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The Role of Soil Mineralogy in Potassium Uptake by Wine Grapes

Investigators: Ernest Beasley, PG   Lucie Morton   Clifford Ambers, PhD
Geologist   *Viticulturist*   *Clay Mineralogist*

Objective: To help Virginia winegrowers better understand the role that soil minerals and Mehlich 3 extractable potassium play in the potassium status of vines and grapes.

Introduction
Potassium (K) in fruit plays a critical role in the pH of must and wine (Keller 2010). pH is known to be a major influence on a number of wine quality factors including color, acid balance and microbiological stability (Zoecklein et al 1990). Potassium availability in the soil can vary greatly and deficiencies can occur; however, in Virginia excess K absorption by wine grapes is much more common than K deficiency (Wolf 2007). Growers are commonly led to believe by laboratory analysis that potassium levels in their soils are low, when petiole analysis from the same location often shows elevated K levels in the plant tissue.

In her many decades of working in Virginia vineyards, Lucie Morton has virtually never seen K deficiency in mature vineyards. In her opinion, this study will start a conversation about why that is the case. Clearly the current approach to soil testing, based on an assumption of six inch top soil layer, makes no sense for grapevines that are known to for their deep rooting and ability to grow well in nutrient poor conditions. Interpretations of the availability of K to grapevines based on a five minute acid extraction do not reflect what is actually available to vines in soils. She works with several Virginia vineyards where the K status of the soils is the only difference between blocks with the same rootstocks, varieties, and canopy management. In all cases, the winemakers prefer the blocks where the K status in soils and vines is lower. It is her opinion that, in the absence of clear deficiency symptoms, any recommendations to add any potash to any soil in Virginia is misguided. In the few instances where she has worked with young vineyards needing additional K, foliar applications corrected the deficiency.

Background
Our study examines the relationship between bedrock geology, vineyard soil mineralogy, soil chemistry, and the potassium levels (and pH) of the fruit.

It is very important to recognize the distinction of the geological usage of "mineral" here with the common biological and nutritional usage of "mineral" that refers to a dissolved ionic species that is used by an organism as a nutrient. We do not use "mineral" in the biological sense anywhere in this study except in this clarification. Mineral as used here in the geological sense <u>only</u> means the solid, crystalline components (grains) of rocks that exist at nearly constant composition and crystallography regardless of the bulk composition and fabric of the rocks containing them.

As an example, quartz is the most common mineral found in the soils of Earth. It is always nearly pure SiO_2 and crystallized with trigonal crystal symmetry. It is essentially the same material regardless of whether it is found in granite, sandstone, shale, schist, gneiss, flint or vein quartzite.

Other common minerals that are discussed in this study include the primary, high temperature, parent rock minerals: feldspar group (subdivided into the K-Na-bearing "alkali feldspars" and the Ca-Na-bearing "plagioclase" feldspars), micas (subdivided into low Mg-Fe and K-rich "muscovite", high Mg-Fe and K-rich "biotite", and Low Mg-Fe and Na-rich "paragonite"), chlorite, epidote, hornblende, pyroxene; and the secondary, low temperature minerals formed by surface weathering of primary minerals: clay minerals

(kaolinite, degraded mica, vermiculite, chlorite, smectite, and interlayerings thereof), Fe-Mn oxyhydroxides (goethite, pyrolusite), and non- to poorly-crystalline Al-Si-Fe-Mn precipitates (allophane). **Figure 1** is a collection of photomicrographs of the main parent material rocks as seen in thin section.

A few of the aforementioned minerals are of particular interest in this study because of their high potassium contents which makes them the main source of natural potassium in the soils derived from them. The feldspars as a group include the plagioclases, which do not contain more than 10% potassium feldspar dissolved in them, and the alkali feldspars which do not contain more than 10% calcium feldspar dissolved in them.

The micas (muscovite and biotite) are the second group of potassic minerals common in Virginia. Natural muscovites run about 11.2% K_2O whereas biotites run about 8.5% K_2O. Even though they contain less K_2O than potassium feldspar, the micas are "sheet silicates" with their silica and alumina components arranged in 2:1, sandwich-like sheets, which gives these minerals structural weakness that contributes to their very rapid weathering. Between the 2:1 layers of silica and alumina sheets are housed potassium atoms. The mica minerals are famous for their "perfect cleavage" which allows them to be split into vanishingly thin sheets with a knife or razor blade. Impact or bending can also cause the crystals to cleave into seemingly infinite thinner sheets. Also, the edges of the layers do not have bridges of silica or alumina that would retard the entry of water along the potassium interlayers. This makes the potassium vulnerable to hydration and removal even without making water access very easy by cleaving the crystal.

The end result is micas release their potassium at a remarkably faster rate than K-feldpsar and, while they persist, are a large source of soil potassium. Another important aspect of mica weathering is that they may have most or all of their potassium removed and replaced with another cation (including K from fertilizers) along with its hydration water. When added potassium is reintroduced to the interlayer spaces in the mica structure, it remains there as "fixed K" that can become available over time to grape roots.

Accomplishments/Benefits to date:

Methodology

We implemented the following methods at each of ten (10) research sites:
- Bedrock sample collection and mineralogical analysis via petrographic microscope (completed at 7 of 10 sites)

- Soil auger holes at specific locations to log horizons and collect soil samples from discrete depths

- Soil mineralogical analysis via Scanning Electron Microscopy (SEM/EDS) and X-Ray Diffraction (XRD) at the James Madison University Geology Lab; samples analyzed from discrete depths at each auger hole

- Soil texture and moisture analysis; samples analyzed from discrete depths at each auger hole

- Soil chemical analysis by A&L Labs; samples analyzed from discrete depths at each auger hole

- Bloom and veraison petiole analysis for 2014 and 2015 from vines around soil sample points

- Fruit sample collection from same locations (at 8 of 10 sites) for analysis of K, sugar levels, TA and pH

Inter-laboratory variability of soil analyses and the choice of laboratory for this study
An initial concern at the outset of this study was the reproducibility of soil test results from the two main labs processing soil samples for vineyards in Virginia (VA-Tech and A&L Laboratories). Lucie Morton had observed conflicting results at various sites where analyses were available from both labs, however, the samples were not

taken at the same time, by the same collector, or in the same year. This uncertainty suggested an experiment was warranted to examine the potential problem further.

We collected a suite of samples from five backhoe trenches dug to saprolite at an undeveloped pasture in typical Hayesville soil in western Albemarle County, Virginia. A suite of five samples were screened to <1/4" particle size, homogenized, then split evenly between sample bags that were sent to the VA-Tech and A&L laboratories for analysis. Results of the analyses were extremely variable between the labs (**Table 1**).

Cross plots of the data in Table 1 provide an immediate visual guide to the results (**Figure 2**). Of all the analysis fields, pH is the only one that gives a direct, 1:1 correlation between labs. Mg and Ca give reasonable correlations, but the magnitude of the values is substantially higher in the A&L results than in the VT results. Communication with the labs revealed A&L used Mehlich 3 extraction solution (Mehlich, 1984) and VT used Mehlich 1 extraction solution (Mehlich, 1953). Because all the cation values depend on the extraction solution used, the values for each nutrient should be different from these labs. However, because these analysis pairs were performed on the same samples, we expected a good correlation between the values obtained at the different labs. This is not generally the case. We decided to use A&L Laboratories for this study based on the greater magnitude of the values resulting from their Mehlich 3 extraction that might provide better sample discrimination. These results clearly indicate that growers should not use soil results from different laboratories when considering nutrient additions.

Findings
We noted that for all samples (even those with what the laboratory considers low soil K levels) petiole K levels fall into the range that is considered high to very high. We have consistently seen this phenomenon at every research site studied in this work. Such is the paradox encountered by commercial growers year after year.

We have found that, particularly on sites with a farming history involving past additions of potassium, the potassium uptake dynamic is difficult to study. We can identify the mineralogy and postulate about its contribution to plant tissue K and fruit chemistry, but collecting representative soil chemical data to pinpoint naturally-occurring K is not possible on such sites (the majority of our research sites have reportedly undergone potassium additions at some point). For these reasons, our 2015-2016 work scope includes greenhouse trials and soil sampling on our research sites in adjacent areas less likely to have undergone K additions (wooded areas, fencelines, etc.) in attempt to control for many of the confounding variables encountered thus far.

Study Site Soils
The vineyards selected for study cover a broad range of Virginia geography and geology, however, all but three of the sampled profiles are on ultisols (NRCS, 1999). Ultisols are defined as mineral soils which contain no calcareous material anywhere within the soil, have less than 10% weatherable minerals in the extreme top layer of soil, and have less than 35% base saturation throughout the soil. Ultisols are highly developed that occur in humid temperate or tropical regions.

The remaining three study site soils are alfisols, which are less deveoped than ultisols, having undergone less leaching and thus they chemically and mineralogically resemble their parent material more closely than do ultisols.

The red clay soils of the southern United States are dominantly ultisols, and in the Blue Ridge Foothills from Charlottesville to Lynchburg the bright red ultisols were historically known as "The Redlands" (the name extended from Redlands plantation near Covesville in Albemarle County) and were renowned for their fertility (Tom Burford, personal communication). Virgin ultisols support forests dominated by pine, oak and hickory, and have a topsoil of brown sandy loam. The subsoil is a red clay which is dominated by kaolinite and often contains visible phyllosilicates (micas, mica-vermiculite, vermiculite, chlorite).

Few ultisols in the southeast U.S. are in their virgin state because most have been cultivated at one time or another and favorable sites continuously since European settlement. Poor land management since European settlement has allowed many Southeastern ultisols to lose their topsoils and substantial parts of their B horizons through soil erosion, exposing what was originally thick, deep, acidic, red clay subsoil. This clay is amenable to cultivation, responds well to careful management and liming, and supports good growth of pine where allowed to revert to forest. This is the substrate of most of the vineyard sites studied.

Thin Sections and Primary Mineral Weathering
To fully understand and compliment the soil chemical analyses in this study, thin sections of parent materials (rocks) collected from each vineyard site were prepared and analyzed. Thin sections are slices of rock 30 microns thick prepared on a glass microscope slide backing and typically mounted and covered with an epoxy cement with a refractive index the same as quartz. These mounts are viewed through a polarizing microscope designed for the analysis of crystalline materials which allows the identification of the rock forming minerals present, their sizes, and textural relationships between them.

Thin section analysis of vineyard rocks supports the discussion of potassium mineral weathering on pages 1-2. Progressive argillization of each of the main rock types was observed, and key features of primary mineral weathering are shown in **Figure 3**.

X-Ray Diffraction and Scanning Electron Microscopy
To complete our assessment of the potassium-bearing mineralogy of premium vineyard soils in Virginia we also obtained preliminary powder X-ray diffraction (XRD) scans of selected soils aimed at identifying the clay minerals present, as well as scanning electron microscope images (SEM) to see if any evidence of primary mineral dissolution is present in the samples. The work was performed in the James Madison University geology department's laboratories by cooperating scientist Dr. Lance Kearns.

For the XRD analysis, Dr. Kearns ran "smear mounts" of selected soils designed to accentuate X-ray reflections off of the flat clay surfaces that are generally diagnostic. Dr. Kearns summarized the XRD results as follows:

> "The dominant clay mineral is kaolinite. The presence of illite (K-bearing clay) is sporadic. Expandable clays (smectites) like montmorillonite are rare if present at all. A poorly crystallized chlorite, vermiculite and/or interlayer chlorite-vermiculite is common in a few samples."

This result strongly supports the clay mineralogy of the soils indicated by their classification as ultisols, and the outliers containing the 14 Angstrom chloritic reflections are from the outlier alfisol and inceptisol sites on chlorite-bearing parent materials.

Vermiculites have the highest cation exchange capacity of the soil clays and are extremely important in ultisols (which exist at most of our sites) at very low quantities for exchangeable storage of soil nutrients because the dominant kaolinite in these soils has very low CEC.

SEM analysis was restricted to observation of mineral fragments sieved from the soils at only a few sites. As expected in these highly weathered soils, surface dissolution and pitting of feldspars was common. See **Figure 4** for SEM images.

Interpretation of Soil Chemical Analyses
We approached interpretation of soil analytical data by plotting soil parameters versus the depth the samples were collected and by cross plotting those showing potential relationships. We did not expect the depth plotting of all samples together to reveal much relationship in the group, if any, because of the distribution of the sites over a region a hundred miles in radius, different parent materials, different textures/rockiness, different cover crops or recently cleared forest, and different farm management histories. However, this was not the case and the exercise turned out to be very revealing about the behavior of nutrients in Virginia ultisols

in general and verifies their overall "two zone" (aric tillage/bioturbation zone over ancient B accumulation zone) nature (**Figure 5**).

Soil pH vs. Depth
Figure 5 is divided into plates (A and B) with rows of graphs in each (top, middle and bottom) organized by related parameters. The composite pH profile shows several high pH samples in the top two feet with none above 6.50 below that depth. A few samples from S1, T1 and M1,2 have pH's between 5.50-6.50 at nearly six feet depth.

T1 is underlain by carbonate rock, M1 and 2 are over Coastal Plain sediments containing marine shells (Dicken et al., 2008), and S1 is over Catoctin Greenstone that has peculiarities in Ca, Mg and Na content as well as clay mineralogy that cause that locality to stand out in most parameters. If these sites are considered anomalous, the pH at most sites falls from around 6.00 at two feet to below 5.00 by five feet depth. Buffer pH shows nearly all samples rising to above 6.65 except those from site R which is developed on very acidic quartz syenite.

Soil Trace Elements vs. Depth
In **Figure 5A**, row 2, we plotted soil trace elements at their collection depths. Generally there are very low values of these elements in the soils and they tend to increase within six inches of the soil surface. We interpret this to reflect vineyard application of foliar micronutrients and fungicides containing Cu, Zn, and B. Cu, Zn, and B are all much higher in the plow zone at L2 suggesting a fertilization effect. Boron also decreases linearly with depth at L2 supporting rapid downward transport of a large one-time application of B. Zinc is enhanced at depth at T1 which is developed on Valley and Ridge carbonate rock and a mid-depth sample from W1 on the Swift Run Formation. Both are very deeply leached soils and high Zn levels are not found at the surface for these sites. A good geo/pedological explanation is not apparent for these samples. The hand auger bucket was galvanized, however, so it is possible the values result from abrasion of Zn off the auger bucket. In general, the micronutrients are at very low levels throughout the soils reflecting very long and deep leaching of the subsoil.

Effects of Liming and Significance of CEC Values
Our first look at the potential affect liming materials has on these soils is shown in row 3 of **Figure 5A**. Ca and Mg show very similar depth trends with a decrease from the surface to about three feet depth with low values below that. The deep "tails" of <500 ppm Ca and <100 ppm Mg likely approach background values present in the soils before modern lime application increased surface values and initiated a renewed migration of Ca and Mg down the soil profiles.

The CEC with depth is closely related to the sum of the Ca and Mg values because the CEC reported by A&L Laboratories is estimated from the cation values determined instrumentally on the Mehlich 3 extraction solution and Ca and Mg dominate the base cations (Pauric McGroary, personal communication; Cornell University Cooperative Extension, 2007). These soil test CEC's are not directly measured CEC, but rather a calculated mingling of cation and acidity measurements. Interestingly, the calculated CEC's act as a sort of proxy for liming material applied at a site in this region because the background Ca and Mg values are so low in the ultisols and these ions play heavily in the CEC calculation.

Three sites (T1, P1, and S1) stand out with high Ca and Mg contents at depth. T1 is on carbonate rock, and P1 and S1 are on Catoctin Formation (metabasalt). The shallow samples are not high in Ca and Mg at P1 and S1, however, and Na also shows an anomaly at these sites (see below), so recent liming does not explain their high Ca and Mg but historical liming could.

Soil Texture and Organic Matter vs. Depth
Soil texture and organic matter are plotted in **Figure 5B**, row 1. The sampling sites tend to separate into columns in the texture plots reflecting the unique texture of each site resulting from the parent material mineralogy and grain size. The soils have a wide range of clay and sand contents but mostly fall into the general loamy textural classes.

Organic matter contents reported by the laboratory are highly suspect and are interpreted to be showing several percent of very degraded/poorly crystallized clay and/or Al-Si-Fe-Mn amorphous materials in the soils that dehydrate at the temperatures the samples are heated to in order to remove organic matter. Such amorphous material is found in the soils as aggregate impregnations, particle coatings, coatings of dissolution voids, and/or linings of root tubules (**Figure 6**). At 2% or greater organic matter content these soils should appear brown and very organic-rich, but rather, they are light brown in the aric zone and red in the subsoil. Clearly the OM estimations being provided for vineyard soils need better calibration. There is probably not 2% soil organic matter at six feet of depth anywhere in Virginia soil except in swamps, on old coal spoil piles, or on rare organic-rich shales.

Major Nutrients vs. Depth
The major nutrients are plotted in row 2 of **Figure 5B**. Again, a general drifting of nutrients to lower values with depth is observed. Enhanced phosphorus is tightly restricted to the top six inches of soil with very low values down the profiles except at site M where bone and teeth fragments (Dicken et al., 2008) in the Coastal Plain sediments are able to yield a small amount of phosphorous.

Potassium shows enrichment to about three feet depth with highest values in the plow zone. Well known, rapid, downward potassium movement compared with general phosphorous immobility is well supported by the data and reveals the fate of P and K fertilizers in these soils over time. The deep "tails" of <10 ppm P and <30 ppm K likely approach background values present in the soils before modern fertilizer application increased surface values.

Estimated N release (ENR) is an estimation based on organic matter content and because we find the organic matter results suspect, we do not place much meaning on the ENR trend to lower values with depth. It may reflect a decrease in amorphous mineral content with depth due to increasing compactness and less pore space for amorphous materials to precipitate into. The organic matter and ENR plots are very similar because ENR is derived from OM values.

Other Soil Elements vs. Depth
Soil analysis elements typically not applied in fertilizers source elements are shown in row 3 of **Figure 5B**. Mehlich 3 solution extractable Fe and Mn is highest within three feet of the surface as was found for Ca and Mg. Sodium is nearly constant with depth at about 15 ppm, but is elevated in the mid-depth Coastal Plain site (M2) which may be sea water related. The mid-depth sample from P1 is also elevated, but sodium is over twice the value of the other sites at S1 where XRD suggested the presence of montmorillonite clay and both Ca and Mg are elevated at depth. Clearly the soil at S1 is the odd soil in this study and P1 is similar.   Ratios of Fe:Mn in all soils range from 20:1 to 1:2.3 and represent the wide variability in Fe and Mn contents of the parent rocks. Higher extraction amounts for Fe and Mn in the plow zone likely reflect complexation with organic material in the heavily rooted zone or finer particle size of Fe-Mn oxyhydroxides in the aric zone due to mixing processes (See the fracturing of amorphous material shown in **Figure 6**). Freeze-thaw and repeated desiccation are very effective at breaking up allophane type soil phases.

Soil Cross Plots
The previous analysis of depth relationships led us to examine similarly behaving parameters in cross plots (**Figure 7**). The pH, Ca, and Mg depth trends and involvement of liming materials suggested interrelated behavior of these parameters so we plotted Ca and Mg against pH and Ca and Mg against each other in Row 1 of **Figure 7A**.

As part of the study we sent in a sample of dolomitic limestone rock powder from the Staunton Quarry and also had a quarry analysis of the Berryville Quarry liming product available. For Mg and Ca plotted against pH, there is a fair correlation of most of the sites except P1 and S1 that have much higher extractable Ca and Mg than the soils from the rest of the sites of similar pH. Our lime sample analyzed by Mehlich 3 extraction falls on the trend

of the correlation line for pH versus Ca, but yields somewhat higher in Mg than the soil sample correlation for pH versus Mg. This is expected because lime is used to replace missing base cations in these soils and neutralize hydrogen ions thereby raising pH. The Mg value we obtained for dolomitic lime is high compared to the trend in the soils as we sent in material from a quarry with the maximum Mg content we could find. Most liming materials that have been used probably are not as high magnesium which is recorded in the Ca/Mg ratio of the soils. As usual, sites P1 and S1 do not behave as most of the soils reflecting a different ability to hold base cations in those samples.

We wondered if total clay content of the soils was responsible for variable pH and CEC which is largely related to Ca and Mg content (**Figure 7A**, row 2). There is no relationship of the pH with total clay content, but CEC shows sites P1 and S1 clustering in their own group of low clay content and elevated CEC, again showing a different soil charge system in those samples than the rest with low clay content relating to their less mature development (alfisols).

We examined the values of Ca and Mg directly with CEC (**Figure 7A**, row 3). Both cations show a very strong relationship with CEC because the calculation of CEC is strongly influenced by their concentrations. The R^2 of the linear correlation for Mg versus CEC is similar to that for CEC versus Ca, but we left our lime sample in the plot which had a stronger influence in the CEC-Mg regression than the Ca-CEC regression where the lime falls of the trend of the soils. Again, soils P1 and S1 stand out with their high Ca and Mg contents and estimated CEC's. We were surprised that the Mehlich 3 extractant was able to recover more Ca in the P1 and S1 soils than it did from the lime. We suspect the coarse grind of the lime limits its solubility over the 5 minute shake time used by A&L laboratories during extraction and the buffer limits lime reaction rate.

Sites S1 and P1: The Outliers
Throughout this discussion we have repeatedly shown sites S1 and P1 to segregate from the rest of the sample sites. P1 and S1 have the anomalous soil classification as alfisols, which indicates they should have a high base saturation along with high Al and Fe, which they do. Both S1 and P1 are developed on mafic Catoctin Formation greenstone and associated rocks. The Catoctin metabasalts form the ridge above P1, and P1 is developed on metabasalt colluvium.

Johnston (1962) measured Catoctin groundwater cations from three separate wells in the Catoctin Formation and found the following values for dissolved ions: Ca: 35, 11, 44; Mg: 22, 7.3, 10; Na: 5.8, 2.9, 2.2 ppm, respectively, with near-zero K in each water. These analyses show what cations are exiting the rock weathering system on the greenstone and, not surprisingly, they are the same cations available for Mehlich 3 extraction found in our P1 and S1 soils.

This helps provide an explanation for the S1 and P1 Ca, Mg and Na anomalies, but is not clear cut because two other sites (L2 and O2) are also from soils developed on Catoctin Formation. L2 and O2 are not distinct from the rest of the ultisols in the study, however. It appears the explanation is in the soil maturity and relative water saturation of sites. S1 is a relatively low slope lowland site. It is very rocky and the upper mixed zone extends to rock in some areas of the farm. Where thicker soil is developed, the red subsoil gives way to buff saprolitic colluvium or bedrock containing reduced clasts, and the reduced material content increases downward (**Figure 8**).

We interpret retention of reduced rock fragments as evidence for soil water movement being temporarily impeded during wet periods at the top of the parent material coupled with a shorter soil forming period as is also the case for the inceptisol at site K1 which is not far from S1 and is in related lowland rocks. Reduction keeps the reactive surfaces in the soil available for exchange instead of being coated by oxyhydroxides and youthfulness of the soils preserves high CEC chlorite-vermiculite type clays that are lost in long leaching. Where soil drainage was sufficiently deep and the soil was not removed or buried by Catoctin mass movements,

leaching, acidification, and oxidation were able to transform the metabasalt and associated basic rocks into typical ultisol to the depths we sampled (maximum six feet).

Interpretation of Petiole Analyses

A main question of this study was if the grafted *vinifera* grape vines planted on the soils studied accumulate potassium in relation to the extractable soil K. **Figure 9A** shows there is essentially no universal relationship across all of our sites. Soils varied over a large K range, yet petiole K values at bloom and harvest were generally high or very high in K for soils very low in K through soils very high in K. In fact, soil parameters did not show any clear relationship to petiole K.   Shown are plots of petiole K versus Ca, Mg, and pH. Petioles did tend to have higher K and Mg at harvest and lower B.

Petioles tended toward higher Mg and lower Ca from bloom to harvest (**Figure 9A**, row 3 left). The plot of petiole K versus Mg is given in **Figure 9B**. Bloom (green squares) and harvest (purple diamonds) analyses clearly separate in this space showing a strong increase from bloom to harvest in K and Mg for some sites (O1, O2, L1, and L2), strong increase in K with slight to modest Mg gain for some (K1, P2, S1, and T1), strong K increase and slight loss of Mg for R1 and R2, and strong K loss and Mg gain at sites P1 and M2.

None of these associations relate to variations in the soils discussed above, so we are left with the possibilities of either vine culture or climate controlling the changes. We collected these data within one year in order to minimize growing season (climate) effects. Because 2014 was a relatively wet year, we will assume here that differences in rainfall, humidity and solar insolation averaged out across the region. This leaves us with canopy management, foliar nutrient applications, water availability, rootstock, and weather conditions as possible primary causes of petiolar nutrient composition. Thus, soil nutrient variation may well be a secondary or tertiary factor in influencing K uptake and transfer into grapes after veraison in Virginia.

Petiolar K and Wine pH

Petiolar K is commonly used to determine vine K status. **Figure 10** shows that pH of our new wine samples and petiolar K have positive correlations for both bloom and harvest petioles. Samples U1 and U2 were determined on nearly finished wine and have the highest pH's because the wines completed malolactic fermentation and were near bottle ready. We expect similar high pH values would have resulted had our new wine samples progressed through malolactic fermentation without developing acetobacter infections. It is tempting to interpret the low petiole K contents from sites K1 and M1 as indicative of improved wine chemistry due to lower soil K contents, which these sites exhibit, however, as noted above in discussing petiole-soil relationships, several other lower K soils produced petioles spanning the entire K-content range we measured for petioles (**Figure 9A**, row 1 left).

Likewise, soil with the highest extractable K contents did not generate anomalously high pH wines. Even at sites with the lowest soil K, the petiole data show that the vines are getting enough (if not too much) potassium. This study suggests that potassium additions to vineyard soils in Virginia are not necessary.

Future Work

The data analyzed in this phase of our project suggest that no universal relationship between soil K and petiole K exists across our study sites and that, even at sites with the lowest soil K, the vines are finding sufficient amounts of potassium. It is widely known that different rootstocks and scions have different K uptake behaviors, and that hydrologic and climatic variations can affect the bioavailability of soil nutrients. We have seen significant correlations between soil K and petiole K (and petiole K/Mg ratio) on individual sites where many of these environmental and viticultural factors are controlled. The next phase of this study incorporates continued sampling on existing sites, greenhouse trials, and virgin soil sampling in attempt to eliminate many of the confounding factors encountered thus far.

Significant Outreach Activities:
- February 2015: Research Update Presentation at 2015 VVA Winter Technical (Lucie Morton and Ernest Beasley; Charlottesville, VA)
- February 2015: "Soils, Geology and Wine Quality" Keynote Presentation at Maryland Grape Growers Association Winter meeting (Ernest Beasley; Baltimore, MD)
- February 2015: "Soils, Geology and Wine Quality" Presentation at NC State University Cooperative Extension Winter 2015 Grape School (Ernest Beasley; Hendersonville, NC)
- March 2015: "Postmodern Winegrowing Forum" Craft Beverages Unlimited Panel Discussion (Lucie Morton; Richmond, Virginia)
- March 17-19 2015: "7 Best (and Worst) Ways to Start a Vineyard" Presentation at the Eastern Winery Exposition (Lucie Morton; Syracuse, NY)

We have also been in constant contact with research professionals at Virginia Tech and commercial laboratories regarding our potassium studies. Our goal is to communicate to the industry that potassium additions are very seldom needed for wine grapes in Virginia and that additions of K, if needed, should be based on petiole data – not soils data, as it so often grossly underestimates the reservoir of K available to the vines. Tony Wolf already recommends this approach, yet the commercial laboratories continue to recommend adding K to vineyards based on soil tests, which we know do not accurately represent bioavailable K. We hope to stop this harmful practice of unnecessary K additions, as it is wasteful and most likely detrimental to Virginia wine quality.

Sample Code:		W2B	W2B	W3B	W3B	W4B	W4B	W5B	W5B	W6B	W6B
Laboratory:		A&L	VT	A&L	VT	A&L	VT	A&L	VT	A&L	VT
Organic Matter	%	2.1	na	2.2	na	2.7	na	3.4	na	2	na
pH		6.5	6.6	5.3	5.3	5.3	5.4	5.2	5.3	5.6	5.6
Buffer index		na	6.39	6.8	5.67	6.85	5.58	6.68	5.5	6.82	5.92
Acidity (H)	meq/100g	0.3	na	1.3	na	0.8	na	2.5	na	1.1	na
Acidity	%	7.5	2.2	30.8	74.7	31.4	81.3	34	63.4	23.4	52.7
Base Sat	%	92.5	97.8	69.2	25.3	68.6	18.7	66	36.6	76.6	47.3
CEC	meq/100g	4.4	2.7	4.1	5.8	2.5	6	7.3	8.4	4.7	5.4
Est. N2. Release	lbs/ac	86	na	88	na	100	na	108	na	83	na
Phosphorus (Mehlich3)	ppm	1	1	1	0.5	1	1	1	11.5	1	4.5
Phosphorus	lbs/ac		2		1		2		23		9
Potassium (K)	ppm	113	65.5	163	74.5	65	28.5	40	62.5	47	34
Potassium (K)	lbs		131		149		57		125		68
Potassium (K)	Base Sat.%	6.6	6.1	10.2	3.3	6.7	1.2	1.4	1.9	2.6	1.6
Magnesium (Mg)	ppm	29	19.5	60	40	59	40.5	88	90.5	30	29
Magnesium (Mg)	lbs		39		80		81		181		58
Magnesium (Mg)	Base Sat.%	5.5	5.9	12.2	5.7	19.7	5.6	10	8.8	5.3	4.4
Calcium (Ca)	ppm	705	469	366	190	205	143	780	437.5	637	446
Calcium (Ca)	lbs/ac		938		380		286		875		892
Calcium (Ca)	Base Sat.%	80.1	85.8	44.6	16.4	41	11.9	53.4	26.9	67.8	41.2
Sodium (Na)	Base Sat.%	1.3	na	1.5	na	2.4	na	0.8	na	1.3	na
Hydrogen (H)	Base Sat.%	7.5	2.2	30.8	74.7	31.4	81.3	34	63.4	23.4	52.7
Sulfur (SO4-S)	ppm	30	na	70	na	57	na	95	na	58	na
Zinc (Zn)	ppm	19.2	8.6	4.6	2.3	4	3	1.9	2.5	4	3.2
Manganese (Mn)	ppm	21	2.1	22	1.5	2	1	5	11.6	5	5
Iron (Fe)	ppm	28	7.1	37	11.8	26	11.6	24	38.7	31	18.2
Copper (Cu)	ppm	0.9	0.2	0.9	0.1	0.8	0.1	0.7	0.3	0.9	0.1
Boron (B)	ppm	0.4	0.1	0.2	0.1	0.1	0.1	0.6	0.3	0.2	0.1
Aluminum (Al)	ppm	739	na	1105	na	1090	na	1269	na	872	na
Sodium (Na)	ppm	13	na	14	na	14	na	14	na	14	na

Table 1. Lab results for identical soil samples from site W1 sent to the Virginia Tech soil lab (VT) and the A&L Laboratories lab (A&L).
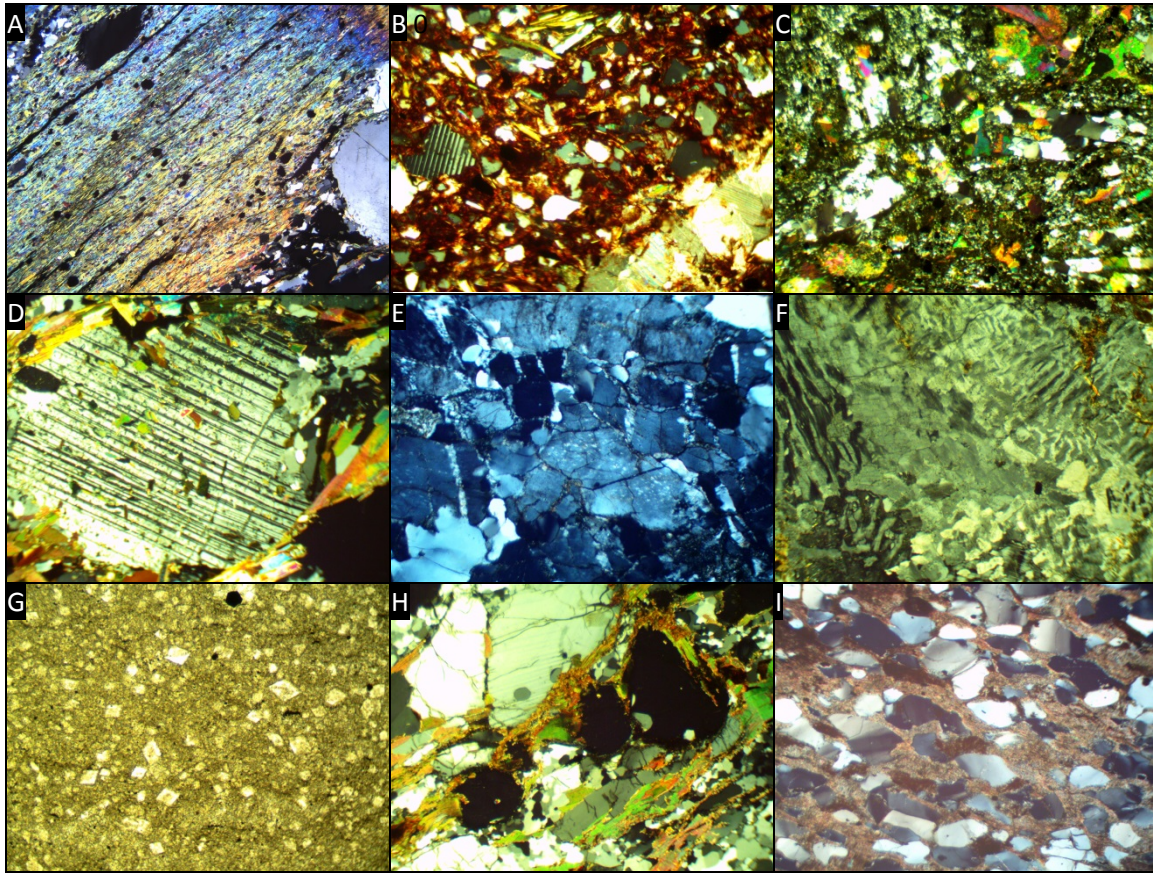
Figure 1. Low magnification (40X) polarized light photomicrographs of the main parent material rocks from the study sites. Rock types and main three minerals visible in decreasing abundance are as follows: A: phyllite (muscovite, quartz, chlorite), B: sandstone (quartz, sodic plagioclase, muscovite), C: greenstone (quartz, epidote, chlorite), D: augen gneiss (Ca-Na plagioclase, biotite, quartz), E: pyroxene granulite (quartz, alkali feldspar), F: quartz-bearing alkali syenite (alkali feldspar, Na-rich plagioclase, quartz), G: dolomitic limestone (calcite, dolomite, pyrite), H: garnet biotite gneiss (quartz, Ca-Na plagioclase, biotite, garnet [black]), I: metasandstone (quartz, kaolinite, fine grained muscovite).
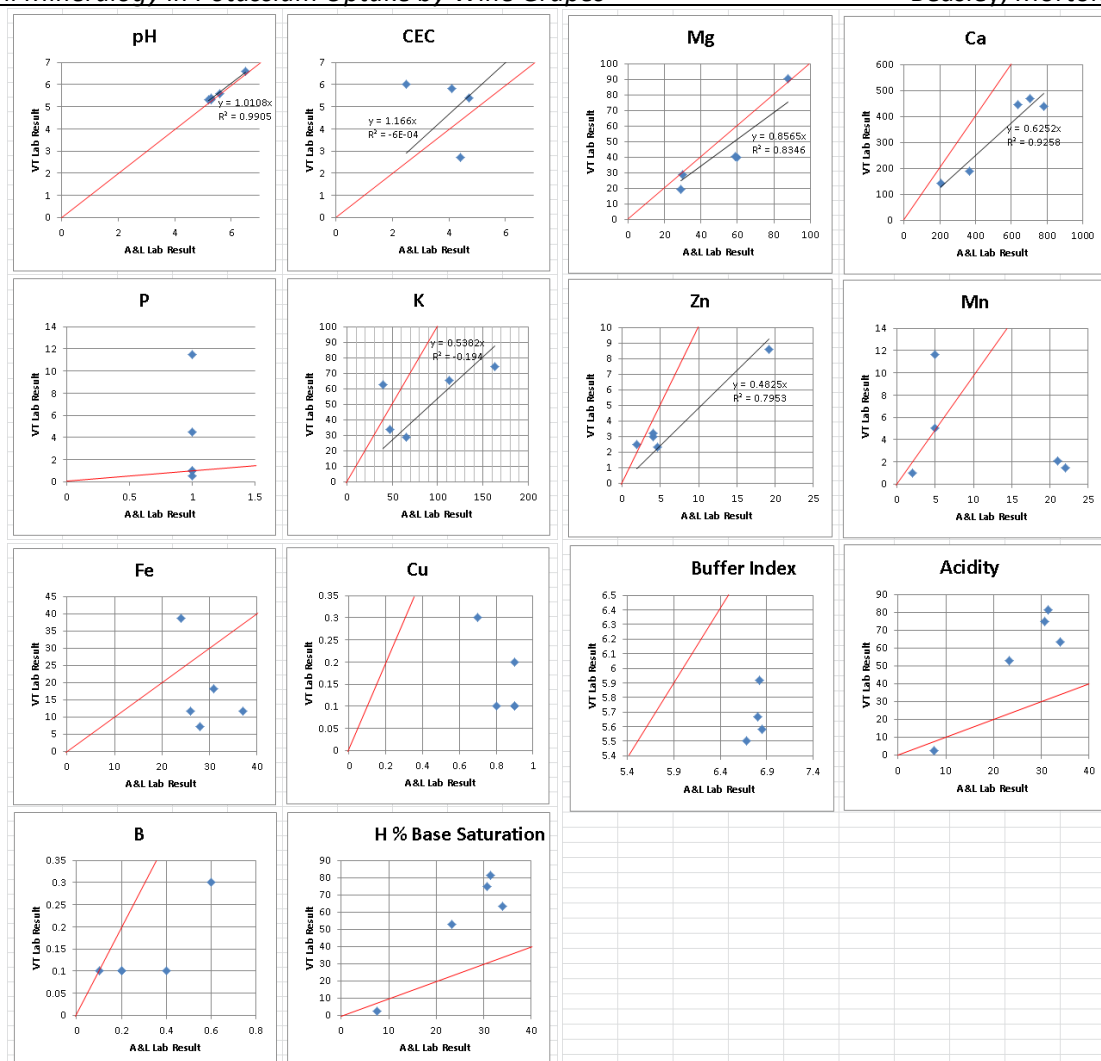
Figure 2. Cross plots of the lab results for five samples that were split and sent to VA-Tech and A&L soil labs for analysis. The red lines indicate the position of a perfect 1:1 correlation between the labs. Actual regression lines forced through (0,0) along with their R^2 values are shown for a few nutrients.
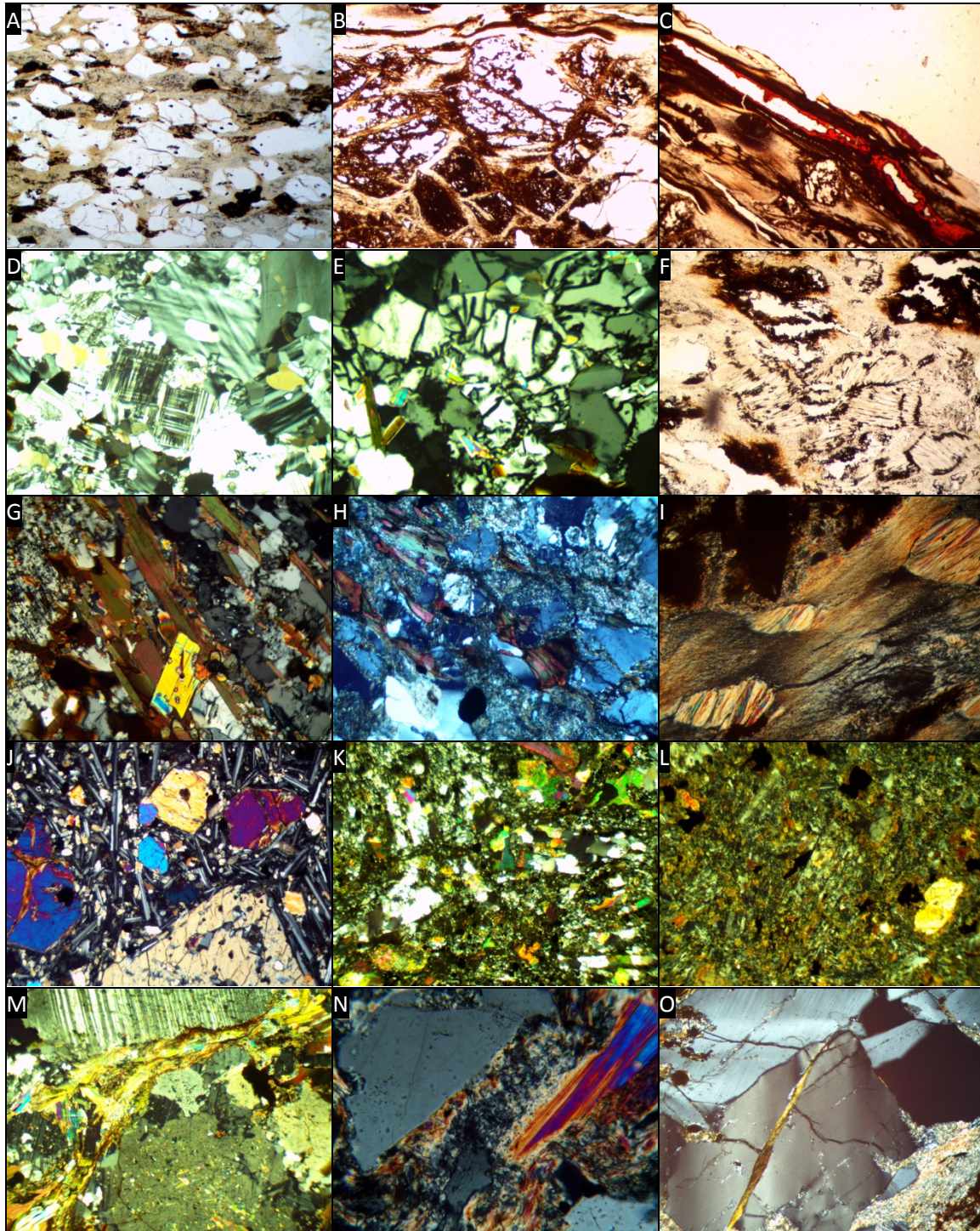
Figure 3. Low and medium magnification of clay formation from primary minerals as seen in vineyard rocks. A-C: progressive kaolinization of feldspar in metasandstone. D-F: progressive kaolinization of feldspar in granite. G-I: progressive kaolinization of feldspar and mica in biotite-muscovite gneiss. Note micas expanded into kaolinite vermicules in I. J-L: an example of fresh basalt from Mole Hill near Staunton (J) followed by unweathered greenstone (K) resulting from basalt metamorphism, then strongly weathered and argillized greenstone (L). M-O: features of mica weathering in preference over feldspars. M: Biotite (brown) andmuscovite (blue) converted to hydrated mica (yellow) between slightly altered plagioclase. N: Muscovite exfoliating and converting to kaolinite in a sandstone pore. O: Micas converted to kaolinite with traces of hydrated mica betweeen unaltered feldspar and quartz in granitic gneiss.
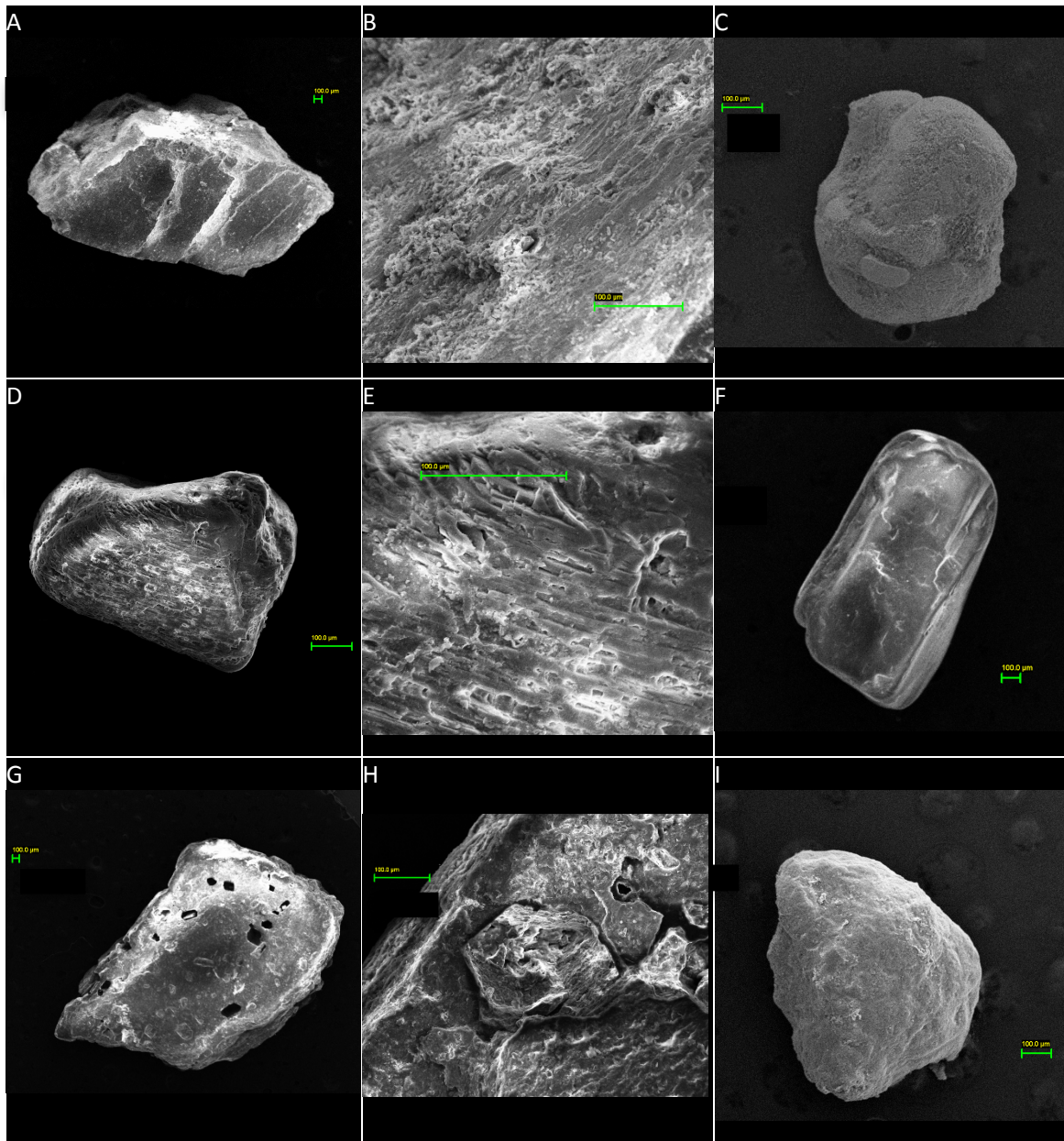
Figure 4. Scanning Electron Microscope images of sand-sized grains from soils at research sites. A-B: potassium feldspar grain from a residual soil over alkali syenite in the Blue Ridge Province at low- and high magnification. C: amorphous mineral phase (Fe- and Al-oxides) from same sample as A and B. D-E: low- and high magnification images of a well-rounded potassium feldspar grain found in the soils of the Eastern Shore. The rounded nature suggests transport by fluvial processes. Note the geometric etching pattern seen on the face of the grain as K and other elements are weathered out of the feldspar's framework structure. The source rock of this sand grain was probably located at least 100 miles to the west in the Piedmont. F: another well-rounded K-felspar grain found on the Eastern Shore. G-H: low-and high magnification images of a phyllite grain from the Piedmont. The predominant mineral in this rock is muscovite, a potassium-bearing mica. I: amorphous mineral phase (Fe- and Al-oxides) from an ultisol in the Blue Ridge Province.
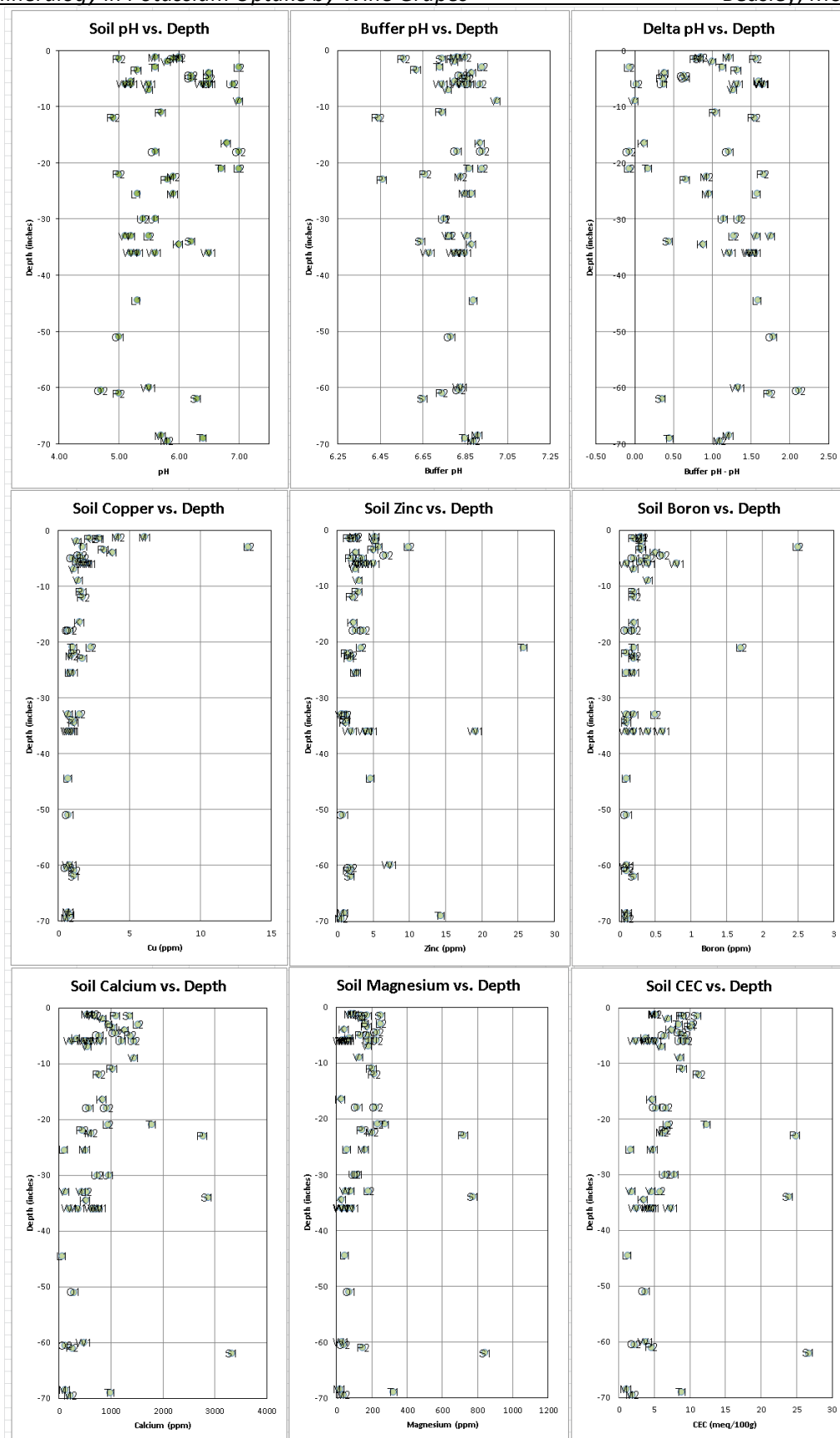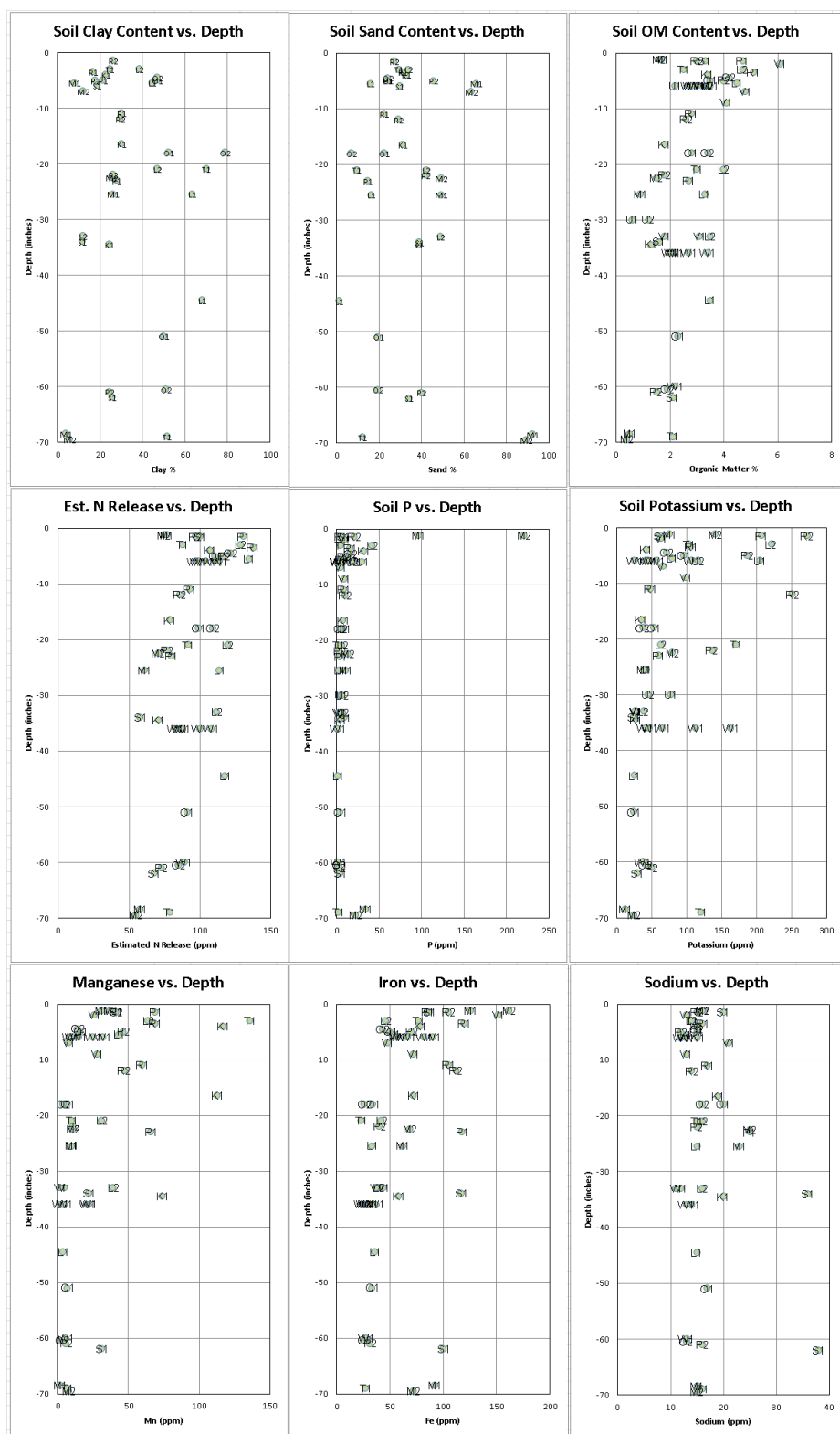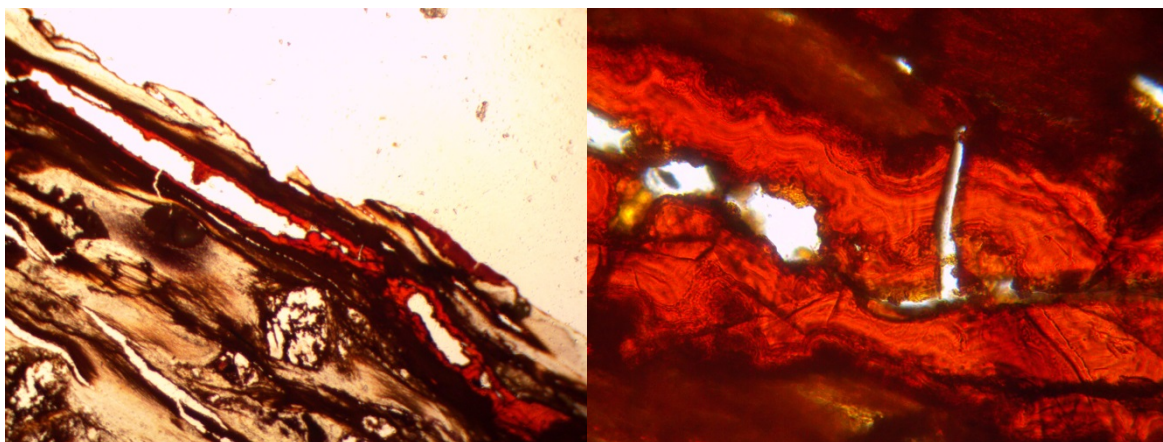
Figure 5A.

Figure 5B.

Figure 6. Amorphous Al-Si-Fe-Mn oxyhydroxide coating of a void in saprolite from site W1. The elongate, uniform, coated opening could be a fracture or a root tubule. At high magnification (right) the botryoidal character of the coating is visible indicating precipitation from soil solution. The smooth, glass-like amorphous character of the filling is evident along the fracture filled with colorless epoxy. The amorphous material impregnates the clays surrounding the void coloring it red as it does throughout the overlying B accumulation horizon.
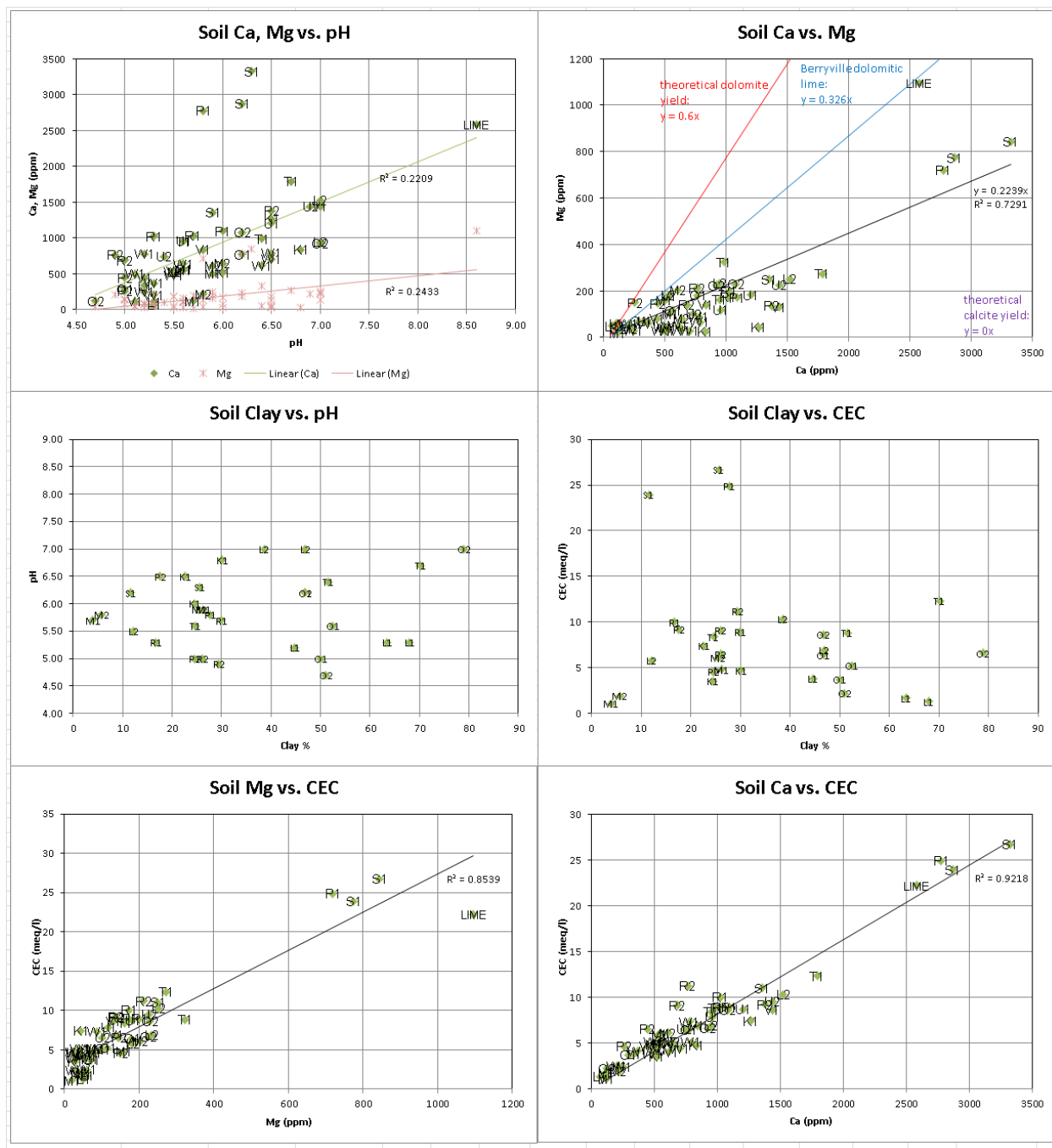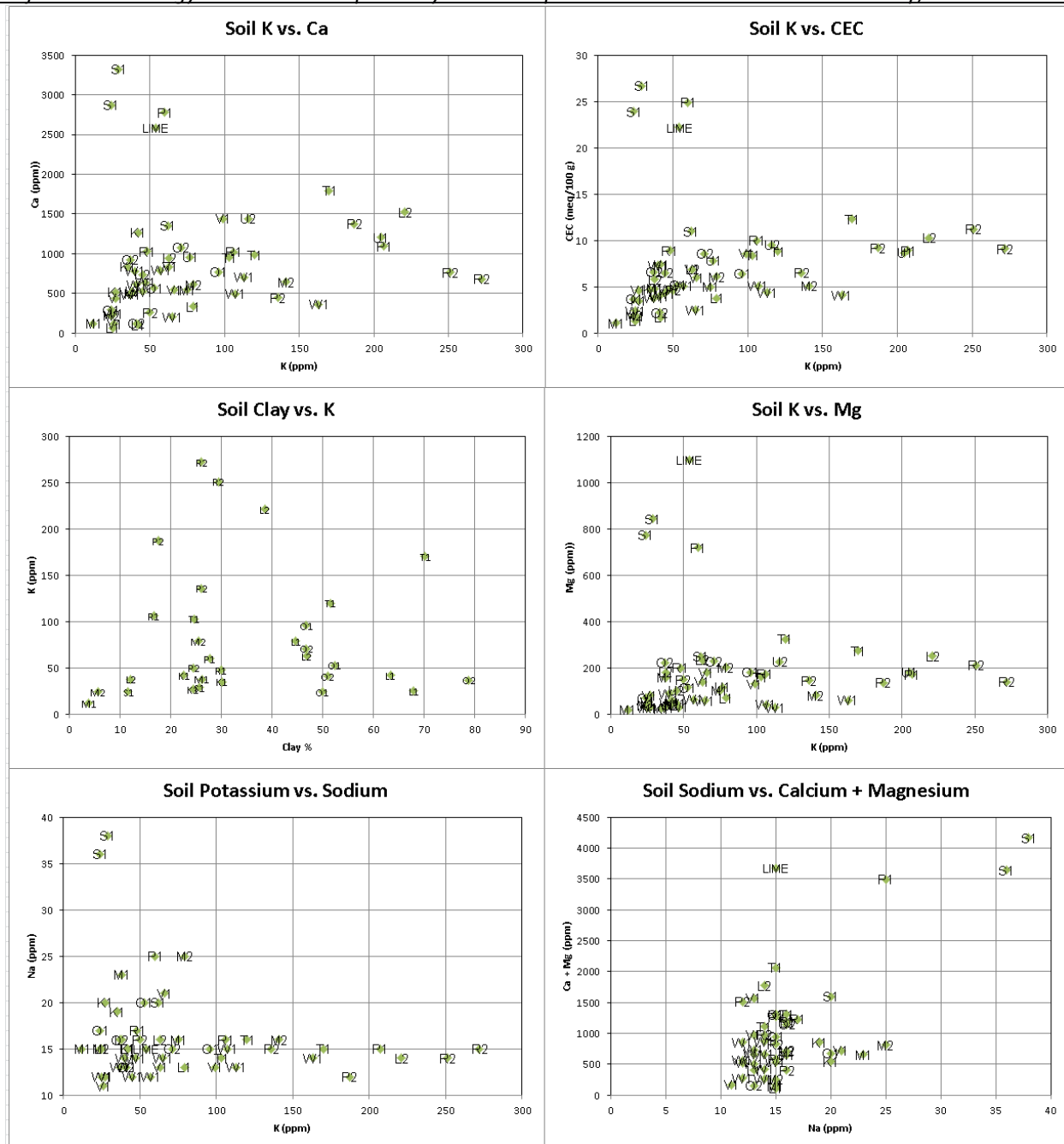
Figure 7A.

Figure 7B. Soil K results (**Figure 7B**, top and middle rows) revealed a large range of K contents in the soils from around 15 up to 275 ppm. Plotting against Ca, CEC and Mg reveal a slight positive correlation for all these parameters with the highest K contents in soils in those samples also elevated in Ca and Mg which leads to them also being in the highest CEC range of the main group. The P1 and S1 subgroup has fairly low K contents despite having extractable Ca and Mg at the levels of our lime sample. We know from depth plotting that K is highest in the plow zone (**Figure 5B**, row 2), so the main group trends are likely reflecting liming and fertilization. It is tempting to ascribe the anomalously high Ca and Mg values for P1 and S1 to dolomitic lime application until one examines their Na content (**Figure 7B**, row 3). S1 is high in Na and P1, M1 and M2 from mid depths (**Figure 7B**, row 3) are elevated in Na. We also observe that these higher Na values are in low K soils, which indicates the Na cannot be from a halite impurity in a muriate of potash fertilizer applied to the high Na sites. Once again we are left with the question of high Ca and Mg in S1 and P1 with high Na in S1 as well.
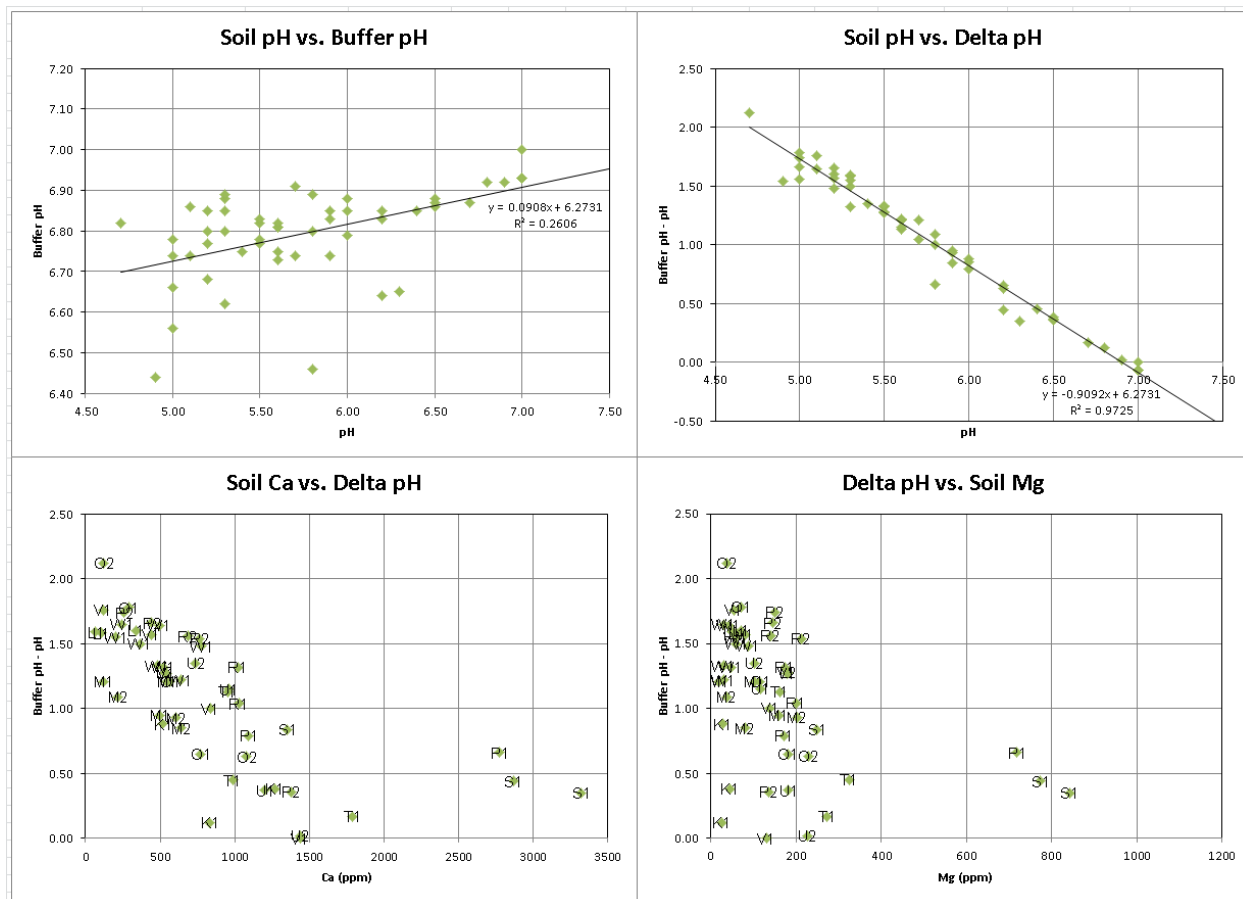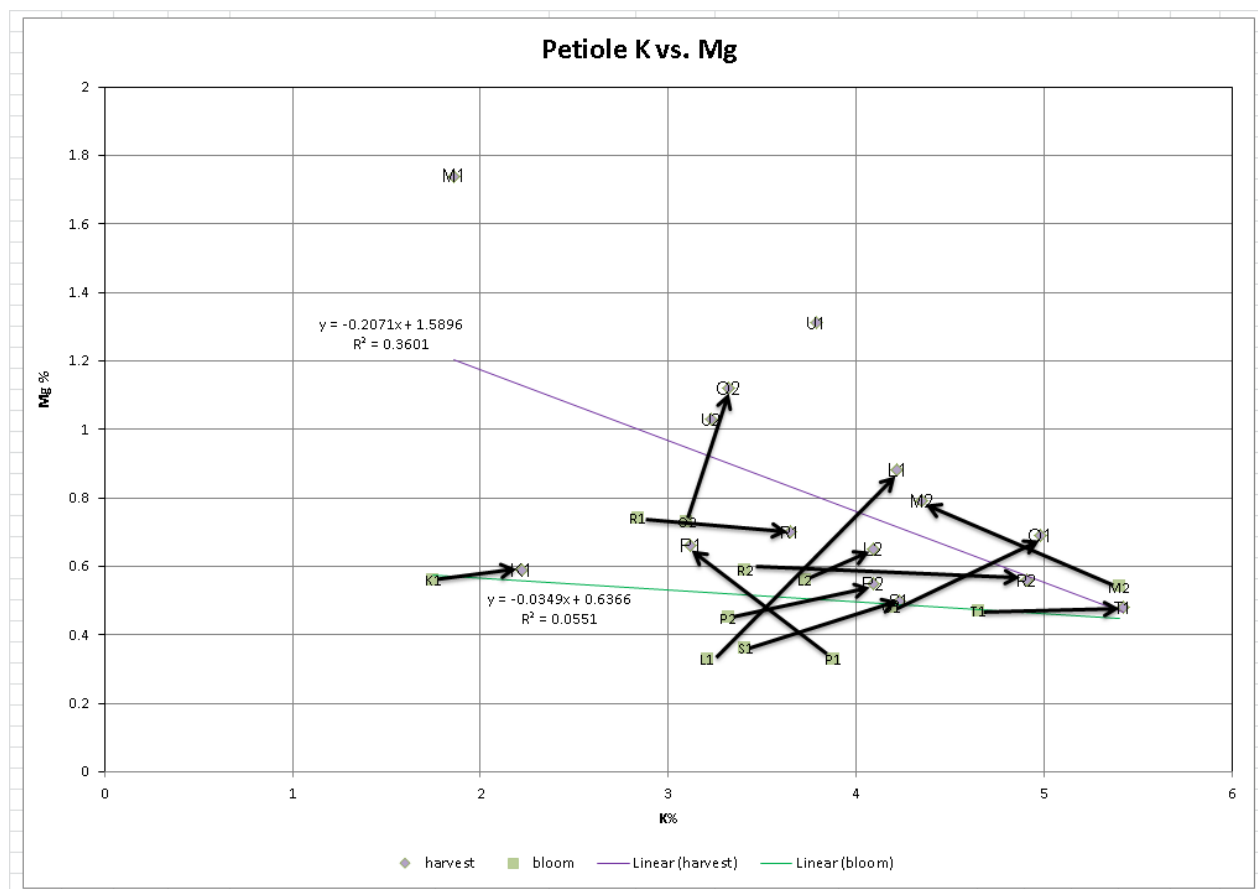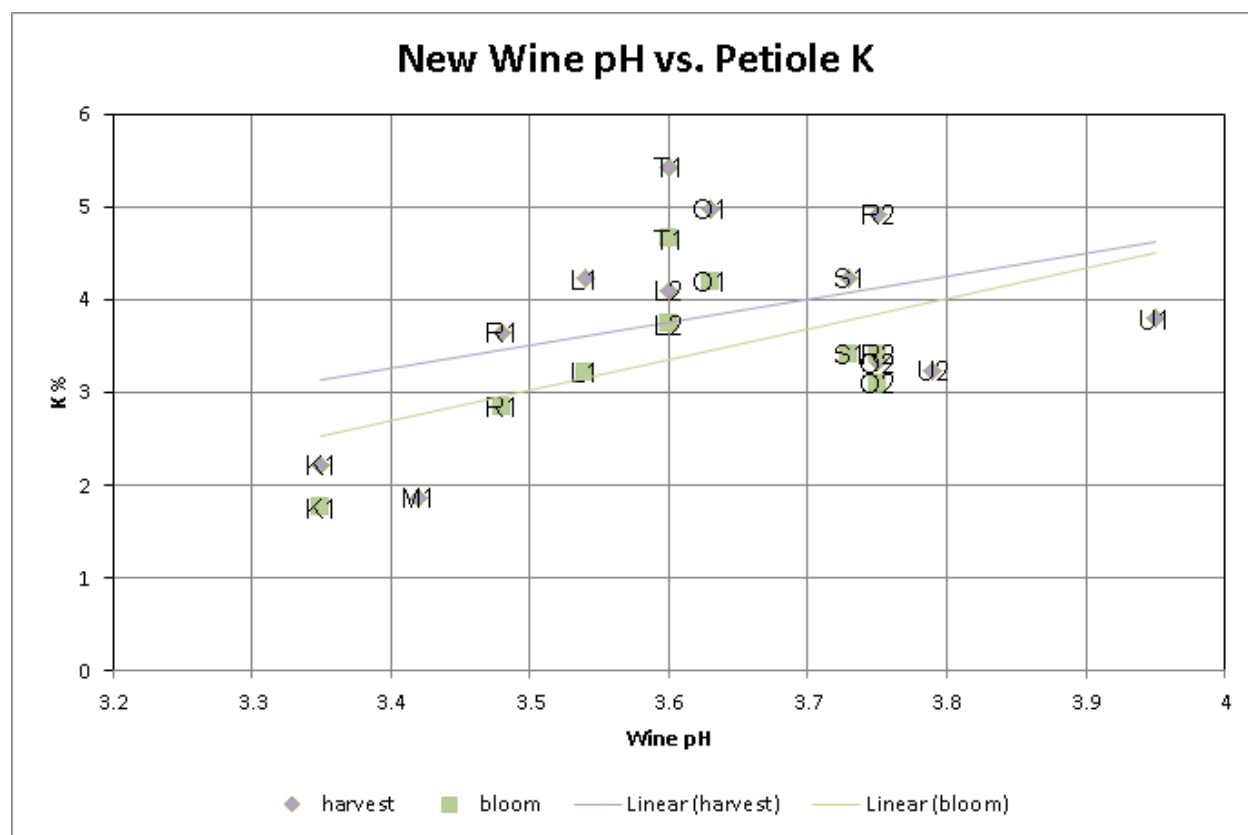
Figure 7C.

Figure 8. Pit exposures of soils from site S1. The left two photos are from the same pit. A relatively thin mixed plow zone and B accumulation zone are underlain by a very rocky, increasingly grayer and dense C horizon. Rocks in the B horizon are often reduced (blue-gray in right hand photo) when fractured as are all the rocks in the lower part of the profile.

Figure 9A.

Petiole K vs. Mg

$y = -0.2071x + 1.5896$
$R^2 = 0.3601$

$y = -0.0349x + 0.6366$
$R^2 = 0.0551$

Figure 9B. Petiole K and Mg compositions. All samples are from Merlot except U1,2 which are Cabernet Franc and P1 and S1 which are Petit Verdot. The bloom petiole sample for M1 was lost and those for U1,2 were unavailable.

Figure 10. New wine pH from fruit samples compared to petiole K. Micro-vinified wines were monitored for pH and the highest pH near dryness was used. Some samples developed volatile acidity and dropped in pH after dryness. Wine from Petite Verdot sampled at M2 was not included as it had noticeable volatile acidity at the time of the highest pH measurement which was 3.23.