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Distribution of Available Phosphorus in the Subsoil of Selected Pedons of the Warm Springs Series

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DISTRIBUTION OF AVAILABLE PHOSPHORUS IN THE SUBSOIL OF SELECTED PEDONS OF THE WARM SPRINGS SERIES

by

Duane Altman Lammers

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Soil Science and Biometeorology

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Duane A. Lammers

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ABSTRACT

Distribution of Available Phosphorus in the Subsoil of Selected Pedons of the Warm Springs Series

by

Duane Altman Lammers, Doctor of Philosophy

Utah State University, 1975

Major Professor: Dr. Alvin R. Southard
Department: Soil Science and Biometeorology

The Warm Springs soil series which contained variable amounts of subsoil available (sodium bicarbonate extractable) phosphorus was studied to explain the variability and distribution of the $NaHCO_3$-P in the subsoil. Four pedons ranging in subsoil $NaHCO_3$-P from less than 10 ppm to greater than 30 ppm were selected in an area of less than 200 ha located on a nearly level, low lake terrace east of the Great Salt Lake in Weber County, Utah.

The morphology of each pedon was described in the field and samples collected from each genetic horizon or contrasting layer. Each soil sample was analyzed for total phosphorus, $NaHCO_3$-P, water-soluble phosphorus, pH, extractable iron, calcium carbonate equivalent, electrical conductivity and water-soluble sodium. Four horizons were selected from each pedon for analysis of particle-size distribution, clay-size carbonate and non-carbonate clay. The very fine sand fraction of four horizons from two of the pedons were studied petrographically to determine the amount of apatite present. Thin strata with higher chroma were separated from adjacent layers and analyzed for extractable iron and $NaHCO_3$-P. Cicada casts and their surrounding matrix were separated and analyzed for $NaHCO_3$-P. Selected soil samples were shaken with sodium-phosphate solutions and then analyzed for $NaHCO_3$-P to determine the influence of the amount of phosphorus in solution on the amount of phosphorus extracted.

$NaHCO_3$-P below the calcic horizons was highly variable, 10 ppm or less in two pedons and up to 40 ppm in the other two. Subsoil horizons with pH values greater than 10.0 and relatively large amounts of water-soluble sodium contained more than 10 ppm $NaHCO_3$-P. Extractable iron and $NaHCO_3$-P were concentrated in subsoil strata with higher chroma. The results indicated that large amounts of $NaHCO_3$-P in the subsoil were primarily due to the presence of readily soluble sodium phosphate. Weathering of apatite in the surface horizons did not contribute the $NaHCO_3$-P below the calcic horizons. The most likely source of $NaHCO_3$-P in the Warm Springs subsoil, however, was the sediments deposited in the low lake terraces and river flood plains by the Weber and Bear Rivers. Lateral flow and vertical fluctuations of the water table were suggested as a means by which the $NaHCO_3$-P could be extracted from some areas and concentrated in others. Although certain soil properties might indicate the probable occurrence of more than 10 ppm $NaHCO_3$-P in the subsoil, this study did not provide a method for identifying all subsoils with appreciable amounts of $NaHCO_3$-P.

(85 pages)

INTRODUCTION

The Great Basin section of the Basin and Range Province (Fenneman, 1931) consists of a large number of enclosed basins separated by desert mountain ranges extending across most of Nevada and western Utah. During the Pleistocene geologic period, Lake Bonneville filled the basin covering most of northern Utah and extending into Idaho and Nevada. The Great Salt Lake is a shrunken remnant of Lake Bonneville. The study area is located on low lake terraces adjacent to the Great Salt Lake shoreline in Weber and Davis counties, Utah.

Previous investigations covering widely distributed areas in Utah have established that the amount of phosphorus for plant utilization is highly variable both in the surface soil and subsoil (Bendixen, 1961; Nielson, Van Epps, and Thorne, 1961; and Lamborn, 1970). Analysis of the plow layer does not accurately predict the crop response to phosphate fertilizer in areas where plant available phosphorus is low in the surface soil but an adequate supply exists in the subsoil. This condition was found to exist for the Warm Springs soil series (Nielson, Van Epps and Thorne, 1961). Lamborn (1970) determined the vertical distribution of sodium bicarbonate-extractable phosphorus ($NaHCO_3$-P) for five pedons representing the Warm Springs series and found amounts of phosphorus exceeding 20 ppm in several subsoil horizons.

The primary objective of this study was to explain the $NaHCO_3$-P distribution in the subsoil of representative pedons of the Warm Springs soil series. The influence of weathering and a fluctuating water table acting on the lacustrine sediments to differentiate genetic soil horizons was used to evaluate the distribution of $NaHCO_3$-P. The soils were studied with respect to the following questions:

1. What is the distribution of $NaHCO_3$-P in the subsoil?
2. With what soil properties are subsoil horizons with high amounts of $NaHCO_3$-P associated?
3. What are the sources of the subsoil $NaHCO_3$-P?
4. How can the subsoils with high amounts of $NaHCO_3$-P be identified in the field?

REVIEW OF LITERATURE

Description of the study area

Land forms. The Warm Springs series is extensive, more than 8,000 hectares, on low lake terraces in the Davis-Weber Area, Utah (Erickson and Wilson, 1968). Figure 1 shows the extent and location of the Warm Springs and associated series. The low lake terraces were described by Feth et al. (1966) as lacustrine or flood-plain deposits of recent age which occupy extensive areas at elevations between 1,280 and 1,320 meters. The study area is located along the east shore of the Great Salt Lake and mostly separated from the lake shoreline by a narrow strip of very saline, poorly drained soils on recent lake plains or flood plains. Although the level of the Great Salt Lake fluctuates, the historic high water mark is at an elevation of about 1,280 to 1,282 meters. The study area is west of the Wasatch Mountains, a high barrier rising more than 2,700 meters above sea level. The Ogden and Weber Rivers which cut through the Wasatch Mountains emerging near Ogden and the Bear River which enters the Great Salt Lake through Bear River Bay to the north of the study area provided the sediment that formed extensive lake terraces in Lake Bonneville and recent flood plains.

Climate. The climate of the study area is characterized by warm dry summers and cold winters. July and August are

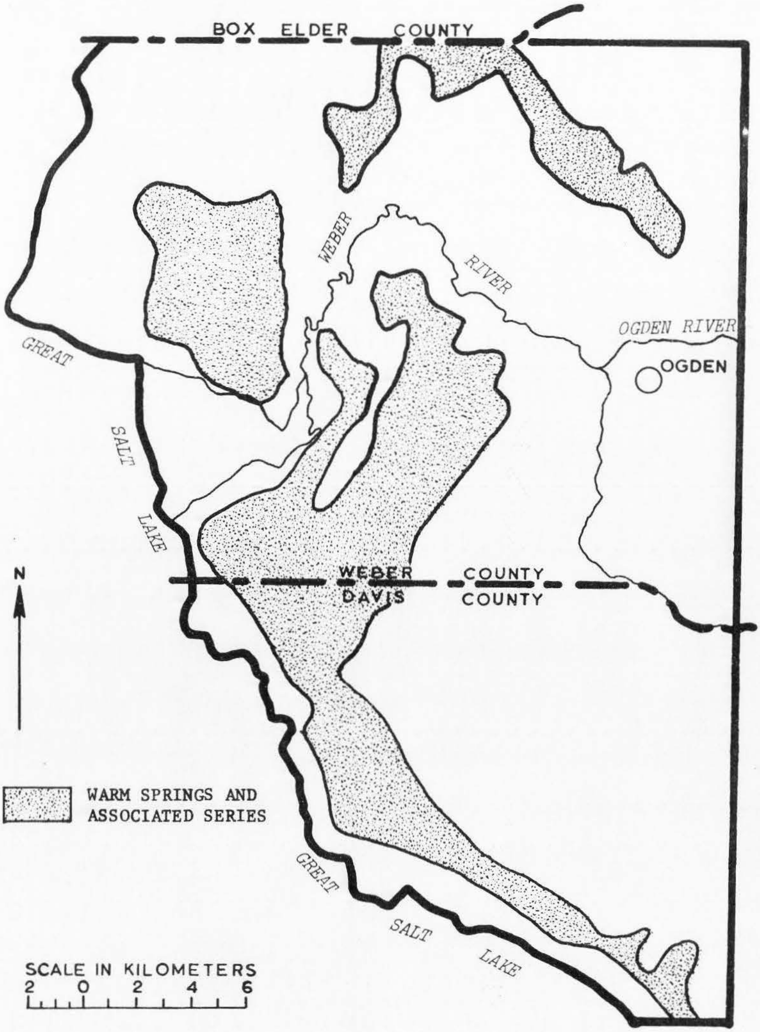

Figure 1. Extent of Warm Springs and associated series on low terraces in the study area. (From Erickson and Wilson, 1968)

normally the warmest and driest months. Mean annual precipitation is about 30 cm with about two thirds of the total precipitation occurring in the October-April period. About half of the October-April precipitation comes as snow during the months of December through March. The mean monthly temperature and precipitation for two climatological stations in the area are shown in Table 1. The Bear River Bay station is located

Table 1. Mean monthly temperature and precipitation at Bear River Bay and Ogden Sugar Factory[1]

	Mean temperature (°C)		Mean precipitation (cm)	
Month	Bear River Bay	Ogden Sugar Factory	Bear River Bay	Ogden Sugar Factory
January	-3.4	-3.4	2.97	4.22
February	0.2	0.2	1.88	3.66
March	5.2	4.7	1.98	3.91
April	8.4	10.0	3.40	5.38
May	15.6	14.7	1.14	4.22
June	21.1	19.1	2.01	3.12
July	25.1	24.3	1.32	1.35
August	24.7	22.9	1.27	1.85
September	17.3	17.3	2.59	2.08
October	10.1	11.4	4.37	3.84
November	3.8	3.8	2.69	3.86
December	-1.2	-1.2	2.41	4.27
Annual	10.6	10.3	28.04	41.76

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[1] Unpublished summaries of Utah Climatological Data. E. A. Richardson, Soils and Biometeorology Department, Utah State University, Logan, Utah.

about 8 kilometers northwest of the study site at an elevation of 1,281 meters and the Ogden Sugar Factory station is about 16 kilometers east at an elevation of 1,287 meters. Precipitation is lowest near the Great Salt Lake and increases eastward toward the Wasatch Mountains. The mean annual soil temperature and mean summer soil temperature were estimated from the air temperature data to be about $11^{\circ}C$ and $23^{\circ}C$, respectively. According to soil family criteria, the soil temperature regime in this area is mesic.

Sodium bicarbonate extractable phosphorus

The determination of available soil phosphorus by a chemical method is influenced primarily by calcium, iron and aluminum phosphates. The amount of phosphorus extracted is dependent upon the relative amounts of calcium, iron and aluminum phosphates in the soil and the solubility of these phosphates in the extractant (Chang and Juo, 1963).

The estimation of available phosphorus in soils by extraction with sodium bicarbonate has received wide use and attention since its development by Olsen et al. (1954). This procedure has been evaluated with respect to yield, phosphorus uptake by plants, other methods of estimating available phosphorus and the forms of phosphorus which it extracts (Bendixen, 1961; Bisen and Ramamoor, 1971; Chang and Juo, 1963; Franklin and Reisenauer, 1960; Grigg, 1965; Roberts, 1968; Sherrell, 1970; Susuki, Lawton and Doll, 1963; and Thomas and Peasley, 1973). A comparison of phosphorus extracted by sodium bicarbonate with yield and phosphorus uptake by white clover (Sherrell, 1970) showed a high correlation between phosphorus extracted and relative yield, yield, and phosphorus uptake.

In theory the main effect of $NaHCO_3$ in calcareous soils is to decrease the Ca^{++} activity which in turn increases the solubility of phosphorus (Olsen et al., 1954). In a subsequent study Olsen, Watanabe, and Cole (1960) found that only small changes in Ca^{++} activity were caused by additions of $NaHCO_3$ to calcareous soils. Grigg (1965), Chang and Juo (1963), Sherrell (1970), and Susuki, Lawton, and Doll (1963) have reported that $NaHCO_3$-P was highly correlated with aluminum phosphate in the soil. Chang and Juo (1963) found that, although $NaHCO_3$-P was highly correlated with aluminum phosphate in soils with calcium phosphate as the major source of phosphorus, calcium, aluminum and iron phosphate were all highly correlated with $NaHCO_3$-P in soils containing iron phosphate as the major source of phosphate. Relatively larger amounts of phosphorus were extracted from those soils with iron phosphate as the major source of phosphate than those with calcium phosphate as the major source, since the alkaline extractant can hydrolize iron and aluminum phosphate but cannot dissolve calcium phosphate. These results indicated that relatively small amounts of calcium phosphate were extracted with sodium bicarbonate.

Solubility of phosphorus compounds

The phosphorus compound which is readily water soluble is readily translocated by water and removed by plant roots.

Lindsay and Morino (1960) and Hsu and Jackson (1960) have determined the influence of soil pH on phosphorus transformations and solubility. In unweathered parent material, most of the phosphorus is present as apatite, therefore, the amount of phosphorus in solution is controlled by the solubility of apatite. Before appreciable amounts of phosphorus are released the soil reaction must drop below pH 7.5.

In a system containing calcium, iron and aluminum, phosphorus is most soluble at pH 7.0. Below pH 7.0 the solubility of phosphorus is governed by iron and aluminum phosphates and decreases rapidly as pH decreases. Above pH 7.0 the solubility of phosphorus is governed by calcium phosphate and decreases rapidly as pH increases (Lindsay and Moreno, 1960). Reducing conditions resulting from flooding or poor drainage lower the activity of Fe^{3+} due to its reduction to Fe^{2+} releasing previously insoluble ferric phosphates.

The influence of sodium on phosphorus solubility and the formation of sodium phosphates has received little attention in studies involving transformation and translocation of phosphorus in soils. Pratt and Thorne (1948) developed a solubility curve for sodium phosphate by increasing the pH with additions of sodium hydroxide. There was a marked increase in water-soluble phosphorus as the pH increased from 7.0 to 10.0. They concluded that, in soils with large amounts of exchangeable sodium, the activity of calcium ions was greatly reduced and there was a large increase in the amount of water-soluble phosphorus. The influence of exchangeable Ca, Mg, NH_4, K, and Na on the solubility of phosphorus in soils was investigated by Ravikovitch (1938). With Na saturating the exchange complex, twice as much water-soluble phosphorus was extracted than when any of the other cations dominated the exchange complex. Ten times more phosphorus was extracted from a sodium-saturated than from a calcium-saturated sandy soil.

Distribution of available phosphorus

Paired soil and plant samples were collected from 617 locations in Utah and analyzed for $NaHCO_3$-P and percent phosphorus in the plant material, respectively (Nielson, Van Epps and Thorne, 1961). The soil samples were collected from the 0 to 15 cm depth and the plant sample consisted of the entire above-ground portion of an alfalfa plant collected from the immediate vicinity of the soil sample. Eight of the 15 soil samples collected from the Warm Springs series were low (<6 ppm) in $NaHCO_3$-P; however, four of the eight corresponding plant samples indicated the plant was not deficient in phosphorus. Considerable variation in $NaHCO_3$-P was found both between and within soil series. This was interpreted to be due in part to farming and fertilizing practices.

Lamborn (1970) determined $NaHCO_3$-P on 847 samples from 146 soil pedons representing 23 soil series primarily in Cache, Box Elder, Weber and Davis counties in northern Utah. $NaHCO_3$-P was determined on each genetic horizon and a weighted average calculated for the 30 to 102 cm depth. This weighted average or subsoil phosphorus ranged from 1.9 to 45 ppm for five pedons representing the Warm Springs series. A further evaluation of Lamborn's data showed that three of the five pedons indicated there was a $NaHCO_3$-P maximum immediately above or in the uppermost horizon of lime accumulation. $NaHCO_3$-P varied with changes in texture of stratified sediments in one pedon. Alternating strata of sandy loam and loamy sand texture contained about 45 and 20 ppm $NaHCO_3$-P, respectively. Two of the Warm Springs pedons indicated a second $NaHCO_3$-P maximum occurring below the calcic horizon and possibly coinciding with the top of a fluctuating water table.

Sims (1971) reported that yield response of dryland small grains to applied phosphorus was not well correlated with $NaHCO_3$-P in the surface sample. There was little or no response to phosphate fertilizer if either the first or second foot of soil contained more than 10 ppm $NaHCO_3$-P.

In studies on soils from Iowa and Illinois reviewed by Smeck (1973) available phosphorus followed a characteristic distribution pattern. Available phosphorus was high in the surface, decreased to minimum amounts in the lower A and upper B horizons, increased to maximum amounts in the lower B or upper C horizons, and then decreased to a level characteristic of the parent material. This distribution of available phosphorus has been interpreted by Runge and Riecken (1966). The high amounts in the surface were due to either fertilizer additions or easily mineralized organic phosphorus compounds from plant residues. Leaching by percolating water and removal by plant roots resulted in the available phosphorus minima in the lower A and upper B horizons. Maximum amounts in the lower B and upper C horizons were due to weathering of phosphate-bearing minerals and illuviation accompanied by a lack of removal by plant roots.

Distribution of total phosphorus

Allaway and Rhodes (1951), Bauwin and Tyner (1957), Godfrey and Riecken (1954), Runge and Riecken (1966), and Smeck and Runge (1971b) have reported a vertical distribution of total phosphorus similar to that for the available phosphorus discussed above. Runge and Riecken (1966) interpreted the distribution of total phosphorus as resulting from eluvial-illuvial processes. A phosphorus eluvial horizon, the horizon of minimum phosphorus, resulted from upward movement of phosphorus by plants and downward movement by percolating water. Percolating water accompanied by a reduction or lack of phosphorus removal by plant roots enriched an illuvial phosphorus horizon below the eluvial phosphorus horizon.

Factors influencing the distribution of phosphorus

In the dynamic soil system, pedogenetic processes continually have their effect on transformations and translocations of soil phosphates. Although phosphorus is generally considered to be immobile in soils, the long term effects of soil weathering processes can and do move considerable amounts of phosphorus. Not only does phosphorus move in the soil, but as weathering selectively removes ions from one horizon and accumulates them in another, the pH changes as well as the relative activities of the various ions. These changes in turn influence transformations of the soil phosphorus. For example, as calcium is leached from the surface of calcareous parent material the pH normally decreases and Ca^{++} activity is reduced. The amount of iron and aluminum phosphates then increases in proportion to calcium phosphates.

These pedogenetic effects on phosphorus distribution have been investigated by numberous researchers (Alexander and Robertson, 1968; Allaway and Rhodes, 1951; Bauwin and Tyner, 1957; Chang and Jackson, 1958; Dahnke, Malcom and Menendez, 1964; Godfrey and Riecken, 1954; Hsu and Jackson, 1960; John and Gardner, 1971; Lipps and Cessin, 1950; MacLean, Willis, and Hoffman, 1971; Runge, 1973; Runge and Riecken, 1966; Runge, Walker, and Howarth, 1974; Saunders, 1965; Smeck and Runge, 1971a; Smeck and Runge, 1971b; Syers and Walker, 1969a; Syers and Walker, 1969b; Syers, Shah and Walker, 1969; Westin and Buntley, 1966; Westin and deBrito, 1969; Williams and Walker, 1969a; Williams and Walker, 1969b) and have recently been reviewed by Smeck (1973).

Parent material. Smeck (1973) and Williams and Walker (1969b) state that the initial source of phosphorus in soils is apatite in unweathered parent materials. Minor amounts of phosphorus may be present in other primary phosphate minerals or added by precipitation. Williams and Walker (1969b) showed that apatite decreased as soil development progressed. Phosphorus from the apatite goes into solution and then may be leached, be taken up by plants, form secondary phosphates, or in calcareous soils be precipitated as calcium-phosphate and recrystallized as apatite. As previously reviewed (p. 8) significant amounts of phosphorus are not released from apatite until the soil pH drops below about 7.5.

Shipp and Matelski (1960) reported a correlation coefficient of 0.896 between percent apatite and total phosphorus in the sand and coarse silt fractions of three soils in Nebraska. Apatite increased with depth in two of the soils and was interpreted to indicate a higher degree of soil weathering in the surface horizons. Uniform distribution of apatite throughout the third soil was associated with minimal weathering.

Calcium carbonate. Studies on distribution of available phosphorus have considered calcium carbonate to be an effective immobilizer of the phosphorus. In soils with calcareous horizons, total phosphorus tends to be greatest just above the calcium carbonate contact (Allaway and Rhodes, 1951; Runge and Riecken, 1966; Smeck and Runge, 1971b). Calcium-phosphate was the dominant form of phosphorus in alkaline soils and was especially high in soils with free calcium carbonate. Calcium-phosphate, consequently, was generally related to pH and calcium carbonate equivalent (Alexander and Robertson, 1968; Smeck and Runge, 1971b).

Extractable iron. The influence of iron distribution on phosphorus distribution has been reported by Runge (1963) and Smeck and Runge (1971b). Runge (1963) separated the brown and gray parts of some poorly drained soils and found the brown part to contain 2.5 to 5.1 times more extractable iron and more total phosphorus than the gray part. A transect in Illinois representing a soil development sequence, Typic Haplaquoll-Mollic Albaqualf, was studied by Smeck and Runge (1971b). Two distinct total phosphorus maxima were obvious in the soils at the more highly developed, Albaqualf end of the transect. The upper maximum was associated with high iron oxide concentrations, suggesting that iron was an effective immobilizer of the phosphate.

Drainage. The influence of natural drainage on the distribution of phosphorus was studied by Runge and Riecken (1966). Total phosphorus was generally less for the poorly drained soil than the imperfectly and moderately well-drained soils and minimum total phosphorus values were reported at a shallower depth in the poorly drained soils. Available phosphorus was also less in the poorly drained soils. The lesser amounts of available phosphorus in the top 50 cm of the poorly drained soils was attributed to eluviation and increased recycling by plants because of the restricted rooting depth caused by high water tables. Lesser amounts of available phosphorus below 50 cm was attributed to higher pH values of 7.5

to 8.2 and a corresponding decrease in phosphate solubility. The published data indicate that the pedons selected by the authors to depict the relationship of depth of total phosphorus minima to drainage class biased the reported result.

Several investigators have reported that avilable or soluble phosphorus increased with flooding or waterlogging the soils (Islam, 1970; Mahapatra and Patrick, 1969; McGregor, 1953; and Shapiro, 1958). Mahapatra and Patrick (1969) studied the influence of waterlogging on transformation of inorganic soil phosphates and extraction of available (Bray No. 2) phosphorus. They reported that iron and aluminum phosphate increased and reductant-soluble (iron oxide occluded) iron phosphate decreased as a result of waterlogging while calcium phosphate remained relatively unchanged. The conversion of reductant-soluble iron phosphate to iron phosphate was explained as resulting from the dissolution of hydrated ferric oxide coatings around the soil particles and the consequent release of iron phosphate. Available phosphorus increased with waterlogging and the increase was greatest in soils with the largest amount of iron phosphate. Islam (1970) reported that water-soluble phosphorus first increased and then decreased with time of submergence under rice cropping. However, his suggestion that the decrease was due in part to the formation of insoluble calcium phosphates at pH values between 6.0 and 7.0 conflicts with the soil pH-phosphorus transformation relationships reported by Lindsay and Morino (1960).

Texture. The influence of soil texture on the distribution of phosphorus has been studied in relation to the accumulation of clay during pedogenesis and the phosphorus fractions associated with different particle-size separates. Godfrey and Riecken (1954), Pearson and Simonson (1939), Runge and Riecken (1966), and Smeck and Runge (1971b) found that total phosphorus was lowest in the horizons of maximum clay content. Their results indicated that pedogenetic processes influenced phosphorus distribution at greater depths than clay and that clay was not an effective factor in immobilization of phosphorus. The results of Syers, Shah and Walker (1969) and Williams and Saunders (1956a) indicated that total phosphorus was greater in the clay fraction than in the silt or sand fractions.

Soluble phosphorus extracted by acetic acid and Truog methods was extracted mainly from fine sand in subsoils studied by Williams and Saunders (1956b). The readily soluble phosphorus varied inversely with the phosphate-sorption capacity of the soil. When sands (low sorption capacity) were rich in phosphorus, soluble phosphorus values were high. The extraction of soluble phosphorus by these methods, therefore, was limited by the clay with its relatively high phosphate-sorption capacity.

Cicada. Hugie and Passey (1963) reported on the occurrence and activity of Western species of cicada in Southern Idaho, Northern Utah, and Northeastern Nevada. Their observations indicated that the cicada nymphs moved about in the soil to secure food, escape freezing temperatures and upon maturity emerge from the soil. The open portion of burrows rarely exceeded 8 cm suggesting that the cicada nymphs continually backfill their burrows with local materials, thereby, limiting the mixing of soil horizons. Cicada casts were usually most readily observed in horizons of calcium carbonate accumulation in soils that have calcareous horizons. Whether this was an indication of maximum cicada activity or whether the cicada casts were better preserved in calcareous horizons was not certain.

Higher amounts of $NaHCO_3$-P have been measured in the cicada casts than in the surrounding matrix.[2] However, phosphorus equilibration might be expected between the cicada casts and the surrounding matrix with increasing age of the casts.

Summary of the review of literature

The Warm Springs soil series was mapped on low lake terraces and river flood plains at elevations ranging from 1,280 to 1,320 meters above sea level. The Ogden, Weber, and Bear Rivers provided much of the sediment in the terraces and flood plains. Mean annual precipitation in the study area is about 30 cm and the soil temperature regime is mesic.

The amount of phosphorus extracted by $NaHCO_3$ is dependent upon the relative amounts of the different forms of phosphate

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[2] Personal Communication. Alvin R. Southard. Soils and Biometeorology Department, Utah State University, Logan, Utah.

in the soil and the solubility of those phosphates in $NaHCO_3$. In soils with relatively high amounts of calcium phosphate, little of the calcium phosphate is soluble in $NaHCO_3$. Above pH 7.0 the solubility of phosphorus is governed by calcium phosphate (not iron and aluminum phosphates) and decreases rapidly as pH increases. However, sodium phosphate is quite soluble in water and water-soluble phosphorus increases when sodium saturates the exchange complex. The solubility of sodium phosphate increases as pH values increase from 7.0 to 10.0.

Considerable variation in subsoil $NaHCO_3$-P has been reported for several soil series in Utah. Available phosphorus has been reported to have a characteristic vertical distribution pattern for soils studied in Iowa and Illinois. The distribution was interpreted in terms of fertilizer additions, leaching by percolating water, removal by plant roots and weathering of primary phosphate-bearing minerals. Total phosphorus has been interpreted in terms of eluvial and illuvial phosphorus horizons resulting from percolating water and removal by plant roots.

The initial source of phosphorus in soils is apatite in unweathered parent materials, however, appreciable phosphorus is not released from apatite until the soil pH drops below 7.5. Immobilization of phosphorus by calcium carbonate is indicated by the presence of total phosphorus maxima just above the calcium carbonate accumulation in soils with calcareous subsoil horizons. Immobilization of phosphorus by iron is indicated by the presence of total phosphorus maxima in horizons or zones of iron oxide concentrations. Total phosphorus maxima below horizons of clay accumulation were reported as evidence that clay did not immobilize phosphorus. Soluble phosphorus is most readily extracted from sands with low phosphate-sorption capacity and extraction is limited from clay fractions with their relatively high phosphate-sorption capacity.

Total phosphorus and available phosphorus are less for poorly drained soils than for imperfectly and well-drained soils. Available phosphorus, however, is increased by reducing conditions imposed by flooding and waterlogging. The reduction of Fe^{+3} to Fe^{+2} releases insoluble ferric phosphates.

In some soils of the Great Basin, higher amounts of $NaHCO_3$-P have been extracted from cicada casts than from the surrounding matrix. However, phosphorus equilibrium might be expected between casts and matrix with increasing age of the cicada casts.

SOILS AND METHODS

Soils studied

Criteria used in the selection of a study area were (i) variability of phosphorus distribution in a small area, (ii) uniformity of landscape and parent material, and (iii) minimal effects of land use and management. The latter two criteria were necessary to minimize differences in soil-forming factors and phosphate fertilizer additions. Fulfillment of the first criterion was an exercise in trial and error to obtain pedons with less than 10 ppm and greater than 30 ppm subsoil $NaHCO_3$-P in a contiguous area of less than 300 ha.

The area is located about 1.6 km south and 2 km west of West Warren in Weber County. Locations of the four pedons which were described in the field and sampled for laboratory analysis are shown on a soils map of the area (Figure 2).

All pedons sampled were developed on level, lacustrine or river flood plain deposits which may have been reworked by wind. The area is presently used as winter range for sheep and cattle. Alkali sacaton (Sporobolus airoides) and salt grass (Distichlis sp.) are the dominant plants. Figure 3 is a photograph of the study area.

The Warm Springs series has been classified as a member of the fine-loamy, mixed, mesic family of Typic Calciaquolls. After a review of pedon descriptions and analytical data on

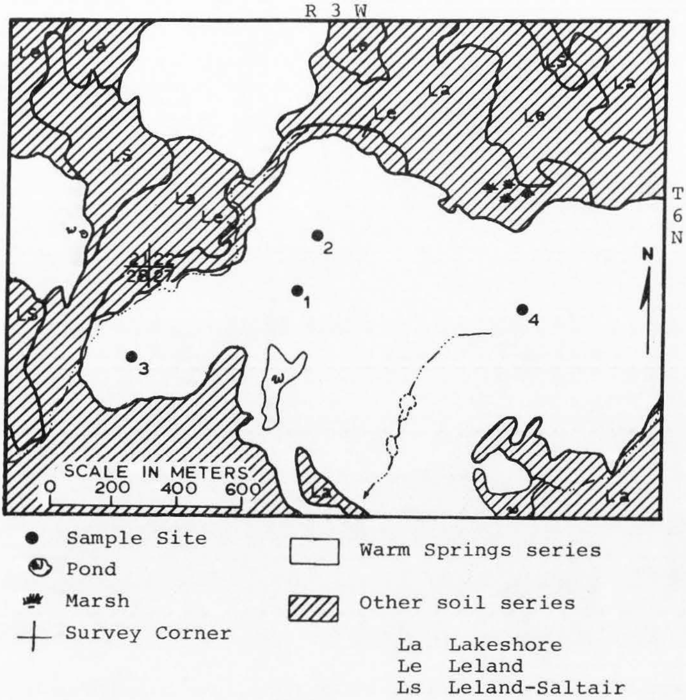

Figure 2. Soils map of the study area showing the pedon locations (Adapted from Erickson and Wilson, 1968)

Figure 3. Photograph of the study site, looking east toward the Wasatch Mountains

file, the author believes the Warm Springs series and the four pedons studied would be better classified as a member of the coarse-loamy, mixed, mesic family of Aquic Calciustolls. Typically, these soils have grayish brown, mildly alkaline, fine sandy loam A horizons; light gray, very strongly alkaline, fine sandy loam C horizons; and distinct horizons of carbonate accumulation. Depth to the water table is generally 1 to 2 meters.

Descriptions of the four pedons sampled for this study follow:

<u>Pedon #1: Warm Springs fine sandy loam</u>. (Colors are for dry soil unless otherwise noted.)

A1	0 to 15 cm -- Grayish brown (10YR5/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; weak fine platy structure; slightly hard, friable, slightly sticky, slightly plastic; plentiful very fine and plentiful fine roots; non-calcareous; moderately alkaline (pH 8.3); abrupt smooth boundary.
C1ca	15 to 25 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; moderate coarse blocky structure; hard, firm, sticky, plastic; few fine and few very fine roots; moderately calcareous; very strongly alkaline (pH 9.7); clear smooth boundary.
C2ca	25 to 38 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; weak medium subangular blocky structure; hard, friable, slightly sticky, slightly plastic; plentiful very fine and few fine roots; moderately calcareous; very strongly alkaline (pH 10.2); clear smooth boundary.
C3ca	38 to 56 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; moderate medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; plentiful very fine roots; strongly calcareous; very strongly alkaline (pH 10.3); gradual smooth boundary.

C4ca	56 to 74 cm -- Light gray (10YR7/2) fine sandy loam; pale brown (10YR6/3) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.4); abrupt wavy boundary.
C5ca	74 to 86 cm -- Pinkish gray (7.5YR7/2) fine sandy loam; light brown (7.5YR6/4) moist; massive; slightly hard, firm, slightly sticky, slightly plastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.3); abrupt wavy boundary.
C6	86 to 102 cm -- Pale brown (10YR6/3) loamy fine sand; yellowish brown (10YR5/4) moist; massive; slightly hard, friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 10.4); abrupt smooth boundary.
C7	102 to 117 cm -- Pale brown (10YR6/3) loamy fine sand; brown (10YR5/3) moist; massive; slightly hard, friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 10.1); gradual smooth boundary.
C8	117 to 140 cm -- Pale brown (10YR6/3) loamy fine sand; brown (10YR5/3) moist; massive; slightly hard, very friable; nonsticky, nonplastic; very few, very fine roots; moderately calcareous; very strongly alkaline (pH 10.1); gradual smooth boundary.
C9	140 to 173 cm -- Light gray (2.5YR7/2) loamy fine sand; grayish brown (2.5Y5/2) moist; massive; soft, very friable, nonsticky, nonplastic; strongly calcareous; very strongly alkaline (pH 10.2).

Location: 42 meters south and 400 meters east of the northwest corner of Section 27, T.6N., R.3W.

Pedon #2: Warm Springs fine sandy loam. (Colors are for dry soil unless otherwise noted.)

A11	0 to 8 cm -- Grayish brown (10YR5/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; weak fine granular structure; soft, friable, nonsticky, slightly plastic; plentiful fine and abundant very fine roots; non-calcareous; mildly alkaline (pH 7.8); clear smooth boundary.

A12	8 to 25 cm -- Grayish brown (10YR5/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; moderate medium subangular blocky structure; slightly hard, friable, nonsticky, nonplastic; few medium few fine and plentiful very fine roots; slightly calcareous; strongly alkaline (pH 8.5); clear smooth boundary.
C1ca	25 to 43 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; moderate medium subangular blocky structure; slightly hard, firm, slightly sticky, slightly plastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.1); clear smooth boundary.
C2ca	43 to 61 cm -- Pinkish gray (7.5YR7/2) fine sandy loam; light brown (7.5YR6/4) moist; weak medium subangular blocky structure; slightly hard; firm, slightly sticky, slightly plastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.2); gradual smooth boundary; cicada casts make up about 20 percent of the soil volume.
C3	61 to 91 cm -- Light gray (10YR7/2) loamy fine sand; brown (10YR5/3) moist; massive; soft, very friable, nonsticky, nonplastic; plentiful very fine roots; moderately calcareous; very strongly alkaline (pH 9.9); abrupt broken boundary.
C4	91 to 99 cm -- Pale brown (10YR6/3) loamy fine sand; brown (10YR5/3) moist; platy structure (dense finely varved); slightly hard, very friable, nonsticky, nonplastic; few very fine roots between plates; moderately calcareous; very strongly alkaline (pH 10.0); abrupt broken boundary.
C5	99 to 114 cm -- Pale brown (10YR6/3) fine sand; brown (10YR5/3) moist; massive; loose, very friable, nonsticky, nonplastic; few very fine roots; slightly calcareous; very strongly alkaline (pH 9.9); abrupt smooth boundary.
C6	114 to 117 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; massive; slightly hard, friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 10.0); abrupt smooth boundary.

C7 117 to 150 cm -- Pale brown (10YR6/3) fine sand; brown (10YR5/3) moist; massive (stratified); loose, very friable, nonsticky, nonplastic; few very fine roots; slightly calcareous; very strongly alkaline (pH 10.0); clear smooth boundary.

C8 150 to 163 cm -- Pale brown (10YR6/3) very fine sandy loam; brown (10YR5/3) moist; massive; soft, friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 9.8); clear smooth boundary.

C9 163 to 198 cm -- very pale brown (10YR7/3) very fine sandy loam; grayish brown (10YR5/2) moist; massive (stratified); soft, very friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 9.8); abrupt smooth boundary; many thin horizontal yellow (10YR7/6) lines.

C10 198 to 208 cm -- Light gray (2.5Y7/2) very fine sandy loam; grayish brown (2.5Y5/2) moist; massive (stratified); soft, very friable, nonsticky, nonplastic; moderately calcareous; very strongly alkaline; water table at 198 cm.

Location: 150 meters north and 400 meters east of the southwest corner of Section 22, T.6N., R.3W.

Pedon #3: Warm Springs fine sandy loam. (Colors are for dry soil unless otherwise noted.)

A11 0 to 5 cm -- Dark grayish brown (10YR4/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; weak very fine granular structure; loose, friable, nonsticky, nonplastic; abundant very fine and few fine roots; noncalcareous; mildly alkaline (pH 7.5); abrupt smooth boundary.

A12 5 to 18 cm -- Grayish brown (10YR5/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; weak fine platy structure; soft, friable, slightly sticky, slightly plastic; plentiful very fine and few fine roots; slightly calcareous; moderately alkaline (pH 8.0); clear smooth boundary.

A13	18 to 33 cm -- Grayish brown (10YR5/2) fine sandy loam; dark grayish brown (10YR4/2) moist; moderate medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; few fine and plentiful very fine roots; moderately calcareous; moderately alkaline (pH 8.3); clear smooth boundary.
C1ca	33 to 51 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; weak medium subangular blocky structure; slightly hard, firm, slightly sticky, slightly plastic; plentiful very fine and few fine roots; strongly calcareous; very strongly alkaline (pH 10.1); gradual smooth boundary.
C2ca	51 to 63 cm -- Pale brown (10YR6/3) fine sandy loam; brown (10YR5/3) moist; weak medium subangular blocky structure; slightly hard, firm, slightly sticky, slightly plastic; plentiful very fine roots; strongly calcareous; very strongly alkaline (pH 10.2); gradual smooth boundary.
C3ca	63 to 81 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.4); gradual smooth boundary.
C4ca	81 to 119 cm -- Light gray (10YR7/2) fine sandy loam; pale brown (10YR6/3) moist; massive; soft, firm, nonsticky, nonplastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.4); gradual smooth boundary.
C5	119 to 147 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; massive; slightly hard, very friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 10.3); very abrupt smooth boundary.
C6	147 to 162 cm -- Thin layers (3 to 7 cm thick) of pink (7.5YR7/4) silty clay loam; light reddish brown (5YR6/4) moist; moderate fine subangular blocky structure; hard, firm, sticky, plastic; and pale brown (10YR6/3) loamy fine sand; brown (10YR5/3) moist; massive; loose, friable, nonsticky, nonplastic; moderately calcareous; very strongly alkaline (pH 10.3); very abrupt smooth boundary.
C7	162 to 211 cm -- Pale brown (10YR6/3) loamy very fine sand; brown (10YR5/3) moist; massive; loose, very friable, nonsticky, nonplastic; moderately calcareous; very strongly alkaline (pH 10.3).

Location: 300 meters south of the northeast corner of Section 28, T.6N., R.3W.

Pedon #4: Warm Springs fine sandy loam (Figure 4).

(Colors are for dry soil unless otherwise noted.)

A11	0 to 8 cm -- Dark grayish brown (10YR4/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; moderate fine granular structure; loose, friable, nonsticky, nonplastic; abundant very fine and few fine roots; slightly calcareous; moderately alkaline (pH 8.3); clear smooth boundary.
A12	8 to 15 cm -- Grayish brown (10YR5/2) fine sandy loam; very dark grayish brown (10YR3/2) moist; weak medium subangular blocky structure; soft, friable, nonsticky, nonplastic; plentiful fine and few very fine roots; slightly calcareous; moderately alkaline (pH 8.3); clear smooth boundary.
A13	15 to 30 cm -- Grayish brown (10YR5/2) fine sandy loam; dark brown (10YR3/3) moist; weak medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; plentiful fine and plentiful very fine roots; slightly calcareous; strongly alkaline (pH 8.8); clear smooth boundary.
C1ca	30 to 46 cm -- Brown (10YR5/3) fine sandy loam; dark brown (10YR4/3) moist; moderate medium subangular blocky structure; hard, firm, slightly sticky, slightly plastic; few fine and plentiful very fine roots; slightly calcareous; very strongly alkaline (pH 9.8); clear smooth boundary.
C2ca	46 to 61 cm -- Light gray (10YR7/2) fine sandy loam; brown (10YR5/3) moist; moderate medium subangular blocky structure; slightly hard, firm, slightly sticky, plastic; few very fine roots; strongly calcareous; very strongly alkaline (pH 10.0); clear smooth boundary; cicada casts present.
C3ca	61 to 79 cm -- Pinkish gray (7.5YR7/2) fine sandy loam; brown (7.5YR5/4) moist; moderate medium subangular blocky structure; slightly hard, very firm, slightly sticky, slightly plastic; strongly calcareous; very strongly alkaline (pH 9.9); gradual smooth boundary.

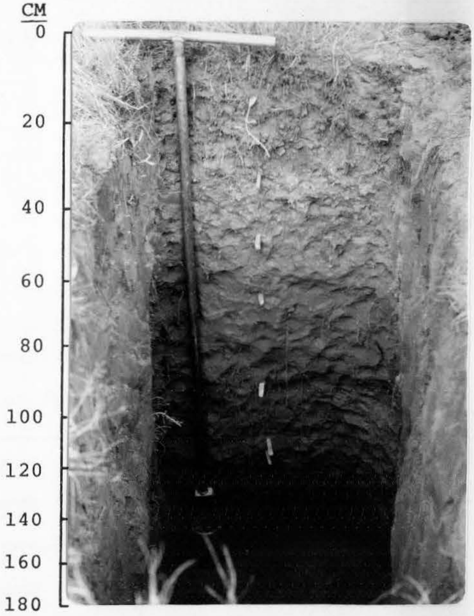

Figure 4. Photograph of the Warm Springs fine sandy loam, pedon 4

C4	79 to 96 cm -- Pale brown (10YR6/3) loamy fine sand; brown (10YR4/3) moist; massive; loose, friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 9.9); gradual smooth boundary.
C5	96 to 135 cm -- Light brownish gray (10YR6/2) loamy fine sand; brown (10YR5/3) moist; massive; loose, friable, nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 9.8); gradual smooth boundary.
C6	135 to 165 cm -- Light gray (10YR7/2) loamy fine sand; brown (10YR5/3) moist; massive; loose, friable; nonsticky, nonplastic; few very fine roots; moderately calcareous; very strongly alkaline (pH 9.9); water table at 157 cm.

Location: 450 meters west and 60 meters south of the northwest corner of Section 27, T.6N., R.3W.

Laboratory procedures

$NaHCO_3$-P. $NaHCO_3$-P was determined by the sodium bicarbonate method of Olsen et al. (1954), with adaptations of the Murphy and Riley method (Watanabe and Olsen, 1965).

Total phosphorus. Total phosphorus was determined by the procedure used by the Soil, Plant and Water Analysis Laboratory at Utah State University. The phosphorus was digested with 60 percent perchloric acid and the extracted phosphorus determined colorimetrically using ammonium molybdate and ammonium vanadate in nitric acid.

Water-soluble phosphorus. Phosphorus was extracted with distilled water instead of sodium bicarbonate using the same procedures used in determining $NaHCO_3$-P.

Reaction (pH). Soil reaction was determined on a 1:1 soil-water dilution using a Corning Model 10 pH meter with a glass electrode.

Calcium carbonate equivalent. A modification of Williams' (1948) manometric method was used to determine the calcium carbonate equivalent.

Extractable iron. Iron was extracted with pyrophosphate and sodium dithionite according to the procedure of Franzmeier, Hajek and Simonson (1965). The iron was determined with a Jarrel-Ash model 800 atomic absorption spectrophotometer.

Electrical conductivity. Electrical conductivity of the saturation extract was determined by the procedure described by the United States Salinity Laboratory Staff (1954) using a Solu-Bridge Soil Tester for measuring the conductivity.

Water-soluble sodium. Sodium was determined on the saturation extract according to procedure 6Plb (Soil Conservation Service, 1972). A Jarrel-Ash model 800 atomic absorption spectrophotometer was used to make the determination.

Particle-size distribution. Particle-size distribution was determined by the pipette method of Kilmer and Alexander (1949) using sodium hypochlorite for removal of organic matter (Anderson, 1963).

Non-carbonate clay. A 50 ml sample of clay-size particles was collected during the particle-size analysis and the clay-size carbonate determined manometrically. Non-carbonate clay was determined by subtracting the clay-size carbonate from the total clay.

Apatite mineralogy. Percent apatite was determined on the very fine sand fraction separated for the particle-size analysis. The heavy mineral fraction was then separated using tetrabromoethane and the technique of Shipp and Matelski (1960) using 10.7 N H_2SO_4 to produce gypsum crystals was used to identify the apatite grains.

Na-P solution--$NaHCO_3$ extractable phosphorus. Sodium bicarbonate extractable phosphorus was determined after shaking soil samples with sodium-phosphate (Na-P) aqueous solutions. The Na-P solutions used contained 10, 20, 30, and 40 ppm phosphorus of NaH_2PO_4. Sodium hydroxide was added to increase the sodium in solution to 3,000 ppm and the pH adjusted to 10.0 with HCl. A 2.5 g soil sample was shaken with 50 ml of Na-P solution for 48 hours and then centrifuged at 7,000 rpm for 30 minutes to remove suspended soil particles from the supernatant. Two ml of supernatant was pippeted into flasks and diluted with 50 ml of water for determination of phosphorus by the ascorbic acid method of Murphy and Riley (1962). The remaining supernatant was decanted using an aspirator. The moist soil was then weighed, let air dry overnight, and weighed again to determine the moisture difference gravimetrically. $NaHCO_3$-P was then determined on the air-dry sample. Values for $NaHCO_3$-P were adjusted for the amount of P in solution in the moist "decanted" soil sample.

RESULTS AND DISCUSSION

Distribution of total phosphorus

The distribution of total phosphorus (perchloric acid digestion) in four pedons of the Warm Springs series is shown in Figure 5. Maximum amounts of total phosphorus were found just below the surface in the lower A or upper C horizons above the calcic horizon. The occurrence of maximum total phosphorus values above horizons of calcium carbonate accumulation was reported by Allaway and Rhodes (1951), Runge and Riecken (1966), and Smeck and Runge (1971b). In soils with B horizons, as those which were studied by Allaway and Rhodes (1951), Runge and Riecken (1966) and Smeck and Runge (1971b), total phosphorus minima occurred in the lower A or upper B horizons and there was more total phosphorus in the lower B and upper C horizons than in the surface A horizons.

Although B horizons have not developed in the Warm Springs series, the relationship of total phosphorus between the surface and calcic horizons in the Warm Springs series was similar to that reported in soils by the other researchers. In the Warm Springs pedons, total phosphorus decreased below the calcic horizons. Generally, total phosphorus below the calcic horizons of the Warm Springs pedons appeared to be associated with particle-size distribution of the layered sediments. A sequence of five horizons in pedon 2, horizons C4

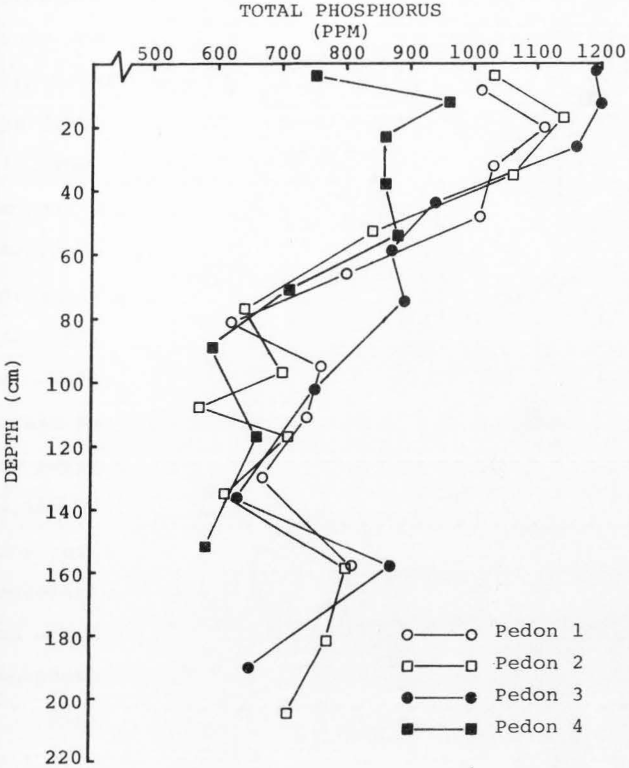

Figure 5. Distribution of total phosphorus in four pedons of the Warm Springs series

through C8, had textures of loamy fine sand, fine sand, fine sandy loam, fine sand and very fine sandy loam, respectively, with total phosphorus values of 700, 570, 710, 610, and 800 ppm (Table 2).

The total phosphorus distribution in the Warm Springs pedons, was interpreted in terms of eluvial-illuvial horizons (Runge and Riecken, 1966): the total phosphorus eluvial horizon was the surface 0 to 10 cm, the total phosphorus illuvial horizons occurred between 10 and 60 cm with maximum values between 10 and 25 cm, and the total phosphorus of the parent material occurred below 60 cm depth. The eluvial horizon resulted from the weathering of apatite and greater solubility of calcium-phosphates in the mildly to moderately alkaline surface. Downward movement of soluble phosphorus by percolating water was arrested by an increase in alkalinity and a concomitant accumulation of phosphorus in the illuvial phosphorus horizon.

Distribution of apatite. Apatite grains were counted in the heavy mineral fraction of the very fine sand fraction of eight horizons selected from pedons 1 and 2. The vertical distribution of apatite determined for four horizons of each pedon is shown in Table 3. Apatite in the very fine sand fraction was low near the surface, increased to maximum values between 50 and 70 cm depth, and then decreased below the calcic horizons. To assume that apatite was initially uniformly distributed with depth would be highly speculative;

Table 2. Chemical analyses of four pedons representing the Warm Springs series

Horizon	Depth cm	pH 1:1 H_2O	Phosphorus			Extractable iron %	$CaCO_3$ equivalent %	Electrical conductivity mmhos/cm	Water-soluble sodium meq/l
			Total ppm	$NaHCO_3$ extractable ppm	Water-soluble ppm				
				PEDON 1					
A1	0-15	8.3	1020	6	15	0.085	0.3	0.9	3.0
C1ca	15-25	9.7	1110	17	11	0.040	13.7	11.0	91.4
C2ca	25-38	10.2	1030	34	20	0.035	10.4	18.0	193.5
C3ca	38-56	10.3	1010	32	12	0.030	12.5	27.5	247.8
C4ca	56-74	10.4	800	22	9	0.025	23.2	39.0	317.4
C5	74-86	10.3	620	24	24	0.035	23.2	47.0	386.9
C6	86-102	10.4	760	28	27	0.085	10.1	55.0	434.8
C7	102-117	10.1	740	36	32	0.090	10.1	97.0	>650.0
C8	117-140	10.1	670	40	38	0.080	10.1	114.0	>650.0
C9	140-173	10.2	810	36	30	0.075	10.7	94.0	565.2
				PEDON 2					
A11	0-8	7.8	1030	11	15	0.090	0.0	1.1	6.2
A12	8-25	8.5	1140	6	11	0.040	1.5	3.0	17.4
C1ca	25-43	10.1	1060	33	14	0.040	18.3	11.0	106.5
C2ca	43-61	10.2	840	34	15	0.025	19.8	26.0	208.7
C3	61-91	9.9	640	14	8	0.050	10.4	20.0	167.4
C4	91-99	10.0	700	8	6	0.055	8.2	25.0	200.0
C5	99-114	9.9	570	7	5	0.055	6.7	19.0	158.7
C6	114-117	10.0	710	10	8	0.055	11.6	48.0	426.1
C7	117-150	10.0	610	10	6	0.065	7.0	39.0	347.8
C8	150-163	9.8	800	10	7	0.070	10.1	38.0	317.4
C9	163-198	9.8	770	24	15	0.230	11.0	24.0	182.6
C10	198-208	10.0	710	4	3	0.185	10.7	18.0	147.8

Table 2. Continued

Horizon	Depth cm	pH 1:1 H_2O	Phosphorus			Extractable iron %	$CaCO_3$ equivalent %	Electrical conductivity mmhos/cm	Water-soluble sodium meq/l
			Total ppm	$NaHCO_3$ extractable ppm	Water-soluble ppm				
					PEDON 3				
A11	0-5	7.5	1190	12	8	0.070	0.8	1.8	2.3
A12	5-18	8.0	1200	6	4	0.095	3.4	0.9	1.3
A13	18-33	8.3	1160	2	3	0.060	7.6	5.2	20.6
C1ca	33-51	10.1	940	11	5	0.030	13.1	16.0	178.3
C2ca	51-63	10.2	870	26	11	0.030	14.3	28.0	217.4
C3ca	63-81	10.4	880	32	13	0.030	14.9	29.0	256.5
C4ca	81-119	10.4	750	36	21	0.040	16.8	44.0	395.6
C5	119-147	10.3	630	37	35	0.090	11.6	40.0	356.5
C6	147-162	10.3	870	40	38	0.130	12.5	33.0	295.6
C7	162-211	10.3	650	20	22	0.095	9.5	39.0	326.1
					PEDON 4				
A11	0-8	8.3	750	13	7	0.085	2.7	1.9	9.2
A12	8-15	8.3	960	11	7	0.115	1.2	2.6	10.9
A13	15-30	8.8	860	7	5	0.115	0.9	5.1	30.4
C1ca	30-46	9.8	860	12	5	0.125	2.7	8.5	73.9
C2ca	46-61	10.0	880	26	1	0.050	16.8	16.3	143.5
C3ca	61-79	9.9	710	12	0	0.055	14.0	8.0	63.0
C4	79-96	9.9	590	7	1	0.055	10.1	5.0	34.8
C5	96-135	9.8	660	8	1	0.050	9.5	5.7	43.5
C6	135-165	9.9	580	3	2	0.045	8.2	10.7	97.8

Table 3. Particle-size distribution, clay-size carbonate, non-carbonate clay and percent apatite of selected horizons of four pedons representing the Warm Springs series

		Particle-size distribution					
Horizon	Depth cm	Sand %	Silt %	Clay %	Clay-size carbonate %	Non-carbonate clay %	Apatite in very fine sand %
				PEDON 1			
A1	0-15	54.6	36.3	9.0	0.2	8.8	0.21
C2ca	25-38	52.5	32.3	15.2	2.2	13.0	0.23
C4ca	56-74	72.1	17.8	10.1	3.1	7.0	0.36
C8	117-140	80.4	16.2	3.4	0.5	2.9	0.24
				PEDON 2			
A12	8-25	61.3	29.5	9.2	0.4	8.8	0.15
C2ca	43-61	58.8	24.0	17.4	4.0	13.4	0.27
C5	99-114	89.1	8.6	2.3	0.5	1.8	0.21
C9	163-198	62.4	31.0	6.6	0.4	6.2	0.13
				PEDON 3			
A11	0-5	61.4	29.4	9.0	0.4	8.6	-[1]
A13	18-33	65.0	26.2	8.8	0.4	8.4	-
C5	119-147	77.6	12.3	10.1	1.0	9.1	-
C7	162-211	86.5	10.8	2.7	0.3	2.4	-
				PEDON 4			
A11	0-8	74.4	18.4	7.1	0.2	6.9	-
A13	15-30	64.3	26.0	9.7	0.3	9.4	-
C2ca	46-61	56.6	26.1	17.2	3.8	13.4	-
C4	79-96	83.1	10.1	6.8	1.7	5.1	-

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[1] Values not determined for pedon 3 and 4

therefore, the results did not conclusively indicate that apatite had been precipitated in some horizons or weathered in others. Since the apatite grains that were counted had been subjected to sodium hypochlorite and dispersing agents during particle-size fractionation, and since water-soluble phosphorus was equal to $NaHCO_3$-P in many subsoil horizons, the apatite most likely did not contribute to $NaHCO_3$-P. However, over long periods of time the apatite may be a source of $NaHCO_3$-P in horizons below the calcic horizons.

Distribution of $NaHCO_3$-P

Vertical distribution. Vertical distribution of $NaHCO_3$-P in the four pedons is illustrated in Figure 6. $NaHCO_3$-P was about 12 ppm in the surface, decreasing to minimum values of 7 ppm or less in the lower A horizons and then increasing to 25 ppm or greater in calcic horizons. The amount of $NaHCO_3$-P was about the same in all four pedons, 25 ppm, near the 60 cm depth. Below this depth $NaHCO_3$-P increased in pedons 1 and 3 but decreased in pedons 2 and 4. The distribution of $NaHCO_3$-P in the A and calcic horizons was similar to that reported by other investigators (Runge and Riecken, 1966; Smeck and Runge, 1971). However, $NaHCO_3$-P did not decrease below the calcic horizons of pedons 1 and 3 as had been reported in the other studies.

Distribution of subsoil $NaHCO_3$-P in the Davis-Weber area. The distribution of subsoil $NaHCO_3$-P for pedons analyzed by

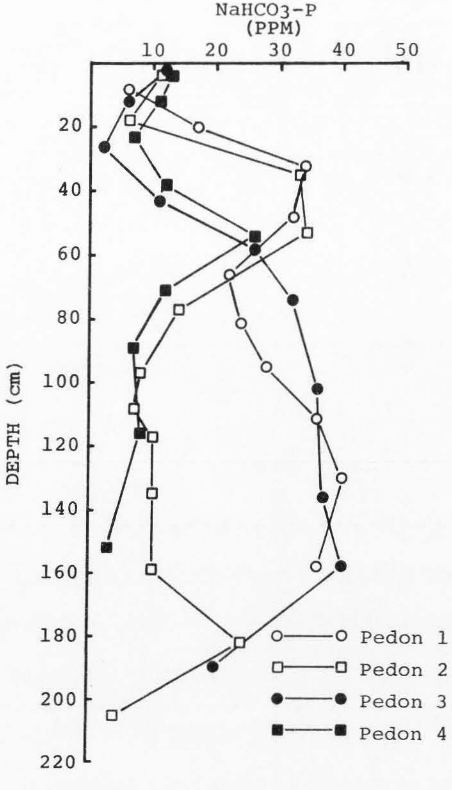

Figure 6. Distribution of $NaHCO_3$-P in four pedons of the Warm Springs series

Lamborn[3] in the Davis-Weber area was interpreted in terms of genetic horizons instead of the weighted average for the 30 to 102 cm depth. The 43 pedons were separated into three groups as those with the following characteristics: (I) no subsoil horizons (excluding all A horizons) had more than 10 ppm $NaHCO_3$-P, (II) all subsoil horizons (excluding all A horizons) with greater than 10 ppm $NaHCO_3$-P had a pH value (saturated paste) of 8.0 or less, (III) some subsoil horizons (excluding all A horizons) with greater than 10 ppm $NaHCO_3$-P had a pH value (saturated paste) greater than 8.0.

The number of pedons of each soil series in the above groups is shown in Table 4. Of the 10 soil series represented, three had pedons in just one group (Leland and Kilburn are represented by only two pedons), six were represented in two groups and the Kidman series had at least one pedon in each of the three groups. Of the six soil series represented by pedons in two groups, the two groups were either I and II or I and III. Pedons of those soil series, therefore, had greater than and less than 10 ppm $NaHCO_3$-P, but were segregated by the alkalinity of the subsoil horizons in which there were more than 10 ppm $NaHCO_3$-P. All pedons represented in group II occurred at elevations higher than 1,340 meters and those in group III occurred below that elevation.

Subsoil $NaHCO_3$-P in group II pedons decreased to less than 10 ppm when pH values became greater than 8.0. Runge and

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[3] Unpublished data. Reuel Lamborn, Soils and Biometeorology Department, Utah State University, Logan, Utah.

Table 4. Number of pedons for each soil series in groups I, II, and III

	Group I	Group II	Group III
	$NaHCO_3$-P	$NaHCO_3$-P >10 ppm	
Soil series	<10 ppm	pH <8.0	pH >8.0
Ironton	1		1
Kidman	5	1	2
Kilburn		2	
Leland			2
Logan	4		
Parleys	8	4	
Payson	1		1
Syracuse	1		1
Timpanogos	3	1	
Warm Springs	1		4

Riecken (1966) explained a similar decline in available phosphorus with increasing alkalinity as being due to a decrease in the solubility of calcium phosphates with increasing pH values above 7.5. Their argument seems valid for subsoils in the Davis-Weber Area at elevations above 1,340 meters and which do not have pH values greater than 10.0 or the relatively high amounts of sodium. The 11 pedons in group III occurred at elevations lower than 1,340 meters, their subsoils were strongly to very strongly alkaline, generally associated with sodic conditions, and there was usually evidence of a water table occurring at less than 2 meters depth. This evaluation of Lamborn's data showed that the subsoil $NaHCO_3$-P was highly variable in most of the soil series and those soils with greater than 10 ppm $NaHCO_3$-P on the high terraces and alluvial fans could be separated from those on the low terraces and flood plains. The subsoil $NaHCO_3$-P cannot be interpreted in the same manner for both group II and group III soils since $NaHCO_3$-P decreased with increasing alkalinity in the pedons of group II, but large amounts, 20 to 40 ppm, of $NaHCO_3$-P were extracted from pedons in group III which were very strongly alkaline.

$NaHCO_3$-P in river and lake sediments. Sediment samples were collected along the present shoreline of the Great Salt Lake, and in the Weber and Bear Rivers, for $NaHCO_3$-P analysis. The Great Salt Lake samples were collected north and south of the Antelope Island causeway along the eastern shore of the lake. The Weber River sample was collected in the Ogden Waterfowl Management Area about 2 km south of the study site and the Bear River sample was collected at the Highway 83 bridge east of Corrine. Samples of the Salt Lake-north of the causeway, Salt Lake-south of the causeway, Weber River and Bear River sediments contained 28, 12, 31, and 22 ppm $NaHCO_3$-P respectively. Water samples taken from the Great Salt Lake, Weber River and Bear River contained 3, 0.4, and <0.1 ppm phosphorus, respectively. The sediments, therefore, contained much higher amounts of $NaHCO_3$-P than there was soluble phosphorus in the waters. The river sediments with 31 and 22 ppm $NaHCO_3$-P indicated that the sediments deposited in the low lake terraces and river flood plains were likely a major source of the subsoil $NaHCO_3$-P. Sediments carried by the rivers were likely derived mostly from sheet and rill erosion due to raindrop splash and snowmelt runoff. Relatively large amounts of $NaHCO_3$-P might, therefore, be expected in sediments derived from surface soils.

Factors influencing the distribution of $NaHCO_3$-P

Calcium carbonate equivalent. In the Warm Springs pedons the calcium carbonate was nearly zero in the surface and increased with depth to maximum amounts in the calcic horizons (Figure 7). Alexander and Robertson (1968) reported that calcium-phosphate was the dominant form of phosphorus in alkaline soil with free calcium carbonate. Therefore, in the Warm Springs subsoils with pH values of about 10 and a calcium carbonate equivalent of 10 percent or greater, the expected dominant form of phosphorus was calcium-phosphate.

Extractable iron. The amount of extractable iron (pyrophosphate-dithionite) was nearly the same in the surface for all four pedons, about 0.08 percent, but in pedons 1 and 2 the extractable iron decreased and in pedons 3 and 4 it increased in horizons immediately below the surface (Figure 8). Extractable iron was at a minimum in the calcic horizons

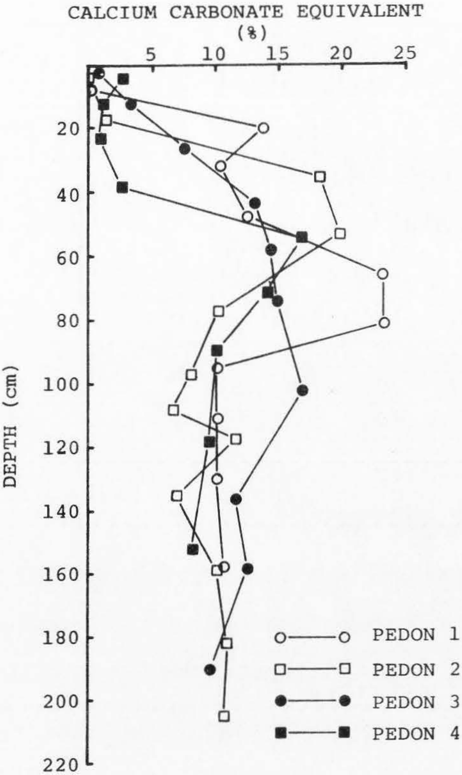

Figure 7. Distribution of calcium carbonate equivalent in four pedons of the Warm Springs series

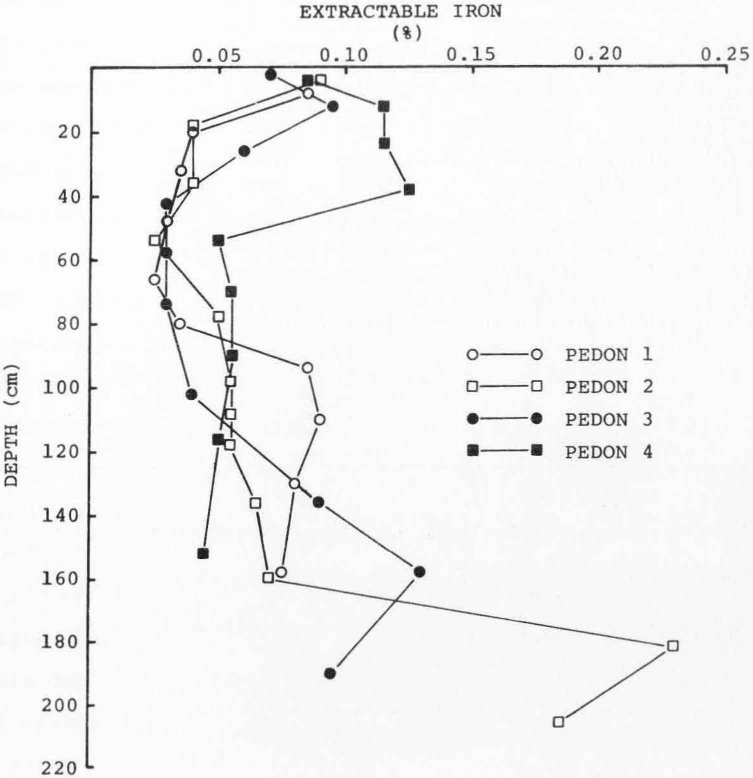

Figure 8. Distribution of extractable iron in four pedons of the Warm Springs series

and with the exception of pedon 4 increased below the calcic horizons. The amount of $NaHCO_3$-P appeared to be related to the amount of extractable iron in horizons below the accumulation of calcium carbonate. In pedon 1, below 100 cm, high amounts of $NaHCO_3$-P (Figure 6) corresponded with an increase in extractable iron. An extractable iron maximum corresponded with a $NaHCO_3$-P maximum in horizon C9 at about 180 cm depth. A gradual increase in $NaHCO_3$-P in the lower C horizons of pedon 3 was accompanied by an increase in extractable iron to a depth of 160 cm below which there was a decrease in both $NaHCO_3$-P and extractable iron similar to that in pedon 2. In pedon 4, below 60 cm, the extractable iron decreased to relatively low amounts and the amount of $NaHCO_3$-P decreased to less than 10 ppm. The association of $NaHCO_3$-P with extractable iron in the calcareous, very strongly alkaline subsoil horizons suggested that the two were concentrated by the same processes but not that the concentration of the iron necessarily influenced the concentration of $NaHCO_3$-P.

Drainage. As indicated in the pedon field descriptions, a fluctuating water table was evident in the four pedons sampled at depths varying from about 1 to 2 meters. Horizontal pink or yellow strata assumed to be accumulations of iron oxide were observed in pedons 1, 2, and 3. Similar horizons of iron accumulations were interpreted by Runge (1963) as occurring at the top of the fluctuating water table.

Evidence of a fluctuating water table for the four pedons in this study was as follows: (pedon 1) a reddish-yellow stratum at 102 cm, present water table not encountered to a depth of 173 cm; (pedon 2) yellow streaks at 163 cm, water table at 198 cm; (pedon 3) reddish-yellow stains in pink, silty clay loam strata from 147 to 162 cm, no water table encountered to a depth of 211 cm; (pedon 4) water table at 157 cm. The distribution of extractable iron supported the assumption that the higher chroma strata were accumulations of iron. Generally, the yellow strata occurred at the contact of stratified layers of sediment. A change in particle-size acted as a barrier to the movement of water and influenced the accumulation of iron.

Characteristics of the iron accumulations were as variable as the lacustrine sediments. Pedon 1 had 1 to 3 mm, reddish-yellow strata found at abrupt contacts; pedon 2 had 2 to 6 cm, yellow zones where there was little apparent textural difference between the yellow and very pale brown sandy loam (Figure 9), and in pedon 3, iron was concentrated in 1 to 3 cm, pink, silty clay loam strata between pale brown, loamy fine sand (Figure 10).

An attempt was made to sample the thin layers of iron enrichment. Extractable iron and available phosphorus were greater in the zones with higher chroma than in the surrounding strata with lower chroma (Table 5).

Texture. The amount of $NaHCO_3$-P contributed by each particle-size fraction (sand, silt and clay) was determined

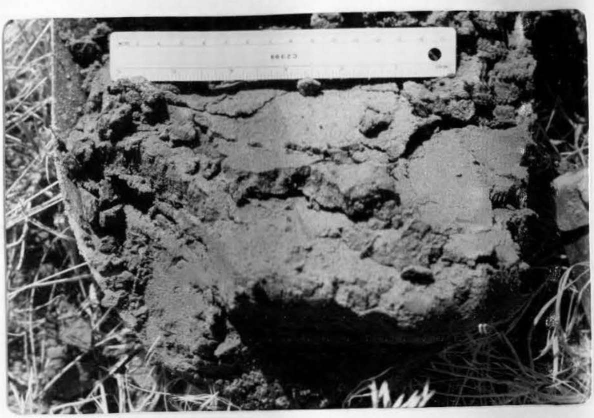

Figure 9. Photograph of horizons C9 and C10, pedon 2

Figure 10. Photograph of horizon C6, pedon 3

Table 5. Extractable iron and $NaHCO_3$-P in samples of finely stratified sediments

Hori- zon	Depth cm	Description of sample	Extract- able iron %	$NaHCO_3$-P ppm
		Pedon 2		
C9	163-198	yellow, very fine sandy loam	0.295	21
C9	163-198	very pale brown, very fine sandy loam	0.185	17
C10	198-208	light gray, very fine sandy loam	0.185	6
		Pedon 3		
C6	147-162	pink, silty clay loam	0.100	36
C6	147-162	pale brown, loamy fine sand	0.075	23

on samples of four horizons selected from pedon 1. The $NaHCO_3$-P for each particle-size fraction was multiplied by the ratio of each fraction to the whole soil to obtain a weighted $NaHCO_3$-P value. Thereby, the sum of the weighted $NaHCO_3$-P values represented the $NaHCO_3$-P for the whole soil. Amounts of $NaHCO_3$-P determined on the whole soil are shown in Table 6 for comparison.

The amount of $NaHCO_3$-P was greatest in the clay fraction and lowest in the sand fraction for all four soils. The A1 horizons contained nearly twice as much $NaHCO_3$-P calculated from the three fractions as was extracted from the whole soil. Considerably more $NaHCO_3$-P was extracted from whole soil

Table 6. Amount of $NaHCO_3$-P extracted from sand, silt and clay particle-size fractions from four horizons of pedon 1

Particle-size	$NaHCO_3$-P particle-size fractions ppm	Weighted $NaHCO_3$-P ppm	$NaHCO_3$-P of whole soil ppm
	A1, 0-15 cm		
Sand	2	1.1	
Silt	10	3.6	
Clay	78	7.0	
	Sum	11.7	6
	C2ca, 25-38 cm		
Sand	2	1.0	
Silt	16	5.2	
Clay	51	7.8	
	Sum	14.0	34
	C4ca, 56-74 cm		
Sand	3	2.2	
Silt	19	3.4	
Clay	38	3.8	
	Sum	9.4	22
	C8, 117-140 cm		
Sand	2	1.6	
Silt	4	0.7	
Clay	22	0.8	
	Sum	3.1	40

samples of the three subsoil horizons than that calculated from extractions on the three fractions. The difference in the amount of $NaHCO_3$-P calculated from the three particle-size fractions and that extracted from whole soil samples was attributed to solubility of phosphorus in the dispersing solution (distilled water).

The soil samples were first dispersed by shaking with distilled water and then washed on a 300-mesh sieve. Next the silt was separated from the clay by centrifuging and decanting. This procedure in effect removed water-soluble phosphorus from the sand and silt fractions and concentrated it in the clay solution. The clay solution was reduced in volume with filter candles and evaporated to air dryness before the $NaHCO_3$-P was determined. Some of the water-soluble phosphorus was removed through the filter candle and the rest concentrated with the clay sample upon evaporation. The $NaHCO_3$-P values for the sand and silt fractions actually represented the amount of phosphorus extracted with sodium bicarbonate after water-soluble phosphorus was removed. Whether the clay fraction, prior to extraction with sodium bicarbonate, contained more or less water-soluble phosphorus than it did originally could not be determined from the experimental data. Williams and Saunders (1956b) also indicated the difficulty of assessing the amount of soluble phosphorus contributed by each particle-size fraction due to the solubility of phosphorus in the dispersing solution.

The particle-size distribution on selected horizons of the four pedons (Table 3) indicated that Cca horizons with maximum amounts of $NaHCO_3$-P were associated with an increase in percent clay. The C2ca horizon in pedons 1, 2, and 4 have

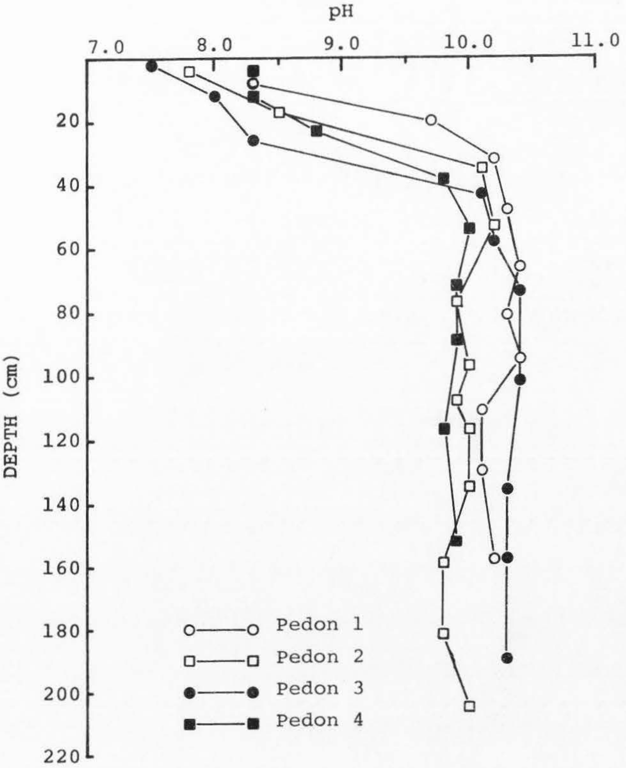

Figure 11. Distribution of pH (1:1 H_2O) values in four pedons of the Warm Springs series

15.2, 17.4, and 17.2 percent clay, and 34, 34, and 26 ppm $NaHCO_3$-P, respectively. The increase in clay from A horizon to C2ca horizon resulted from increases in both clay-size carbonate and non-carbonate clay (Table 3). However, the amount of clay-size carbonate did not exceed 25 percent of the total clay in any of these horizons.

pH. In all four pedons there was a characteristic increase in pH values (Figure 11). Surface horizons were mildly to moderately alkaline (pH 7.5 to 8.4). The pH increased rapidly to very strongly alkaline (pH greater than 9.0) in Cca horizons and remained very strongly alkaline throughout the subsoil. According to the solubility product principles of Lindsay and Moreno (1960) and Hsu and Jackson (1960), very small amounts of soluble phosphorus would be expected in a soil with a pH of 10. Above pH 7 the solubility of phosphorus is governed by calcium phosphates and solubility rapidly decreased with increasing pH. A decrease in $NaHCO_3$-P in lower C horizons was interpreted by Runge and Riecken (1966) as being due to an increase in pH to values of about 7.5 to 8.2. The high amounts of $NaHCO_3$-P extracted from these subsoils with high pH values indicated that the sodium bicarbonate was extracting phosphorus of a form other than calcium phosphate.

Water-soluble phosphorus. Soil samples were shaken with distilled water to determine the amount of phosphorus extracted and to aid in the interpretation of $NaHCO_3$-P extracted from particle-size separates. Also, the results were used to interpret the solubility of phosphorus in percolating water or the subsoil solution.

The results (Table 2) showed that water-soluble phosphorus was highest in the subsoil horizons of pedons 1 and 3, the same pedons that had the highest levels of $NaHCO_3$-P. Almost the same amount of water-soluble phosphorus was extracted from horizons below the calcic horizons of pedons 1, 2, and 3 as was extracted with sodium bicarbonate. The influence of water-soluble phosphorus on the determination of $NaHCO_3$-P on particle-size separates was discussed in the section on texture (p. 48). The water-soluble phosphorus results were interpreted as an indication that in many of the subsoil horizons an amount of phosphorus equal to the $NaHCO_3$-P would be soluble in the subsoil solution. Therefore, nearly all of the $NaHCO_3$-P in those horizons would be water soluble and readily translocated by soil water movement. No attempt was made to determine the direction of water movement in these pedons. However, the vertical distribution of calcium carbonate, electrical conductivity and water-soluble sodium indicated that A horizons were leached by percolating water. During the warm dry summer months, upward capillary flow of water from the water table might be expected.

The subsoil horizons which had 20 ppm $NaHCO_3$-P or more and nearly equal amounts of water-soluble phosphorus also contained more than 300 meq/l water-soluble sodium in the saturation extract (Table 2). The relationship between water-soluble sodium, water-soluble phosphorus and $NaHCO_3$-P indicated that the phosphorus extracted with sodium bicarbonate from those horizons might be sodium phosphate.

Cicada. Cicada casts were separated from the surrounding matrix in selected horizons. It was difficult to determine what part of the soil was cast and what part was matrix. Generally, the cast was harder than the material that surrounded it and had a characteristic structure as described by Hugie and Passey (1963). Some horizons have been so extensively worked by the cicada that there was very little or no matrix material and more recent casts intersect with older castings. Cicada casts in a sandy loam were not as distinct as those often found in soils of finer texture. Cicada casts were sampled from the Clca and C2ca horizons of pedon 2, the C4ca horizon of pedon 3, and A13 horizon of pedon 4 and contained 32, 36, 32, and 5 ppm $NaHCO_3$-P, respectively. The values nearly equal the $NaHCO_3$-P values reported for those horizons in Table 2. A concentration of phosphorus in the cicada casts was not indicated by the results as had been observed by Southard.[4] However, if there was an accumulation of $NaHCO_3$-P either the separation was not successful in distinguishing a difference or $NaHCO_3$-P equilibrium had been reached between the casts and matrix.

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[4] Personal Communication. Alvin R. Southard. Soils and Biometeorology Department, Utah State University, Logan, Utah.

Influence of sodium-phosphate solutions on $NaHCO_3$-P

The above results suggested that the subsoil $NaHCO_3$-P was sodium phosphate which was soluble in water and, therefore, could be readily translocated by movement of the subsoil solution. Furthermore, there was evidence of a fluctuating water table and concentration of $NaHCO_3$-P at the contacts of the finely stratified sediments. An attempt, therefore, was made to study the relationship of soil solution to $NaHCO_3$-P.

Four subsoil samples were shaken with Na-P solutions to determine how the amount of P in solution influenced $NaHCO_3$-P. The soils selected were horizons C4ca and C8 from pedon 1, and C2ca and C5 from pedon 2. Phosphorus initially extracted from these four soils with sodium bicarbonate was 22, 40, 34, and 7 ppm of the horizons 1-C4ca, 1-C8, 2-C2ca, and 2-C5, respectively (Table 7).

Table 7. $NaHCO_3$-P, $NaHCO_3$-P maxima, clay and calcium carbonate equivalent for selected soil horizons

Soil pedon-horizon	$NaHCO_3$-P, initial (ppm)	$NaHCO_3$-P, maximum (ppm)	Clay (%)	$CaCO_3$ equiv. (%)
1-C4ca	22	110	10.1	23.3
1-C8	40	23	3.4	10.1
2-C2ca	34	130	17.4	19.8
2-C5	7	24	2.3	6.7

The amounts of $NaHCO_3$-P versus amounts of P in Na-P solution for the four soils are plotted in Figure 12. The data indicated that as the solution P was increased there was a corresponding increase in $NaHCO_3$-P up to some maximum value. There was apparently a $NaHCO_3$-P maximum for each soil. The $NaHCO_3$-P maxima were estimated from the graph as 110, 23, 130, and 24 ppm, respectively, for soils 1-C4ca, 1-C8, 2-C2ca and 2-C5. Generally, the $NaHCO_3$-P maxima were higher for the soils with greater amounts of clay. Olsen and Watanabe (1957) found that phosphate adsorption maxima were closely related (r = .98 for alkaline soils) to the surface area of the soil and that essentially all of the phosphate adsorbed initially would equilibrate with added P^{32}. The adsorbed phosphate that would equilibrate with P^{32}, or surface phosphate, was suggested to be closely related to plant response. The relationship of $NaHCO_3$-P values to clay content in these soils might be expected from the surface area-surface phosphate-plant response phosphate relationship found by Olsen and Watanabe.

The influence of calcium carbonate on the amount of $NaHCO_3$-P appeared to be overshadowed by the clay content or surface area of the soils studied. However, the $NaHCO_3$-P was not appreciably depressed by an increase in calcium carbonate. This suggested that for the soils equilibrated with the Na-P solutions, within the conditions of the experiment, higher amounts of calcium carbonate present did not result in the formation of greater amounts of calcium phosphates from which the phosphorus could not be extracted with $NaHCO_3$.

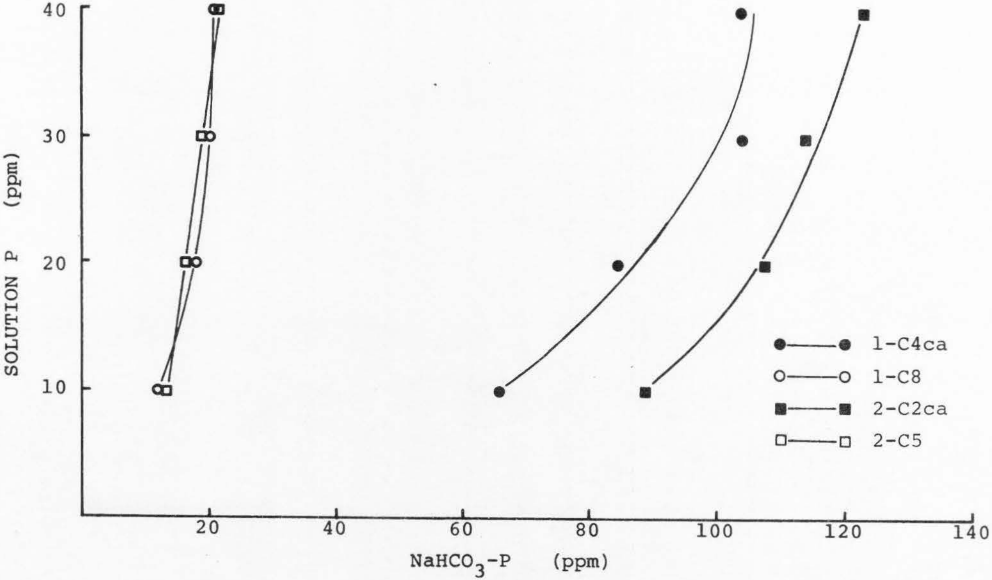

Figure 12. Amount of NaHCO$_3$-P extracted from selected soils after shaking with Na-P solutions

The amount of $NaHCO_3$-P initially extracted from horizons 1-C8 and 2-C5, 40 and 7 ppm respectively, apparently did not influence the amount of phosphorus extracted with $NaHCO_3$ after shaking with the Na-P solutions (Figure 12). Together with the relationship of $NaHCO_3$-P to phosphorus in the Na-P solutions this suggested that the amount of $NaHCO_3$-P in the subsoil of these Warm Springs pedons is a consequence of the concentration of phosphorus in the subsoil solution. Subsoil solutions with low amounts of phosphorus effectively reduce the level of $NaHCO_3$-P in the subsoil and high amounts of $NaHCO_3$-P result in the subsoils where the phosphorus in solution is concentrated.

A $NaHCO_3$-P maximum of 23 ppm was suggested for horizon 1-C8, whereas, 40 ppm $NaHCO_3$-P was measured in the soil initially. The amount of $NaHCO_3$-P in this horizon, therefore, exceeds its $NaHCO_3$-P maximum. However, the unadjusted value, that which included the phosphorus in solution in the moist soil, for horizon 1-C8 after shaking with the 40 ppm phosphorus, Na-P solution was 38 ppm. The amount of moisture retained in the soil from a receding water table might be approximated by the moisture content of the laboratory sample after decanting. By making this assumption the laboratory data would predict that horizon 1-C8 was subjected to a water table with a phosphorus content greater than 40 ppm. The subsoil solution near pedon 1 contained 47 ppm phosphorus. Near pedon 4, where the $NaHCO_3$-P in the subsoil decreased to

3 ppm at the depth to the water table the subsoil solution contained 1 ppm phosphorus. Therefore, the relationship of the amount of phosphorus in the subsoil solution to the $NaHCO_3$-P in the subsoil confirms the relationship predicted from the laboratory experiment.

SUMMARY AND CONCLUSIONS

Summary

Previous soil fertility investigations in Utah have indicated that subsoil horizons, below the plow layer commonly sampled for fertilizer recommendations, supplied the plant requirement for phosphorus when the surface soil was low in available phosphorus. Available or sodium bicarbonate extractable phosphorus ($NaHCO_3$-P) was determined for the genetic horizons of 146 soil pedons in northern Utah (Lamborn, 1970). A weighted average $NaHCO_3$-P was calculated for the 30 to 102 cm depth and an attempt was made to explain the subsoil phosphorus variability in terms of soil series and geographic distribution. Variation in subsoil $NaHCO_3$-P within most soil series was too great to draw conclusions and there was no apparent separation of soils with low, medium, or high amounts of $NaHCO_3$-P by geographical area. However, the study did identify soil series which have a wide range in the amount of subsoil $NaHCO_3$-P and also those pedons which have subsoil horizons with greater than 20 ppm $NaHCO_3$-P. The weighted average subsoil $NaHCO_3$-P for the Warm Springs series ranged from 1.9 to 45 ppm. Also $NaHCO_3$-P was often greater in the subsoil than in the surface horizon.

Therefore, this study was initiated to explain the distribution of $NaHCO_3$-P in the subsoil of the Warm Springs series.

Specifically, the purpose was to determine the source and distribution of the subsoil $NaHCO_3$-P, soil properties associated with high amounts of $NaHCO_3$-P, and how subsoils with high amounts of $NaHCO_3$-P might be identified in the field. The Warm Springs soil has formed on nearly level, low lake terraces east of the Great Salt Lake in Davis and Weber counties. The Weber and Bear Rivers were the major sources of sediment deposited in the low lake terraces which range in elevation from 1,280 to 1,320 meters above sea level (about 10 to 50 meters above the present surface of the Great Salt Lake). The Warm Springs series has been classified as a member of the fine-loamy, mixed, mesic family of Typic Calciaquolls, however, the author believes the more correct classification to be coarse-loamy, mixed, mesic family of Aquic Calciustolls.

A study area was selected where the subsoil $NaHCO_3$-P ranged from less than 10 ppm to greater than 30 ppm in an area of less than 200 ha. The morphology of four pedons, members of the Warm Springs series, was described in the field and samples collected from the genetic horizons or differentiated layers. The samples were analyzed in the laboratory for total phosphorus, $NaHCO_3$-P, water-soluble phosphorus, pH, extractable iron, calcium carbonate equivalent, electrical conductivity and water-soluble sodium. Four horizons were selected from each pedon for analysis of particle-size distribution, clay-size carbonate and noncarbonate clay. The apatite content of the very fine sand fraction was determined for the four horizons from two of the pedons. $NaHCO_3$-P was determined on the sand, silt and clay particle-size fractions from four horizons of pedon 1. Yellow and pink layers in finely stratified sediments were separated from adjacent strata, and extractable iron and $NaHCO_3$-P determined. Cicada casts were separated from surrounding matrix and analyzed for $NaHCO_3$-P. Selected soil samples were shaken with sodium-phosphate solutions and then analyzed for $NaHCO_3$-P to determine the influence of the amount of phosphorus in solution on the amount of phosphorus extracted.

Total phosphorus was highest just below the surface soil and immediately above the horizons of calcium carbonate accumulation and then decreased to amounts in the lower C horizons associated with the varved lacustrine sediments. Higher total phosphorus values in lower C horizons appeared to be in response to increased clay. Total phosphorus was low in the surface due to weathering of apatite and leaching of the soluble phosphorus by percolating water. The downward movement of phosphorus was arrested by an increase in alkalinity resulting in the probable formation of insoluble calcium-phosphates, and corresponding with $NaHCO_3$-P minima. Apatite in the very fine sand fraction was low near the surface and increased to maximum values between 50 and 70 cm.

$NaHCO_3$-P was high (12 ppm) in the surface, decreased to minimum values (7 ppm) in the lower A horizons and then increased to about 25 ppm in the calcic horizons. $NaHCO_3$-P remained high or increased below the calcic horizons of pedons 1 and 3 but decreased with depth in pedons 2 and 4.

Pedons of the Warm Springs and associated soil series on low lake terraces below 1,340 meters elevation in the Davis-Weber Area were effectively separated from series occurring on higher terraces. Some subsoil horizons in those pedons below 1,340 meters which had greater than 10 ppm $NaHCO_3$-P also had pH values greater than 8.0. Sediments in the Weber and Bear Rivers contained more than 20 ppm $NaHCO_3$-P suggesting that sediment deposited in the low lake terraces and flood plains may have contained appreciable amounts of $NaHCO_3$-P at time of deposition.

Calcium carbonate equivalent was less than 3 percent in the surface, increased to between 15 and 28 percent in the calcic horizons and then decreased to between 5 and 15 percent below the calcic horizons. Extractable iron was generally lowest in calcic horizons where calcium carbonate and $NaHCO_3$-P was highest. Below the calcic horizons, yellow or pink horizontal layers, interpreted to be evidence of a water table, contained more extractable iron and more $NaHCO_3$-P than adjacent pale brown and light gray strata. Surface horizons were mildly to moderately alkaline, and the pH increased to values greater than 9.0 below the A horizons. Below 60 cm pedons 1 and 3 had pH values greater than 10.0 and pedons 2 and 4 had values less than 10.0. Therefore, lower C horizons of pedons 1 and 3 with greater than 20 ppm $NaHCO_3$-P and lower C horizons of pedons 2 and 4 with generally less than 15 ppm $NaHCO_3$-P were effectively separated by a pH value of 10.0.

Distilled water extracted about the same amount of phosphorus as was extracted with sodium bicarbonate from lower C horizons with greater than 20 ppm $NaHCO_3$-P. These same subsoil horizons also contained greater than 300 meq/l water-soluble sodium. Therefore, most of the $NaHCO_3$-P in those horizons was probably sodium phosphate.

Although undoubtedly enhanced by the laboratory procedure, the clay contained more $NaHCO_3$-P than the silt and the silt contained more $NaHCO_3$-P than the sand fraction. The increase in phosphorus extracted with sodium bicarbonate from successively decreasing particle-size fractions did not agree with the relationship between readily soluble phosphorus and phosphate-sorption capacity reported by Williams and Saunders (1956b). Sodium phosphate adsorbed on the surface of the clay-size particles was readily extracted with $NaHCO_3$. $NaHCO_3$-P was not concentrated in the cicada casts of the four pedons.

When soil samples were shaken with a Na-P solution and then extracted with $NaHCO_3$, some maximum $NaHCO_3$-P value was approached. Some subsoils contained more $NaHCO_3$-P than their predicted maxima as evidenced by the solution phosphorus remaining after decanting and initial amount of $NaHCO_3$-P in horizon 1-C8. The capacity of the soil to retain sodium bicarbonate extractable phosphorus from sodium phosphate solutions, increased with increasing clay and did not decrease with additional calcium carbonate. Subsoil horizons were enriched in $NaHCO_3$-P above their capacity for $NaHCO_3$-P by desiccation of a saturated soil with high amounts of phosphate in solution.

Conclusions

Distribution of $NaHCO_3$-P in the subsoil. In the four pedons, $NaHCO_3$-P was about 12 ppm in the surface, decreased to about 7 ppm in lower A horizons and increased to 25 ppm or greater in calcic horizons. Below the calcic horizon the $NaHCO_3$-P was highly variable decreasing to 10 ppm or less in two pedons and increasing to 40 ppm in the other two.

Physical and chemical soil properties associated with $NaHCO_3$-P. All subsoil horizons of the four pedons, which had a pH value greater than 10.0, contained more than 10 ppm $NaHCO_3$-P. Those subsoil horizons with pH values greater than 10.0 also usually contained more than 200 meq/l water-soluble sodium. Extractable iron and $NaHCO_3$-P were accumulated in the same strata indicating that concentration of the two resulted from the same conditions. The amount of phosphorus extracted from the subsoil horizons was governed by the amount of readily soluble sodium phosphate present. This was demonstrated by extracting soil samples which had been shaken with Na-P solutions with sodium bicarbonate. Soil samples with greater amounts of clay had a greater capacity for $NaHCO_3$-P and the amount of $NaHCO_3$-P was not depressed by increases in calcium carbonate. Therefore, the results suggested that the sodium phosphate was adsorbed on the surface of carbonate and other mineral particles and was readily extracted with either water or sodium bicarbonate.

Sources of subsoil $NaHCO_3$-P. Phosphorus weathered from apatite in the surface horizons moved downward with percolating water but was arrested immediately below the surface and formed relatively insoluble calcium-phosphates. Total phosphorus maxima, $NaHCO_3$-P minima and an increase in pH values, calcium carbonate and apatite all supported this conclusion of limited downward movement of phosphorus from the surface horizons to lower A and upper Cca horizons. Weathering of apatite in the surface soil, therefore, did not contribute to the $NaHCO_3$-P in the C horizons below the calcic horizons.

However, the most likely source of $NaHCO_3$-P in the Warm Springs subsoil was the sediments which were deposited in the low lake terraces and flood plains. The more than 20 ppm $NaHCO_3$-P in the sediments presently being deposited by the Weber and Bear Rivers supported the river sediments as a source.

The results suggested that the readily soluble sodium phosphate may have been distributed by lateral subsurface flow of the water table. Phosphorus may have been extracted by flowing water from some areas and concentrated in other areas where the water stagnates, thereby, creating highly variable amounts of $NaHCO_3$-P in the subsoil. In addition, the results indicated that the rise and fall of a fluctuating water table resulted in the soil solution being perched above the contacts of stratified layers, thereby, increasing the $NaHCO_3$-P in the sediments by the amount of phosphorus in solution.

Field identification of subsoils with large amounts of $NaHCO_3$-P. This study did not provide a method for identifying all subsoils that have greater than 10 ppm $NaHCO_3$-P. However, soils on the low lake terraces in the Davis-Weber Area, with subsoil pH values greater than 10.0 and evidence of a water table occurring at less than 2 meters below the surface, might be expected to have greater than 10 ppm $NaHCO_3$-P in some subsoil horizons.

Suggestions for further research

Whether apatite distribution in the subsoil results from depositional nonuniformity or dissolution of apatite in the very strongly alkaline sodic subsoil solution was not determined. Therefore, a study of the uniformity of the subsoil sediments and the solubility of apatite in the soil solution would aid in interpreting the apatite distribution. Extensive sampling of sediments in the Weber and Bear Rivers and $NaHCO_3$-P analysis of the samples would determine the amount of $NaHCO_3$-P in the river sediments and identify subwatersheds which contribute high or low $NaHCO_3$-P sediment. Monitoring of phosphorus in the Warm Springs subsoil and subsoil water before, during, and after implementation of a drainage system might aid in interpreting the translocation of $NaHCO_3$-P by subsoil water flow.

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