Generating productive topsoil substitutes from hard rock overburden in the Southern Appalachians

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ABSTRACT

Natural soils on steeply sloping landscapes in the Appalachian coal fields of Virginia, West Virginia, Kentucky, and Tennessee are often thin, rocky, acidic and infertile, making the topsoiling of surface mined sites impractical in many cases. Topsoil substitutes composed of blasted rock fragments are commonly used in this region. The proper selection and placement of designated topsoil substitutes is therefore critical to long term reclamation success. These mine soil surfaces are not in equilibrium and with the surface environment, and it is quite difficult to diferentiate among dissolution, adsorption, desorption and precipitation reactions as these surfaces weather with time. Severe compaction limits the productivity of many otherwise suitable topsoil substitutes. A minimum non-compacted thickness of 1 m is desirable to insure long run mine soil productivity for a variety of post-mining land uses. Significant changes in the physical, chemical, and mineralogical properties of mine soils occur within one year after placement. Mine soils high in silt content often form hard vesicular surface crusts, particularly when left unvegetated. The long term survival of plant communities on these mine soils is dependent upon mine soil organic matter accumulation and N and P cycling. Little is currently known about N and P dynamics in these mine soils, but P-fixation is a profound problem in high Fe^{3+} spoils. Revegetation practices that were designed to meet 2-year bond release requirements may not be sufficient to meet new 5-year release standards. Hard rock derived mine soils can often equal or exceed native topsoil in productivity and post mining land use potential.

INTRODUCTION

Steeply sloping topography and hard, resistant, flat lying parent materials have led to shallow natural soils over much of the southern Appalachian coal fields. Deposits of colluvium in toe slope positions and heads of drainageways may be quite deep, but overall the natural soils tend to be thin, rocky, acidic, and infertile. It is usually quite difficult to separate the topsoil (A + E horizon) from underlying B, C or CR horizons before mining, and as a result the material used as topsoil is a composite of these various horizons. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 allows for the use of overburden strata as topsoil substitutes when it can be shown that the physical and chemical properties of the substitute material are at least as suitable as the natural soil materials for supporting vegetation and the post-mining land use. This suitability is usually determined by a few relatively simple laboratory analyses such as acid-base accounting, extractable plant nutrients and soluble salts. The true suitability of a given overburden strata for use as a mine soil medium is dependent upon a myriad of other factors including overall mineralogy, degree of oxidation, particle size distribution after blasting and handling, relative compaction after placement, and mine soil transformations over time. Since 1977 we have conducted a series of studies in southwest Virginia and southern West Virginia with the following broad objectives:

1. To determine physical chemical and mineralogical properties of southern Appalachian overburden strata that are critical to reclamation success.
2. To identify mine soil properties which have limited reclamation success in the past and to determine how to avoid these problems in current mining practice.
3. To determine which combinations of rock type and surface treatments are optimal for long term reclamation success.

In this paper we will attempt to summarize our major findings to date along with those from other relevant studies in surrounding states.

Local Geology and Mining Techniques

Our studies have concentrated on overburden derived from the Pennsylvanian age Pottsville series at two locations in Virginia and one in West Virginia (see Fig. 1). In Virginia, the Pottsville series consists of the Lee, Norton and Wise formations and in West Virginia the Kanawha, New River and Pocahontas formations. The Pottsville series is exposed extensively throughout the region which is deeply dissected with narrow valleys and extremely steep sideslopes. Howard[1] conducted a detailed study of mine spoils derived from fluvial-deltaic facies of the Wise Formation exposed at the Virginia Energy Company study site in buchanan County, Virginia and found the strata to be "characterized by abrupt lithologic and geochemical facies changes involving micaceous, calcareous, and ferruginous sandstones and siltstones, shales, mudstones, conglomerates and coals. The portion of the Wise Formation exposed at this locality consists of about 70% sandstone, 20% siltstone and 10% shale, mudstone and coal. The thicker sandstones and siltstones are comprised of medium to fine sand and silt sized quartz (70–80%) with lesser amounts of rock fragments, feldspar, mica, Fe-oxides, carbonates, clay and accessory minerals. Goethite is the dominant Fe-oxide and the dominant mica in the rocks is muscovite. The carbonates are a complex mixture of species or complex (Fe, Mn, Ca, Mg, Zn) phosphatic carbonates or

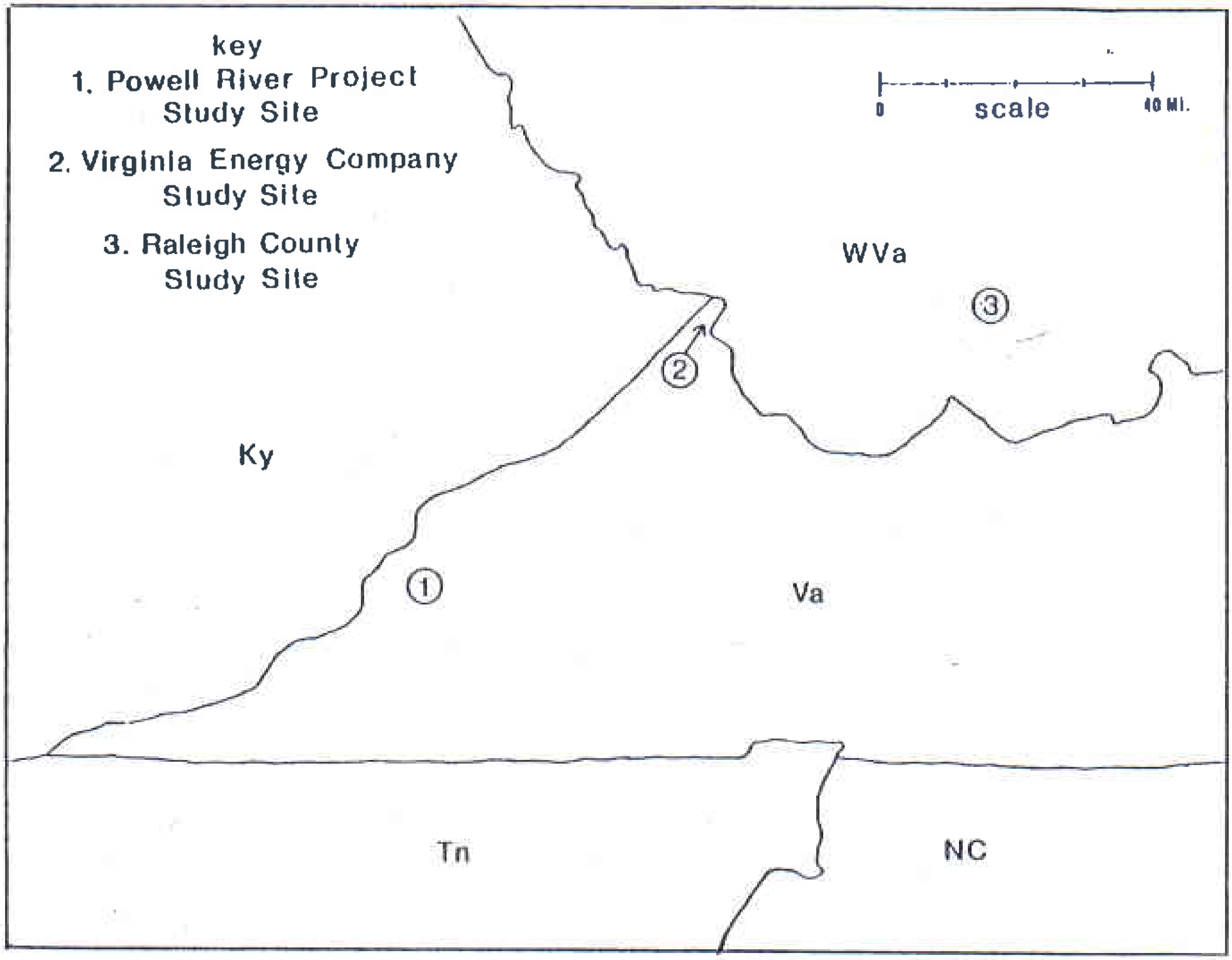

Figure 1 *Map of study site locations.*

carbonate apatites." The Wise Formation strata exposed at the Powell River Project study site are nearly identical in type and distribution, while those samples by Sweeney[2] in Raleigh County, West Virginia contain more siltstones and shales. The coal seams within the Pottsville series tend to be thin, but are generally high rank and low in sulfur. Rock strata lying close to the surface tend to be leached and oxidized to brownish-red hues (as described by Smith et al.[3]) with resultant destruction of pyrites, loss of carbonates and increased porosity. The depth of oxidation is dependant upon the depth of local fracturing which has been shown to be related primarily to stress relief fracturing during down cutting of the deeply incised stream valleys.[4] Thus, strata high on exposed ridges tend to be deeply fractured and oxidized when compared with straa which are lower in the landscape or lie deeply buried beneath the original surface.

Current surface mining is conducted primarily by contour/haul-back and mountain-top removal/valley fill methods, frequently removing multiple seams. Contour surface mines are returned to approximate original contour (AOC), and the resultant back-fills are quite steep (>25°), and limited in post-mining land use. Mountaintop removal mining, however, often generates hundreds of acres of flat land with a high potential post-mining land use. Before 1977 more than 385,000 hectares of land had been disturbed by surface mining in Appalachia.[5] Contour mining completed before the application of the SMCRA generated a highwall-bench-outslope topography (see fig. 2) after mining with the outslope portion often subject to progressive slumping and failure.

Revegetation and the 1977 Act

Prior to the enactment of the 1977 Act (SMCRA) and the resultant State Permanent Regulatory Programs, revegetation bonds in Virginia were generally returned one to two years after a healthy vegetative cover was established and maintained. Under the new regulations a healthy, self-sustaining vegetative cover must be maintained for a minimum period of five years beyond the last fertilizer, lime or seeding augmentation for bond release. The implications of this regulation are yet to be seen in many areas since most State Permanent Regulatory Programs were not enacted until several years after the 1977 Federal Act. It is obvious, however, that the potential cost to an operator of a revegetation failure at year 5 with subsequent augmentation and an additional 5 years of bonding could be considerable. A basic understanding of overburden

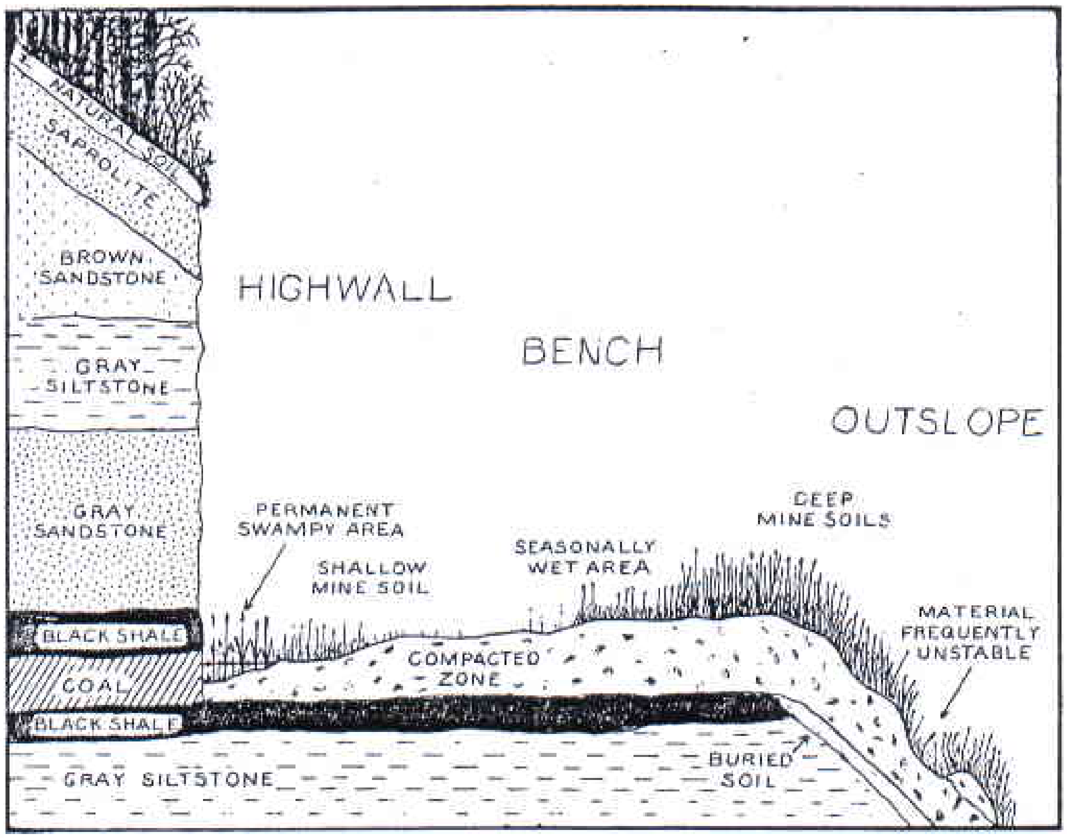

Figure 2 *Diagram of typical southern Appalachian surface mine bench and associated mine soils produced by contour mining prior to the implementation of the 1977 Surface Mining Control and Reclamation Act.*

properties, placement techniques, and their interactions with revegetation success over time is essential to the avoidance of this possibility.

Mine Spoil vs Mine Soil

Once blasted overburden strata or *mine spoil* is placed at a final reclaimed surface, and once it is exposed to the soil forming factors of climate, vegetation, and time it becomes *mine soil*. By studying the weathering of various spoil types into mine soils on older benches and fills of various ages, some inferences into the effects of spoil properties on reclamation success can be drawn.

Physical, chemical and biological weathering processes combine to significantly alter the character of original spoils in a fairly short period of time. The <2mm particle size distribution and gross chemical characteristics of mine soils are controlled directly by those of the paent rocks.[6] Sandstone strata yield mine soils with sandy loam textures, and mixtures of sandstone and siltstone generate loamy textured mine soils. Siltstones tend to be higher in iron and soluble salt content than sandstones, and the inclusion of pyritic black shales, underclays, and waste coal in spoils usually render them highly acidic. Over time however, all of these basic properties may change considerably. Sweeney[2] studied 2, 5 and 10-year old mine soils derived from the New River Formation in Raleigh County, West Virginia and found that pedogenetic horizonation occured within 10 years. He described distinct A horizons in 5-year old mine soils and several weak cambic B horizons in 10-year mine soils. When compared with surrounding natural soils, the mine soils were higher in pH and exchangeable bases, and approximately the same in A horizon coarse fragment content. In a parallel study at the Powell River Project site in SW Virginia, Daniels and Amos[7] examined 30 mine soils ranging from 5 to 20 years in age and found similar pedogenetic horizonation with age. As mine soils leach, weather and accumulate organic matter, the A horizons thicken, surface pH drops, and coarser rock and soil particles are weathered into finer particles (Table 1). Within six months significant weathering of sand sized particles into silts has been detected in a controlled overburden placement experiment along with a dramatic increase in cation exchange capacity (Table 2). This increase in CEC is probably due to carbonate dissolution, organic matter incorporation and increased mine soil surface area.[8] Once carbonate dissolution slows and excess salts are leached from the system the level of exchangeable bases in older mine soils declines somewhat, but remains greatr than that in surrounding natural soils.[2] Exchangeable K increases over time as micas in the surface are exposed to chemical and biological weathering processes (Table 1), and weathering of mica to vermiculite in one year was observed by Everett[9] in a greenhouse weathering experiment using spoils from the Virginia Energy Company site. Thus it is evident from these studies that rapid changes in the morphological, chemical, physical and mineralogical properties of mine soils derived from the Pottsville series occur in as short of a period of time as six months

Table 1 *Selected mean physical and chemical characteristics of 15 5-year old mine soils derived from the Wise Formation at the Powell River Project Study Site.*[1]

PHYSICAL CHARACTERISTICS

Horizon	*Depth*	*Course Fragments*	*Sand*	*Silt*	*Clay*	*Organic Matter*
	cm	%	%	%	%	%
A	13	41.0	43.5	41.2	15.3	1.4
C	>13	42.9	51.8	34.6	13.6	0.9

CHEMICAL CHARACTERISTICS

Horizon	*Depth*	*pH*	*Soluble Salts*	*Ca*	*Mg*	*K*	*Al*	*CEC*[2]
	cm		ppm			meq/100g		
A	13	5.2	74	2.6	2.2	0.22	1.02	6.04
C	>13	5.3	112	2.6	2.1	0.15	0.91	5.76

[1]Adapted from Daniels and Amos.[7]
[2]CEC taken as sum of exchangeable Ca + Mg + K + Al.

Table 2 *pH, cation exchange properties and particle size distribution of mine soils in the Controlled Overburden Placement Experiment at the Powell River Project Site before (May, 1982) and six months after (October, 1982) reclamation.*[1]

	May 1982					*October 1982*				
Rock Type	*Median pH*	*CEC*[2]	*Sand*	*Silt*	*Clay*	*Median pH*	*CEC*	*Sand*	*Silt*	*Clay*
		meq/100g	%	%	%		meq/100g	%	%	%
Pure Sandstone (ss)	5.65	3.28d	69a	22a	9a	5.30	5.33c	71a	20c	9b
2:1 ss:sis	7.10	4.41bc	65ab	25a	10a	6.65	7.72ab	65b	26b	9b
1:1 ss:sis	7.10	4.21c	62ab	28a	10a	6.70	7.50b	63b	27b	10b
1:2 ss:sis	7.70	4.89ab	65ab	25a	10a	7.25	8.98a	61b	29b	10b
Pure Siltstone (sis)	8.05	5.17a	59b	30a	11a	7.40	8.61ab	49c	39a	12a

[1]Adapted from Daniels, et al.,[8] column means followed by different letters are significantly different (= 0.05).
[2]CEC taken as sum of exchangeable CA + Mg + K + Al.

to a year. The proper selection and management of a productive topsoil substitute must therefore be based on a thorough understanding of initial spoil characteristics and how they will change over time.

Factors limiting Reclamation Success

While much has been written concerning the adverse effects of pyritic spoil materials on revegetation and water quality, several other factors including compaction and Fe-oxide content are critical as well. Ten of the 30 weathered mine soils described[7] at the Powell River Project site were barren or sparsely vegetated, but of these only one was extremely acid (pH<4.5). The remaining nine contained compacted traffic pans within 30 cm of the surface or were shallow to intact rock. Subsequent investigations at many other locations in SW Virginia have revealed that at least half of the mine soils on flat benches are underlain by shallow (<70 cm deep) traffic pans with bulk densities ≥1.7g/cc. These layers substantially reduce downward penetration of roots and water, and thereby limit water availability during summer droughts. This is a particular problem in hard rock derived mine soils since 30 to 60% of the material is coarse fragments (>2mm) which hold only limited amounts of plant available water.[6] The bulk density of the surfaces of these mine soils decreases over time due to physical weathering processes and aggregation, but the subsurface traffic pans will persist over time unless the material is ripped or regraded. These pans occur wherever haul roads and parking-/maintenance areas were reclaimed without a subsequent lift of cover materials, and create a distinctive pattern of vegetation on many older benches (Fig. 2). Plant growth on the outslopes and outer portion of the benches is often quite luxuriant when compared to areas closer to the highwall which are often underlain by the traffic pans or shallow bedrock. These highly compacted zones often perch water tables and create swampy areas in unexpected locations. Hard, silty, vesicular surface crusts are a common problem as well, and form rapidly on non-vegetated mine soils, particularly those derived from siltstones.[7] These crusts impede seedling emergergence and inhibit water infiltration, seedling root penetration, and overall reclamation success. Many mine spoils with otherwise excellent physical and chemical characteristics for plant growth are almost totally barren due to crusting or excessive compaction. The physical and chemical characteristics of one well vegetated and one nearby non-vegetated mine soil from the Power River Project study site are presented in Table 3. The only major difference between these mine soils was the severe compaction in the non-vegetated mine soil.

The chemical characteristics of mine soils over time are intrinsically tied to their original mineralogy and weathering products. Aside from mine soils where excessive pyritic materials result in excessive amounts of soil acidity and soluble salts, the major chemical-/mineralogical factor limiting long term revegetation potential of these minerals is P availability. Phosphorus fixation by Fe-oxides is a profound problem in many SW Virginia mine soils. Iron oxides in the form of intergranular cements, nodules, beds, concretions, and fossil materials are ubiquitous throughout these strata and have the potential to fix large amounts of applied P into insoluble forms.[1] The total amount of iron and the ratio of Fe^{3+} to Fe^{2+} in a given rock type directly controls its P-fixation potential. The Fe^{3+}:Fe^{2+} ratio increases as a given spoil weathers and oxidizes. Siltstones are generally higher in iron and P-fixation potential than sandstones, and the vast majority of P in weathered mine soils rapidly becomes fixed by Fe-oxides. Mine soils initially high in goethite and other Fe-oxides may therefore need extensive P fertilization. The total iron content of fresh spoil materials generally ranges from 0.5 to 5% and may be in excess of 10% in highly ferruginous strata. Phosphorus fertilization rates as high as 780 kg/ha did not significantly increase the plant available-P levels of mine soils at the Powell River Project site beyond the first several years[16] indicating rapid fixation over time. Low mine soil P levels are commonly cited throughout the Appalachian region[11] and may in turn limit mine soil N levels by suppression of legumes.[12] Mine spoil materials high in Fe-oxides should be avoided for use as topsoil substitutes whenever possible.

Table 3 *Selected characteristics of two adjacent 5-year old mine soils from the Powell River Project Study Site. The barren mine soil was highly compacted (>1.8g/cc) below 23 cm, while the well vegetated mine soil contained no compacted layers.*

	Horizon	*Depth*	*pH*	*Organic Matter*	*CEC*[1]	*HCO_3-Ext. P*	*Sand*	*Silt*	*Clay*	*Course Frag-ments*	*Bulk Density*
		cm		%	meq/100g	ppm	%	%	%	%	g/cc
Barren Mine Soil	A1	0–10	5.35	0.71	3.10	1.5	74	19	7	36	1.5
	AC	10–23	4.91	0.64	3.34	1.5	71	15	14	38	1.6
	C	23–110+	5.19	0.85	3.93	0.0	61	26	13	31	1.8
Well Vegetated Mine Soil	A1	0–10	5.75	0.48	4.03	4.5	72	20	8	43	1.4
	A2	10–32	5.13	0.21	4.05	4.5	76	17	7	55	1.5
	C1	32–52	5.91	0.21	4.17	3.0	76	17	8	50	1.5
	C2	52–100+	6.06	0.30	3.88	3.0	77	16	7	62	1.6

[1]CEC taken as sum of CA + Mg + K + Al.

Selecting A Topsoil Substitute

Overall strata thickness, acid-base balance, pH, soluble salts, and plant available nutrients are the most commonly used criteria for evaluating a potential topsoil substitute. Our research has indicated that a number of other criteria should be considered as well. The acid-base balance approach of Smith et al.[3] is certainly a good general guide for eliminating potentially toxic strata but its use in accurately predicting acid production over time is limited.[13] Used in combination with other criteria, however, it is a valid test for the selection of optimal strata. Spoil pH is a very misleading quality indicator due to the fact that it may drop drastically due to pyrite oxidation or leaching of salts. Once potentially toxic strata have been eliminated, spoils with saturated conductivities in excess of 5 to 8 mmhos/cm should be eliminated if possible to avoid problems with soluble salts. The evaluation of the potential plant available nutrient status of mine spoils if complicated by the fact that many of the standard analytical procedures for Ca, Mg, K and P were designed for use with weathered natural soil systems, and care must be taken in their use with blasted or sheared rock fragments. These surfaces are dominated by broken bonds in sheared mineral grains and frayed intergranular cements. These surfaces are not in equilibrium with a surface environment, and it is difficult to differentiate among dissolution, desorption, adsorption, and precipitation reactions as these surfaces weather with time. Values for extractable Ca, Mg, K and P are often seriously inflated,[14] particularly when an acid extractant is used on spoil materials containing appreciable quantities of carbonates such as those from the Pottsville series. Calcium Mg, and K are seldome limiting nutrients in young mine soils derived from these materials,[1,9,15] so errors in their estimation are usually inconsequential. The accurate estimation of plant available P, however, is critical to reclamation planning. The vast majority of natural P in rocks of the Wise Formation is in the Ca-P