 |

Site 13a, Pedon CR2

| DEPTH (cm) | HORIZON | TOC % | paste pH | CaCO3 % | CaSO4 % | Sand | ---Silt--- | | | Clay | BULK DENS. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 50-20um | 20-5um | 5-2um | <2.0um | |
| | | | | | | --- | --- | --- % --- | --- | --- | g/cu.cm. |
| 0-7 | A | 1.01 | 6.8 | 0.2 | 0.06 | 56.0 | 12.7 | 9.5 | 3.9 | 17.9 | 1.2 |
| 7-16 | Bt1 | 0.76 | 6.8 | 0.7 | 0.15 | 53.0 | 8.1 | 6.9 | 2.9 | 29.1 | 1.41 |
| 16-27 | 2Bt2 | 0.53 | 7.1 | 0.5 | 0.21 | 64.1 | 5.6 | 5.3 | 1.8 | 23.2 | 1.64 |
| 27-43 | 2Bt3 | 0.49 | 7.5 | 0.7 | 0.23 | 75.2 | 3.1 | 4.3 | 1.7 | 15.7 | 1.61 |
| 43-55 | 3Btk | 0.79 | 7.9 | 22.5 | 0.73 | 81.4 | 5.2 | 7.5 | 1.6 | 4.3 | 1.58 |
| 55-86 | 3Bkm1 | 0.69 | 8.0 | 55.9 | 0.55 | 62.3 | 7.8 | 12.3 | 4.8 | 12.8 | 1.34 |
| 86-110 | 4Bkm2 | 0.44 | 8.3 | 29.3 | 0.23 | 69.0 | 4.7 | 6.3 | 2.2 | 17.8 | 1.31 |
| 110-145 | 4Bk1 | 0.01 | 8.5 | 8.2 | 0.22 | 92.5 | 1.4 | 2.8 | 0.1 | 3.2 | 1.6 |
| 145-190 | 4Bk2 | | | | | | | | | | |
| 190-260 | 5C | 0.02 | 8.8 | 0.8 | 0.01 | 97.0 | 0.7 | 0.4 | 0.1 | 1.7 | 1.7 |

* 4Bk1 and 4Bk2 were analyzed together

Site 13b, Pedon BLS2

| | | | paste | | Sand | ---------------Silt--------------- | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | | 50-20u | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | ------------------------------ | | % | -------------------- | | g/cu.cm. |
| 0-7 | A | 0.61 | 6.7 | 0.2 | 68.2 | 8.6 | 8.0 | 4.6 | 10.6 | 1.2 |
| 7-17 | Bt1 | 1.17 | 7.4 | 0.7 | 58.6 | 10.7 | 5.4 | 2.6 | 22.7 | 1.31 |
| 17-29 | Bt2 | 0.68 | 7.5 | 1.4 | 62.1 | 9.4 | 6.0 | 2.6 | 19.9 | 1.39 |
| 29-53 | 2Btk | 1.13 | 8.1 | 14.0 | 66.5 | 9.1 | 6.1 | 1.0 | 17.3 | 1.46 |
| 53-81 | 2Bk1 | 0.63 | 8.2 | 47.8 | 78.6 | 7.5 | 3.4 | 0.2 | 10.3 | 1.3 |
| 81-100 | 3Bk2 | 0.68 | 8.5 | 38.9 | 81.8 | 5.8 | 3.7 | <0.1 | 8.8 | 1.4 |
| 100-137 | 4Bkm | 0.19 | 8.7 | 18.5 | 85.4 | 4.2 | 3.0 | 0.1 | 7.3 | 1.5 |
| 137-174 | 4Bk3 | 0.14 | 8.7 | 14.4 | 86.5 | 3.4 | 2.2 | 0.3 | 7.6 | 1.6 |
| 174+ | 4BCk | 0.13 | 8.7 | 12.5 | 86.1 | 3.6 | 2.4 | <0.1 | 7.9 | 1.7 |

Site 15, Pedon BLS1

| | | | paste | | Sand | ----------------Silt---------------- | | | Clay | BULK |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | pH | CaCO3 | | 50-20u | 20-5um | 5-2um | <2.0um | DENS. |
| DEPTH (cm) | HORIZON | % | | % | ----------------------------------%---------------------- | | | | | g/cu.cm. |
| 0-6 | A | 1.00 | 6.7 | 0.2 | 61.8 | 7.7 | 7.3 | 3.5 | 19.8 | 1.2 |
| 6-13 | AB | 0.92 | 7.1 | 0.2 | 65.3 | 6.6 | 5.7 | 2.8 | 19.7 | 1.3 |
| 13-24 | Bt1 | 0.68 | 7.3 | 0.4 | 60.1 | 5.9 | 5.4 | 2.8 | 25.9 | 1.4 |
| 24-38 | Bt2 | 0.65 | 7.4 | 0.4 | 65.5 | 5.0 | 5.5 | 3.5 | 20.5 | 1.49 |
| 38-57 | 2Btk | 0.84 | 7.7 | 5.6 | 79.9 | 6.1 | 6.0 | 2.1 | 5.9 | 1.44 |
| 57-81 | 2Bkm | 0.64 | 8.1 | 25.3 | 79.3 | 7.4 | 5.4 | 0.6 | 7.4 | 1.32 |
| 81-110 | 3Bk1 | 0.55 | 8.3 | 57.2 | 81.0 | 5.0 | 8.7 | 0.5 | 4.8 | 1.37 |
| 110-153 | 3Bk2 | 0.20 | 8.7 | 40.8 | 80.0 | 6.1 | 7.5 | 2.4 | 4.1 | 1.5 |
| 153-230 | 3Bk3 | 0.09 | 8.9 | 21.2 | 91.0 | 2.9 | 3.1 | 0.7 | 2.3 | 1.6 |
| 230+ | 3BCk | 0.07 | 8.8 | 13.4 | 92.4 | 2.1 | 3.3 | <0.1 | 2.2 | 1.7 |

# APPENDIX C

Total Profile Contents for $CaCO_3$, Organic C, and Clay

Values in g $cm^{-2}$

| SITE | AGE (ky) | $CaCO_3$ | ORGANIC C | CLAY |
|---|---|---|---|---|
| 0 | floodplain | 10.17 | - | 7.84 |
| 1b | 10 | 14.1 | 1.14 | 13.31 |
| 3a | 100 | 27.56 | 2.55 | 14.87 |
| 3b | 100 | 30.13 | 0.61 | 13.77 |
| 4 | 130 | 24.81 | 1.63 | 19.66 |
| 8 | 870 | 40.75 | 1.51 | 25.48 |
| 9a | 950 | 42.18 | 1.69 | 24.38 |
| 9b | 950 | 55.08 | 1.81 | 28.61 |
| 11 | 1090 | 58.57 | 1.94 | 27.05 |
| 12a | 1110 | 27.89 | 1.26 | 21.27 |
| 12b | 1110 | 43.81 | 3.71 | 31.28 |
| 13a | 1320 | 47.71 | 1.46 | 29.54 |
| 13b | 1320 | 57.32 | 1.81 | 31.38 |
| 15 | 1740 | 74.71 | 1.73 | 21.72 |