THE DISTRIBUTION OF SOIL PHOSPHORUS COMPOUNDS

IN SOME REPRESENTATIVE SOILS OF OKLAHOMA

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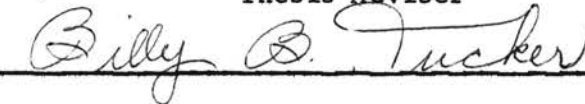University of Ibadan

Ibadan, Nigeria

1959

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
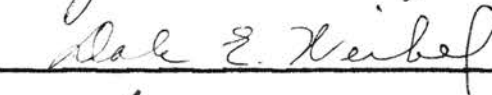for the degree of
MASTER OF SCIENCE
August, 1963

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ACKNOWLEDGEMENTS

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INTRODUCTION

Phosphorus is one of the key plant nutrients in the soil. Its relatively low availability to plants even in situations of high reserve in the soil, will pose a problem to man as long as man tills the soil for food.

For a long time scientists have realized that a knowledge of the forms and the distribution of phosphate compounds in the soil can be of significant value in understanding the chemistry of soil phosphorus and its availability to plants.

In fertilizer practice, various chemical extractants are used to measure the "available" phosphorus in the soil as a basis for fertilizer recommendations. Reports from various sources, however, have indicated that when crop yields or crop responses to phosphate fertilizers are correlated with phosphorus determined by the various chemical extractants, results have not always been satisfactory. Also the determination of "available" phosphorus by different chemical methods differs in respect to the phosphorus status of the soil concerned. The available phosphorus removed from the soil by the chemical extractants comes from the discrete chemical forms of phosphorus in the soil. The total and the relative amount of "available" phosphorus extracted is greatly influenced by the chemical forms, their relative amount, distribution, the specific surface area of the phosphate bearing minerals and also the relative solubilities of these phosphorus forms in the extractant.

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Therefore it becomes necessary to determine the amount and distribution of the various forms of phosphate in the soil in order to assess its phosphate potential (supplying power of "available" phosphate) and the suitability or adaptability of certain chemical extractants to determine the "available" phosphorus of a particular soil. The "Chang and Jackson" (13)[1] phosphorus fractionation procedure is so far the best chemical method in use to fractionate soil phosphorus. It is the aim of this investigation to employ these techniques to determine among other things, the amount and distribution of various forms of phosphate in five representative Oklahoma soil profiles, and fate of applied phosphate in short term "availability" studies.

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[1]Numbers in paranthesis refer to literature cited.

LITERATURE REVIEW

Soil Phosphorus Fractionation - Method

Phosphorus has long been recognized to occur in the soil in a large number of inorganic and organic compounds possessing various degrees of solubility and "availability." Many attempts have been made by several investigators to devise analytical methods that would estimate and differentiate between these various phosphorus forms.

The earliest attempt at separation of soil phosphorus fractions by selective extractants was by Fisher and Thomas (24). By the use of acetic acid-sodium acetate buffer at pH 5.0 and dilute H_2SO_4 at pH 2.0 for soil extraction, they attempted to fractionate soil phosphate[1] into three groups:

    a. Calcium, magnesium, and manganese phosphate

    b. Iron and aluminum phosphate

    c. Adsorbed phosphate and apatite

In 1937, Williams (73), used NaOH as an extractant and divided the soil phosphorus into (a) alkali soluble organic phosphate, exchangeable phosphate, and soluble inorganic phosphates such as those of sesquioxide, di-calcium phosphate and water soluble phosphate and (b) alkali insoluble

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[1]$Fe-PO_4$ = all iron phosphates, $Al-PO_4$ = all aluminum phosphates, $Ca-PO_4$ = all calcium phosphates.

fractions such as apatites, titanium phosphate and crystal lattice phosphate.

Dean (20) made the first attempt at a complete systematic fractionation of soil phosphorus. From his analysis, he divided the phosphorus compounds of the soil into three fractions, Viz;

1. Organic phosphorus compounds soluble in $0.25N$ NaOH.

2. Inorganic compounds dissolved by extraction with sodium hydroxide followed by $0.5N$ H_2SO_4.

3. Insoluble compounds

Ghani (26) modified Dean's procedure to obviate the interference effect of exchangeable calcium and magnesium in the alkali extraction. He first extracted with acetic acid and then by successive extractions with NaOH and finally with H_2SO_4. He obtained five phosphorus fractions which he identified as follows:

1. Acetic acid soluble phosphorus compounds consisting of mono-, di-, and tri-calcium phosphates.

2. Alkali soluble inorganic phosphorus compounds consisting of iron and aluminum phosphates.

3. Alkali soluble organic phosphorus compounds.

4. Sulfuric acid soluble phosphorus compounds.

5. Insoluble phosphorus compounds.

In a later study Ghani (28) suggested the use of 8 - hydroxy-quinoline to block the re-sorption or reprecipitation of phosphate by active iron and aluminum. This was necessary because some of the phosphate brought into solution by acetic acid was reabsorbed by iron and aluminum and then extracted in the NaOH extraction.

Bray and Dickman (9) fractionated soil phosphorus into four fractions:

1. Fraction soluble in 0.1N neutral NH_4F which contained all of the easily replaceable phosphates and some of the more strongly adsorbed forms.

2. Fraction soluble in 0.1N NH_4F and 0.01N HCl.

3. Fraction soluble in 1.0N neutral NH_4F. Fractions 2 and 3 are a measure of the strongly adsorbed phosphate.

4. Acid soluble (.002N H_2SO_4) fraction consisting of calcium and magnesium phosphates, iron, aluminum and manganese phosphates and other forms as fluor apatite, and rock phosphate (hydroxy apatite). Bray and Kurtz (10) fractionated soil phosphorus into acid soluble, adsorbed, and organic forms. Chirikov and Volkova (17) fractionated soil phosphorus into five fractions:

1. Fraction soluble in CO_2 colution (alkali phosphates, acid phosphates, and di-phosphates of calcium, magnesium, and some phosphorites).

2. Fraction soluble in 0.5N acetic acid (some apatites, phosphorites and salts of alcohols, phosphoric acids and sugar phosphoric acids).

3. Fraction soluble in 0.5N HCl (phosphorites, apatites, aluminum phosphates, Fe-phosphates, some of the more basic phosphates of iron and phytin).

4. Fraction soluble in 0.2N NaOH (organic phosphates - nucleins, nucleoprotein and similar compounds of humic acid).

5. Fraction insoluble in any of these solvents (titanium phosphate and phosphorus compounds of unweathered minerals of the parent material).

The fractionation method developed by Williams (70) was a further modification of Ghani's procedure. He used 8-hydroxy-quinoline as introduced by Ghani and extracted successively with 2.5% acetic acid -

1% 8-hydroxy-quinoline and 0.1N NaOH. His fractions were identified as:

1. Phosphorus extracted by 2.5% acetic acid containing 1% 8-hydroxy-quinoline consisting primarily of calcium, magnesium, and manganese phosphates.

2. Phosphorus extracted by 0.1N NaOH following the #1 extraction, consisting of inorganic phosphates (adsorbed phosphates, basic iron and aluminum phosphates and titanium phosphates), and organic phosphorus.

3. Phosphorus insoluble in either of the above extractants consisting primarily of chloro and fluoro-apatites, crystal lattice phosphorus compounds and resistant phosphate minerals.

Bhango and Smith (6) fractionated the phosphorus in various Kansas soils into four fractions:

1. Phosphorus soluble in 0.1N HCl (calcium phosphate).

2. Cold alkali soluble phosphorus after the #1 extraction, was identified as adsorbed phosphrous.

3. Hot alkali soluble phosphorus after the #1 and #2 extraction was identified as aluminum phosphate.

4. Organic phosphorus compounds.

Mattson et al, (48) while investigating the forms of phosphorus in some profiles in Sweden determined seven forms of phosphorus as follows:

1. Acid oxalate soluble phosphorus (sesquioxide bound phosphorus which included some inorganic and organic phosphorus compounds).

2. Phosphorus soluble in 0.2N H_2SO_4 (mainly calcium bound and sesquioxide bound).

3. Organic phosphorus compounds.

4. Phosphorus soluble in 2.5% acetic acid (mainly calcium bound and aluminum bound phosphorus).

5. Neutral 0.5N NH_4F - soluble phosphorus which was identified as more active forms of sesquioxide bound phosphorus.

6. Lactate soluble phosphorus.

7. Water soluble phosphorus in 1:10 extracts.

Vahtras (62) another Swedish soil scientist modified Mattson's fractionation into five fractions:

1. 0.2N H_2SO_4 soluble phosphorus.

2. Organic phosphorus compounds.

3. 2.5% acetic acid soluble phosphorus.

4. Lactate soluble phosphorus.

5. 0.02N $CaCl_2$ soluble phosphorus.

These methods are a few of the various attempts to fractionate the soil phosphorus into discrete chemical forms. All of these investigations had limited success, however, in 1956, Chang and Jackson (13) introduced a new phosphorus fractionation procedure based on the solubilities of the discrete phosphorus compounds in various solutions. Since then the "Chang and Jackson" phosphorus fractionation procedure has found extensive application and has remained the most widely adopted method of soil phosphorus fractionation.

The discrete chemical forms of phosphate according to Chang and Jackson are:

1. Aluminum phosphate extracted by neutral (pH 7.0) 0.5N NH_4 F.

2. Iron phosphate extracted by 0.1N NaOH after the extraction with #1.

3. Calcium phosphate extracted with 0.5N H_2SO_4 after the extraction with #1 and #2.

4. Reductant soluble iron phosphate extracted with 0.3M citrate and sodium dithionite, $Na_2S_2O_4$.

5. Occluded aluminum phosphate extracted with neutral NH_4F or Al-Fe-phosphate extracted with 0.1N NaOH, after extraction with #1 through #4.

6. Organic phosphate is separately determined.

Several criticisms and suggestions for modifications have been made in their fractionation. In the extraction of aluminum phosphate, use of alkaline NH_4F in the pH range of 8 to 8.5, as an extractant has been very strongly suggested by Glenn et al. (29), Fife (22, 23), and Khin and Leeper (43). Glenn et al. suggested 9 to 17 hours extraction of iron phosphate rather than the 17 hours originally proposed, and the extraction of all occluded phosphate before removal of calcium phosphate as the 0.5N H_2SO_4 used to extract calcium phosphate tends to remove some of the occluded phosphate. Jackson (39) further modified the dithionite-citrate extraction for the removal of iron oxide from soils and clays (1), in the determination of reductant soluble iron phosphate, to include a sodium-bicarbonate buffer at pH 8.2 according to Mehra and Jackson (50).

Chu and Chang (18) while fractionating some soils of Taiwan (Formosa) modified the "Chang and Jackson" procedure to exclude separate fractionation of reductant soluble iron phosphate and occluded aluminum phosphate. After the extraction of aluminum, iron, and calcium phosphates, they analyzed their samples for total occluded phosphate by digesting the residual sample with 6N HCl and after precipitation of the soluble iron

with 2N NaOH, determined the phosphorus in the extract. The phosphorus determined represented the occluded phosphate (reductant soluble iron phosphate and occluded aluminum phosphate). Chang (11) after reviewing all the criticisms and suggestions so far made, described a systematized extraction sequence and proposed a modification of the original "Chang and Jackson" procedure as follows:

1. Removal of exchangeable calcium and the more soluble phosphates largely mono- or di-calcium phosphates, with N NH_4Cl after shaking for 1 hour (in place of 30 minutes as originally proposed).

2. Extraction of aluminum phosphate with 0.5N NH_4F of pH 7.0 for paddy soils and pH 8.2 for upland soils for one hour.

3. Extraction of $Fe-PO_4$ with 0.1N NaOH for 9 to 17 hours.

4. Extraction of reductant soluble $Fe-PO_4$ with dithionite-citrate with a bicarbonate buffer at pH 8.0. The extract is treated with activated charcoal if colored by organic matter.

5. Extraction of occluded iron-aluminum-phosphate complex with 0.1N NaOH for 9 to 17 hours.

6. Extraction of calcium phosphate with 0.5N H_2SO_4 for one hour. Chang and Liaw (16) remodified the "Chang and Jackson" procedure to accept the original proposal of extracting $Al-PO_4$ with neutral 0.5N NH_4F. According to them, their own experiments indicated that within limits of experimental error, the pH of NH_4F in the range of 7 to 8.5 does not affect the amount of phosphate extracted. In neutral NH_4F they found that reprecipitation of phosphate occurs when released from $Al-PO_4$ by the ferric ion as shown by Fife (23), and at the same time the dissolution of $FePO_4$ as found by Chang and Jackson (13). The phosphate

form extracted by neutral NH_4F rather than the alkaline NH_4F, may represent the total amount of aluminum phosphate with no more need for correction for dissolved iron phosphate assuming that the two amounts are approximately counter balanced.

Sen Gupta and Cornfield (31) analyzing for the different forms of phosphorus in calcareous soils adopted the "Chang and Jackson" procedure but differentiated between apatitic calcium phosphate and non-apatitic.

Saunders (57), Yuan and Fiskell (76) maintained that the use of neutral citrate-dithionite or alkaline buffered citrate-dithionite removed considerable aluminum from the soil and that the procedure should not be used uncritically for the study of soil phosphate. This probably indicates that what was determined to be reductant soluble iron phosphate actually contained some occluded $Al-PO_4$.

Concerning all the criticisms and the attendant problems in soil phosphorus fractionation, Chang (11) wrote: "Fractionation of soil phosphorus into the total amount of each discrete form by use of the selectivity of different extraction solutions has unsurmounted difficulties. The exact discreteness is subject to doubt. Nevertheless by use of the proper extractant, solid-solvent ratio, extraction time and extraction sequence, the result obtained would be very close to the truth".

Distribution of Forms of Phosphorus in the Soil

Several investigations have been made on the distribution of forms of phosphorus in studies mainly related to chemistry of soil phosphorus and soil fertility.

Dean (21) fractionated 36 soils from locations in Africa, Britain,

Hawaii, Soviet Union and the United States, and found that the amount of
phosphorus in the insoluble form constituted a large part of the phosphorus
in the soil. Ghani and Aleem (27) fractionated some Indian soils using
Ghani's procedure and found that the acetic acid soluble fraction
(calcium phosphate) was extremely small in acid soils over the pH range
of 4.2 to 5.8, but was highest at the neutral point and then decreased
again as the pH rose towards the alkaline side of the pH scale. Iron
and aluminum phosphate were more abundant in acid soils and decreased
with pH increase. The same was true of organic phosphate, but after
attaining a minimum at neutrality it increased again as the pH increased
toward the alkaline side. These authors attributed organic phosphate
accumulation to microbial activities. Godfrey and Reicken (30) from their
studies on the vertical distribution of phosphates on some genetically
related Iowa soils, observed that total phosphate decreased vertically
in all the profiles.

Bauwin and Tyner (4) investigated the chemical nature of the insoluble
phosphorus fraction, and fractionated the native phosphates of some
Illinois soil profiles into inorganic (acid soluble) adsorbed or replaceable;
organic; and insoluble phosphates. They observed that the insoluble
fraction was about 50% of the B horizon phosphates of the soils investigated.

In Sweden, Matson et al. (49) investigated the forms of phosphorus
in the soil series of the Dala brown earth and Unden Podsol and also (48)
the Brannalt limed and unlimed podsol series. Wiklander et al. (69)
investigated the different forms of phosphorus in the "gytta" soils of
Northern Sweden. Wiklander and Hallgren (68) also determined the phosphorus
forms on a "gytta" soil from Kungsangen and found organic phosphate

fairly constant throughout the profile; acetic acid soluble phosphate
(Ca and Al-PO$_4$) was higher in the surface soil and decreased with depth
and rose again with increasing depth while the 0.2N H$_2$SO$_4$ soluble
fraction (mainly calcium phosphate and sesquioxide bound phosphates)
did not show great variations with depth. Vahtras (62) fractionated
Swedish soils into 5 fractions and correlated these with several soil
properties.

IL'IN, (38) fractionated the chestnut brown soils of Central
Kulunda (USSR) and found total phosphate highest in the topsoil and
decreased with depth. Organic phosphate continued to decrease with depth
and virtually disappeared at a depth of about 190 to 210 cm. depth. In
the inorganic fractions, calcium phosphate was about 50 to 80% of the
total and the rest was Al-PO$_4$ and Fe-PO$_4$. Chang and Jackson (13, 14)
introduced the "Chang and Jackson" procedure, now most widely accepted,
and used it to fractionate some 10 representative soils and found that
the phosphorus fractions in latosols were dominantly iron phosphates
a majority of which were "occluded". This was the same fraction as
Bauwin and Tyner's "insoluble" (4) or Dean's "inert" (20) phosphate.
The quantities of calcium and aluminum phosphate were small in the latosols.
Phosphate in the chernozems was dominantly Ca-PO$_4$, with no occluded phosphate
and little Al-PO$_4$, while the rest of the soil that showed intermediate
weathering had Al, Fe, and Ca-PO$_4$ evenly distributed. Chu and Chang (18)
fractionated some representative soils of Taiwan (Formosa) according to
the "Chang and Jackson" procedure. Results showed that organic phosphate
ranged from 10 to 25% in the surface and less than 10% in the subsoil.
Occluded phosphate constituted about 33% of the total phosphate in the

surface and about 50% in the subsoil. Hamilton and Lassard (33) found that the total phosphate in some soils of Quebec increased with depth; while calcium phosphate was about 41% of the total phosphate in the surface and about 88% in the 18 to 24" depth. Aluminum phosphate was highest in the top 6" and dropped to 5% in the lower horizons. Iron phosphate was negligible throughout, organic phosphate decreased with depth while the quantity of occluded phosphate was a substantial portion of the whole in surface soil. MacKenzie (46) investigated the water soluble and inorganic phosphate associated with aluminum, iron and calcium in some Ontario soils. His findings indicated that aluminum phosphate supplied most of the phosphate found in the soil solution. Red'kin and Kubansk (56) showed in their work that organic phosphate constituted about 43 to 46% of the total phosphate in the tilled surface horizon of the Krasnoder Region (USSR), while calcium phosphate exceeded 20% of the total phosphate in the upper part of the soil and increased with depth; reaching 40-50% at the 200 cm. depth. The easily mobile phosphate did not exceed 10% throughout. Voikin (63) investigated 45 soils and found organic phosphate to comprise 40-50% of the total phosphate. The phosphorus in the "Forest" and "Podsol" soils was largely present as insoluble phosphorus compounds and the chernozem contained the least insoluble phosphorus compounds. Scheffer et al. (58) working on 9 German soils found that calcareous soils with high pH values were 46 to 64% calcium phosphate, 24 to 29% iron phosphate and a small quantity of aluminum phosphate. Bates and Baker (3) studied the forms of phosphorus in two tropical soil series of Western Nigeria and found high levels of phosphorus compounds throughout the profiles but the

concentration was higher in the topsoil. Organic phosphate decreased with depth and rose again at greater depth. Considerable amounts of iron phosphate, and small quantities of calcium phosphate were found through-out the profile. Nye and Bertheux (53) determined the phosphorus fractions in the soils of the forest and savannah lands of the Gold Coast (Ghana). They found the total phosphate was highest in the surface of the forest soils but no consistent change with depth was observed in Savannah soils. $Ca-PO_4$ decreased sharply with depth and alkali soluble inorganic phosphate (mostly $Fe-PO_4$) decreased more slowly. Hesse (36) analyzed the mangrove swamp soil of Sierra Leone and found that the distribution of phosphate in the mud to be as follows: Organic phosphate 87% of the total phosphate and the remainder was entirely $Fe-PO_4$ and $Ca-PO_4$. There was no occluded-PO_4 and practically no $Al-PO_4$.

Benavides (5) carried out soil phosphorus fractionation on some representative soils of Colombia, S. A. and found total phosphate was highest in the topsoil and lowest in the top layer of the parent material. Organic phosphate constituted the largest fraction (57 to 77%) of total phosphate, while the reductant soluble iron phosphate dominated the inorganic phosphorus fraction.

The above results despite some local variations are consistent with the generalization of Chang and Jackson (14) that the least weathered, or calcareous soils have $Ca-PO_4$ as the principal form of phosphate and the proportion of Al and $Fe-PO_4$ increases as weathering proceeds. In cases of extreme weathering occluded phosphate is the predominant fraction.

Forms of Phosphorus in the Soil and Soil Genesis

Soil phosphorus fractionation is now a new tool in the furthering of man's knowledge of soil genesis. Little research work has been done on soil phosphorus and soil genesis.

Chang and Jackson (14) fractionated 10 different soil profiles from different soil types and showed that the latosol samples (most weathered) had most of their phosphorus compounds as iron phosphate and most of it was occluded. The chernozem samples (the least weathered) had calcium phosphate dominant over iron and aluminum phosphate, while the soils of intermediate weathering had all the three types evenly distributed. This led them to postulate that the degree of or the stage of weathering of soils can be determined by the relative percentage of the discrete phosphorus forms in the soil and that the sequence of chemical weathering is in the order: $Ca-PO_4$----$Al-PO_4$----$Fe-PO_4$----occluded phosphate.

Chu and Chang (18) after fractionating some soils of Taiwan also found the discrete fractions distributed in a pattern influenced by soil genesis. Iron phosphate was dominant in the pattern to which highly weathered latosols belong; calcium phosphate was dominant in the pattern for calcareous soils, mudstones, alluvial soils, saline alluvial, slate alluvial and schist alluvial soils; while iron phosphate and calcium phosphate were dominant in acid sandstones and shale alluvial soils. Hawkins and Kunze (35) fractionated the phosphorus compounds of Texas Grumusols and related the inorganic forms to soil weathering. Mattson (47) suggested that calcium phosphate was transformed into sesquioxide bound phosphate as a consequence of the increase in soil acidity during

soil genesis. Hsu and Jackson (37) investigating the inorganic phosphorus compounds in some major soil groups indicated that the distribution of the inorganic phosphate in the major soil groups is related to the degree of chemical weathering during soil development and confirmed the finding of Chang and Jackson (14). Significant also is the work of Hesse (36) who showed that the mangrove swamp of Sierra Leone contained practically no Al-PO_4 and the comparatively unweathered situation was demonstrated by the complete absence of occluded phosphate.

In the process of weathering the relatively more stable aluminum phosphate, variscite, $\left[Al\ (OH)_2 \cdot H_2PO_4 \right]$ and iron phosphate, strengite, $\left[Fe\ (OH)_2\ H_2PO_4 \right]$ are formed, or are present as a mixed system of Al-Fe phosphate such as Barrandite $\left[(Al,\ Fe)\ (OH)_2\ H_2PO_4 \right]$. By processes of hydrolysis of iron phosphate, followed by dehydration of the resulting ferric hydroxide, a shell or coat of iron oxide is produced.

$$FePO_4 + 3\ H_2O \longrightarrow H_3PO_4 + Fe\ (OH)_3$$

$$2\ Fe(OH)_3 \longrightarrow Fe_2O_3 + 3\ H_2O$$
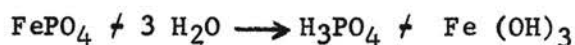
This shell protects the inner phosphate nucleus from solvent action and in the course of soil chemical weathering iron phosphate accumulates in the "occluded form." Aluminum phosphate may precipitate, or co-precipitate with iron in barrandite-like form, having a solubility product close to the solubility product of iron phosphate. This can also be occluded by an iron oxide coating. Thus the occluded phosphate which marks the highest stage of weathering is of secondary origin, highly resistant to further weathering and is a product of accumulation during the centuries of soil development. This fraction is not influenced by fertilizer practice and can be said to be constant.

"Available Phosphorus" in Relation to Forms of Phosphorus in the Soil

The forms and the amount of phosphorus in the soil whether native
or applied as fertilizer have considerable effect on the amount that
may be available to plants. The source of phosphate available to
plants is probably that of the inorganic phosphate fractions although
possibly the organic fraction by mineralization may contribute sub-
stantially particularly in areas of high weathering activity.

Fractionation of soil phosphorus has lately been employed to aid
in the studies and evaluation of available phosphorus in the soil. The
"Chang and Jackson" method is most widely used.

Chang and Jackson (14), Chang and Chu (12) have by soil phosphorus
fractionation demonstrated that under flooded conditions, the phosphorus
previously considered to be difficultly available is fairly available.
Basak and Battacharya (2) adopted the soil phosphorus fractionation
method of Bhango and Smith (6) and studied phosphorus transformation
in rice soil under flooded condition. They concluded that in such a
situation, there was an increase in the quantity of "available phosphorus"
by a process of mineralization of organic phosphate and the reductive
transformation of iron and aluminum phosphate. Another investigator
Sperker (59) had shown that H_2S generated in the soil under anaerobic
conditions could solubilize phosphate from soil minerals. This could
partly account for the observation of Basak and Battacharya.

Chang and Juo (15) fractionated the phosphates of some soils of
Taiwan and significantly correlated the different fractions with
available phosphorus determined by the seven most commonly used methods.

It illustrated that in a particular situation, the extractant which can dissolve selectively the forms of phosphorus which are the main supply of available phosphorus, would extract phosphorus which best represented the status of "available phosphorus" in the soil.

Williams (71) showed through his own fractionation procedure that in the acid redbrown earth (pH 5.6 to 6.1) he investigated, calcium phosphate was most utilized by wheat despite the predominant amount of $Al-PO_4$ and $Fe-PO_4$. MacKenzie (46) on the other hand showed that $Al-PO_4$ supplied most of the water soluble phosphate in the soils he investigated.

Laverty and McLean (45) correlated the soil phosphorus fractions with the uptake of phosphate by oat seedlings and to the available phosphorus as determined by the Bray #2 procedure (10). Westerman (67) carried out field and greenhouse tests with different levels of phosphate fertilizers in order to evaluate techniques for the determination of available phosphorus including "Chang and Jackson" phosphorus fractionation method. He found that short term nutrient absorption techniques and leaf analysis were not adequate for the determination of available soil phosphorus, and the phosphate needed for maximum yield.

Suzuki et al. (61) by chemical fractionation procedure, greenhouse experiments and chemical extraction measurements for "available" phosphorus correlated significantly the short term uptake of phosphorus and seasonal availability to the forms of phosphorus in the soil. Calcium and alumimum phosphate correlated significantly with short term uptake, and $Al-PO_4$ alone correlated significantly with the seasonal availability. $Fe-PO_4$ and organic phosphate did not contribute to any of the phosphorus removed

by the extractants of available phosphorus.

These examples serve to illustrate the importance of soil phosphorus fractionation in the studies of phosphate availability. It can, along with chemical determination of available phosphorus, greenhouse and field experiments, give a picture of the forms of phosphorus available to plants in a given situation. It can also show that where an extractant for the determination of available phosphorus has been shown to be significantly correlated with growth response then that same extractant or another with the same or similar selectivity for the forms of soil phosphorus, can be used in another situation with the same or similar phosphorus fraction distribution, regardless of pH, to determine the available phosphorus of the soil. This in turn will affect fertilizer recommendations.

Fate of water soluble phosphate applied to the soil

The study of the fate of applied phosphate in the soil is mainly one of phosphorus "fixation" and transformation. This is important in understanding more of the soil phosphorus chemistry (behavior) which is also relevant in soil phosphorus availability studies. Soil phosphorus fractionation is a useful tool, since phosphorus retention and "fixation" in the soil is mainly a chemical process as shown by Kittrick and Jackson (44).

Wright and Peech (74), employing a modified procedure of Chang and Jackson on some acid soils, showed that in some soils with predominantly native Fe-PO$_4$, the phosphate applied was converted principally to iron phosphate, while in others the fertilizer was usually converted

into $Al-PO_4$. $Ca-PO_4$ in general was increased less by fertilization, and lime application had little influence on the course of chemistry of applied phosphorus. This illustrates clearly what Jackson (41) described as competition between Al and Fe for phosphate retention in the soil system.

Chang and Chu (12) fractionated native and applied phosphate forms in some soils of Taiwan and found that added phosphate in six soils with pH range of 5.3 to 7.5 at field capacity retained $Al-PO_4$ followed by iron phosphate and $Ca-PO_4$ in the short run but in the long run $Al-PO_4$ and $Ca-PO_4$ decreased while $Fe-PO_4$ increased. Under flooded or paddy conditions $Fe-PO_4$ was the dominant form fixed. They also reported $Fe-PO_4$ predominant over $Al-PO_4$ in two latosols, a deviation from the general trend. These results led them to conclude that the first stage of phosphate fixation was governed more by surface energy than ionic activity, but as time proceeded and in higher moisture condition the ionic activity became more appreciable and the principle of the "solubility product" takes over.

Chang and Jackson (14) had also determined the fate of applied phosphate by their fractionation method on a podzolic soil at a pH of 7.5. They found that the application of soluble phosphate fertilizer greatly increased the $Al-PO_4$ and $Fe-PO_4$ at all lime levels applied but increased the $Ca-PO_4$ content only slightly at the highest lime level. Occluded-PO_4 was not affected. In the long run, $Ca-PO_4$ and $Al-PO_4$ changed gradually into $Fe-PO_4$ (the least soluble).

Laverty and McLean (45) by fractionation procedures, studied the fate of applied soluble phosphate. They reported "abnormal recovery"

of applied phosphate for an average of 108% of the applied PO_4. They could not ascertain whether the abnormal recovery was due to random variation or to the solubilization of occluded phosphate.

Onken and Reed (54) also used Chang and Jackson's procedure. They studied the fate of applied rock phosphate and superphosphate fertilizer and found the major portion of phosphorus from superphosphate and lesser quantities from rock phosphate was converted to iron and aluminum phosphate regardless of lime level applied.

Volk and MacLean (64) studied the fate of applied phosphorus in four Ohio soils by "tracer techniques" and Chang and Jackson's procedure. They found that in acid soils about 90% of the applied phosphate was recovered as $Al-PO_4$ and $Fe-PO_4$. They showed that soils with higher "fixation capacity" converted applied phosphate to $Fe-PO_4$ while that with lower "fixation capacity" precipitated more phosphorus as $Al-PO_4$. This was also reported by Laverty and McLean (45) and has not been accounted for. They reported abnormal recovery of the applied phosphate and also justified the use of phosphorus fractionation procedures to study the fate of applied phosphorus.

The works of these people among others justify and recommend the use of phosphorus fractionation procedures in studying the fate of applied phosphate. The knowledge gained is of immense value in the study of the chemistry of soil phosphorus and availability to plants and the processes of soil genesis.

MATERIALS AND METHODS

The soil materials are soil profile samples from different locations
in Oklahoma. They belong to the soil series - Carey, Hollister, Altus,
Grant, Okemah and Norge. Their descriptions are contained in the
appendix on pages 88-93.

Laboratory Method

Phosphate determinations:

1. <u>Total elemental phosphorus</u> was determined according to Harper's
method (35) of digesting a soil sample with 72% perchloric acid. Color
was developed by reducing the molybdenum which combined with the phosphate
ion with hydrazine sulphate. 5 gm. of soil was used.

2. <u>Organic phosphate</u>: Phosphate was determined colorimetrically according
to the procedure of Mehta et al. (51) by an alkaline extraction in NaOH
following acid pretreatment. Two gm. of soil was used for Norge and 1
gm. for the remainder of the soils. The organic phosphate was determined
by difference between the total phosphate (determined from the combined
acid and alkali extractions along with flocculated organic materials)
and inorganic phosphate (determined from the acid and alkali extraction
excluding the flocculated material).

Total - inorganic phosphate = organic phosphate.

3. <u>Inorganic phosphorus fractions</u>: Were determined according to the
procedure developed by Chang and Jackson (13) with some modifications.

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a. <u>Aluminum phosphate</u>: 1 gm of soil (2 gms. for Norge) was extracted with 50 ml. 1N NH_4Cl for 1 hour on a reciprocating shaking machine to remove water soluble and loosely bound phosphorus. The quantity determined was considered to be very small and negligible. The ammmonium soil was extracted with 50 ml. neutral (pH 7.0) 0.5N NH_4F; the soil suspension centrifuged and the phosphorus determined on the supernatant by chloromolybdic acid and stannous chloride. Boric acid was added to eliminate flouride interference in the molybdenum blue.

b. <u>Iron phosphate</u>: The soil sample saved after aluminum phosphate extraction was washed twice with 25 ml. portions of saturated NaCl solution. The soil was extracted with 50 ml. 0.1N NaOH for 17 hours on a reciprocating shaking machine. The soil suspension was centrifuged and phosphate determined on the supernatant using sulfomolybdic acid and stannous chloride.

c. <u>Calcium phosphate</u>: The soil saved after iron phosphate extraction was washed twice with 25 ml. portions of saturated NaCl and the phosphate extracted with 50 ml. of 0.5N H_2SO_4 for one hour on a shaking machine. The suspension was centrifuged again and the phosphate determined colorimetrically on the supernatant using sulfomolybdic acid and stannous chloride.

d. <u>Total occluded phosphate</u>: Was determined according to the method used by Chu and Chang (18). The soil saved after calcium phosphate extraction was washed twice with 25 ml. portions of saturated NaCl. The sample was digested with 6N HCl and the iron precipitated with 2N NaOH. After removing the precipitate by filtration the phosphate was determined by Jackson's No. 2 (39) method using chloromolybdic acid and stannous chloride.

e. <u>Occluded aluminum phosphate</u>: In order to determine the portion of occluded phosphate attributed to occluded aluminum phosphate, a separate

sample was run. After the removal of Al-, Fe-, Ca-PO$_4$ and reductant soluble iron phosphate according to Chang and Jackson, the occluded aluminum phosphate was determined by washing the residual soil with two 25 ml. portions of saturated NaCl and the phosphate extracted and determined as Al-PO$_4$. Where further extraction with 0.1N NaOH indicated more phosphorus, the occluded Al-PO$_4$ extracted was present as a complex of occluded AlFe-PO$_4$.

f. Reductant soluble iron phosphate was obtained by difference between total occluded phosphate and occluded Al-PO$_4$.

Soil Properties

Physical properties:

1. Mechanical Analysis: Determined by method of Day et al. (19) using the hydrometer with Bouyoucos scale and 2% Na$_2$CO$_3$ was used as a dispersion agent. Carbonate and bivalent cations were removed by use of 1N Na-acetate buffered at pH 5.0.

Chemical properties:

1. Soil pH: Determined by the paste method and 1:1 soil:1N KCl method using the Beckman Zeromatic pH meter.

2. Cation Exchange Capacity: Was determined by Bower's method (8) using 1N Na-acetate at pH 8.2. Na$^+$ was the displacing cation and determined by flame method using Beckman quartz-spectrophotometer model DU with photomultiplier. 4 gm. sample for the soil samples and 6 gm. for Norge was used.

3. Exchangeable Cations: Ca^{++}, Mg^{++}, K$^+$, Na$^+$ determined by flame photometry on the 1.0N NH$_4$ acetate extract.

4. Exchangeable Acidity, H$^+$ and Al^{+++}: By the method of Yuan (75).

5. <u>Free Iron Oxide</u>: The soil saved from the calcium phosphate extraction in phosphorus fractionation procedure was washed twice with saturated NaCl. Iron oxide (in form of hematite Fe_2O_3 and geothite FeO_2H) was extracted by dithionite - citrate - bicarbonate method, sodium dithionite ($Na_2S_2O_4$) being employed for reduction, sodium bicarbonate as a buffer and sodium citrate as a chelating or complexing agent for ferrous and ferric iron. Iron was determined by the Tiron method (40).

6. <u>Total Nitrogen</u>: Was determined by Kjeldhal's method (34).

7. <u>Organic Matter</u>: Was determined by Schollenberger - Allison Volumetric method as modified by Harper (34). Organic carbon was derived by the factor -

Carbon x 1.724 ▪ O.M

Fate of Applied Water Soluble Phosphate

Fate of applied phosphate in the short run was determined as follows:

1. 50 gm. of soil was treated with KH_2PO_4 (potassium dihydrogen phosphate) at 500 ppm in order to give concentrations of 200 ppm in the soil (20 mls. KH_2PO_4 to 50 gm. soil). The moisture was kept at approximately field capacity for 3 days at room temperature. After 3 days the soil was air dried, ground and mixed and 1 gram taken for phosphorus fractionation.

2. Another 50 gm. of soil was similarly treated but kept for 30 days. The soil phosphorus was also fractionated by Chang and Jackson's method. There was no fractionation for occluded phosphate.

Available Phosphorus

Available phosphorus was determined on the original and treated soil

samples according to Brays #1 method. (10) Statistical analyses were
carried out according to the method of Steel and Torrie (60).

RESULTS AND DISCUSSION

Physical Properties of the Soils

With regard to particle size distribution (Table Ia-e), all the soils
are loams. The individual horizon analysis ranged from sandy loam in Norge
to clay in Okemah. The clay fraction increased from the surface soil to
the deeper layers. The higher level of clay in the subsurface horizons
was perhaps due to clay formed in place, and clay elluviated from the
surface soil and deposited in the deeper horizons. The plow layer in
all the soils contained the least amount of clay.

Chemical Properties of the Soils

The pH increased with depth except in Norge and Okemah soils as shown
in Tables IIa-e. The high pH in the plow depth of the Norge soil was due
to increase in base saturation due to liming. The pH of Okemah decreased
with depth unlike the rest. The soil reaction of the horizons analyzed
ranged from an extremely acid condition with a pH of 4.60 (paste) in B_{21}
horizon of Okemah to a highly alkaline condition, pH 8.30 (paste) in C_{ca}
horizon of Carey.

Cation exchange capacity ranged from 6.04 m.e./100 gm. (oven dry) in
A_{12} horizon of Norge to 34.10 in Okemah B_{21} horizon. The high level of
the cation exchange capacity in this horizon was due mainly to a high
level of exchangeable magnesium and sodium. Cation exchange capacity

TABLE Ia

PHYSICAL PROPERTIES: CAREY SILT LOAM

Lab. no. Depth inches Horizon	61-S-79 0-12 A_1	61-S-80 12-22 B_{21}	61-S-81 22-28 B_{22}	61-S-82 28-34 C_1	61-S-83 34-54 C_{ca}
Particle size distribution %					
Clay <2 M	14	18	20	26	19
Silt 2-50 M	41	51	49	49	50
Sand >50 M	45	31	31	25	31
Textural class	Loam	Silt Loam	Loam	Loam	Silt Loam
% moisture	1.56	1.81	1.61	1.00	1.28

TABLE Ib

PHYSICAL PROPERTIES: HOLLISTER CLAY LOAM

Lab. no. Depth inches Horizon	61-S-73 0-5 A_p	61-S-74 5-11 A_1	61-S-75 11-23 B_2	61-S-76 23-31 B_3	61-S-77 31-44 C_{ca}	61-S-78 44-50 C
Particle size distribution %						
Clay $<2\mu$	23	24	39	41	45	53
Silt $2-50\mu$	38	46	25	28	29	30
Sand $>50\mu$	39	30	36	31	26	17
Textural class	Loam	Loam	Clay Loam	Clay	Clay	Clay
% moisture	2.42	2.46	4.07	4.04	3.48	7.15

TABLE Ic

PHYSICAL PROPERTIES: GRANT SILT LOAM

Lab. no. Depth inches Horizon	3219 0-5 A_p	3220 5-12 A_{12}	3221 12-20 A_3	3222 20-36 B_2	3223 36-48 C
Particle size distribution %					
Clay $<2M$	10	14	18	25	23
Silt $2-50M$	36	37	39	32	29
Sand $>50M$	54	49	43	43	48
Textural class	Sandy Loam	Loam	Loam	Loam	Loam
% moisture	1.03	1.49	2.07	2.89	2.35

TABLE Id

PHYSICAL PROPERTIES: NORGE SANDY LOAM

Lab. no. Depth inches Horizon	0-6 A_p	6-14 A_{12}	14-24 B_{2t}	24-50 C
Particle size distribution %				
Clay $<2\mathcal{M}$	9	18	19	14
Silt 2-50 $\mathcal{M}$	12	14	13	7
Sand $>50\mathcal{M}$	79	68	68	79
Textural class	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
% moisture	0.95	1.61	2.18	1.92

TABLE Ie

PHYSICAL PROPERTIES: OKEMAH SILT LOAM

Lab. no.	2532	2533	2534	2545
Depth inches	0-11	11-14	14-20	42-54
Horizon	A_1	B_1	B_{21}	C
Particle size distribution %				
Clay $<2\mu$	20	28	36	54
Silt $2-50\mu$	64	58	42	34
Sand $>50\mu$	16	14	22	12
Textural class	Silt Loam	Silt Clay Loam	Clay Loam	Clay
% moisture	2.26	2.81	5.01	5.31

TABLE IIa

CHEMICAL PROPERTIES: CAREY SILT LOAM

Lab. no. Depth inches Horizon	61-S-79 0-12 A_1	61-S-80 12-22 B_{21}	61-S-81 22-28 B_{22}	61-S-82 28-34 C_1	61-S-83 34-54 C_{ca}
pH paste	7.00	7.80	8.05	8.15	8.30
pH 1:1 KCl	6.00	6.95	7.30	7.45	7.50
C.E.C.* m.e./100 gm.	9.61	9.85	9.39	8.57	8.92
Extractable cations					
m.e./100 gm.	16.13	20.44	28.47	32.75	32.02
Calcium	6.90	9.25	17.55	21.00	18.75
Magnesium	8.41	10.58	10.41	11.25	12.75
Potassium	0.64	0.38	0.28	0.28	0.30
Sodium	0.08	0.13	0.13	0.17	0.17
Hydrogen	0.10	0.10	0.10	0.05	0.05
Aluminum	0.00	0.00	0.00	0.00	0.00
% Base saturation	166.81	206.50	302.13	381.56	358.40
Exch. acidity					
m.e./100 gm.	0.10	0.10	0.10	0.05	0.05
% Organic matter	1.51	1.01	0.74	0.61	0.79
% Carbon •	0.87	0.59	0.43	0.35	0.46
% Nitrogen	0.08	0.06	0.05	0.04	0.05
C/N	10.88	9.83	8.60	8.75	9.20
% Free Fe_2O_3	0.78	1.14	1.07	1.05	1.03
Bray's #1 phosphorus					
ppm	9.00	3.00	3.00	0.00	2.00

* Cation Exchange Capacity

TABLE IIb

CHEMICAL PROPERTIES: HOLLISTER CLAY LOAM

Lab. no. Depth inches Horizon	61-S-73 0-5 A_p	61-S-74 5-11 A_1	61-S-75 11-23 B_2	61-S-76 23-31 B_3	61-S-77 31-44 C_{ca}	61-S-78 44-50 C
pH paste	6.50	6.40	6.95	7.50	7.75	7.90
pH 1:1 KCl	6.00	5.90	6.30	6.85	7.00	7.20
C.E.C.* m.e./100 gm.	10.92	10.70	17.45	17.22	17.57	18.73
Extractable cations						
m.e./100 gm.	21.56	22.65	33.83	52.26	38.97	44.78
Calcium	10.00	10.20	15.00	15.90	17.25	21.00
Magnesium	9.00	10.00	16.08	16.60	18.75	19.50
Potassium	1.38	1.33	1.05	0.84	0.84	0.71
Sodium	1.08	1.04	1.65	1.60	2.00	3.47
Hydrogen	0.10	0.08	0.05	0.10	0.13	0.10
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00
% Base saturation	196.52	210.93	193.58	202.32	221.06	238.55
Exch. acidity						
m.e./100 gm.	0.10	0.08	0.05	0.10	0.13	0.10
% Organic matter	1.76	1.74	1.31	0.88	0.56	0.45
% Carbon	1.02	1.01	0.76	0.51	0.33	0.26
% Nitrogen	0.09	0.09	0.07	0.04	0.03	0.04
C/N	11.33	11.22	10.86	12.75	11.00	6.50
% Free Fe_2O_3	0.61	0.70	0.94	0.84	0.79	0.89
Bray's #1 phosphorus						
ppm	13.00	14.00	3.00	2.50	2.50	2.00

* Cation Exchange Capacity

TABLE IIc

CHEMICAL PROPERTIES: GRANT SILT LOAM

Lab. no.	3219	3220	3221	3222	3223
Depth inches	0-5	5-12	12-20	20-36	36-48
Horizon	A_p	A_{12}	A_3	B_2	C
pH paste	6.15	6.00	6.60	7.40	7.50
pH 1:1 KCl	5.50	4.95	5.80	6.60	6.60
C.E.C.* m.e./100 gm.	8.24	8.57	10.76	11.42	10.24
Extractable cations					
m.e./100 gm.	10.43	12.64	17.11	22.34	21.10
Calcium	5.00	6.20	8.65	11.10	9.85
Magnesium	4.25	5.50	7.66	10.41	10.41
Potassium	1.00	0.76	0.61	0.56	0.53
Sodium	0.08	0.08	0.13	0.17	0.21
Hydrogen	0.10	0.10	0.06	0.10	0.10
Aluminum	0.00	0.00	0.00	0.00	0.00
% Base saturation	125.36	146.32	158.46	194.75	205.09
Exch. acidity					
m.e./100 gm.	0.10	0.10	0.06	0.10	0.10
% Organic matter	1.46	1.33	1.24	1.01	0.63
% Carbon	0.85	0.77	0.72	0.59	0.37
% Nitrogen	0.07	0.07	0.07	0.06	0.06
C/N	12.14	11.00	10.29	9.83	6.17
% Free Fe_2O_3	0.43	0.45	0.53	0.66	0.60
Bray's #1 phosphorus					
ppm	14.00	13.00	5.00	2.50	5.00

*Cation Exchange Capacity

TABLE IId

CHEMICAL PROPERTIES: NORGE SANDY LOAM

Lab. no. Depth inches Horizon	0-6 A_p	6-14 A_{12}	14-24 B_{2t}	24-50 C
pH paste	7.15	5.70	5.80	5.70
pH 1:1 KCl	6.30	5.10	5.00	4.90
C.E.C.* m.e./100 gm.	5.85	6.04	6.22	7.09
Extractable cations				
m.e./100 gm.	9.57	12.56	14.82	11.36
Calcium	6.00	6.55	6.90	4.90
Magnesium	3.08	5.33	7.25	5.91
Potassium	0.28	0.30	0.30	0.23
Sodium	0.13	0.13	0.17	0.17
Hydrogen	0.03	0.25	0.20	0.10
Aluminum	0.05	0.00	0.00	0.05
% Base saturation	162.22	203.81	235.05	158.11
Exch. acidity				
m.e./100 gm.	0.08	0.35	0.20	0.15
% Organic matter	0.79	1.25	0.88	0.43
% Carbon	0.25	0.51	0.73	0.46
% Nitrogen	0.05	0.06	0.05	0.03
C/N	5.00	8.50	14.60	14.33
% Free Fe_2O_3	0.24	0.35	0.39	0.28
Bray's #1 phosphorus				
ppm	5.00	2.50	1.00	2.50

* Cation Exchange Capacity

TABLE IIe

CHEMICAL PROPERTIES: OKEMAH SILT LOAM

Lab. no.	2532	2533	2534	2545
Depth inches	0-11	11-14	14-20	42-54
Horizon	A_1	B_1	B_{21}	C
pH paste	5.10	4.70	4.60	5.00
pH 1:1 KCl	4.90	4.35	4.10	4.50
C.E.C.* m.e./100 gm.	14.46	14.99	34.10	19.05
Extractable cations				
m.e./100 gm.	17.55	22.50	47.65	44.92
Calcium	6.35	6.90	14.40	25.50
Magnesium	9.00	10.58	21.25	15.00
Potassium	0.21	0.21	0.46	0.38
Sodium	1.86	4.26	9.78	3.69
Hydrogen	0.10	0.25	0.33	0.05
Aluminum	0.03	0.30	1.43	0.30
% Base saturation	120.47	146.43	232.60	129.31
Exch. acidity				
m.e./100 gm.	0.13	0.55	1.76	0.35
% Organic matter	2.68	1.60	2.05	0.50
% Carbon	1.55	0.93	1.19	0.29
% Nitrogen	0.13	0.09	0.10	0.05
C/N	11.92	10.33	11.90	5.80
% Free Fe_2O_3	1.00	1.80	3.00	5.20
Bray's #1 phosphorus				
ppm	5.00	2.50	1.00	2.50

* Cation Exchange Capacity

increased with depth, and there was a highly significant correlation between cation exchange capacity and clay content for all the samples, of r (correlation coefficient) $= \neq 0.72$[1].

Base saturation was generally more than 100%, and it increased with depth. This super saturation was because the extractable cations included soluble and exchangeable cations. Exchange acidity was low throughout except in Norge and Okemah soils where exchangeable aluminum was an important contributing factor.

Organic matter accumulated at the surface and decreased with depth. It varied from 0.43% in C horizon of Norge to 2.68% in A_1 horizon of Okemah. The percentage of carbon and nitrogen followed the same trend. "Available phosphorus" by Bray's #1 method (10) was generally low but was highest in the surface soil and decreased with depth. Bray's #1 method is the standard technique used in this study for available phosphorus.

Phosphorus Forms and Distribution

The results of the amount and the distribution of the various forms of phosphorus compounds are shown on Table IIIa-e. The percentages of each form contributed to total phosphorus are shown in Table IVa-e.

Phosphates in the soil are divided into two main portions - the organic phosphates and the inorganic phosphates. The inorganic are further divided into active and inactive fractions. The active fraction represents that which can be readily extracted by ordinary laboratory "soil test" techniques, and which supplies most of the phosphorus required by plants. The inactive

[1]Significant at 1% level of confidence.

TABLE IIIa

DISTRIBUTION OF FORMS OF PHOSPHORUS

	Carey Silt Loam				
Lab. no.	61-S-79	61-S-80	61-S-81	61-S-82	61-S-83
Depth inches	0-12	12-22	22-28	28-34	34-54
Horizon	A_1	B_{21}	B_{22}	C_1	C_{ca}
Total phosphorus ppm	370.00	530.00	586.00	596.00	530.00
Organic phosphorus ppm	130.00	190.00	186.00	186.00	150.00
Inorganic phosphorus fractions					
$Al-PO_4$ ppm	13.44	4.06	4.06	4.06	4.06
$Fe-PO_4$ ppm	11.25	6.25	0.00	0.00	0.00
$Ca-PO_4$ ppm	150.00	256.25	337.50	362.50	318.75
Occluded phosphates					
R. Sol. $Fe-PO_4$ ppm	58.12	57.50	66.87	29.37	31.87
Oc $Al-PO_4$ ppm	0.00	0.00	8.13	8.13	5.63
Oc $Al-Fe-PO_4$ ppm	4.38	5.00	0.00	0.00	0.00
Total additive ppm	367.19	519.06	602.56	590.06	510.31

TABLE IIIb

DISTRIBUTION OF FORMS OF PHOSPHORUS

	Hollister Clay Loam					
Lab. no.	61-S-73	61-S-74	61-S-75	61-S-76	61-S-77	61-S-78
Depth inches	0-5	5-11	11-23	23-31	31-44	44-50
Horizon	A_p	A_1	B_2	B_3	C_{ca}	C
Total phosphorus ppm	300.00	310.00	270.00	240.00	230.00	225.00
Organic phosphorus ppm	120.00	150.00	85.00	110.00	95.00	85.00
Inorganic phosphorus fractions						
$Al-PO_4$ ppm	14.69	12.50	2.81	2.20	Trace	1.41
$Fe-PO_4$ ppm	16.25	15.63	5.63	3.44	1.25	0.00
$Ca-PO_4$ ppm	63.75	65.00	56.25	67.50	70.00	85.00
Occluded phosphates						
R. Sol. $Fe-PO_4$ ppm	81.25	62.50	99.38	56.87	45.63	56.87
Oc $Al-PO_4$ ppm	0.00	0.00	0.00	0.00	0.00	5.63
Oc $Al-Fe-PO_4$ ppm	6.25	6.25	6.88	5.63	4.38	0.00
Total additive ppm	295.94	311.88	255.95	245.64	216.26	233.91

TABLE IIIc

DISTRIBUTION OF FORMS OF PHOSPHORUS

Grant Silt Loam

Lab. no.	3219	3220	3221	3222	3223
Depth inches	0-5	5-12	12-20	20-36	36-48
Horizon	A_p	A_{12}	A_3	B_2	C
Total phosphorus ppm	300.00	295.00	300.00	220.00	156.00
Organic phosphorus ppm	115.00	115.00	125.00	80.00	36.00
Inorganic phosphorus fractions					
$Al-PO_4$ ppm	18.75	7.47	2.81	2.20	4.06
$Fe-PO_4$ ppm	13.75	9.38	6.88	5.00	7.81
$Ca-PO_4$ ppm	107.50	97.50	87.50	44.50	22.50
Occluded phosphates					
R. Sol. $Fe-PO_4$ ppm	46.25	60.26	81.25	85.94	78.75
Oc $Al-PO_4$ ppm	0.00	0.00	0.00	0.00	0.00
Oc $Al-Fe-PO_4$ ppm	3.75	5.00	6.25	7.81	8.75
Total additive ppm	305.00	294.61	309.69	225.45	157.87

TABLE IIId

DISTRIBUTION OF FORMS OF PHOSPHORUS

	Norge Sandy Loam			
Lab. no.				
Depth inches	0-6	6-14	14-24	24-50
Horizon	A_p	A_{12}	B_{2t}	C
Total phosphorus ppm	140.00	168.00	144.00	132.00
Organic phosphorus ppm	65.00	98.00	69.00	67.00
Inorganic phosphorus fractions				
$Al-PO_4$ ppm	5.62	2.81	1.41	Trace
$Fe-PO_4$ ppm	11.25	4.38	5.63	5.63
$Ca-PO_4$ ppm	5.63	8.75	6.88	3.75
Occluded phosphates				
R. Sol. $Fe-PO_4$ ppm	39.38	56.88	43.13	45.63
Oc $Al-PO_4$ ppm	0.00	0.00	0.00	0.00
Oc $Al-Fe-PO_4$ ppm	4.38	5.63	6.88	4.38
Total additive ppm	131.26	176.45	132.93	126.39

TABLE IIIe

DISTRIBUTION OF FORMS OF PHOSPHORUS

Okemah Silt Loam

	2532	2533	2534	2545
Lab. no.	2532	2533	2534	2545
Depth inches	0-11	11-14	14-20	42-54
Horizon	A_1	B_1	B_{21}	C
Total phosphorus ppm	430.00	370.00	340.00	670.00
Organic phosphorus ppm	255.00	220.00	205.00	160.00
Inorganic phosphorus fractions				
Al-PO_4 ppm	2.81	Trace	Trace	1.41
Fe-PO_4 ppm	51.25	25.63	22.50	165.00
Ca-PO_4 ppm	15.00	13.75	15.00	45.00
Occluded phosphates				
R. Sol. Fe-PO_4 ppm	101.25	98.75	59.38	236.25
Oc Al-PO_4 ppm	0.00	0.00	0.00	0.00
Oc Al-Fe-PO_4 ppm	11.25	13.75	15.63	51.25
Total additive	436.56	371.88	317.51	658.91

TABLE IVa

FRACTIONS OF THE SOIL PHOSPHORUS AS PERCENTAGE
OF THE TOTAL PHOSPHORUS

	Carey Silt Loam				
Lab. no.	61-S-79	61-S-80	61-S-81	61-S-82	61-S-83
Depth inches	0-12	12-22	22-28	28-34	34-54
Horizon	A_1	B_{21}	B_{22}	C_1	C_{ca}
Inorganic phosphorus fractions					
Active Al-PO_4 %	3.66	0.78	0.67	0.68	0.79
Active Fe-PO_4 %	3.06	1.20	0.00	0.00	0.00
Active Ca-PO_4 %	40.85	49.37	56.01	61.43	62.46
Inactive R. Sol. Fe-PO_4 %	15.82	11.07	11.09	4.97	6.24
Inactive OcAl-PO_4 %	0.00	0.00	1.35	1.37	1.10
Inactive OcAl-Fe-PO_4 %	1.19	0.96	0.00	0.00	0.00
Total inorganic phosphorus %	64.58	63.38	69.12	68.45	70.59
Organic phosphorus %	35.42	36.62	30.88	31.55	29.41

TABLE IVb

FRACTIONS OF THE SOIL PHOSPHORUS AS PERCENTAGE
OF THE TOTAL PHOSPHORUS

			Hollister Clay Loam			
Lab. no.	61-S-73	61-S-74	61-S-75	61-S-76	61-S-77	61-S-78
Depth inches	0-5	5-11	11-23	23-31	31-44	44-50
Horizon	A_p	A_1	B_2	B_3	C_{ca}	C
Inorganic phosphorus fractions						
Active Al-PO_4 %	4.96	4.00	1.09	0.89	0.00	0.60
Active Fe-PO_4 %	5.49	5.01	2.19	1.40	0.57	0.00
Active Ca-PO_4 %	21.54	20.84	21.97	27.47	32.36	36.33
Inactive R. Sol. Fe-PO_4 %	27.45	20.03	38.82	23.15	21.09	24.31
Inactive OcAl-PO_4 %	0.00	0.00	0.00	0.00	0.00	2.40
Inactive OcAl-Fe-PO_4 %	2.11	2.00	2.68	2.29	2.02	0.00
Total inorganic phosphorus %	61.55	51.88	66.75	55.20	56.04	63.64
Organic phosphorus %	38.45	48.12	33.25	44.80	43.96	36.36

TABLE IVc

FRACTIONS OF THE SOIL PHOSPHORUS AS PERCENTAGE
OF THE TOTAL PHOSPHORUS

	Grant Silt Loam				
Lab. no.	3219	3220	3221	3222	3223
Depth inches	0-5	5-12	12-20	20-36	36-48
Horizon	A_p	A_{12}	A_3	B_2	C
Inorganic phosphorus fractions					
Active Al-PO_4 %	6.14	2.54	0.91	0.97	2.57
Active Fe-PO_4 %	4.50	3.18	2.22	2.21	4.94
Active Ca-PO_4 %	35.24	33.10	28.25	19.73	14.25
Inactive R. Sol. Fe-PO_4 %	15.16	20.45	26.24	38.11	49.88
Inactive OcAl-PO_4 %	0.00	0.00	0.00	0.00	0.00
Inactive OcAl Fe-PO_4 %	1.22	1.70	2.02	3.46	5.54
Total inorganic phosphorus %	62.26	60.97	59.64	64.48	77.18
Total organic phosphorus	37.74	39.03	40.36	35.52	22.82

TABLE IVd

FRACTIONS OF THE SOIL PHOSPHORUS AS PERCENTAGE
OF THE TOTAL PHOSPHORUS

	Norge Sandy Loam			
Lab. no. Depth inches Horizon	0-6 A_p	6-14 A_{12}	14-24 B_{2t}	24-52 C
Inorganic phosphorus fractions				
Active Al-PO_4 %	4.28	1.59	1.06	0.00
Active Fe-PO_4 %	8.57	2.48	4.23	4.45
Active Ca-PO_4 %	4.28	4.96	5.17	2.96
Inactive R. Sol. Fe-PO_4 %	30.00	32.24	32.44	36.10
Inactive OcAl-PO_4 %	0.00	0.00	0.00	0.00
Inactive OcAl-Fe-PO_4 %	3.33	3.19	5.17	3.46
Total inorganic phosphorus %	50.46	44.46	48.05	46.97
Organic phosphorus %	49.54	55.54	51.95	53.03

TABLE IVe

FRACTIONS OF THE SOIL PHOSPHORUS AS PERCENTAGE
OF THE TOTAL PHOSPHORUS

	Okemah Silt Loam			
Lab. no.	2532	2533	2534	2545
Depth inches	0-11	11-14	14-20	42-54
Horizon	A_1	B_1	B_{21}	C
Inorganic phosphorus fractions				
Active Al-PO$_4$ %	0.64	0.00	0.00	0.21
Active Fe-PO4 %	11.73	6.89	7.80	25.04
Active Ca-PO$_4$ %	3.43	3.69	4.72	6.82
Inactive R. Sol. Fe-PO$_4$ %	23.19	26.55	18.70	35.85
Inactive OcAl-PO$_4$ %	0.00	0.00	0.00	0.00
Inactive OcAl-Fe-PO$_4$ %	2.57	3.69	4.92	7.77
Total inorganic phosphorus %	41.56	40.82	35.42	75.69
Organic phosphorus %	58.44	59.18	64.58	24.31

or inert portion cannot readily be extracted by ordinary laboratory methods;
it is highly insoluble in the common solvents used in phosphorus extraction,
and it is strongly resistant to further weathering. This phosphate does
not under ordinary circumstances contribute to plant nutrition. The
active phosphates include; aluminum phosphate ($Al-PO_4$), iron phosphate
($Fe-PO_4$), and calcium phosphate ($Ca-PO_4$). The inactive phosphate
includes the occluded phosphates. Occluded phosphates occur as reductant
soluble iron phosphate (Re Sol $Fe-PO_4$) and occluded aluminum phosphate
(Oc $Al-PO_4$), or as the occluded aluminum-iron phosphate complex (Oc $Al-Fe-PO_4$).

Total Phosphorus

There was a difference in the distribution of total phosphorus within
and among the soil profiles. In Carey Silt Loam, the total phosphorus
in the A horizon was less than that in B and this in turn was less than
that in C horizon. The relationship can be represented as follows:
$P-A < P-B < P-C$ (P represents total phosphorus; A, B and C, the genetic
horizons). In Hollister, Grant and Norge the relationship was in the
reverse order: $P-C < P-B < P-A$. Okemah had a totally different relationship:
$P-B < P-A < P-C$. Considering the solum which is comprised essentially of
the A and B horizons and which is important in plant nutrition, the
results indicated that generally the surface soils were richer in total
phosphorus reserve than the subsurface soils.

The average total phosphorus for each horizon of the profiles was as
follows: Carey 522.4 ppm, Okemah, 452.5 ppm, Hollister 262.5 ppm, Grant
254.4 ppm and Norge 148.5 ppm. Carey and Okemah were the richest in
total phosphorus, Norge the poorest; Hollister and Grant occupied inter-

mediate positions. The average total phosphorus for all the horizons analyzed was 327.2 ppm.

Several factors such as physical and chemical properties, geologic origin and agricultural practice were largely responsible for the distribution of total phosphorus within and among the soil profiles.

Organic Phosphorus

Because of the low rate at which microbial organisms mineralize organic phosphates in the temperate regions, it has not been considered very important in phosphorus nutrition of the plant. However, in the tropical regions and in areas of high weathering activities, organic phosphates contribute very substantially to plant nutrition. In most soils organic phosphates constitute a relatively large proportion of the total phosphorus in the soil. Unfortunately the true nature of about half of the total organic phosphates in the soil remains obscure. The other fraction consists of 3 types of phosphates: inositol phosphate, ribonucleic acid and their derivatives, and phospholipids.

Distribution of organic phosphorus in Oklahoma soils. With the exception of Carey, the organic phosphates were accumulated in the surface soils. The level in the surface soil exceeded that in the subsurface soil and this in turn exceeded the level in the C-material. The amount of organic phosphate varied from 65 ppm in the A_p horizon of Norge to 255 ppm in the A_1 horizon of Okemah. The organic phosphate contribution to total phosphorus ranged from 35.42% in A_1 horizon of Carey to 59.10% in the B_1 horizon of Okemah. The peculiar distribution pattern in Carey soil can be compared to that in Pima Clay Loam soil reported by Fuller and

McGeorge (25) in their work on Arizona calcareous soils. In the Pima
soil the level of organic phosphate rose with increase in depth. In
most of the soils Fuller and McGeorge analyzed, organic phosphate as
percentage of total phosphorus also increased with depth. Wiklander
and Hallgren (68) reported organic phosphate fairly constant throughout
the profile while Gupta (32) found organic phosphate significantly
correlated with percentage of $CaCO_3$ in the calcareous soils investigated.

The average total organic phosphate for all the soils analyzed was
129 ppm and its average percentage of the total phosphorus was 41.7%.
Thus one can conclude that organic phosphate constituted a large part
of the total phosphorus in the soils investigated.

Carbon:Phosphorus ratio (C:P). The results obtained by comparing
carbon, nitrogen and phosphorus ratios are shown in Table V. Organic
phosphorus is related to carbon and nitrogen in the soil organic matter.
In the soils analyzed C:P varied markedly within the individual
profiles, and also among the profiles. The extreme variation was from
18.1:1 in the C horizon of Okemah to 105.8:1 in the B_{2t} horizon of Norge.
The soil variation was from 34.10:1 in Carey to 74.86:1 in Grant when
averaged over the profile. However, the variation in C:P for the surface
soils was not great. The range was from 45:1 to 76:1 (Hollister 76:1,
Carey 67:1, Grant 66:1, Okemah 61:1, Norge 45:1). Several workers
(42, 55, 66, 72) have also reported wide variation in C:P for soils.

Nitrogen Phosphrous Ratios (N:P). This ratio has been reported to
be less variable than C:P (42, 66, 72). Results showed that N:P variation
was generally small in all the samples; and within individual profiles
this variation was less marked than C:P. The N:P was fairly uniform

between the surface soils of the different profiles (Norge 6.9:1, Hollister
6.7:1, Carey 6.2:1, Okemah 5.1:1, and Grant 5.9:1). The range was
between 5.1:1 and 6.9:1. This was comparable to the results of Walker
and Adams (66) on some British soils where N:P ratio for the 0-7"
layer for all soils analyzed varied from 10:3.2 to 10:1.2.

Carbon, Nitrogen, Phosphorus ratios (C:N:P). The results indicated
that in all the surface soils analyzed, the C:N:P ratio was not very
variable: Hollister 76:7:1, Carey 67:6:1, Grant 66:6:1, Okemah 61:5:1
and Norge 45:7:1. The average C:N:P for all the surface soils was
approximately 63:6:1, subsurface or B horizon 59:6:1 and C-material
44:6:1. Average C:N:P for all the samples analyzed was 56:6:1. Williams
et al. (72) reported C:N:P 147:10:2.5 for Scottish soils. Black and
Goring (7) reported average C:N:P for organic matter in mineral soils
as 100:9:1. Results from tropical soils reported by Nye and Bertheux
(53) show ratios of 233:22:1 and 247:20:1 for the Forest and Savannah
soils respectively, of Ghana. Benavides (5) showed 81:10:1 for tropical
soils of Colombia, South America.

The significance of C:N:P ratio is that, it showed that organic
phosphorus was an important factor in the build up of organic matter in
the soil. Walker and Adams (66) emphasized that "the major factor
governing the accumulation of organic matter in the soil was the phosphorus
content of the parent material." The higher the C:P and N:P ratios of
a soil, the more deficient the soil is likely to be in phosphorus. This
deficiency will affect the build up of micro-organisms which require
high phosphorus in the presence of carbon and nitrogen, to meet their
narrow C:P and N:P ratios of 20:1 and 3:1 respectively. Walker (65)

TABLE V

CARBON, NITROGEN AND ORGANIC PHOSPHORUS RATIOS
IN SOME OKLAHOMA SOIL PROFILES

Lab. No.	Depth Inches	Horizon	C:N	C:P	N:P	C:N:P
		Carey Silt Loam				
61-S-79	0-12	A_1	11.20	66.9	6.2	67:6:1
61-S-80	12-22	B_{21}	10.37	31.1	3.2	31:3:1
61-S-81	22-38	B_{22}	9.20	23.1	2.7	23:3:1
61-S-82	28-34	C_1	8.21	18.8	2.2	19:2:1
61-S-83	34-54	C_{ca}	8.67	30.7	3.3	31:3:1
		Hollister Clay Loam				
61-S-73	0-5	A_p	11.33	85.0	7.5	85:8:1
61-S-74	5-11	A_1	11.22	67.3	6.0	67:6:1
61-S-75	11-23	B_2	11.08	89.4	8.2	89:8:1
61-S-76	23-31	B_3	11.86	46.4	3.6	46:4:1
61-S-77	31-44	C_{ca}	10.46	34.7	3.2	35:3:1
61-S-78	44-50	C	7.44	34.7	5.3	35:5:1
		Grant Silt Loam				
3219	0-5	A_p	12.78	73.9	6.1	74:6:1
3220	5-12	A_{12}	10.95	67.0	6.1	67:6:1
3221	12-20	A_3	10.51	57.6	5.6	58:6:1
3222	20-36	B_2	10.02	73.0	7.5	73:8:1
3223	36-48	C	5.90	102.8	16.7	103:17:1
		Norge Sandy Loam				
	0-6	A_p	9.8	38.5	7.7	39:8:1
	6-14	A_{12}	11.6	52.0	6.1	52:6:1
	14-24	B_{2t}	10.4	105.8	7.2	106:7:1
	24-50	C	9.1	68.7	4.8	69:5:1
		Okemah Silt Loam				
2532	0-11	A_1	11.9	60.8	5.1	61:5:1
2533	11-14	B_1	10.3	42.3	4.1	42:4:1
2534	14-20	B_{21}	11.9	58.1	4.9	58:5:1
2545	42-54	C	5.9	18.1	3.1	18:3:1

noted that either a deficiency of sulfur or phosphorus will limit nitrogen fixation by micro-organisms.

Inorganic Phosphorus Fractions

Results indicated that all the forms of phosphorus analyzed were distributed in the 5 soil profiles regardless of soil reaction.

Aluminum phosphate. Aluminum phosphate was very low in all the soils, and within some profiles it was completely absent or present in trace quantities in some horizons. It was most highly accumulated within the surface soils, particularly in the plow depth and it decreased with increase in depth. Its contribution to the total phosphorus content was not appreciable: (Range: 0-6.2%).

Iron phosphate. Like aluminum phosphate, the level of iron phosphate was very low and its contribution to the total phosphorus was rather small except in the Okemah soil where it was substantial. It was totally absent in the calcareous horizons despite the high level of iron oxide. Range of iron phosphate level was from 0.0 ppm in calcareous horizons of the Carey and Hollister soils to 165 ppm in the C horizon of the Okemah soil, and its contribution to total phosphorus ranged from 0% in the calcareous horizons to 25% in the C horizon of Okemah. In the Okemah soil iron phosphate constituted the largest fraction of active inorganic phosphorus.

Calcium phosphate. This constituted a very large portion of total phosphate and the active inorganic fraction. In the calcareous soils it increased with depth. The total amount ranged from 3.75 ppm in C horizon of Norge to 362.50 ppm in C_1 horizon of Carey and its portion of the total phosphate varied from 2.96% in C horizon of Norge to 62.46%

in C_{ca} horizon of Carey.

Occluded phosphate. This was well distributed in all the profiles but remarkably high in Okemah. It ranged from 37.50 ppm in C_{ca} horizon of Carey to 287.50 ppm in C horizon of Okemah, but as a percentage of total phosphorus, the range was from 6.34% in C_1 horizon of Carey to 55.42% in C horizon of Grant. It occurred mainly as reductant soluble iron phosphate and a complex of occluded aluminum and iron phosphate which Chang and Jackson (13) described as barrandite-like.

Reductant soluble iron phosphate. This constituted the larger fraction of the occluded phosphate. With the possible exception of Okemah where it was very high, it was well distributed in all the profiles. Its contribution to total phosphate was low in Carey, but fairly constant in the other soils. In the Reddish Chestnut soils it was concentrated more in the surface soils and decreased with increased depth, but in the Reddish Prairie and Prairie soils it tended to be higher in the lower horizons. It ranged from 39.38 ppm in the plow layer of Norge to 236.25 ppm in the C horizon of Okemah, and its percentage of total phosphorus varied from 4.97% in the C_1 horizon of Carey to 49.88% in the C horizon of the Grant soil.

Occluded aluminum phosphate. This was not important in any of the soils. It was mostly absent and where it occurred it tended to be concentrated in the C horizon.

Occluded aluminum-iron phosphate complex. Occluded aluminum phosphate occurred mainly as a complex. It was low for all soils, but was quite appreciable in Okemah profile. In the calcareous soils it was concentrated in the surface soils and decreased with increased

depth, while in the rest of the profiles it tended to concentrate in the subsurface and deeper horizons.

From the results of the analyses, it was found that organic phosphorus contributed most to the total phosphorus reserve with an average value of 42%. Occluded phosphate and calcium phosphate contributed about evenly to the total phosphorus: occluded phosphate 28% and calcium phosphate 25%. Iron phosphate and aluminum phosphate contributed very little to total phosphorus, the average values being 4% and 2% respectively. In the surface soils organic phosphate contributed most to total phosphorus followed by occluded phosphate and calcium phosphate. The contribution of iron phosphate and aluminum phosphate was small: (Organic phosphate 46%, $Oc-PO_4$ 25%, $Ca-PO_4$ 20%, $Fe-PO_4$ 6%, $Al-PO_4$ 3%). In the subsurface soil layers the contribution of the various phosphorus forms showed again organic phosphate was dominant followed by occluded phosphate and calcium phosphate. Iron phosphate contributed little while the aluminum phosphate contribution was negligible: (O.P. 44%, $Oc-PO_4$ 28%, $Ca-PO_4$ 21%, $Fe-PO_4$ 5%, $Al-PO_4$ <1%).

Among the individual profiles the relationships of the various forms of phosphorus were as follows:

Carey: $Ca-PO_4 > O.P > Oc-PO_4 > Al-PO_4 > Fe-PO_4$.

Hollister: $O.P. > Oc-PO_4 > Ca-PO_4 > Fe-PO_4 > Al-PO_4$.

Grant: $O.P. > Oc-PO_4 > Ca-PO_4 > Fe-PO_4 > Al-PO_4$.

Norge: $O.P. > Oc-PO_4 > Fe-PO_4 > Ca-PO_4 > Al-PO_4$.

Okemah: $O.P. > Oc-PO_4 > Fe-PO_4 > Ca-PO_4 > Al-PO_4$.

O.P. = organic phosphates, $Oc-PO_4$ = occluded phosphates, $Al-PO_4$ = aluminum phosphates, $Fe-PO_4$ = iron phosphates, $Ca-PO_4$ = calcium phosphates.

The dominance of occluded phosphate over each of the inorganic forms was not expected in the soils of Reddish Chestnut and Reddish Prairies. Possibly the cause was geological, occluded phosphate being inherited directly from the parent material. This will be discussed in full in the next chapter on soil weathering. The manner of distribution of active phosphate fractions which will influence the determination of available phosphorus is shown in Table VI.

Therefore any chemical extractant that would extract $Ca-PO_4$ selectively would best give indication of available phosphorus for Carey, Hollister and Grant. In Norge any chemical extractant that would dissolve the 3 phosphate fractions selectively would give the best indication of the available phosphorus of the soil. For Okemah the best test extractant should be one that will dissolve $Ca-PO_4$ and $Fe-PO_4$ selectively. The chemical extractant can be determined from experiments or from the findings of Chang and Juo (15).

TABLE VI

FORMS OF PHOSPHATES AS PERCENTAGE OF
TOTAL ACTIVE PHOSPHATES

Soil Profile	$Al-PO_4$ %	$Fe-PO_4$ %	$Ca-PO_4$ %
Carey Silt Loam	7.60	6.36	85.86
Hollister Clay Loam	14.46	16.97	67.80
Grant Silt Loam	9.96	9.01	81.02
Norge Sandy Loam	21.29	38.73	39.39
Okemah Silt Loam	4.06	74.21	21.72

Soil Phosphorus Forms and Soil Genesis

Chang and Jackson (14) have postulated that the degree of, or the stage of weathering of a soil can be determined by the relative percentages of the discrete phosphorus forms, and that the sequence of chemical weathering is in the order: $Ca-PO_4--Al-PO_4--Fe-PO_4--Oc-PO_4$. The B horizons of the profiles were investigated because the B horizon best represents the stage of development or weathering of a mature soil. The results of the analysis of the distribution of inorganic soil phosphate are shown in Table VII. Applying the "Chang and Jackson" postulation, results indicated that the soils ranged from weakly weathered to highly weathered soils. Carey silt loam represented a soil not strongly weathered, Grant, Norge and Okemah represented soils more strongly weathered, while Hollister represented a moderately weathered soil. The relative percentages of the discrete phosphorus forms of the total inorganic phosphate are shown in Table VIII and the graphs of percentage of chemical forms of inorganic soil phosphorus plotted as a chemical weathering sequence shown in Figures I and II.

Two explanations are possible for the relatively high level of occluded phosphate in the profiles of the Reddish-Chestnut and Reddish Praiire soils. 1. It could be a result of weathering activities considering the climate of Oklahoma in which they are found. Results from other places might strengthen this point. Data from Chang and Jackson (14) for a Dewey A_2 horizon, a podzolic soil developed from calcareous material showed

TABLE VII

DISTRIBUTION OF INORGANIC SOIL PHOSPHORUS FORMS AS A
PERCENTAGE OF THE TOTAL INORGANIC PHOSPHATE

Lab. No.	Depth Inches	Horizon	$Al-PO_4$ %	$Fe-PO_4$ %	$Ca-PO_4$ %	$Oc-PO_4$* %	Added Total Inorganic P p.p.m.
			Carey Silt Loam				
61-S-79	0-12	A_1	5.66	4.74	63.24	26.35	237.19
61-S-80	12-22	B_{21}	1.23	1.89	77.87	18.99	329.06
61-S-81	22-28	B_{22}	0.97	0.00	81.02	18.00	416.56
61-S-82	28-34	C	1.00	0.00	89.71	9.28	404.06
61-S-83	34-54	C_{ca}	1.12	0.00	88.46	10.40	360.31
			Hollister Silt Loam				
61-S-73	0-5	A_p	8.34	9.23	36.23	49.73	175.94
61-S-74	5-11	A_1	7.72	9.65	40.15	42.46	161.88
61-S-75	11-23	B_2	1.64	3.29	32.90	62.15	170.95
61-S-76	23-31	B_3	1.62	2.53	49.76	46.07	135.64
61-S-77	31-44	C_{ca}	0.00	1.03	57.72	41.24	121.26
61-S-78	44-50	C	0.94	0.00	57.08	41.97	148.91
			Grant Silt Loam				
3219	0-5	A_p	9.86	7.23	56.57	26.31	190.00
3220	5-12	A_{12}	4.15	5.22	54.28	36.33	179.61
3221	12-20	A_3	1.52	3.72	47.37	47.37	184.69
3222	20-36	B_2	1.51	3.43	30.59	64.45	145.45
3223	36-48	C	3.33	6.40	18.46	71.79	121.87
			Norge Sandy Loam				
	0-6	A_p	8.48	16.97	8.49	66.04	66.26
	6-14	A_{12}	3.58	5.58	11.15	79.68	78.45
	14-24	B_{2t}	2.20	8.80	10.76	78.22	63.93
	24-50	C	0.00	9.47	6.31	84.20	59.39
			Okemah Silt Loam				
2532	0-11	A_1	1.54	28.22	8.26	61.96	181.56
2533	11-14	B_1	0.00	16.88	9.05	74.09	151.83
2534	14-20	B_{21}	0.00	19.99	13.33	66.66	112.51
2545	42-54	C	0.28	33.07	9.01	57.62	498.91

* Total occluded phosphate

TABLE VIII

PHOSPHORUS FORMS OF THE SOILS AS PERCENTAGE
OF TOTAL INORGANIC PHOSPHATE

Soil	$Al\text{-}PO_4$	$Fe\text{-}PO_4$	$Ca\text{-}PO_4$	$Oc\text{-}PO_4$
Carey Silt Loam	1.0	0.9	79.0	19.0
Hollister Clay Loam	2.0	3.0	41.0	54.0
Grant Silt Loam	1.5	3.0	31.0	65.0
Norge Sandy Loam	2.0	9.0	11.0	78.0
Okemah Silt Loam	0.0	18.0	11.0	70.0

100

80
          Carey Silt Loam
            B Horizon

60

40

20

100   0

80
          Hollister Clay Loam
            B Horizon

60

40

20

0
    Ca-PO$_4$ Al-PO$_4$ Fe-PO$_4$ Oc-PO$_4$

Percentage of each phosphorus form of the total inorganic soil phosphate

Chemical forms of inorganic soil phosphate

Figure 1. The percentage of the chemical forms of inorganic soil
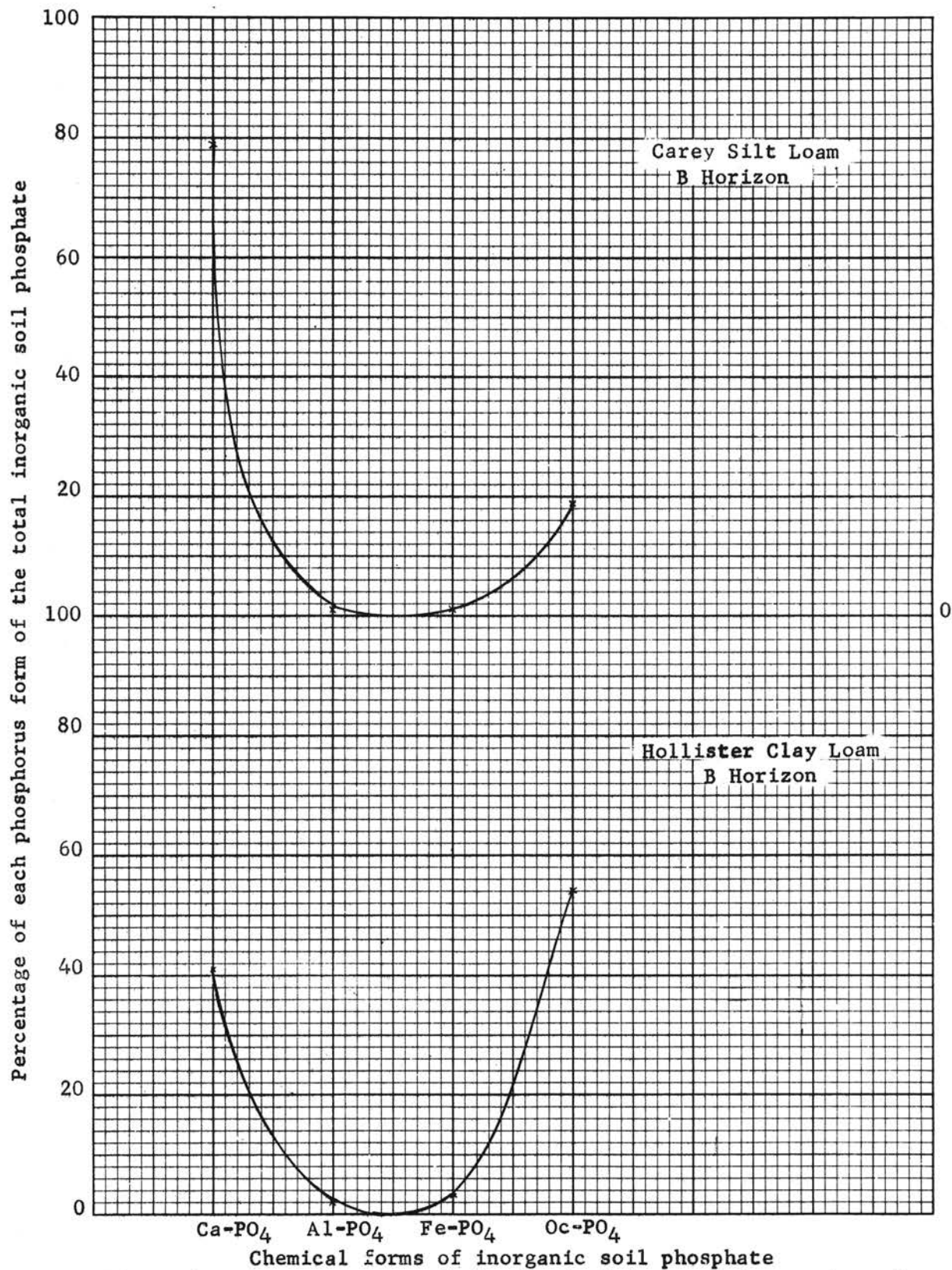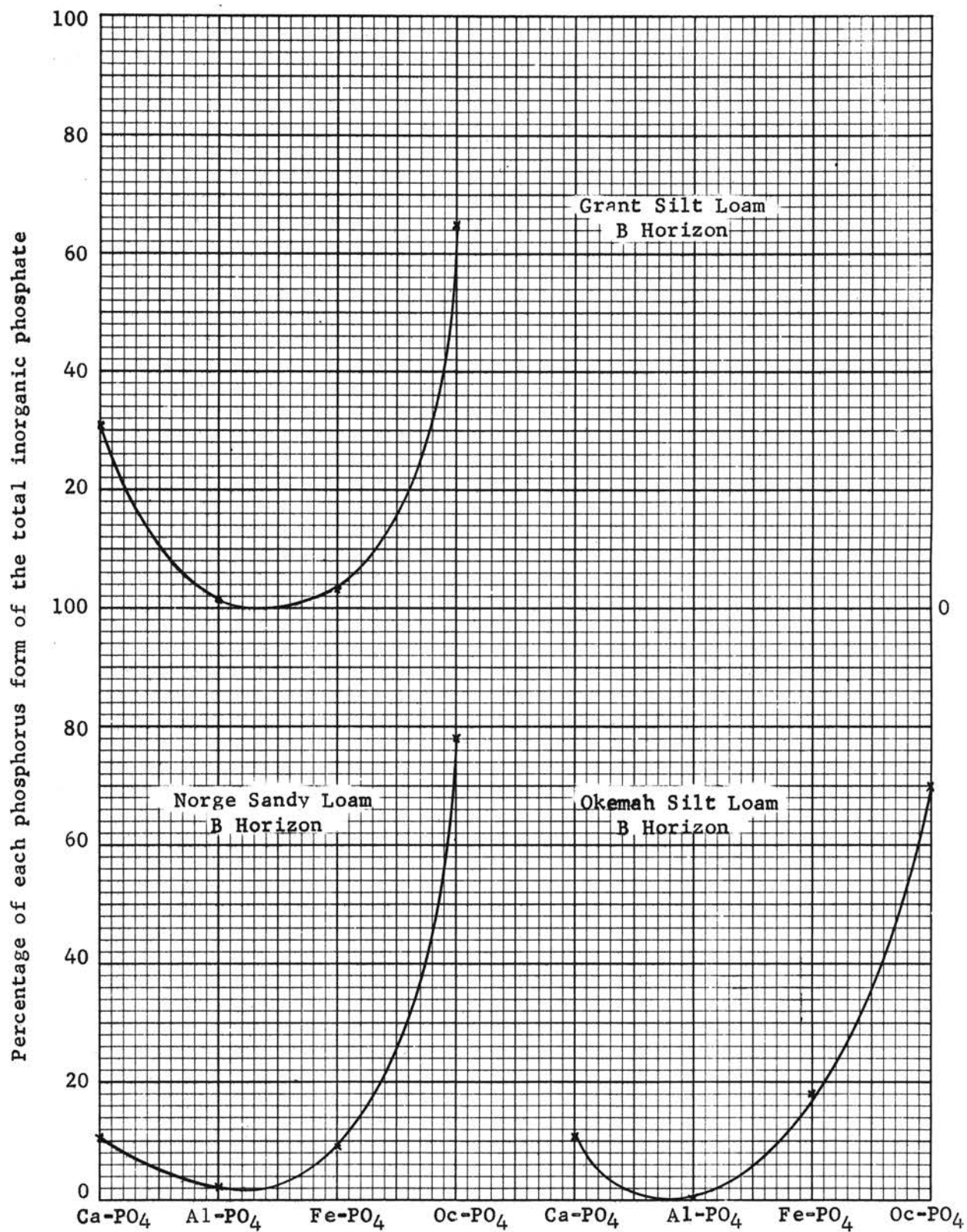phosphate plotted as a chemical weathering sequence

Figure 2. The percentage of the chemical forms of inorganic soil phosphate plotted as a chemical weathering sequence

occluded phosphate dominant over each of the other inorganic phosphorus
forms. Miami silt loam (a grey brown podzol) and Scott (ground water podzol)
were both derived from calcareous material and showed intermediate weathering.
Therefore the results could be comparable although these soils are mostly
podzolic. On the other hand the occluded phosphate might have been derived
directly from the parent material. Weathering or soil development might
not have been wholly responsible considering the fact that the quantities
of iron or aluminum phosphates were very low or even absent in the B-horizon
of some of the soils (unlike the Okemah where $Fe-PO_4$ was substantial although
for other reasons $Al-PO_4$ was absent). The reports of Molthan and Gray (52)
showed two soils usually considered similar, arising from the Permain redbed
and belonging to Reddish Prairies had all of their clay unaltered with
little evidence of weathering. They postulated that the clay minerals were
possibly inherited directly from the clay minerals in the parent material.
One of their profiles had a higher level of total phosphorus because the
Permain redbed close to the gypsiferous deposits of the retreating Permian
sea in Weatern Oklahoma is rich in phosphorus.[2] Permain redbeds contain
much iron oxide, therefore a question might be raised; whether the occluded
phosphate had not been formed long before soil development (possibly by
a slow process) in the parent material and was inherited directly as a
part of the clay. Some of the soils like Carey, Grant and Hollister were
developed on Permian redbeds rich in phosphorus but the Norge soil was
not. This might also account for the low phosphorus level of Norge. There-
fore it is possible that the occluded phosphate of these soils excepting

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[2] Fenton Gray - private communication.

Norge and Okemah was not mainly a result of soil development or soil weathering but mostly inherited directly from the parent material.

The problem needs more investigation, first to determine the type of clay minerals in these soils, and to investigate whether other profiles derived from Permian redbeds rich in phosphorus contained high or reasonable levels of occluded phosphate even in soils known to be young. If the latter was applicable, then the "Chang and Jackson" postulation should be modified to accomodate a situation where clay materials rich in iron oxide and phosphorus, and shown to contain occluded phosphate, is derived directly from the parent material and not a product of weathering in the course of soil development.

<div align="center">Chemical Distribution of Water Soluble
Phosphate Applied to the Soil</div>

Results of the chemical distribution of water soluble phosphate applied to the soil, for 3 and 30 days are shown in Tables IXa-e and Xa-e respectively. Results showed that in 3 and 30 days the water soluble phosphate was retained as phosphate soluble in NH_4Cl or "saloid bound" phosphate, aluminum phosphate, iron phosphate and calcium phosphate. There was a great increase in the level of saloid bound phosphate and aluminum phosphate in the native soil phosphorus. A large portion of the applied phosphate was retained as aluminum phosphate. In the Carey soil, the applied phosphate was retained mostly as "saloid bound" phosphate with aluminum phosphate and calcium phosphate about equal in quantity. In the Hollister, Grant and Norge soils, the applied phosphate was retained mostly as aluminum phosphate while in Okemah it was retained mostly as iron phosphate. Results are shown in Table XI. The average total percentage

TABLE IXa

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS
KH_2PO_4 FROM SOIL HELD AT FIELD
CAPACITY FOR THREE DAYS

			Carey Silt Loam		
Lab. no.	61-S-79	61-S-80	61-S-81	61-S-82	61-S-83
Depth inches	0-12	12-22	22-28	28-34	34-54
Horizon	A_1	B_{21}	B_{22}	C_1	C_{ca}
pH paste	6.40	7.10	7.50	7.60	7.55
pH 1:1 KCl	5.80	6.60	6.95	7.20	7.10
Net increase of P in each form in ppm "saloid bound"					
PO_4	85.00	65.00	100.00	100.00	117.50
$Al-PO_4$	89.06	93.44	52.19	39.69	49.69
$Fe-PO_4$	17.50	33.75	0.00	0.00	0.00
$Ca-PO_4$	6.25	43.75	100.00	87.50	93.70
Total phosphorus recovered ppm	197.81	235.94	252.19	227.19	260.89
% phosphorus recovery	98.90	117.97	126.09	113.59	130.44
Bray #1 available phosphorus ppm	194.00	167.00	0.00	0.00	0.50
% rendered "fixed"	3.00	16.50	100.00	100.00	99.75

TABLE IXb

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS
KH_2PO_4 FROM SOIL HELD AT FIELD
CAPACITY FOR THREE DAYS

	Hollister Clay Loam					
Lab. no.	61-S-73	61-S-74	61-S-75	61-S-76	61-S-77	61-S-78
Depth inches	0-5	5-11	11-23	23-31	31-44	44-50
Horizon	A_p	A_1	B_2	B_3	C_{ca}	C
pH paste	6.40	6.10	6.60	7.10	7.20	7.40
pH 1:1 KCl	5.50	5.45	5.90	6.40	6.90	6.90
Net increase of P in each form in ppm "saloid bound"						
PO_4	57.50	50.00	17.50	32.50	42.50	57.50
$Al-PO_4$	114.06	116.25	125.94	121.55	102.50	84.84
$Fe-PO_4$	23.75	26.87	39.37	41.56	38.75	21.25
$Ca-PO_4$	16.25	8.75	6.25	0.00	15.00	22.50
Total phosphorus recovered ppm	211.56	201.87	189.06	195.61	198.75	186.09
% phosphorus recovery	105.78	100.93	94.53	97.80	99.37	93.04
Bray #1 available phosphorus ppm	190.00	165.00	158.50	159.50	145.50	143.00
% rendered "fixed"	5.00	17.50	20.75	20.25	27.25	28.50

TABLE IXc

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS
KH_2PO_4 FROM SOIL HELD AT FIELD
CAPACITY FOR THREE DAYS

	Grant Silt Loam				
Lab. no.	3219	3220	3221	3222	3223
Depth inches	0-5	5-12	12-20	20-36	36-48
Horizon	A_p	A_{12}	A_3	B_2	C
pH paste	6.20	5.90	6.35	6.88	7.10
pH 1:1 KCl	5.40	5.20	5.60	6.00	6.20
Net increase of P in each form in ppm "saloid bound"					
PO_4	75.00	60.00	53.75	23.75	25.00
$Al-PO_4$	105.00	116.28	115.94	136.55	145.94
$Fe-PO_4$	15.00	19.37	20.62	28.75	29.69
$Ca-PO_4$	17.50	17.50	7.50	0.50	0.00
Total phosphorus recovered ppm	212.50	213.15	197.81	189.55	200.63
% phosphorus recovery	106.25	106.57	98.90	94.77	100.31
Bray #1 available phosphorus ppm	189.00	166.00	156.00	158.50	163.00
% rendered "fixed"	5.50	17.00	22.00	20.75	18.50

TABLE I Xd

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS KH$_2$PO$_4$ FROM SOIL HELD AT FIELD CAPACITY FOR THREE DAYS

Norge Sandy Loam

Lab. no. Depth inches Horizon	0-6 A$_p$	6-14 A$_{12}$	14-24 B$_{2t}$	24-52 C
pH paste	6.60	5.50	5.60	5.60
pH 1:1 KCl	6.15	4.90	4.90	5.00
Net increase of P in each form in ppm				
"saloid bound" PO$_4$	47.50	22.50	10.00	23.75
Al-PO$_4$	118.13	158.44	148.59	133.75
Fe-PO$_4$	20.00	33.12	41.87	31.87
Ca-PO$_4$	8.12	6.25	6.87	13.75
Total phosphorus recovered ppm	193.75	220.31	207.33	203.12
% phosphorus recovery	96.87	110.15	103.66	101.56
Bray #1 available phosphorus ppm	147.00	158.50	143.00	165.50
% rendered "fixed"	26.50	20.75	28.50	17.25

TABLE IXe

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS
KH_2PO_4 FROM SOIL HELD AT FIELD
CAPACITY FOR THREE DAYS

Okemah Silt Loam				
Lab. no.	2532	2533	2534	2545
Depth inches	0-11	11-14	14-20	42-54
Horizon	A_1	B_1	B_{21}	C
pH paste	5.20	4.80	4.50	5.00
pH 1:1 KCl	4.80	4.20	3.80	4.30
Net increase of P in each form in ppm "saloid bound"				
PO_4	10.00	0.00	0.00	0.00
$Al-PO_4$	88.44	70.00	48.75	31.09
$Fe-PO_4$	104.00	115.00	118.13	260.00
$Ca-PO_4$	5.00	0.00	0.00	0.00
Total phosphorus recovered ppm	207.44	185.00	166.88	291.09
% phosphorus recovery	103.72	92.50	83.44	145.54
Bray #1 available phosphorus ppm	83.00	61.50	52.00	16.50
% rendered "fixed"	58.50	69.25	74.00	91.75

TABLE Xa

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS KH_2PO_4 FROM
SOIL HELD AT FIELD CAPACITY FOR THIRTY DAYS

Carey Silt Loam

Lab. no.	61-S-79	61-S-80	61-S-81	61-S-82	61-S-83
Depth inches	0-12	12-22	22-28	28-34	34-54
Horizon	A_1	B_{21}	B_{22}	C_1	C_{ca}
pH 1:1 KCl	5.80	6.70	7.10	7.20	7.20
Net increase of P in each form in ppm					
"saloid bound" PO_4	72.50	61.30	92.50	92.50	100.00
$Al-PO_4$	99.06	87.19	44.70	39.69	49.69
$Fe-PO_4$	16.25	25.00	0.00	0.00	0.00
$Ca-PO_4$	6.25	43.75	112.50	87.50	91.25
Total phosphorus recovered ppm	194.06	217.24	249.70	219.69	240.94
% phosphorus recovery	97.03	108.62	124.85	109.84	120.47

TABLE **Xb**

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS KH_2PO_4 FROM
SOIL HELD AT FIELD CAPACITY FOR THIRTY DAYS

	Hollister Clay Loam					
Lab. no.	61-S-73	61-S-74	61-S-75	61-S-76	61-S-77	61-S-78
Depth inches	0-5	5-11	11-23	23-31	31-44	44-50
Horizon	A_p	A_1	B_2	B_3	C_{ca}	C
pH 1:1 KCl	5.40	5.30	5.70	6.50	6.80	6.90
Net increase of P in each form in ppm.						
"saloid bound" PO_4	40.00	35.00	11.30	22.50	32.50	50.00
$Al-PO_4$	119.06	116.25	125.94	121.55	102.50	84.84
$Fe-PO_4$	26.25	29.40	39.37	36.56	32.50	20.00
$Ca-PO_4$	16.25	8.75	6.25	7.50	32.50	50.00
Total phosphorus recovered ppm	201.56	189.40	182.86	188.11	200.00	204.84
% phosphorus recovery	100.78	94.70	91.43	94.06	100.00	102.42

TABLE Xc

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS KH_2PO_4 FROM
SOIL HELD AT FIELD CAPACITY FOR THIRTY DAYS

			Grant Silt Loam		
Lab. no.	3219	3220	3221	3222	3223
Depth inches	0-5	5-12	12-20	20-36	36-48
Horizon	A_p	A_{12}	A_3	B_2	C
pH 1:1 KCl	4.80	5.10	5.40	6.20	6.30
Net increase of P in each form in ppm					
"saloid bound" PO_4	50.00	44.00	43.80	20.00	22.50
$Al-PO_4$	105.00	116.00	116.00	121.50	134.69
$Fe-PO_4$	15.00	20.00	20.62	32.50	37.19
$Ca-PO_4$	17.50	27.50	12.50	10.50	5.50
Total phosphorus recovered ppm	187.50	207.50	192.92	184.50	199.88
% phosphorus recovery	93.75	103.75	96.46	92.25	99.94

TABLE Xd

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS KH_2PO_4 FROM
SOIL HELD AT FIELD CAPACITY FOR THIRTY DAYS

	Norge Sandy Loam			
Lab. no. Depth inches Horizon	0-6 A_p	6-14 A_{12}	14-24 B_{2t}	24-52 C
pH 1:1 KCl	5.55	4.80	4.80	4.80
Net increase of P in each form in ppm				
"saloid bound" PO_4	40.00	15.00	7.50	22.50
$Al-PO_4$	118.13	153.20	144.60	133.75
$Fe-PO_4$	24.00	35.00	43.87	30.37
$Ca-PO_4$	8.00	6.25	6.50	13.50
Total phosphorus recovered ppm	190.13	209.45	202.47	200.12
% phosphorus recovery	95.06	104.73	101.24	100.06

TABLE Xe

RETENTION OF 200 PPM OF PHOSPHORUS ADDED AS KH_2PO_4 FROM
SOIL HELD AT FIELD CAPACITY FOR THIRTY DAYS

Okemah Silt Loam				
Lab. no.	2532	2533	2534	2545
Depth inches	0-11	11-14	14-20	42-54
Horizon	A_1	B_1	B_{21}	C
pH 1:1 KCl	4.45	4.30	3.85	4.35
Net increase of P in each form in ppm				
"saloid bound"				
PO_4	6.30	Trace	0.00	0.00
$Al-PO_4$	83.50	70.00	50.13	31.09
$Fe-PO_4$	96.50	120.62	122.00	255.00
$Ca-PO_4$	5.00	0.00	0.00	0.00
Total phosphorus recovered ppm	191.30	190.62	172.13	286.09
% phosphorus recovery	95.65	95.31	86.06	143.05

TABLE XI

PERCENTAGE OF ADDED WATER SOLUBLE PHOSPHATE RETAINED
BY EACH PHOSPHORUS FORM AFTER 3 DAYS

Soil	"Saloid bound" - PO_4	$Al\text{-}PO_4$	$Fe\text{-}PO_4$	$Ca\text{-}PO_4$
Carey Silt Loam	39.82	27.60	4.36	28.21
Hollister Clay Loam	21.76	56.22	16.19	5.81
Grant Silt Loam	23.43	61.14	11.19	4.24
Norge Sandy Loam	12.58	67.78	15.38	4.24
Okemah Silt Loam	1.17	28.01	70.20	0.58

of the applied phosphate retained by each chemical form is: aluminum
phosphate 48.15, iron phosphate 23.46, saloid bound phosphate 19.75,
calcium phosphate 8.62.

There was no appreciable difference between the net increase in retained
phosphate in 3 days and 30 days. This period was very short for the trans-
formation of phosphate from one form to another.

pH: There was a general drop in pH level after application of the
water soluble phosphate but the pH remained about the same after 3 and 30
days. The pH comparisons were made in N KCl.

Phosphate recovered: Results showed that after 3 and 30 days it was
possible to recover all of the applied phosphate in the phosphorus forms
discussed. In most samples, the percentages of the phosphate recovered
exceeded that applied. This had also been observed by other workers
(45, 64). There are four probable causes:

1. Some occluded phosphate might have been solubilized, but this is
not very likely since reports of Chang and Jackson (14) showed that
fertilizers have no effect on the amount of occluded phosphate.

2. Organic phosphorus might have been mineralized. However, no lime
was applied to the acid soils and there was therefore no stimulation of
microbial activiiies, and the time was too short to produce any appreciable
amount of phosphorus from the organic phosphorus.

3. Inherent errors associated with colorimetric techniques. Where
"tracer techniques" were used for a similar investigation, the recovered
phosphorus had remained lower than that by colorimetric technique (64).

4. The most likely reason is the difference in solubilities between
freshly formed phosphate compounds and the more aged cyrstalline native

phosphorus compounds in the soil.

There was little or no increase in the calcium phosphate when soils were treated with water soluble phosphate as had been reported be several workers (12, 13, 74). Chang and Chu (12) reported this even for calcareous soils. When water soluble phosphate is applied to the soil, the first stage of the phosphate fixation is governed more by surface energy of the solid phases associated with aluminum, iron and calcium rather than the ionic activities of aluminum, iron and calcium ions in the soil solution (12). Since clay is the main site of phosphate fixation and the content of aluminum in clay is much higher than either iron or calcium, water soluble phosphorus added to the soil is likely to be retained more as aluminum phosphate than iron phosphate or calcium phosphate at the initial stage.

Forms of Phosphorus Compounds and Available Phosphorus

The correlation analysis between available phosphorus determined by Bray's #1 method and the forms of phosphorus in the surface soils of the profiles is shown in Table XII.

Results showed that by Bray's #1 method, aluminum phosphate and calcium phosphate were associated with the available phosphorus but aluminum phosphate more significantly. Organic phosphate and iron phosphate did not contribute to available phosphorus.

After the water soluble phosphate was applied to the soil it was retained mostly as aluminum phosphate and saloid bound phosphate in the surface soils. If the relative amounts and the quantities of the active phosphorus forms indicate their relative availabilities to plants (though

TABLE XII

CORRELATION BETWEEN FORMS OF PHOSPHORUS AND
BRAY'S #1 AVAILABLE PHOSPHORUS

Forms of Phosphorus	Correlation Coefficient	Remarks
Aluminum phosphate	$\neq$ 0.8347	Significant at 1% level
Iron phosphate	- 0.0946	No correlation
Calcium phosphate	$\neq$ 0.2848	Not significant
Organic phosphate	- 0.0045	No correlation

availability is largely governed by the specific surface area), then
aluminum phosphate and saloid bound phosphate would form the main reserve
of available phosphorus in the surface soils. However, reaction time
studied should be followed by a very long reaction interval in an effort
to check on further changes in quantities of phosphate compounds. The
use of Bray's #1 as a selective extractant for available phosphorus in
these soils needs more investigation since it is the distribution pattern
of phosphorus forms that would indicate the suitable soil test extractant
for available phosphorus. Chang and Juo (15) observed that in soils
dominated by calcium phosphate, the available phosphorus determined by
Bray's #1 was highly correlated with aluminum phosphate and considerably
less with calcium phosphate and iron phosphate. In soils dominated by
calcium phosphate and iron phosphate, Bray's #1 available phosphorus was
more significantly correlated with aluminum phosphate and much less with
iron phosphate and least with calcium phosphate. Only in soils dominated
by iron phosphate was there a high correlation between Bray's #1 available
phosphorus and calcium phosphate or iron phosphate.

SUMMARY AND CONCLUSION

The main objective of this research was to fractionate soil phosphorus
of five soil profiles of Oklahoma into chemical compounds and determine
the relative amounts and the distribution of these compounds in the soils.
Other investigations included the stage of soil weathering according to
the relative amounts and the distribution of the phosphorus compounds in
the soil, chemical distribution of water soluble phosphate applied to
the soil, and forms of phosphorus in relation to available phosphorus.

A modified Chang and Jackson method was employed and the soil phosphorus
compounds fractionated into aluminum phosphate, iron phosphate, calcium
phosphate, occluded phosphate, and organic phosphate. Total phosphorus
was higher in the surface soils than in the subsurface soils. With the
possible exception of Norge Sandy Loam, all soils investigated were high
in total phosphorus. Organic phosphorus decreased with depth. About 42%
of the total phosphorus was organic phosphorus. This was the largest
individual phosphorus form contributing to total phosphorus. It was
concentrated in the surface soils of all profiles. The average C:N:P
ratio for all horizons of all soil profiles was 56:6:1.

Aluminum phosphate and iron phosphate were of little importance and
contributed 2% and 4% respectively to the total phosphorus. Aluminum
phosphate was accumulated most in the plow layer of all the soils.
Calcium phosphate contributed about 25% of the total phosphorus and it
was highest in the Carey, Hollister and Grant soil profiles. Occluded

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phosphate was present mainly as reductant soluble iron phosphate and a complex of occluded aluminum-iron phosphate. It was high in all profiles. It contributed about 28% of the total phosphate and was next in rank to organic phosphate and about equal to calcium phosphate. Calcium phosphate dominated the active phosphate fractions.

The soils ranged from weakly weathered to strongly weathered soils with Carey Silt Loam representing the weakly weathered profile. Hollister Clay Loam was moderately weathered, Grant Silt Loam more than moderately weathered but not as strongly weathered as Norge Sandy Loam and Okemah Silt Loam.

It was possible to recover in 3 and 30 days all of the applied water soluble phosphate as aluminum phosphate, iron phosphate, calcium phosphate and "saloid bound" phosphate. The application of water soluble phosphate greatly increased the level of aluminum phosphate and saloid bound phosphate in the soil. Aluminum phosphate and calcium phosphate contributed to the available phosphorus in the surface soils, as determined by Bray's #1 method. Iron phosphate and organic phosphates were not important. Aluminum phosphate and saloid bound phosphate constituted the main supply of available phosphorus in the surface soil after application of water soluble phosphate in 30 days.

While it was not possible to fractionate the soil phosphorus compounds into chemically discrete forms by the Chang and Jackson method, it was possible to fractionate them into general compounds of aluminum, iron and calcium and these were present in all the soils regardless of soil reaction. The relative amounts and the distribution pattern of phosphorus forms in the soil can be of great help in studies related to soil chemistry, soil genesis and soil fertility.

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APPENDIX

CAREY SERIES

Field Description[1]

1. Plot near Custer, Oklahoma. Wheat.

A_1 0-12"   Dark reddish brown (5 YR 3/3 moist) silt loam, moderate medium and fine granular structure; friable moist; pH 6.5 (Hellige); gradual boundary.

B_{2-1} 12-22"   Dark reddish brown (2.5 YR 3/4 moist) heavy silt loam; moderate medium granular; friable moist; many worm casts and roots; pH 7.0, noncalcareous; gradual boundary.

B_{2-2} 22-28"   Dark red (2.5 YR 3/6 moist) light silty clay loam; weak medium prisms separating easily to moderate medium granules; slightly firm moist; hard when dry; few faint films and organic stains on ped faces; many worm casts and roots; pH 7.0, noncalcareous; clear boundary.

C_1 28-34"   Red (2.5 YR 4/6 moist) silt loam; weak medium granular; friable moist; calcareous, with few streaks and blotches of segregated lime; gradual boundary.

C_{ca} 34-54"   Similar to above; porous massive; strongly calcareous with 5-10% lime concretions. This horizon rests on a slightly heavier and darker (buried) layer, not sampled.

Remarks: This is modal Carey silt loam.

Great Soil Group: Reddish Chestnut.

Parent Material: Calcareous permeable sandy Permian redbeds.

Topography: Very gently sloping convex surfaces in erosion upland. Gradient 1-3%.

Drainage: Well drained on surface and internally.

Vegetation: Coarse bunch grasses, mainly little bluestem; some gama grasses.

Use: Very largely in cultivation to cotton, sorghums and small grains. Moderately to highly productive.

Distribution: Western Oklahoma east of the High Plains.

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[1] Description by Roy M. Smith

HOLLISTER CLAY LOAM

0-1% slopes

Sample S63-OK-33-1-1

A$_p$ 0-8"
Very dark grayish brown (10 YR 3/2) clay loam, dark yellowish brown (10 YR 4/4) dry; weak medium granular; friable moist, slightly hard dry; pH 8.0; clear boundary.

Sample S63-OK-33-1-2

B$_1$ 8-13"
Dark brown (7.5 YR 3/2) light clay, brown (7.5 YR 4/2) dry; moderate medium blocky; very firm moist, hard when dry; small lime concretions; weakly calcareous; pH 8.0; gradual boundary.

Sample S63-OK-33-1-3

B$_{2t-1}$ 13-28"
Dark brown (7.5 YR 3/2) clay, brown (7.5 YR 4/2) dry; weak medium and coarse blocky; very firm moist, hard when dry; calcareous; pH 8.0; gradual boundary.

Sample S63-OK-33-1-4

B$_{2t-2}$ 28-34"
Dark reddish brown (5 YR 3/3) clay, reddish brown (5 YR 4/3) dry; weak medium and coarse blocky, few pink granite pebbles and lime concretions present; calcareous in mass; pH 8.0; gradual boundary.

Sample S63-OK-33-1-5

B$_3$ 34-54"
Dark reddish brown (5 YR 3/3) clay loam, reddish brown (5 YR 4/3) dry; massive; calcareous; pH 8.0.

Location: Altus Irrigation Station Oklahoma.

Great Soil Group: Reddish Chestnut.

Parent Material: Reddish calcareous clay mainly Permian

Topography: Nearly level to very gently sloping with gradients not exceeding 3%, dominantly less than 2%.

Drainage and Permeability: Slow to very slow from surface and internally, but the soil is well drained.

Vegetation: Short grasses mainly buffalo and grama grasses with scattered mesquite trees.

Use: Largely cultivated to oats, wheat, cotton and grain sorghums. Moderately fertile and very productive when moisture is adequate.

Distribution: Rolling plains of Western Oklahoma.

PS: The profile described here is not exactly the profile used in this work, but they come from the same area and have many characteristics in common. Description by Roy Smith and Ben Cunningham.

GRANT SERIES

Field Description[2]

1. From Cherokee Station wheat fertility (long time) tests.

A_p 0-5"   Dark brown (7.5 YR 3/2) coarse silt loam, brown (7.5 YR 4/2) dry; very weakly granular; friable moist, tends to crust or "set up" when dry; pH 6.0 (Hellige); plowed boundary.

A_{12} 5-12"   Dark brown (10 YR 3/3 moist) silt loam; weak medium granular; friable; pH 5.8; gradual boundary.

A_3 12-20"   Dark brown (7.5 YR 3/3 moist) silt loam; moderate medium and fine granular; friable moist; pH 6.5; clear boundary.

B_2 20-36"   Dark reddish brown (5 YR 3/4 moist) light clay loam; weak medium prisms separate to weak subangular blocks; friable to slightly firm moist; pH 7.0; gradual boundary.

C   36-48"   Reddish brown (5 YR 4/4 moist) loam, with few small gravels; porous massive; friable moist; pH 7.5; non-calcareous.

Remarks: This is Grant Silt Loam

Great Soil Group: Reddish Prairie.

Parent Material: Late Pleistocene of loess that originated largely in silty Permian redbeds. Parent material may be calcareous.

Topography: Very gently to moderately sloping erosional uplands; surfaces convex to plane gradients 1-4%.

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[2] Description by Roy Smith

Drainage: Free from the surface and internally.

Vegetation: Originally of tall prairie grasses.

Use: Practically all in cultivation, very largely to winter
                   wheat; very fertile productive and highly valued.

Distribution: N.W. Central Oklahoma.

Remarks: Grant series are submature soils with weak textural
                   profiles developed for the most part in deposits
                   younger than middle Pleistocene. Generally classed
                   as Reddish Prairie but are less acid than typical of
                   that soil; and lack the distinct carbonate zone
                   characteristic of Reddish Chestnut soils.

NORGE SERIES

Field Description

A_p 0-6"   Dark brown (7.5 YR 3/2) light loam or fine sandy loam;
                         brown (7.5 YR 5/4) dry; weak fine granular structure;
                         very friable moist; pH 6.0 (Hellige); clear boundary.

A_{12} 6-14"   Dark brown (7.5 YR 3/2) loam, brown (7.5 YR 4/2) dry;
                         moderate medium granular structure; friable moist;
                         pH 6.0; gradual boundary.

B_{2t} 14-24"   Dark reddish brown (5 YR 3/4) clay loam, reddish brown
                         (5 YR 4/4) dry; weak medium subangular blocky; slightly
                         firm moist; pH 5.5; clear boundary.

C   24-50"   Strong brown (7.5 YR 5/6) fine sandy loam, reddish
                         yellow (7.5 YR 6/6) dry; weak granular, almost structure-
                         less; friable moist; pH 5.5; weakly stratified with
                         browner and slightly heavier lenses.

Location: Perkins Experiment Station, Oklahoma.

Great Soil Group: Reddish Prairie.

Parent Material: Calcareous or alkaline old alluvium.

Topography: Nearly level to gently sloping erosional uplands.
                   Convex with gradients 1-7%.

Drainage: Moderate to rapid from the surface, moderately
                   internally.

Vegetation: Originally coarse grasses mainly little bluestem.

Use: Less sloping lands largely farmed to cotton, corn, sorghum, oats, peanuts and sudan grass; some used for vegetable crops and fruits. Only moderate fertility but very responsive to management; very susceptible to erosion under usual cultural practices.

Distribution: Reddish Prairie sections of Oklahoma.

PS: Description by Roy Smith. He considered B_{2t} quite light textured and thin for Norge, suggested Teller.

OKEMAH SILT LOAM

Soil Description

S63-OK-18-1(5 horizons)

A_1 0-15" Very dark grayish brown (10 YR 3/3) silt loam, grayish brown (10 YR 5/2) dry; weak medium granular structure; friable moist; pH 5.5 (Hellige); gradual boundary.

B_1 15-24" Dark grayish brown (10 YR 4/2) clay loam, brown (10 YR 5/3) dry; common fine distinct strong brown (7.5 YR 5/6) and light brownish gray (10 YR 6/2) mottles; strong medium and coarse granular structure; friable moist, hard when dry; pH 5.0; few small black concretions; clear boundary.

B_{2t} 24-35" Dark gray (10 YR 4/1) clay, gray (10 YR 5/1) dry; many (greater than 20 percent of the soil mass) medium (from 5 to 15 mm. in size) prominent (matrix and mottles vary several units in hue, value and chroma) red (2.5 YR 4/6) and strong brown (7.5 YR 5/6) mottles; moderate medium subangular blocky structure; firm moist, very hard dry; pH 5.0; clear boundary.

B_{31} 35-45" Finely mottled strong brown, grayish brown and gray clay loam; weak medium and coarse subangular blocky structure; friable moist, hard when dry; pH 4.8; many black nodules and concretions; gradual boundary.

B_{32} 45-54" Color and structure similar to the above horizon; clay; firm moist; pH 4.5; many black concretions.

Location: Vinita, Oklahoma out-state test plot.

Great Soil Group: Prairie

Parent Material:	Olive and gray mildly alkaline to slightly calcareous weakly consolidated shales and clays generally of Pennsylvanian origin.
Topography:	Nearly level to gently sloping erosional uplands. Surface weakly convex to planes.
Drainage:	Slow to moderate from the surface.
Vegetation:	Thick cover of tall grass mainly bluestems.
Use:	Mainly cultivated. Principal crops are corn, cotton and small grains. Moderately fertile and productive.
PS:	The profile described here is not exactly the profile used in the experiments but they come from the same area and have many characteristics in common. Description by Roy M. Smith and Ben Cunningham.

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