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Phosphate Release: The Effect of Prebiotic Organic Compounds on Dissolution of Merrillite, Whitlockite, Chlorapatite, and Fluorapatite

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PHOSPHATE RELEASE: THE EFFECT OF PREBIOTIC ORGANIC COMPOUNDS ON DISSOLUTION RATES OF MERRILLITE, WHITLOCKITE, CHLORAPATITE, AND FLUORAPATITE

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Abstract

Phosphate is an essential nutrient on Earth, used by life for ATP, DNA, RNA, and phospholipid membranes. Therefore, if life is or ever was present on Mars, phosphorus may have played an important role in determining the habitability of an environment. Phosphorus does not have a significant volatile phase; its release from minerals is consequently critical to phosphorus availability and prebiotic chemistry. Phosphate release from Mars-relevant minerals such as merrillite and chlorapatite has been previously found to differ significantly from phosphate release from fluorapatite, the dominant phosphate phase on Earth. However, the environments in which phosphate release would have been most relevant to potential early martian life likely did not contain solely inorganic solutions. Instead, early potentially habitable environments likely contained abundant organic matter delivered by carbonaceous chondrites and interplanetary dust particles.

To determine the effect of Mars-relevant organic compounds on dissolution of Mars-relevant minerals, batch dissolution experiments dissolving merrillite, whitlockite, chlorapatite, and fluorapatite in solutions of one of acetic, succinic, methylsulfonic, mellitic, and oxalic acids were conducted. Minerals were chosen to include the dominant phosphate-bearing minerals in martian meteorites (merrillite and chlorapatite), whitlockite, which is similar to merrillite and potentially relevant to Mars, and fluorapatite, the dominant primary phosphate-bearing mineral on Earth. Organic compounds were chosen based on compounds measured in carbonaceous chondrites and interplanetary dust particles and therefore likely to be present in the martian soils, as well as the proposed breakdown products of refractory organic matter in martian soils.

Results of our dissolution experiments indicate that a range of organic compounds likely to be present in martian soils are capable of enhancing nutrient release from the dominant phosphate minerals present in martian meteorites. Phosphate release from chlorapatite, whitlockite, and merrillite was enhanced by four of the organic acids examined (mellitic, oxalic, succinic, and acetic) – methylsulfonic had no effect to slightly inhibitory effect. The effects of the organic acids could be explained by the denticity of the ligand, the strength of the complex formed with calcium, and the extent of saturation of the solutions. Interestingly, the more quickly dissolving Mars-relevant minerals (merrillite, whitlockite, and chlorapatite) were more strongly affected by the organic compounds used than fluorapatite. With recent detections of organic compounds on Mars, these results suggest that organic matter has played an important role on weathering and nutrient release on that planet.

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1.0 Introduction

Phosphorous, either as phosphate (Powner et al., 2009) or as a more reduced form (Pasek and Block, 2009; Pasek and Kee, 2011), is considered essential for life to form. Life uses phosphate to stabilize ribonucleic acid (RNA), deoxyribonucleic acid (DNA), and phospholipid membranes. Phosphate likely also played important roles in prebiotic chemistry including as a pH buffer and catalyst (Powner et al., 2009). As phosphorus does not have a significant volatile phase, its release from minerals is critical to its availability to life and prebiotic chemistry. The low solubility of phosphate-bearing phases and the poor reactivity of phosphate with organic compounds has therefore been referred to as the "phosphate problem" (Westheimer, 1987) facing the evolution of life.

Phosphate release is controlled by a variety of factors including mineralogy and pH. Phosphate release from Mars-relevant minerals such as merrillite and chlorapatite has been previously found to differ significantly from phosphate release from fluorapatite, the dominant phosphate phase on Earth (Adcock et al., 2013). However, these previous studies of phosphate-bearing minerals on Mars have included solely inorganic solutions, when phosphate release most relevant to potential early martian life would likely have occurred in solutions that contained abundant prebiotic organic matter.

Annually, 2.4×10^8 g of organic material is deposited on Mars from carbonaceous chondrites and interplanetary dust particles (IDPs) (Flynn, 1996). The organic compounds found in carbonaceous chondrites and therefore likely to be present on early Mars encompass a broad range of compounds including carboxylic acids, dicarboxylic acids, and sulfonic acids (Pizzarello et al., 2006). Carboxylic acids are the most concentrated water soluble organic compounds in the Murchison and many other carbonaceous chondrites

(Huang et al., 2005), and the most abundant carboxylic acid by far is acetic acid (Huang et al., 2005). The highest concentration dicarboxylic acid in the Tagish Lake (CI2) meteorite is succinic acid, (Pizzarello and Huang, 2002), and the highest concentration sulfonic acid in the Murchison meteorite is methylsulfonic acid (Cooper et al., 1992).

In addition to the water soluble organic compounds delivered directly to the martian surface, large amounts of refractory organic matter are also deposited on the martian surface (up to 3% of meteoritic material) (Hayes and Biemann, 1968). Analysis done by Sample Analysis at Mars (SAM) has detected the presence of organic predecessors to chlorobenzene, as well as a range of organics (Freissinet et al., 2015; Miller et al., 2016) Previous work has indicated that the degradation products of this material in martian soils would likely include benzencarboxylic acid (mellitic acid), as well as acetic and possibly oxalic acid, with concentrations of mellitic acid reaching 500 ppm in martian soils (Benner et al., 2000). Water-rock interactions on Mars were therefore likely impacted by these organic compounds, with previous experiments showing enhanced dissolution of fluorapatite and hydroxyapatite in the presence of organic compounds (Tanaka et al., 1989; Neaman et al., 2005; Goyne et al., 2006).

To assess the availability of phosphate from minerals in organic-compound-bearing environments on early Mars, therefore, we measured the dissolution rates of the Mars-relevant phosphate-bearing minerals whitlockite, merrillite, chlorapatite, and fluorapatite in the presence of five prebiotic organic compounds likely present on early Mars: acetate, succinate, oxalate, methylsulfonic acid, and mellitic acid. To the best of our knowledge, prior to this work, no studies have examined the effect of organic compounds on whitlockite, merrillite, or chlorapatite dissolution. Results indicate enhanced dissolution of phosphate in the presence of acetate, succinate, oxalate, and mellitic acid, and decreased dissolution in the presence of methylsulfonic acid, showing the importance of organic compounds specifically and aqueous chemistry more broadly to mineral dissolution and nutrient availability on Mars. These results provide evidence that a number of organic compounds potentially present in martian soils enhance the availability in Mars-relevant environments. This is an important indicator that the organic matter not only delivered to, but also produced on Mars, affected chemical weathering, soil degradation and formations, as well as the aforementioned nutrient release.

2.0 Materials and Methods

Minerals

Three phosphate-bearing minerals were synthesized for use in dissolution experiments: whitlockite ($Ca_9Mg(PO_3OH)(PO_4)_6$); merrillite ($Ca_9NaMg(PO_4)_7$); and chlorapatite ($Ca_5(PO_4)_3Cl$). Whitlockite was synthesized following Hughes et al. (2008). One gram of hydroxyapatite was mixed with 0.300 g magnesium nitrate in 90 ml 18.2 MΩ cm^{-1} water. The mixture was acidified to a pH < 2.8 with phosphoric acid and heated for seven days at 240 °C. Merrillite was also synthesized following Hughes et al. (2008) by heating whitlockite for 24-48 hours (h) at 1095 °C. Chlorapatite was synthesized by combining 3.12 g hydroxyapatite with 3.88 g calcium chloride and heating for 24 h at 1100 °C (Prener, 1967; Prener, 1971; Tacker et al., 1993; Dachs et al., 2010). A very pure form of naturally abundant fluorapatite ($Ca_5(PO_4)_3F$), originating from Durango, Mexico, was purchased from Minerals Unlimited (Ridgecrest, California).

Each mineral was powdered, sieved, and cleaned prior to use in the dissolution experiments. Minerals were crushed in an agate mortar and pestle and then sieved to the size fraction 38-75μm (400-200 mesh) for merrillite, chlorapatite, and whitlockite, and 75-150 μm (200-100 mesh) fraction for fluorapatite. The respective size fraction for each mineral was cleaned by sonicating in spectrographic grade ethanol at three minute intervals, multiple times, until the supernatant was clear.

Batch Dissolution Experiments

For each dissolution batch, 0.1500 g of mineral (i.e. whitlockite, merrillite, chlorapatite, or fluorapatite) were measured into 250 mL polypropylene bottles and autoclave sterilized to prevent microbial contamination during experiments containing organic acids. Organic acid, or potassium nitrate solutions (180 mL), were added to the 250 mL polypropylene bottles. Solutions were made with 18.2 MΩ cm^{-1} deionized water (DI) and 0.01 M solutions of potassium nitrate, with or without the organic compound of interest, were adjusted to pH 5.5 using high purity nitric acid and potassium hydroxide and then filter sterilized with a 0.2 μm polycarbonate filter. Sodium acetate (> 99% purity) and sodium succinate hexahydrate (98 % purity) were purchased from Alfa Aesar. Sodium methyl sulfate (98 % purity) and mellitic acid (> 98 % purity) were purchased from TCI. Sodium oxalate (> 99.5 % purity) was purchased from Sigma Aldrich. Inorganic dissolution control and mineral-free blank experiments were performed for each mineral-organic acid condition. Inorganic dissolution controls contained only potassium nitrate solution and mineral. Blanks were prepared with solutions containing no mineral. All experiments, blanks and controls were performed in duplicate.

Batch dissolution experiments were agitated at 100 rpm in a temperature-controlled shaking water bath at 25.0 °C. Ten mL of solution was removed every hour for six hours as well as once per day for the following 2 days. The pH was measured on a separate, unfiltered aliquot. The remaining sample was filtered using a 0.22 μm polypropylene filter, and acidified to 1% v/v high purity HNO_3 for subsequent analysis of phosphorus and calcium.

Analytical Methods

Samples containing acetic, succinic, methylsulfonic, and mellitic acids, as well as the inorganic controls, were analyzed for phosphorus content using the colorimetric methyl blue/ascorbic acid method (Murphy and Riley, 1962). Phosphate samples were developed for 30 minutes in the presence of the indicator reagents. Reagent A of the colorimetric method is 1.200 g of ammonium molybdate tetrahydrate (in 25 mL DI) to be mixed with 0.029 g potassium antimony tartarate (in 10 mL DI) and 14.1 mL concentrated sulfuric acid (in 86 mL DI). Reagent B is 0.2112 g of ascorbic acid (in 65 mL DI). Reagent A (1 mL) and reagent B (0.35 mL) are added to 1 mL of sample with 4.75 mL of DI for the development period. The emergence of a blue shade indicates the presence of phosphate in the sample (Murphy and Riley, 1962). Sample absorbance was measured on a Thermo Scientific Genesys 10S UV-Vis spectrophotometer at 882 nm wavelength. The absorbance of the colorimetric phosphate complex at 882 nm is linearly correlated to phosphate concentrations from 0.005 mM to 0.100 mM. Linear calibration curves based on 6 standards had R^2 values of 0.98 or better. Analytical uncertainty was estimated as 0.003 mmol/L, based on the average of the standard error of the regression of the calibration.

Phosphate in samples containing oxalic acid could not be measured using the colorimetric ascorbic blue method, as the presence of oxalic acid diminished absorbance readings to zero in both standard and sample solutions. Therefore, oxalic acid samples were analyzed for phosphate only using an Agilent 7700x inductively coupled plasma mass spectrometer (ICP-MS). Samples for ICP-MS analysis were diluted up to 40 x with 18.2 MΩ cm^{-1} water and acidified to 1 % v/v ultra-pure HNO_3. Calibration curves based on six standards had R^2 values of 0.99 or better, with upper and lower detection limits of 0.005 mM and 0.100 mM, respectively.

Calcium concentrations were measured using flame atomic absorption (AA) spectrometry on a Thermo Scientific, iCE 3000 Series AA spectrometer. To prevent phosphorus interference with calcium, 0.36 M lanthanum chloride was added to the samples at 10 % v/v (Willis, 1962). The analytical uncertainty was estimated as 5%, based on values from Standard Methods (Federation, Water Environmental et al., 2005).

Calcium concentrations could not be determined for samples containing oxalic acid. The addition of lanthanum chloride (an inhibitor for phosphorus interference) to oxalic acid AA samples resulted in precipitate formation. Goyne et al. (2006) also observed a decrease in calcium concentration during mineral dissolution in the presence of oxalic acid, noting that a calcium oxalate precipitate likely formed. A similar reaction may have removed aqueous calcium from solution in the mineral-oxalic acid batch experiments.

Negatively Charged Ligands in Solution

Using the mass action equation for ligand protonation and the log K values for each organic acid we calculated the total number of negatively charged ligands at the initial pH and final pH to ensure denticity was not altered over the duration of each experiment.

PhreeqC

Because previous work has found that the solubility of phosphate-bearing minerals is determined by a leached layer with the composition of anhydrous di-calcium phosphate (DCPA) (Chairat et al., 2007), we determined the saturation index (SI) for the initial and sixth point (final used in the dissolution rate calculations) for each mineral using the computer code PHREEQC (Parkhurst and Appelo, 1999) using the equilibrium constant for DCPA determined by Chairat et al., (2007).

3.0 Results

pH Change

Overall, pH values for the dissolution experiments increased over time (Table 1). Increase was greatest for inorganic solutions and solutions containing methylsulfonic and oxalic acid. This is most likely due to the buffering effect of the weak organic acids relative to methylsulfonic acid, which is a strong acid, and the inorganic solution, which contained no organic acids. The increase in pH in the oxalic acid solution is most likely due to the greatly enhanced dissolution in those solutions (Table 1).

Ca and P Release

Moles of calcium and phosphorus released were calculated after Welch and Ullman (2000), by accounting for volume loss during sampling:

$$m_{(t)} = m_{(t-1)} + (c_{(t)} - c_{(t-1)}) * V_{(t-1)} \qquad (Eq\ 1)$$

where $m(t)$ is the moles released at time t, C is the concentration of calcium or phosphate measured at time t and $t\text{-}1$, and V is the volume of solution in L.

Phosphate release and calcium release where calcium was measurable were both linear over the first 6 sampling points used for calculation of dissolution rates (Figure 1) (calcium was not measurable in the presence of oxalic acid likely due to the precipitation of calcium oxalate). For all minerals, except fluorapatite, phosphate release was largest in the presence of oxalic acid, and enhanced for all organic compounds excluding methylsulfonic acid. Similarly, calcium release was enhanced for whitlockite, merrillite, and chlorapatite in the presence of all organic acids except methylsulfonic acid, with mellitic acid generally having the larger effect. Elemental release trends in specific organic acid solutions are discussed further below in the discussion. Release of calcium and phosphate from the minerals showed the same relative trends as those observed by Adcock et al., (2013). As in Adcock et al. (2013) fluorapatite showed the lowest dissolution rate for phosphate and calcium, while chlorapatite showed the greatest for calcium, followed by whitlockite and merrillite.

Stoichiometry

The calcium and phosphate concentrations in solution were compared to the stoichiometric Ca:P ratio in each mineral. Phosphate and calcium stoichiometries of chlorapatite, whitlockite, and fluorapatite used in this study are based on the International Mineralogical Association (IMA) formulae: chlorapatite, $Ca_5(PO_4)_3Cl$; whitlockite, $Ca_9Mg(PO_3OH)(PO_4)_6$; and fluorapatite, $Ca_5(PO_4)_3F$. The Ca:P ratio in merrillite is based on a previous study from Adcock et al., (2013), which used electron microprobe analysis (EPMA) to confirm calcium substitution in synthesized merrillite with the following formula ($Ca_{9.5}Mg(PO_4)_7$).

All minerals showed non-stoichiometric dissolution. All organic acids, and the inorganic control, trend strongly towards the Ca:P stoichiometric ratio when reacted with fluorapatite, and all solutions are close to stoichiometric for merrillite. Whitlockite shows decreased Ca:P ratios for all organic compounds except mellitic acid, and chlorapatite shows enhanced Ca:P ratios for all organic compounds. These trends are further discussed below in the discussion.

Mineral Dissolution Rates

Moles of calcium and phosphorus released calculated as discussed above (Equation 1) as a function of time are fit with a linear regression, where the slope of the line is the rate of calcium or phosphorus release. The rate of dissolution of the mineral is then calculated from either the calcium or phosphate release rate using the expression below.

$$r_{diss} = \frac{\Delta m/\Delta t}{A \times S} \qquad \textit{(Eq 2)}$$

where r_{diss} is the mineral dissolution rate in mol mineral m^{-2} s^{-1}, $\Delta m/\Delta t$ is calcium or phosphate release rate in mol s^{-1}, A is the total surface area of the mineral in m^2, and S is the stoichiometric ratio of the elements calcium or phosphate in the mineral.

Inorganic dissolution rates of merrillite, whitlockite, chlorapatite, and fluorapatite measured in this study were slightly faster than rates previously measured under similar geochemical conditions (Valsami-Jones et al., 1998; Welch et al., 2002; Guidry and Mackenzie, 2003; Adcock et al., 2013) (Figures 1, 2, and 3). Dissolution of all minerals in inorganic solutions are within one order of magnitude of previously published dissolution rates at comparable pH values (Valsami-Jones et al., 1998; Welch et al., 2002; Guidry and Mackenzie, 2003; Adcock et al., 2013) (Figure 3). Autoclaving the minerals prior to dissolution may have altered the mineral surfaces, resulting in higher reactivity and therefore higher dissolution rates. Jenneman et al. (1986) suggests that autoclaving minerals increases pore size as well as penetrable depth of the mineral surface. The dissolution rates are, however, largely comparable with previous rates (i.e. within one order of magnitude).

Four of the five organic acids used in this study enhanced mineral dissolution of chlorapatite, whitlockite, and merrillite (Figure 3). Mellitic acid causes the largest enhancement in dissolution of these minerals, and succinic and acetic acid both slightly enhance dissolution (Figure 3). Methylsulfonic depresses mineral dissolution, and oxalic acid caused significantly enhanced phosphate release (calcium release could not be measured due to the precipitation of calcium oxalate). Relative dissolution rates are further discussed below in the discussion.

Saturation Indices

Saturation indices of the first and sixth points for each inorganic solution relative to the phase likely present in leached layers, Di-Calcium Phosphate Anhydrous (DCPA) indicate that the solutions in the fluorapatite dissolution experiments remain more undersaturated than all other conditions.

4.0 Discussion

Phosphate release from minerals is critical for availability to life and can be enhanced in the presence of organic compounds. Early martian environments likely contained prebiotic organic compounds, deposited by IDPs and carbonaceous chondrites, in addition to phosphate minerals (Flynn, 1996). To test the effect of these compounds on phosphate release from Mars-relevant minerals, we performed dissolution experiments of merrillite, whitlockite, chlorapatite, and fluorapatite in the presence of the organic compounds mellitic acid, acetic acid, succinic acid, oxalic acid, and methylsulfonic acid. Below we discuss the results of these experiments and their implications for Mars.

Stoichiometry of Dissolution

All minerals showed non-stochiometric dissolution, with merrillite and fluorapatite showing Ca:P ratios that are closest to stoichiometry within the minerals, respectively. (Figure 5). Whitlockite shows decreased Ca:P ratios for all organic compounds except mellitic acid, and chlorapatite shows enhanced Ca:P ratios for all organic compounds (Figure 5).

Multiple previous studies of fluorapatite dissolution have shown the initial release of calcium to be greater than the release of other elements such as phosphate or fluorine, with longer term release (up to two months duration) reaching ratios that are closer to stoichiometric ratios (Valsami-Jones et al., 1998; Welch et al., 2002; Guidry and Mackenzie, 2003; Chairat et al., 2007). Enhanced Ca:P release is potentially due to the preferential leaching of calcium from the phosphate mineral surface (Valsami-Jones et al., 1998). Following the initial leaching of calcium, phosphate is released from a calcium-depleted mineral surface layer, resulting in a Ca:P ratio that trends towards stoichiometric dissolution. In addition to the possible formation of a cation-depleted surface layer, re-adsorption of calcium onto the mineral surface could cause non-stoichiometric dissolution (Guidry and Mackenzie, 2003; Goyne et al., 2006). The Ca:P ratios measured here indicate that both processes are likely occurring in our experiments.

Effect of Organic Acids on Dissolution Rates

Organic compounds have been previously found to enhance dissolution by three mechanisms: 1) decreasing the pH of the solution, which can enhance dissolution (Tan, 1986; Furrer and Stumm, 1986); 2) forming surface complexes that enhance dissolution (Furrer and Stumm, 1986; Stumm, 1997); and 3) enhancing dissolution by complexing ions in solution and therefore changing the extent of saturation of the solution with respect to a solid phase (Drever and Stillings, 1997). Our solutions were pH-controlled, and consequently we do not anticipate differences in mineral dissolution rate due to pH. Our experiments do appear to capture both the enhancement of dissolution at the mineral surface, as well as changes in extent of saturation, which we describe below.

Oxalate ions in solution resulted in the largest increase in phosphate release (calcium release could not be measured due to the presumed formation of calcium oxalate as has been previously documented (Goyne et al., 2006)) for all minerals. Oxalate has two carboxyl groups, both of which are fully deprotonated at the pH of our experiments, and it has previously been documented to function as a bidentate ligand (Valsami-Jones et al., 1998; Neaman et al., 2005). Previous work by Furrer and Stumm (1986) found that bidentate ligands can enhance dissolution by ion complexation at the mineral surface, a process that they did not observe for monodentate ligands. Previous work has found that five membered chelate rings, such as oxalate, are particularly effective at enhancing dissolution, one that we also observe here (Furrer and Stumm, 1986; Neaman et al., 2005; Goyne et al., 2006).

Mellitic acid shows, in general, the largest enhancement of calcium release relative to inorganic solutions. Mellitic acid has the largest number of carboxylic acids (4 per molecule at the pH of our experiments) used in our experiments. Previous work by Wu et al. (1996) suggests multiple bonding possibilities for mellitic acid, including acting as a bidentate ligand, chain formation, and monodentate binding. We would therefore expect mellitic acid to preferentially enhance dissolution by both ion complexation at the mineral surface as a bidentate ligand (similar to oxalic acid), but also by complexing calcium ions in solution, and changing the extent of saturation. We observe both effects in our dissolution experiments.

Acetic acid, succinic acid, and mellitic acid all enhance calcium release from whitlockite, merrillite, and chlorapatite significantly relative to calcium release from the inorganic mineral control (Figure 1). In contrast, calcium release from fluorapatite is enhanced to a much greater extent by mellitic acid than by acetic acid or succinic acid. Both succinic and acetic acid are monodentate ligands at this pH, and we would not expect them to significantly enhance dissolution rates by forming surface complexes, a finding that has been previously documented for fluorapatite (Neaman et al., 2005; Goyne et al., 2006). In contrast, mellitic acid behaves at times as a bidentate ligand, and would therefore strongly enhance dissolution by forming a complex at the mineral surface, consistent with our observations of fluorapatite dissolution (Figure 1).

In addition to directly complexing calcium at the surface, organic acids can also complex cations in solution, changing the extent of saturation with respect to a dissolving phase (Drever and Stillings, 1997). Previous work has found that fluorapatite forms a leached surface layer during dissolution experiments that controls the solubility of the reaction (Chairat et al., 2007). To test whether the extent of undersaturation with respect to this potential leached layer might be affecting dissolution rates in our experiments, we calculated the saturation index for the first and sixth point of each of our inorganic experiments with respect to the mineral present in the leached layer (Di Calcium Phosphate) using the numerical program PhreeqC (Parkhurst and Appelo, 1999). Our results (Table 2) show that the solutions present in the fluorapatite dissolution experiments are most undersaturated, with solutions in the chlorapatite, whitlockite, and merrillite experiments significantly closer to equilibrium. We therefore hypothesize that because dissolution in the presence of chlorapatite, whitlockite, and merrillite is occurring closer to equilibrium, all organic compounds enhance dissolution by complexing the calcium ions in solution and changing the extent of saturation. In contrast, for fluorapatite dissolution, we hypothesize that dissolution is occurring far from equilibrium on the dissolution plateau, resulting in little change in dissolution in the presence of the monodentate acetic and succinic acids.

To interpret the behavior of the monodentate ligands that likely enhance dissolution by changing the extent of saturation, we would like to examine the strength of the stability constant for the ligand with the calcium cation, which has previously been used to explain differences in elemental release (Hausrath et al., 2009). However, stability constants have not been measured for the complexation of calcium and magnesium by the organic acids used in this study. The strength of the complex of the ligand with cations is, however, correlated with the pKa of the acid (Fein et al., 2001). We therefore compare the enhancement of the dissolution rate in the presence of each organic compound relative to the inorganic control to the pK_a value for each acid as a proxy for the stability constant (Figure 4, Table 3). The pKa was a good predictor of calcium release from chlorapatite, whitlockite, and merrillite where we expect these complexes to be important. In calcium release from fluorapatite, where we do not expect these complexes to be important due to the greater extent of undersaturation, no such trend is observed (Figure 4).

Dissolution experiments in the presence of methylsulfonic were either slightly decreased relative to, or similar to, the inorganic controls. The lack of enhancement is consistent with the fact that it is a strong acid, and therefore not expected to bind to the calcium (Figure 4). We anticipate also that slight traces of sulfate or sulfite contamination in the methylsulfonic acid may be forming an armoring layer and decreasing dissolution based on previous observations of sulfite as a breakdown product of methylsulfonic acid (Thompson et al., 1995) (Figure 3).

Implications for Mars

The results of this study indicate that acetic, succinic, oxalic, and mellitic acids, all potentially present on early Mars, enhance the dissolution of all the Mars-relevant minerals chlorapatite, merrillite, and whitlockite. Therefore, the organic compounds brought to Mars by IDPs and carbonaceous chondrites, and their degradation products, would have increased the availability of phosphate on early Mars. Below we extrapolate our experimental results to the organic concentrations and pH conditions likely on Mars.

Estimates suggest that the concentrations of benzencarboxylates, such as mellitic acid, present in martian soils may have been as high as 500 ppm organic carbon by weight in the top meter of martian soil (Benner et al., 2000). That corresponds to a concentration of 1.48 millimole per kg soil, which, assuming 50% pore space of the soil, and 50% to 10 % saturation of the pore space, is equivalent to 5.84 mM to 29.2 mM, respectively. This is slightly lower than the concentrations used in these experiments (50 mM) which are also higher than organic concentrations reported in some terrestrial soil solutions (e.g. 0.01 M (Stevenson, 1991; Stillings et al., 1995; Drever and Stillings, 1997). However, elemental release has been shown at concentrations as low as micromolar to millimolar (Goyne et al., 2006; Olsen and Rimstidt 2008). Since previous work has shown that the relationship between the log dissolution rate and the log concentration of oxalic acid is linear (Olsen and Rimstidt, 2008), our results can therefore be extrapolated to a range of Mars-relevant concentrations.

Increase in phosphate release in the presence of organic compounds may have been particularly pronounced at the higher and more habitable pH values found at Gale Crater (Grotzinger et al., 2014) and the Phoenix landing site (Kounaves et al., 2010). Greater deprotonation at higher pH values (above the pKa_s of the organic acids) would provide more reactive, negatively charged ligands to react with phosphate minerals and complex aqueous cations.

These experiments indicate the potential importance of organic compounds on nutrient release and more broadly mineral dissolution, weathering, and soil formation on Mars, and are particularly relevant given recent detections of organic compounds on Mars. Recent data from the Sample Analysis at Mars (SAM) has indicated the presence of perchlorate, benzoic acid, dichloroalkanes and chlorobenzenes (Freissinet et al., 2015; Miller et al., 2016), as well as potential precursors of chlorobenzene formation such as propanol, 1,2-dichloropropane, and benzene carboxylic acids (Miller et al., 2016). Our results indicate that organic acids delivered to, and produced on, Mars can increase phosphate mineral dissolution, and thereby mobilize that important nutrient.

Conclusions

This study provides unequivocal evidence that a range of organic acids likely to be present in martian soils can enhance nutrient release from phosphate minerals relevant to Mars. We found that the effect of the organic acids on mineral dissolution rate and elemental release was dependent upon the denticity of the compound, with bidentate oxalic acid releasing the most phosphate from the minerals in all cases, and mellitic acid, which can behave as a bidentate ligand, also showing an enhanced effect. The strength of the calcium ligand and complex for whitlockite, chlorapatite and merrillite also played an important role in calcium release. These results are similar to previous observations of the effects of bidentate ligands (Furrer and Stumm, 1996; Stumm et al., 1997) and the stability constant (Hausrath et al., 2009) on elemental release.

In addition, the effect of mineralogy also appears to play an important role in the impact of the organic acids on dissolution. Although whitlockite, chlorapatite, and merrillite dissolution is strongly enhanced in the presence of acetic and succinic acids, fluorapatite dissolution is not, consistent with previous work examining fluorapatite dissolution in the presence of organic acids (Neaman et al., 2005; Goyne et al., 2006). This result is attributed to the faster inorganic dissolution rates of these minerals, allowing solutions to approach equilibrium more rapidly, where the effect of the ligands complexing calcium in solution and affecting the extent of saturation is stronger. Interestingly, these results suggest that the dominant phosphate minerals on Mars may be more strongly impacted by the organic compounds found on that planet, enhancing dissolution rates and release of calcium and phosphate.

Results such as these are increasingly important given information about organic compounds currently being detected on Mars. Recent results from the SAM instrument on Mars indicate the presence of organic compounds that may result from refractory organic matter delivered to Mars (Freissinet et al., 2015; Miller et al., 2016). Our results indicate that organic acids delivered to, and produced on, Mars can increase mineral dissolution and nutrient release. The organic matter delivered to the martian surface likely played an important role in nutrient release, chemical weathering, and soil formation on that planet.

Appendix A: Tables and Figures

Table 1. Mineral dissolution rates based on calcium and phosphate.

Experiment ID	Mineral	Organic Acid	Initial pH	pH of 6th sample	K_{diss} (Ca) (mol min. m^{-2} s^{-1})	Uncertainty (Ca) (mol min. m^{-2} s^{-1})	K_{diss} (P) (mol min. m^{-2} s^{-1})	Uncertainty (P) (mol min. m^{-2} s^{-1})
ACE-MER-3	Merrillite	Acetic	5.5	5.54	7.43×10^{-9}	3.98×10^{-10}	7.39×10^{-9}	2.69×10^{-10}
ACE-MER-D-3	Merrillite	Acetic	5.5	5.54	7.87×10^{-9}	3.61×10^{-10}	7.08×10^{-9}	9.26×10^{-10}
SUC-MER-3	Merrillite	Succinic	5.5	5.56	4.86×10^{-9}	1.17×10^{-10}	7.96×10^{-9}	8.97×10^{-10}
SUC-MER-D-3	Merrillite	Succinic	5.5	5.54	5.64×10^{-9}	1.57×10^{-10}	7.78×10^{-9}	3.43×10^{-10}
MES-MER-2	Merrillite	Methylsulfonic	5.5	5.98	2.58×10^{-10}	4.58×10^{-11}	8.06×10^{-10}	6.60×10^{-11}
MES-MER-D-2	Merrillite	Methylsulfonic	5.5	5.72	3.15×10^{-10}	4.80×10^{-11}	9.41×10^{-10}	9.72×10^{-11}
DI-MER-5	Merrillite	Inorganic	5.5	4.57	8.61×10^{-10}	7.18×10^{-11}	1.06×10^{-9}	9.01×10^{-11}
DI-MER-D-5	Merrillite	Inorganic	5.5	5.47	6.21×10^{-10}	9.02×10^{-11}	1.01×10^{-9}	4.23×10^{-11}
MEL-MER-1	Merrillite	Mellitic	5.5	5.71	1.00×10^{-8}	8.45×10^{-10}	1.51×10^{-8}	3.83×10^{-10}
MEL-MER-D-1	Merrillite	Mellitic	5.5	5.61	1.07×10^{-8}	8.35×10^{-11}	1.54×10^{-8}	4.34×10^{-10}
OXA-MER-2	Merrillite	Oxalic	5.5	5.61	n.d.	n.d.	4.00×10^{-8}	4.94×10^{-9}
OXA-MER-D-2	Merrillite	Oxalic	5.5	5.65	n.d.	n.d.	3.81×10^{-8}	3.33×10^{-9}
ACE-WHIT-1	Whitlockite	Acetic	5.5	5.53	2.19×10^{-8}	6.23×10^{-9}	2.16×10^{-8}	3.22×10^{-9}
ACE-WHIT-D-1	Whitlockite	Acetic	5.5	5.54	2.31×10^{-8}	1.73×10^{-9}	2.92×10^{-8}	2.35×10^{-9}
SUC-WHIT-1	Whitlockite	Succinic	5.5	5.59	1.60×10^{-8}	3.77×10^{-10}	2.42×10^{-8}	3.79×10^{-9}
SUC-WHIT-D-1	Whitlockite	Succinic	5.5	5.58	1.58×10^{-8}	7.96×10^{-10}	2.53×10^{-8}	1.52×10^{-9}
MES-WHIT-1	Whitlockite	Methylsulfonic	5.5	6.33	1.76×10^{-9}	1.67×10^{-10}	1.00×10^{-8}	1.24×10^{-9}
MES-WHIT-D-1	Whitlockite	Methylsulfonic	5.5	6.34	1.43×10^{-9}	1.66×10^{-10}	6.55×10^{-9}	1.04×10^{-9}
DI-WHIT-1	Whitlockite	Inorganic	5.5	6.21	4.34×10^{-9}	3.21×10^{-10}	7.44×10^{-9}	1.09×10^{-9}
DI-WHIT-D-1	Whitlockite	Inorganic	5.5	6.42	5.42×10^{-9}	3.24×10^{-10}	7.49×10^{-9}	6.45×10^{-10}
MEL-WHIT-1	Whitlockite	Mellitic	5.5	5.66	2.58×10^{-8}	7.59×10^{-10}	2.18×10^{-8}	1.03×10^{-9}
MEL-WHIT-D-1	Whitlockite	Mellitic	5.5	5.60	2.29×10^{-8}	3.43×10^{-10}	1.79×10^{-8}	1.40×10^{-9}
OXA-WHIT-1	Whitlockite	Oxalic	5.5	5.84	n.d.	n.d.	5.28×10^{-8}	3.85×10^{-9}
OXA-WHIT-D-1	Whitlockite	Oxalic	5.5	5.84	n.d.	n.d.	5.37×10^{-8}	4.43×10^{-9}

Experiment ID	Mineral	Organic Acid	Initial pH	pH of 6th sample	K_{diss} (Ca) (mol min. m^{-2} s^{-1})	Uncertainty (Ca) (mol min. m^{-2} s^{-1})	K_{diss} (P) (mol min. m^{-2} s^{-1})	Uncertainty (P) (mol min. m^{-2} s^{-1})
ACE-CAP-2	Chlorapatite	Acetic	5.5	5.44	$2.32x10^{-8}$	$1.35x10^{-9}$	$2.43x10^{-8}$	$2.16x10^{-9}$
ACE-CAP-D-2	Chlorapatite	Acetic	5.5	5.45	$2.82x10^{-8}$	$1.46x10^{-9}$	$2.52x10^{-8}$	$3.08x10^{-9}$
SUC-CAP-1	Chlorapatite	Succinic	5.5	5.58	$2.13x10^{-8}$	$1.41x10^{-9}$	$2.22x10^{-8}$	$3.23x10^{-9}$
SUC-CAP-D-1	Chlorapatite	Succinic	5.5	5.60	$2.24x10^{-8}$	$1.44x10^{-9}$	$2.49x10^{-8}$	$4.56x10^{-9}$
MES-CAP-1	Chlorapatite	Methylsulfonic	5.5	6.90	$2.46x10^{-9}$	$4.20x10^{-10}$	$1.86x10^{-9}$	$4.67x10^{-10}$
MES-CAP-D-1	Chlorapatite	Methylsulfonic	5.5	7.10	$2.39x10^{-9}$	$4.17x10^{-10}$	$1.33x10^{-9}$	$2.74x10^{-10}$
DI-CAP-2	Chlorapatite	Inorganic	5.5	6.81	$4.66x10^{-9}$	$3.98x10^{-10}$	$5.25x10^{-9}$	$1.58x10^{-9}$
DI-CAP-D-2	Chlorapatite	Inorganic	5.5	6.81	$4.83x10^{-9}$	$3.63x10^{-10}$	$6.43x10^{-9}$	$2.17x10^{-9}$
MEL-CAP-1	Chlorapatite	Mellitic	5.5	5.64	$3.86x10^{-8}$	$1.88x10^{-9}$	$2.04x10^{-8}$	$1.50x10^{-9}$
MEL-CAP-D-1	Chlorapatite	Mellitic	5.5	5.61	$3.08x10^{-8}$	$3.20x10^{-9}$	$1.81x10^{-8}$	$2.31x10^{-9}$
OXA-CAP-1	Chlorapatite	Oxalic	5.5	5.92	n.d.	n.d.	$1.06x10^{-7}$	$1.00x10^{-8}$
OXA-CAP-D-1	Chlorapatite	Oxalic	5.5	6.00	n.d.	n.d.	$8.56x10^{-8}$	$4.32x10^{-9}$
ACE-FLAP-1	Fluorapatite	Acetic	5.5	5.52	$1.56x10^{-9}$	$1.05x10^{-10}$	$2.72x10^{-9}$	$3.15x10^{-10}$
ACE-FLAP-D-1	Fluorapatite	Acetic	5.5	5.53	$1.78x10^{-9}$	$1.08x10^{-10}$	$2.53x10^{-9}$	$2.61x10^{-10}$
SUC-FLAP-1	Fluorapatite	Succinic	5.5	5.56	$2.16x10^{-9}$	$1.78x10^{-10}$	$3.92x10^{-9}$	$5.08x10^{-10}$
SUC-FLAP-D-1	Fluorapatite	Succinic	5.5	5.58	$2.44x10^{-9}$	$2.68x10^{-10}$	$4.06x10^{-9}$	$2.72x10^{-10}$
MES-FLAP-1	Fluorapatite	Methylsulfonic	5.5	4.90	$7.23x10^{-10}$	$1.97x10^{-10}$	$1.88x10^{-9}$	$1.92x10^{-10}$
MES-FLAP-D-1	Fluorapatite	Methylsulfonic	5.5	4.80	$6.44x10^{-10}$	$7.05x10^{-11}$	$1.98x10^{-9}$	$3.54x10^{-10}$
DI-FLAP-1	Fluorapatite	Inorganic	5.5	4.76	$1.34x10^{-9}$	$2.19x10^{-10}$	$2.11x10^{-9}$	$3.83x10^{-10}$
DI-FLAP-D-1	Fluorapatite	Inorganic	5.5	4.76	$1.28x10^{-9}$	$7.03x10^{-11}$	$1.65x10^{-9}$	$2.47x10^{-10}$
MEL-FLAP-1	Fluorapatite	Mellitic	5.5	5.65	$6.11x10^{-9}$	$4.91x10^{-10}$	$7.34x10^{-9}$	$4.83x10^{-10}$
MEL-FLAP-D-1	Fluorapatite	Mellitic	5.5	5.62	$5.11x10^{-9}$	$6.93x10^{-10}$	$6.77x10^{-9}$	$5.51x10^{-10}$
OXA-FLAP-1	Fluorapatite	Oxalic	5.5	5.50	n.d.	n.d.	$8.38x10^{-8}$	$2.27x10^{-9}$
OXA-FLAP-D-1	Fluorapatite	Oxalic	5.5	5.51	n.d.	n.d.	$8.58x10^{-8}$	$4.23x10^{-9}$

Table 2. Saturation indices of the solutions for the first and sixth point of each inorganic experiment with respect to Di-Calcium Phosphate Anhydrous (DCPA) (Chairat et al., 2007). Results indicate that solutions from fluorapatite dissolution experiments remains more undersaturated with respect to this phase than solutions from merrillite, whitlockite and chlorapatite dissolution experiments.

Mineral	DCPA (First concentration)	DCPA (sixth concentration)
Fluorapatite	-7.39	-6.39
Merrillite	-5.91	-5.08
Whitlockite	-3.45	-2.68
Chlorapatite	-5.75	-4.72

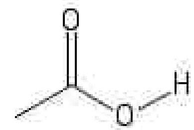
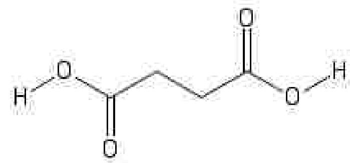
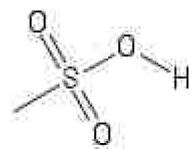
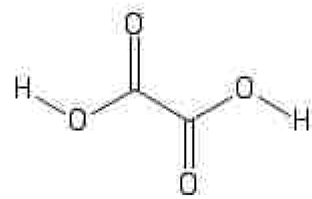
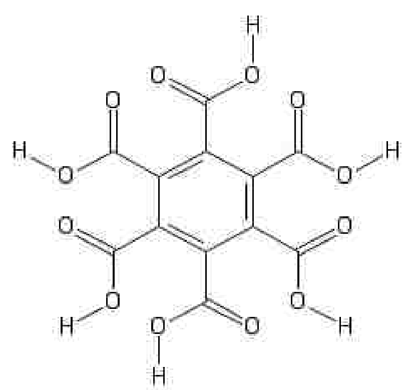
Organic Acid	Chemical Formula	Structure	pka[1]
Acetic Acid	$C_2H_4O_2$		4.76
Succinic Acid	$C_4H_6O_4$		4.21, 5.72
Methylsulfonic Acid	CH_4O_3S		-1.86
Oxalic Acid	$C_2H_2O_4$		1.46, 4.40
Mellitic Acid	$C_{12}H_6O_{12}$		1.40, 2.19, 3.31, 4.78, 5.89, 6.96

Table 3. Chemical formulae, structures, and pKa values for organic acids used in this study.

[1] All pka values obtained from Martell and Smith (1974).

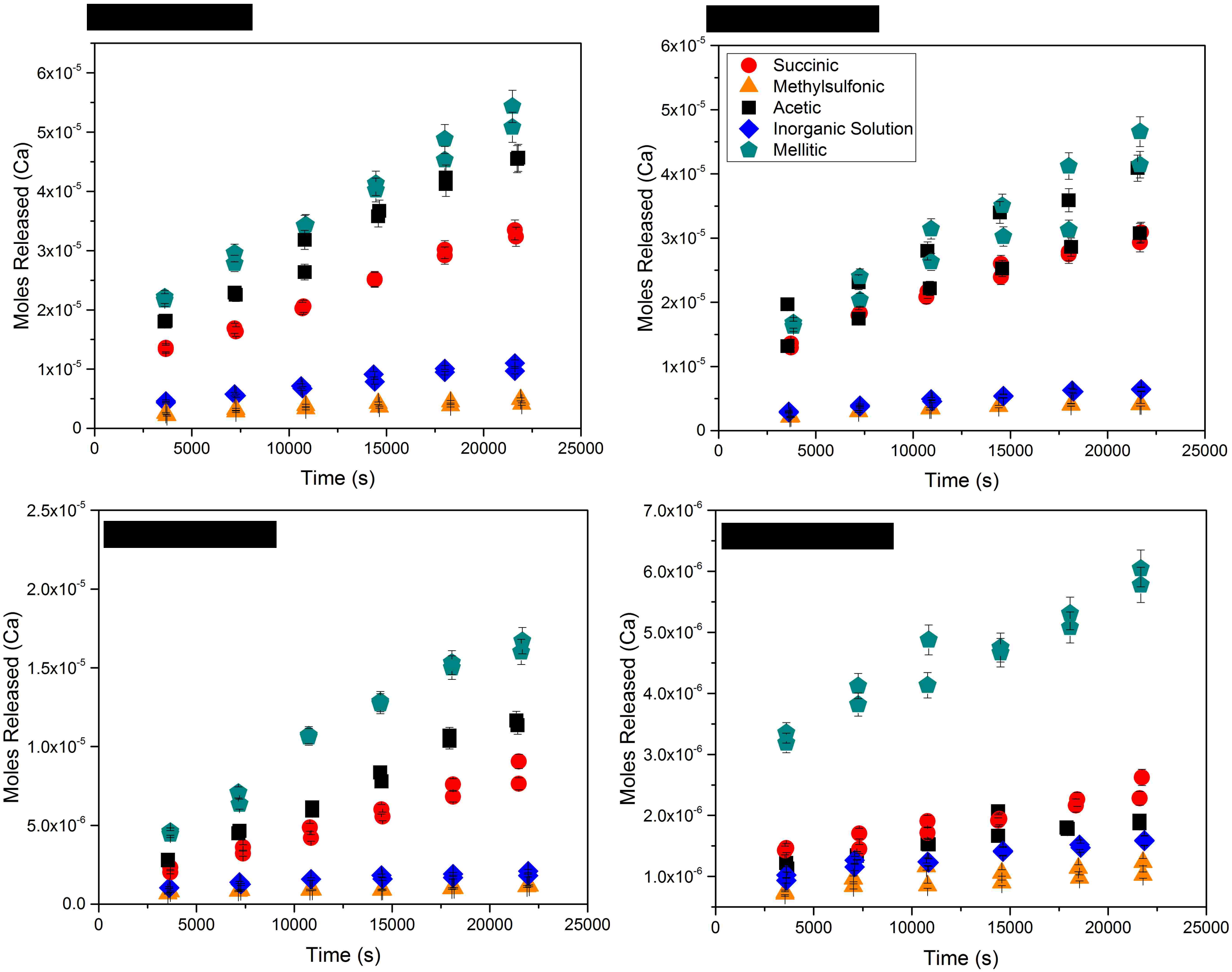
Table 4. Concentration of negatively charged ligands in solution calculated as described in the text.

Merrillite	Organic Acid	Ligands (M) at pH 5.5	Final pH	Ligands (M) at Final pH
	Methylsulfonic	0.050	5.61	0.050
	Duplicate	0.050	6.38	0.050
	Acetic	0.042	5.56	0.043
	Duplicate	0.042	5.54	0.043
	Succinic	0.048	5.58	0.048
	Duplicate	0.048	5.57	0.048
	Oxalic	0.098	7.09	0.100
	Duplicate	0.098	7.08	0.100
	Mellitic	0.200	5.73	0.200
	Duplicate	0.200	5.69	0.200

Chlorapatite	Organic Acid	Ligands (M) at pH 5.5	Final pH	Ligands (M) at Final pH
	Methylsulfonic	0.050	7.13	0.050
	Duplicate	0.050	7.13	0.050
	Acetic	0.042	5.47	0.042
	Duplicate	0.042	5.47	0.042
	Succinic	0.048	5.59	0.048
	Duplicate	0.048	5.60	0.048
	Oxalic	0.098	7.09	0.100
	Duplicate	0.098	7.02	0.100
	Mellitic	0.200	5.64	0.200
	Duplicate	0.200	5.65	0.200

Whitlockite	Organic Acid	Ligands (M) at pH 5.5	Final pH	Ligands (M) at Final pH
	Methylsulfonic	0.050	6.80	0.050
	Duplicate	0.050	6.83	0.050
	Acetic	0.042	5.57	0.043
	Duplicate	0.042	5.57	0.043
	Succinic	0.048	5.62	0.048
	Duplicate	0.048	5.60	0.048
	Oxalic	0.098	7.01	0.100
	Duplicate	0.098	7.01	0.100
	Mellitic	0.200	5.57	0.200
	Duplicate	0.200	5.56	0.200

Fluorapatite	Organic Acid	Ligands (M) at pH 5.5	Final pH	Ligands (M) at Final pH
	Methylsulfonic	0.050	5.02	0.050
	Duplicate	0.050	4.99	0.050
	Acetic	0.042	5.53	0.043
	Duplicate	0.042	5.53	0.043
	Succinic	0.048	5.57	0.048
	Duplicate	0.048	5.55	0.048
	Oxalic	0.098	6.13	0.099
	Duplicate	0.098	6.16	0.099
	Mellitic	0.200	5.71	0.200
	Duplicate	0.200	5.63	0.200



[redacted]
Moles Released (Ca)
Time (s)
Succinic
Methylsulfonic
Acetic
Inorganic Solution
Mellitic
[redacted]
[redacted]
[redacted]

[redacted]

Calcium release from each mineral in the presence of the organic acids. Mellitic acid shows a consistently large enhancement from all four mineral surfaces. Acetic acid and succinic acid show a large enhancement from the mineral surfaces of whitlockite, merrillite, and chlorapatite. However, in the presence of acetic acid and succinic acid, dissolution of fluorapatite was not significantly enhanced relative to the inorganic experiments. We attribute the greater enhancement of mellitic acid relative to other organic acids for fluorapatite (but not other minerals) to the fraction of mellitic acid that behaves as a bidentate ligand, and therefore can enhance dissolution by forming complexes at the mineral surface (Furrer and Stumm 1986). We attribute the greater effect of acetic and succinic on whitlockite, merrillite, and chlorapatite dissolution than fluorapatite dissolution to the fact that these solutions were closer to equilibrium (discussed further in the text) where aqueous complexes likely play a more important role. Error bars represent analytical uncertainty estimated as 5%, based on values from Standard Methods (Federation, Water Environmental et al., 2005). Please note differences in scale on the y axis to accommodate different concentrations.

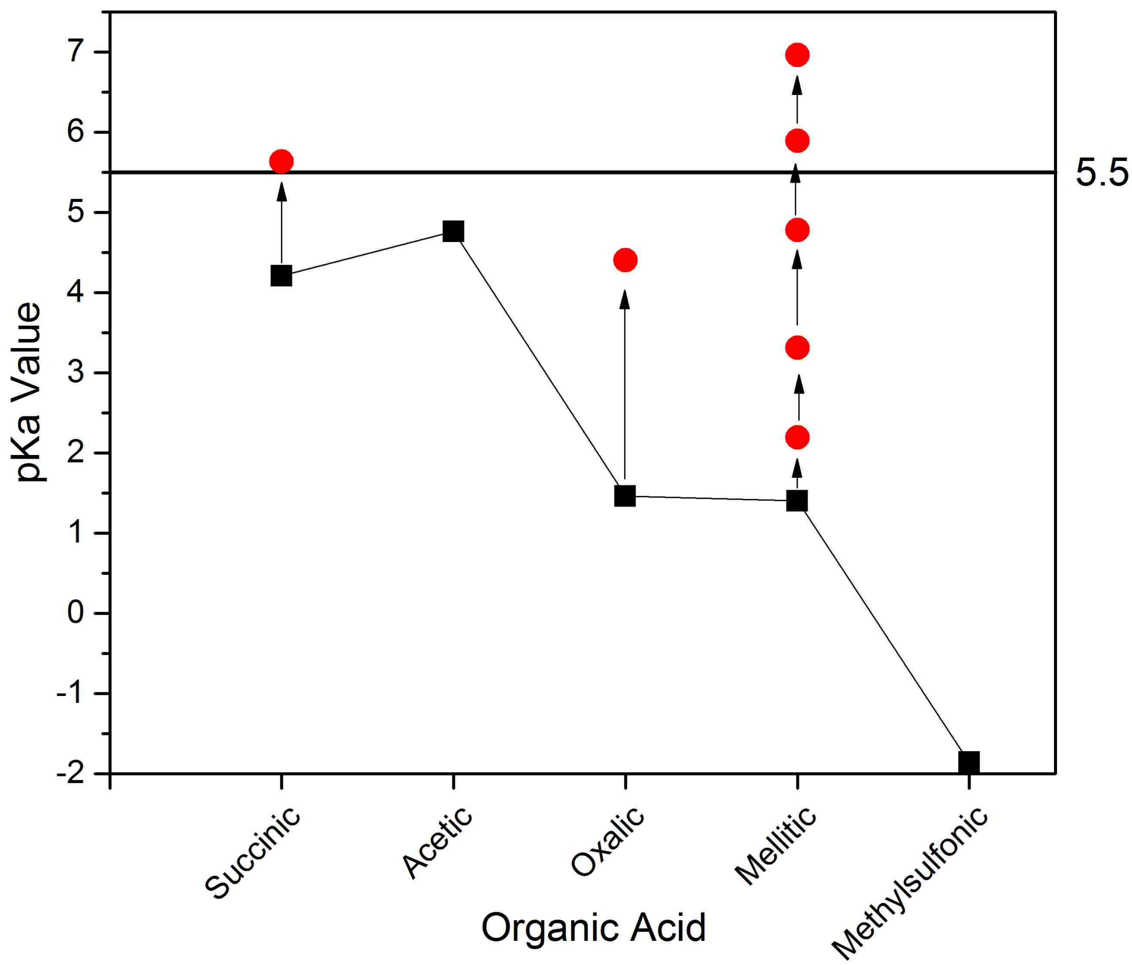


Figure 2

Dissociation constants for each organic acid used in this study. Black squares represent initial pKa values, red circles represent an additional pKa value for additional proton loss. Full dissociation for succinic and oxalic acid occurs at pKa value two. The horizontal line at 5.5 indicates the pH of this study's experiments, indicating full dissociation of all organic compounds except for succinic and mellitic acid. Succinic and mellitic acids likely act as monodentate, and both monodentate and bidentate acids, respectively, as discussed in the text.

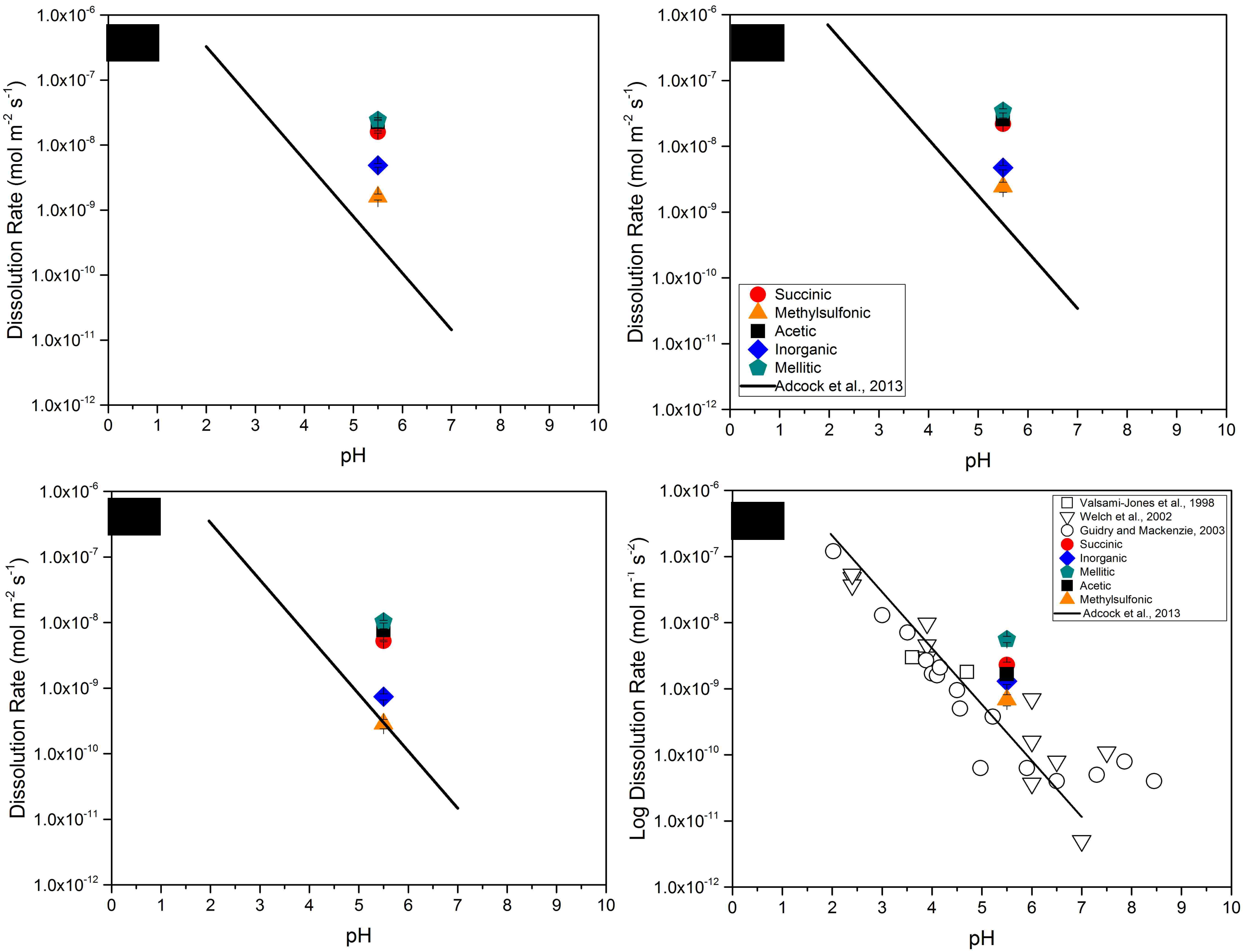

[redacted]
Dissolution Rate (mol m^{-2} s^{-1})
pH
Succinic
Methylsulfonic
Acetic
Inorganic
Mellitic
Adcock et al., 2013
Log Dissolution Rate (mol m^{-1} s^{-2})
Valsami-Jones et al., 1998
Welch et al., 2002
Guidry and Mackenzie, 2003

Figure 3

Mineral dissolution rates measured in this study of A) whitlockite, B) merrillite, C) chlorapatite, and D) fluorapatite in the presence of mellitic, acetic, succinic, and methylsulfonic acids, and inorganic solutions compared to previous data from the literature. Colored points indicate dissolution rates measured in organic solutions in this study, black outlines indicate dissolution rates previously measured, and lines indicate dissolution rate laws from Adcock et al. (2013). All our dissolution rates are slightly faster than previous work, likely due to autoclaving, but are within the expected approximate half an order of magnitude difference for kinetic data (Brantley et al., 2008). Error bars represent analytical uncertainty of the rate.

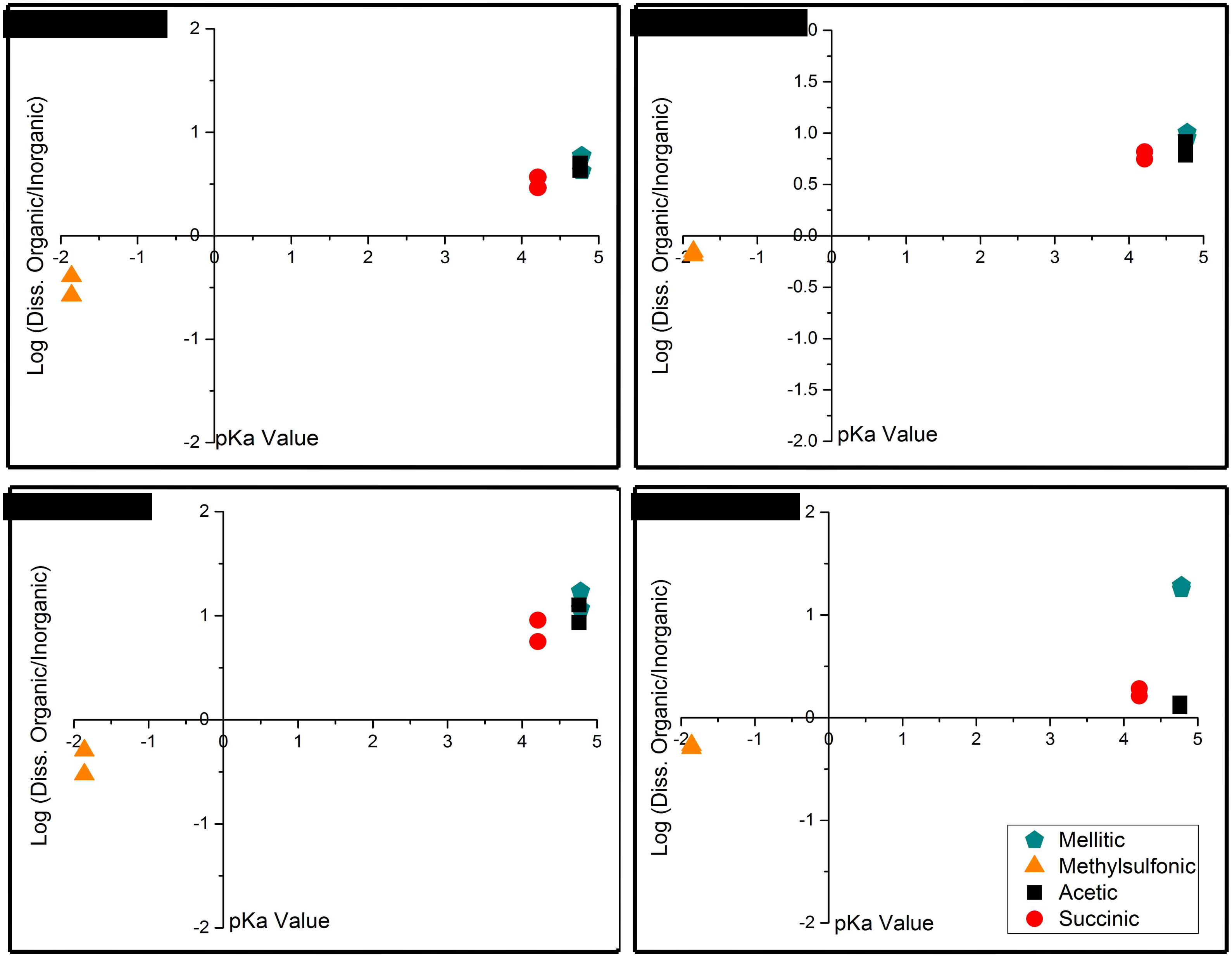

[redacted]
Log (Diss. Organic/Inorganic)
pKa Value
[redacted]
Log (Diss. Organic/Inorganic)
pKa Value
[redacted]
Log (Diss. Organic/Inorganic)
pKa Value
[redacted]
Log (Diss. Organic/Inorganic)
pKa Value
Mellitic
Methylsulfonic
Acetic
Succinic

Figure 4

The log of the ratio of the mineral dissolution rate in the presence of the organic compound to the inorganic dissolution rate (based in each case on calcium) versus the pKa for each organic acid.   These results indicate that the low enhancement of methylsulfonic is consistent with its characteristic as a strong acid, and that the increasing strength of the bond between the ligand and H+ is a reasonable predictor for the enhancement of release of calcium from the surface for whitlockite, merrillite and chlorapatite. The trend does not hold for fluorapatite, which is likely due to a greater extent of undersaturation as discussed in the text.

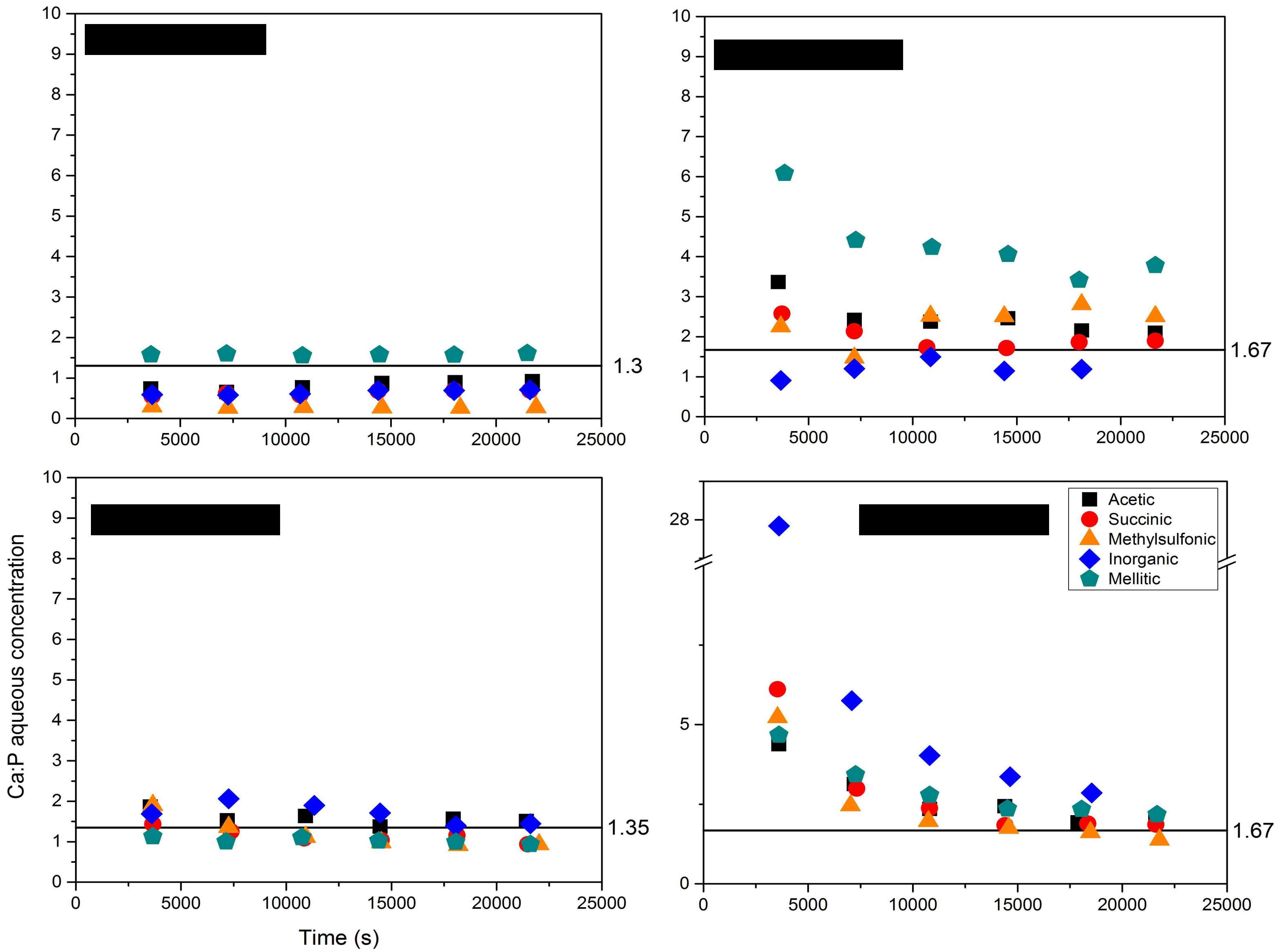

[redacted]
[redacted]
[redacted]
[redacted]
1.3
1.67
1.35
1.67
28
Acetic
Succinic
Methylsulfonic
Inorganic
Mellitic
Ca:P aqueous concentration
Time (s)

Figure 5

The aqueous Ca:P ratio for each mineral in the presence of the organic acids. The stoichiometric ratio in the mineral is indicated with the horizontal line. Fluorapatite Ca:P ratios decrease towards stoichiometric, and merrillite ratios are close to stoichiometric values. In contrast, ratios in the solutions in the whitlockite experiments are consistently below stoichiometric values, and ratios in the experiments with chlorapatite are consistently above stoichiometric ratios. Oxalic acid is not included in this graph as calcium data were not obtained for those dissolution experiments due to the precipitation of calcium oxalate.

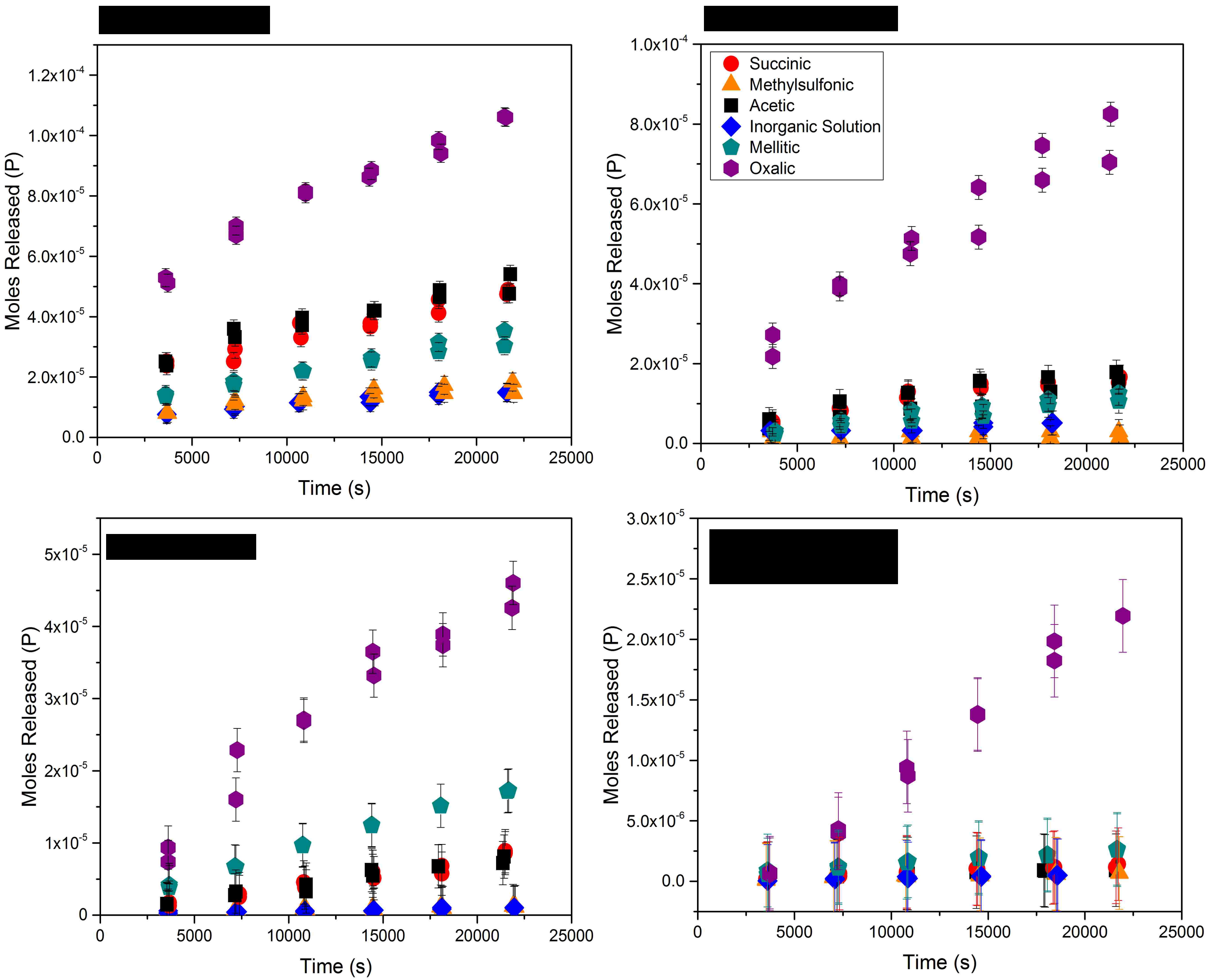

[redacted]
Moles Released (P)
Time (s)
[redacted]
Succinic
Methylsulfonic
Acetic
Inorganic Solution
Mellitic
Oxalic
Moles Released (P)
Time (s)
[redacted]
Moles Released (P)
Time (s)
[redacted]
Moles Released (P)
Time (s)

Figure 6

Phosphate release from each mineral in the presence of the organic acids. Oxalic acid has the greatest effect on phosphate release from all four minerals. We attribute this to the fact that oxalic acid is the only ligand that is behaving primarily as a bidentate ligand and can therefore enhance dissolution by forming complexes at the mineral surface (Furrer and Stumm 1986). Similar to calcium release (Figure 3), phosphate release is more significantly enhanced in the presence of acetic and succinic acid from whitlockite and chlorapatite than fluorapatite and merrillite, which we attribute to the fact that these experimental conditions are occurring closer to equilibrium where the effects of the organic acid on extent of saturation are more pronounced. Error bars represent analytical uncertainty of 0.003 mmol/L, based on the average of the standard error of the calibration. Please note different scales on the y axis.

Appendix B: Supplementary Material

Appendix Table 1

Mineral	Acid Type	Experiment Name	Duplicate Number	Ca and P Analysis	Duplicate Plots
Merrillite	Acetic	ACE-MER-3	1	1	3
Merrillite	Acetic	ACE-MER-D-3	2	2	3
Merrillite	Succinic	SUC-MER-3	1	4	6
Merrillite	Succinic	SUC-MER-D-3	2	5	6
Merrillite	Mellitic	MEL-MER-1	1	7	9
Merrillite	Mellitic	MEL-MER-D-1	2	8	9
Merrillite	Methylsulfonic	MES-MER-2	1	10	12
Merrillite	Methylsulfonic	MES-MER-D-2	2	11	12
Merrillite	Inorganic	DI-MER-5	1	14	16
Merrillite	Inorganic	DI-MER-D-5	2	15	16
Merrillite	Oxalic	OXA-MER-2	1	17	19
Merrillite	Oxalic	OXA-MER-D-2	2	18	19
Merrillite	Blanks	Various	N/A	20	N/A

Mineral	Acid Type	Experiment Name	Duplicate Number	Ca and P Analysis	Duplicate Plots
Whitlockite	Acetic	ACE-WHIT-1	1	21	23
Whitlockite	Acetic	ACE-WHIT-D-1	2	22	23
Whitlockite	Succinic	SUC-WHIT-1	1	24	26
Whitlockite	Succinic	SUC-WHIT-D-1	2	25	26
Whitlockite	Inorganic	DI-WHIT-1	1	27	29
Whitlockite	Inorganic	DI-WHIT-D-1	2	28	29
Whitlockite	Mellitic	MEL-WHIT-1	1	30	32
Whitlockite	Mellitic	MEL-WHIT-D-1	2	31	32
Whitlockite	Methylsulfonic	MES-WHIT-1	1	33	35
Whitlockite	Methylsulfonic	MES-WHIT-D-1	2	34	35
Whitlockite	Oxalic	OXA-WHIT-1	1	36	38
Whitlockite	Oxalic	OXA-WHIT-D-1	2	37	38
Whitlockite	Blanks	Various	N/A	39	N/A

Mineral	Acid Type	Experiment Name	Duplicate Number	Ca and P Analysis	Duplicate Plots
Chlorapatite	Acetic	ACE-CAP-2	1	40	42
Chlorapatite	Acetic	ACE-CAP-D-2	2	41	42
Chlorapatite	Inorganic	DI-CAP-1	1	43	45
Chlorapatite	Inorganic	DI-CAP-D-1	2	44	45
Chlorapatite	Succinic	SUC-CAP-1	1	46	48
Chlorapatite	Succinic	SUC-CAP-D-1	2	47	48
Chlorapatite	Mellitic	MEL-CAP-1	1	49	51
Chlorapatite	Mellitic	MEL-CAP-D-1	2	50	51
Chlorapatite	Methylsulfonic	MES-CAP-1	1	52	54
Chlorapatite	Methylsulfonic	MES-CAP-D-1	2	53	54
Chlorapatite	Oxalic	OXA-CAP-1	1	55	57
Chlorapatite	Oxalic	OXA-CAP-D-1	2	56	57
Chlorapatite	Blanks	Various	N/A	58	N/A

Mineral	Acid Type	Experiment Name	Duplicate Number	Ca and P Analysis	Duplicate Plots
Fluorapatite	Acetic	ACE-FLAP-1	1	59	61
Fluorapatite	Acetic	ACE-FLAP-D-1	2	60	61
Fluorapatite	Succinic	SUC-FLAP-1	1	62	64
Fluorapatite	Succinic	SUC-FLAP-D-1	2	63	64
Fluorapatite	Methylsulfonic	MES-FLAP-1	1	65	67
Fluorapatite	Methylsulfonic	MES-FLAP-D-1	2	66	67
Fluorapatite	Inorganic	DI-FLAP-1	1	68	70
Fluorapatite	Inorganic	DI-FLAP-D-1	2	69	70
Fluorapatite	Mellitic	MEL-FLAP-1	1	71	73
Fluorapatite	Mellitic	MEL-FLAP-D-1	2	72	73
Fluorapatite	Oxalic	OXA-FLAP-1	1	74	76
Fluorapatite	Oxalic	OXA-FLAP-D-1	2	75	76
Fluorapatite	Blanks	Various	N/A	77	N/A

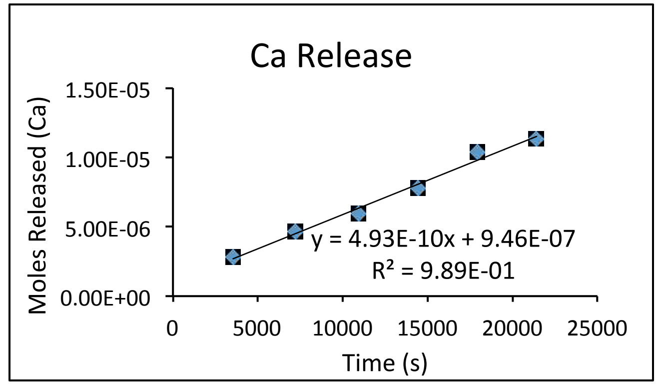
Data Sheet S1

Experiment ACE-MER-3

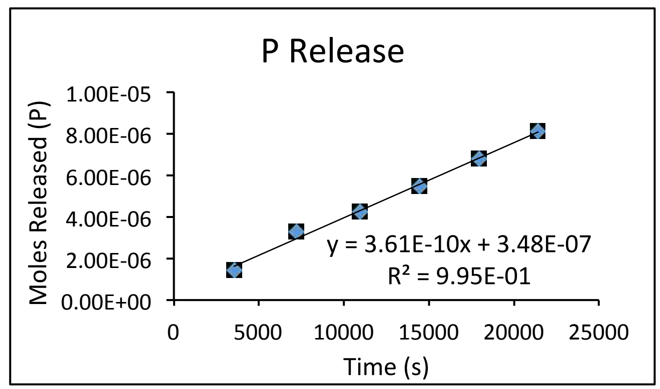
Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Merrillite	**Batch ID:** Batch 5	**Specific Surface Area (BET):** $0.0465 m^2/g$
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** $0.00698 m^2$

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	5.53	1.44E-06	2.81E-06
7200	5.53	3.27E-06	4.65E-06
10920	5.54	4.24E-06	5.94E-06
14460	5.53	5.46E-06	7.80E-06
17940	5.52	6.79E-06	1.04E-05
21420	5.54	8.12E-06	1.14E-05
76080	5.55	1.88E-05	3.14E-05
158280	5.56	2.68E-05	4.72E-05



Ca Regression Statistics		Std. Error
R Square	0.989	3.95E-07
P Regression Statistics		**Std. Error**
R Square	0.995	1.97E-07



Diss. Rate Ca (K_{diss})	7.435E-09	mol min/m^2s
Uncertainty of fit	3.98E-10	mol min/m^2s
Diss. Rate P (K_{diss})	7.388E-09	mol min/m^2s
Uncertainty of fit	2.691E-10	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

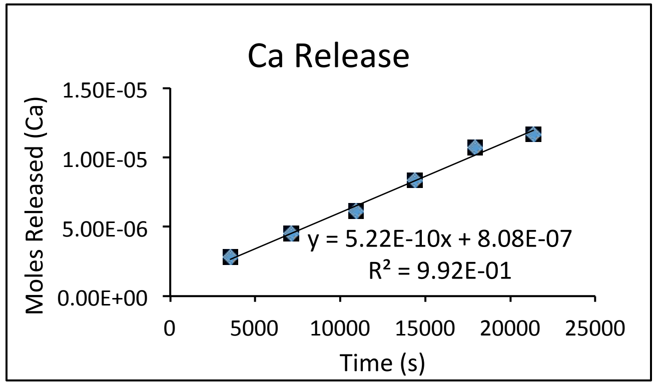
Data Sheet S2

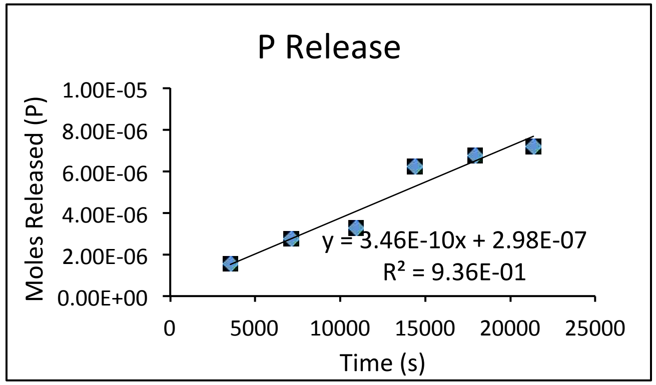
Experiment ACE-MER-D-3

Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Merrillite	**Batch ID:** Batch 5	**Specific Surface Area (BET):** 0.0465m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	5.52	1.56E-06	2.79E-06
7140	5.53	2.76E-06	4.49E-06
10920	5.54	3.29E-06	6.14E-06
14400	5.53	6.24E-06	8.36E-06
17940	5.53	6.76E-06	1.07E-05
21360	5.54	7.20E-06	1.17E-05
76080	5.54	1.87E-05	3.28E-05
158220	5.54	2.75E-05	4.84E-05





Ca Regression Statistics		Std. Error
R Square	0.992	3.58E-07
P Regression Statistics		Std. Error
R Square	0.936	6.76E-07

Diss. Rate Ca (K_{diss})	$\boxed{7.872E-09}$	mol min/m^2s
Uncertainty of fit	3.61E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{7.081E-09}$	mol min/m^2s
Uncertainty of fit	9.257E-10	mol min/m^2s

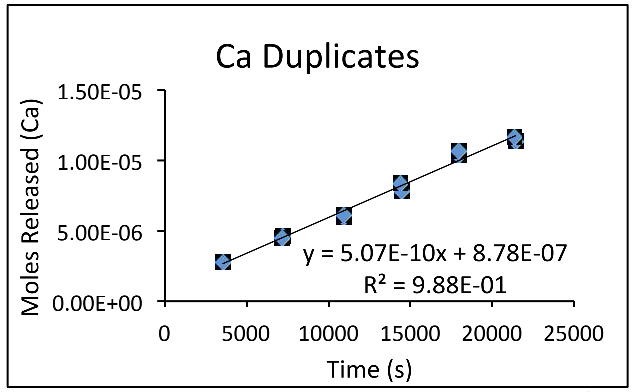
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S3

Organic Acid Duplicates:	Acetic	**Mineral:**	Merrillite

ACE-MER-3

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	1.44E-06	2.81E-06
7200	3.27E-06	4.65E-06
10920	4.24E-06	5.94E-06
14460	5.46E-06	7.80E-06
17940	6.79E-06	1.04E-05
21420	8.12E-06	1.14E-05
76080	1.88E-05	3.14E-05
158280	2.68E-05	4.72E-05

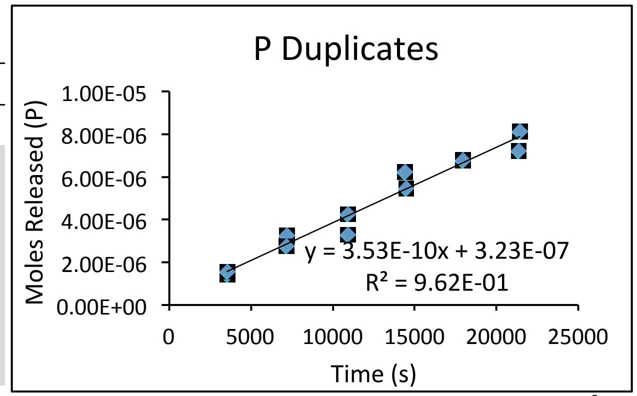


Diss. Rate Ca (K_{diss}) 7.43E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 7.39E-09 mol min/m^{2}s

ACE-MER-D-3

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	1.56E-06	2.79E-06
7140	2.76E-06	4.49E-06
10920	3.29E-06	6.14E-06
14400	6.24E-06	8.36E-06
17940	6.76E-06	1.07E-05
21360	7.20E-06	1.17E-05
76080	1.87E-05	3.28E-05
158220	2.75E-05	4.84E-05



Diss. Rate Ca (K_{diss}) 7.87E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 7.08E-09 mol min/m^{2}s

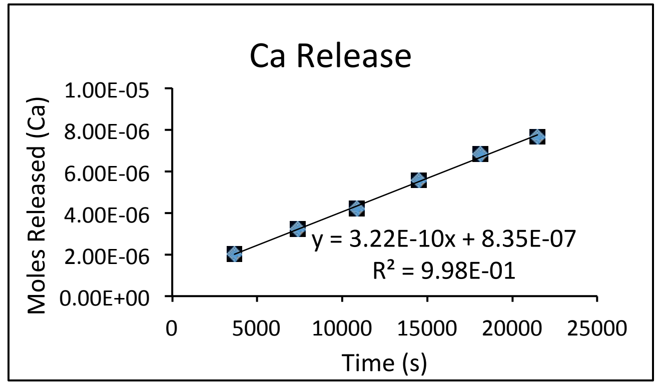
Data Sheet S4

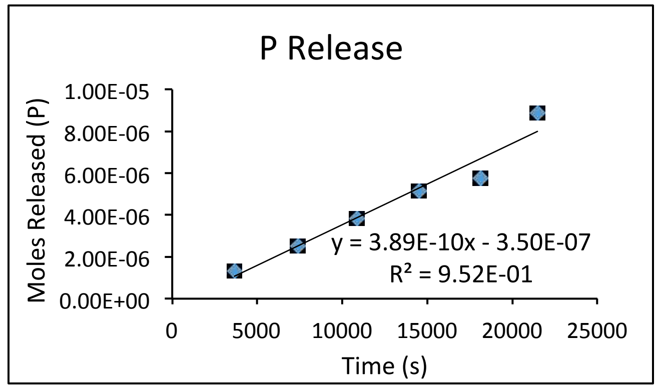
Experiment SUC-MER-3

Organic Acid: Succinic	**Acid Concentration:** 0.05 M

Mineral: Merrillite	**Batch ID:** Batch 5	**Specific Surface Area (BET):** 0.0465m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.52	1.33E-06	2.03E-06
7380	5.53	2.53E-06	3.21E-06
10860	5.55	3.82E-06	4.21E-06
14520	5.54	5.14E-06	5.57E-06
18120	5.56	5.76E-06	6.82E-06
21480	5.56	8.86E-06	7.64E-06
76800	5.54	1.92E-05	2.10E-05
199620	5.60	3.74E-05	3.87E-05
337980	5.58	4.20E-05	4.36E-05





Ca Regression Statistics		Std. Error
R Square	0.998	1.15E-07
P Regression Statistics		Std. Error
R Square	0.952	6.55E-07

Diss. Rate Ca (K_{diss})	$\boxed{4.856E-09}$	mol min/m^{2}s
Uncertainty of fit	1.166E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{7.962E-09}$	mol min/m^{2}s
Uncertainty of fit	8.973E-10	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S5

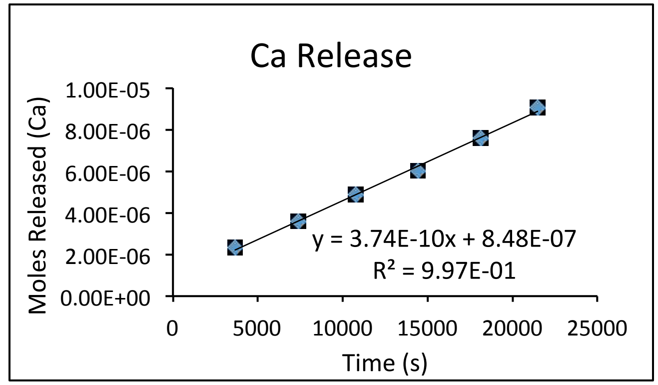
Experiment SUC-MER-D-3

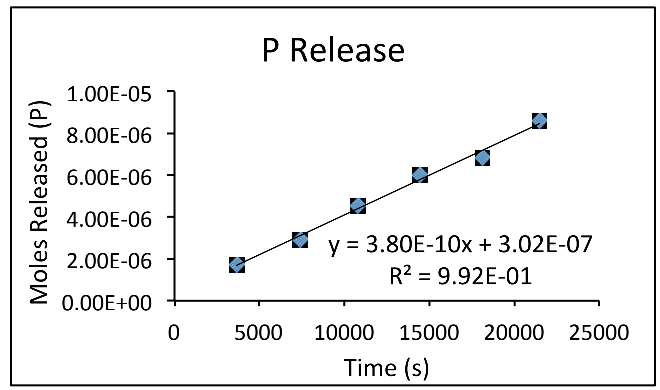
Organic Acid: Succinic **Acid Concentration:** 0.05 M

Mineral: Merrillite **Batch ID:** Batch 5 **Specific Surface Area (BET):** $0.0465 m^2/g$

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** $0.00698 m^2$

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.51	1.73E-06	2.32E-06
7380	5.54	2.93E-06	3.60E-06
10800	5.53	4.54E-06	4.88E-06
14460	5.55	6.01E-06	6.02E-06
18120	5.57	6.82E-06	7.59E-06
21480	5.54	8.60E-06	9.05E-06
76800	5.54	2.43E-05	2.57E-05
199560	5.60	4.25E-05	3.95E-05
337980	5.57	4.57E-05	4.61E-05





Ca Regression Statistics		Std. Error
R Square	0.997	1.56E-07
P Regression Statistics		Std. Error
R Square	0.992	2.50E-07

Diss. Rate Ca (K_{diss})	$\boxed{5.64E-09}$	$mol\ min/m^2s$
Uncertainty of fit	1.571E-10	$mol\ min/m^2s$
Diss. Rate P (K_{diss})	$\boxed{7.777E-09}$	$mol\ min/m^2s$
Uncertainty of fit	3.43E-10	$mol\ min/m^2s$

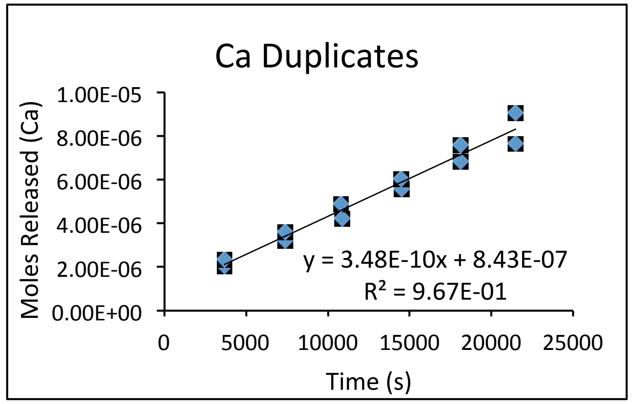
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S6

Organic Acid Duplicates:	Succinic	Mineral:	Merrillite

SUC-MER-3

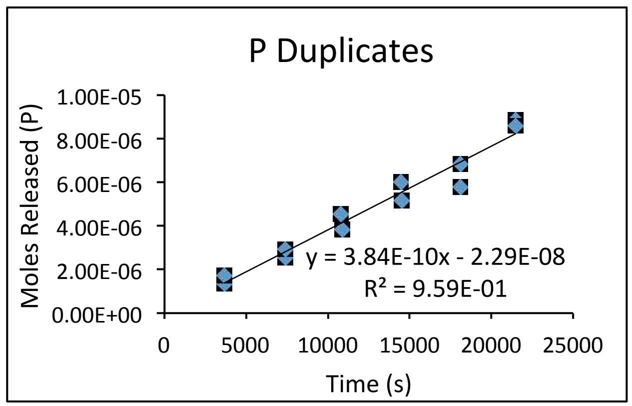
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	1.33E-06	2.03E-06
7380	2.53E-06	3.21E-06
10860	3.82E-06	4.21E-06
14520	5.14E-06	5.57E-06
18120	5.76E-06	6.82E-06
21480	8.86E-06	7.64E-06
76800	1.92E-05	2.10E-05
199620	3.74E-05	3.87E-05
337980	4.20E-05	4.36E-05



Diss. Rate Ca (K_{diss})	4.86E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	7.96E-09	mol min/m^{2}s

SUC-MER-D-3

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	1.73E-06	2.32E-06
7380	2.93E-06	3.60E-06
10800	4.54E-06	4.88E-06
14460	6.01E-06	6.02E-06
18120	6.82E-06	7.59E-06
21480	8.60E-06	9.05E-06
76800	2.43E-05	2.57E-05
199560	4.25E-05	3.95E-05
337980	4.57E-05	4.61E-05



Diss. Rate Ca (K_{diss})	5.64E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	7.78E-09	mol min/m^{2}s

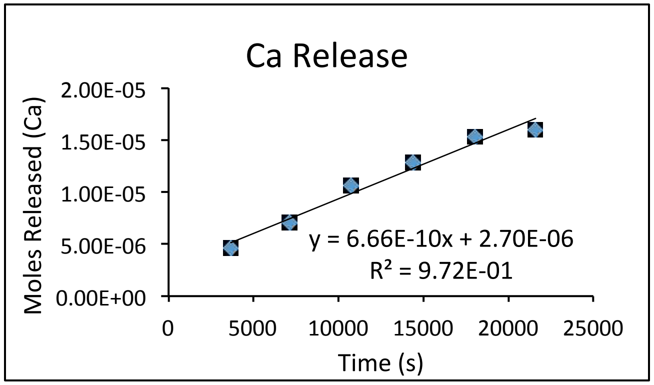
Data Sheet S7

Experiment MEL-MER-1

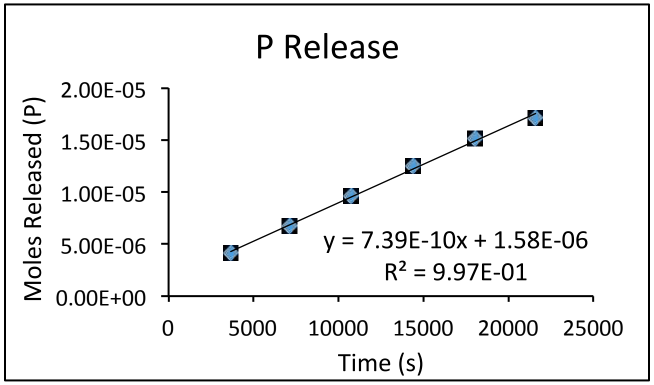
Organic Acid: Mellitic	**Acid Concentration:** 0.05 M

Mineral: Merrillite	**Batch ID:** Batch 5	**Specific Surface Area (BET):** 0.0465m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.65	4.15E-06	4.61E-06
7140	5.65	6.74E-06	7.09E-06
10740	5.76	9.63E-06	1.06E-05
14400	5.71	1.25E-05	1.29E-05
18060	5.72	1.52E-05	1.53E-05
21600	5.71	1.72E-05	1.60E-05
97080	5.71	4.24E-05	5.67E-05
167280	5.73	4.71E-05	7.63E-05



Ca Regression Statistics		Std. Error
R Square	0.972	8.44E-07
P Regression Statistics		Std. Error
R Square	0.997	2.82E-07



Diss. Rate Ca (K_{diss})	1.004E-08	mol min/m^2s
Uncertainty of fit	8.446E-10	mol min/m^2s
Diss. Rate P (K_{diss})	1.512E-08	mol min/m^2s
Uncertainty of fit	3.826E-10	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

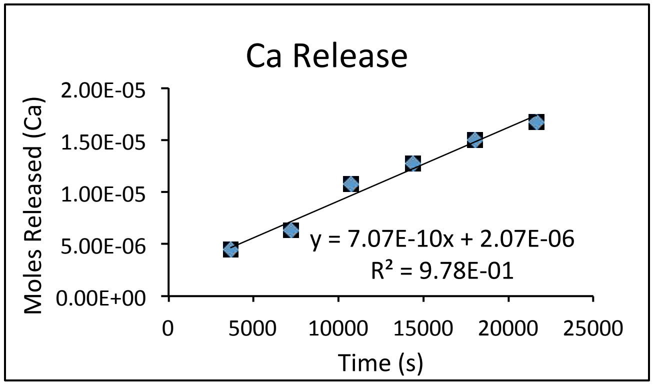
Data Sheet S8

Experiment MEL-MER-D-1

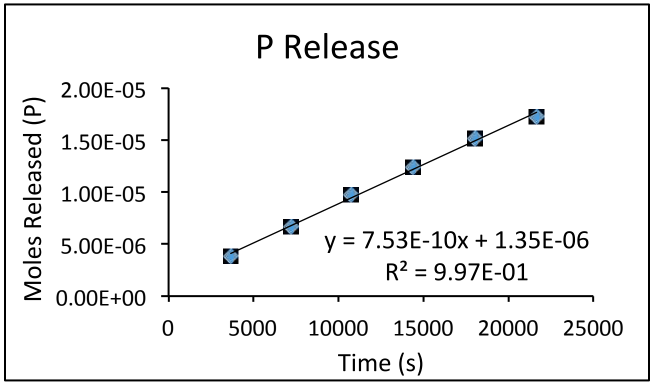
Organic Acid: Mellitic	**Acid Concentration:** 0.05 M

Mineral: Merrillite	**Batch ID:** Batch 5	**Specific Surface Area (BET):** 0.0465m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.64	3.86E-06	4.45E-06
7200	5.64	6.68E-06	6.35E-06
10740	5.76	9.74E-06	1.07E-05
14400	5.63	1.24E-05	1.27E-05
18060	5.67	1.52E-05	1.50E-05
21660	5.61	1.73E-05	1.67E-05
97080	5.66	4.35E-05	5.89E-05
167340	5.69	4.85E-05	7.79E-05



Ca Regression Statistics		Std. Error
R Square	0.978	8.36E-08
P Regression Statistics		Std. Error
R Square	0.997	3.20E-07



Diss. Rate Ca (K_{diss})	1.066E-08	mol min/m^{2}s
Uncertainty of fit	8.352E-11	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.541E-08	mol min/m^{2}s
Uncertainty of fit	4.339E-10	mol min/m^{2}s

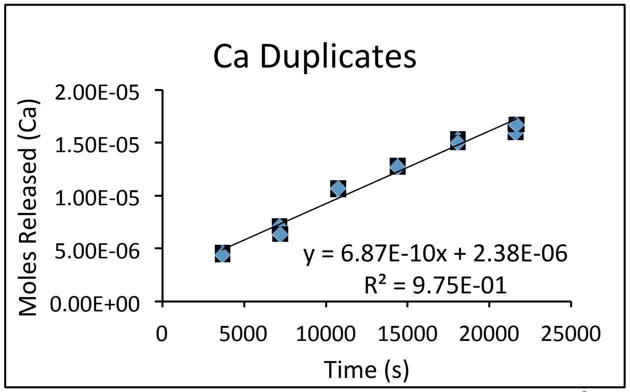
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S9

Organic Acid Duplicates:	Mellitic	Mineral:	Merrillite

MEL-MER-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	4.15E-06	4.61E-06
7140	6.74E-06	7.09E-06
10740	9.63E-06	1.06E-05
14400	1.25E-05	1.29E-05
18060	1.52E-05	1.53E-05
21600	1.72E-05	1.60E-05
97080	4.24E-05	5.67E-05
167280	4.71E-05	7.63E-05

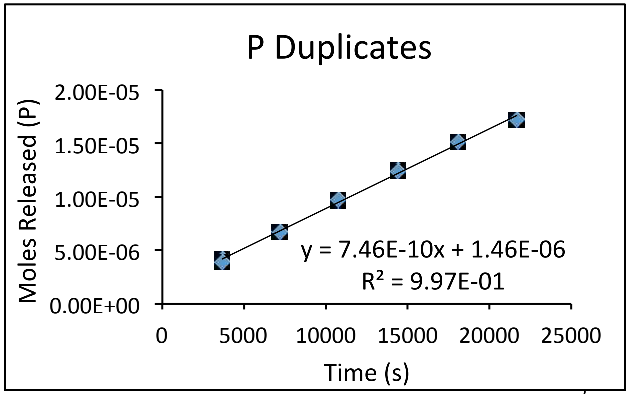


Diss. Rate Ca (K_{diss}) 1.00E-08 mol min/m^2s

Diss. Rate P (K_{diss}) 1.51E-08 mol min/m^2s

MEL-MER-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	3.86E-06	4.45E-06
7200	6.68E-06	6.35E-06
10740	9.74E-06	1.07E-05
14400	1.24E-05	1.27E-05
18060	1.52E-05	1.50E-05
21660	1.73E-05	1.67E-05
97080	4.35E-05	5.89E-05
167340	4.85E-05	7.79E-05



Diss. Rate Ca (K_{diss}) 1.07E-08 mol min/m^2s

Diss. Rate P (K_{diss}) 1.54E-08 mol min/m^2s

Data Sheet S10

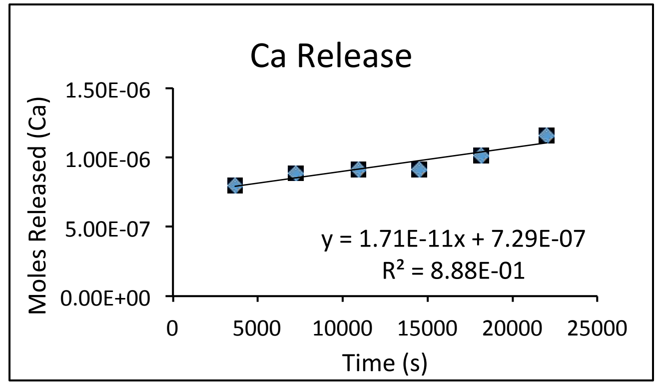
Experiment MES-MER-2

Organic Acid: Methylsulfonic **Acid Concentration:** 0.05 M

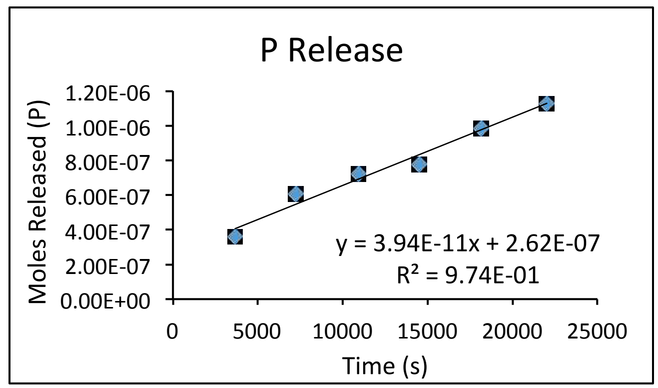
Mineral: Merrillite **Batch ID:** Batch 5 **Specific Surface Area (BET):** 0.0465m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	7.13	3.60E-07	7.98E-07
7260	5.84	6.07E-07	8.87E-07
10920	5.31	7.24E-07	9.11E-07
14520	5.92	7.79E-07	9.14E-07
18180	6.01	9.86E-07	1.01E-06
22020	5.98	1.13E-06	1.16E-06
87120	6.27	2.47E-06	1.43E-06
180360	5.61	3.09E-06	1.67E-06



Ca Regression Statistics		Std. Error
R Square	0.888	4.65E-08
P Regression Statistics		Std. Error
R Square	0.974	4.94E-08



Diss. Rate Ca (K_{diss})	2.579E-10	mol min/m^{2}s
Uncertainty of fit	4.576E-11	mol min/m^{2}s
Diss. Rate P (K_{diss})	8.064E-10	mol min/m^{2}s
Uncertainty of fit	6.6E-11	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S11

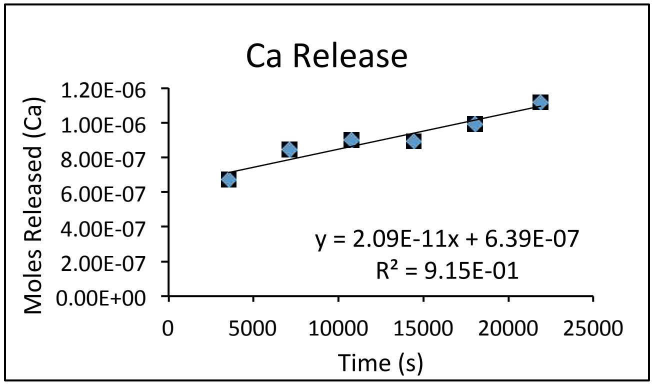
Experiment MES-MER-D-2

Organic Acid: Methylsulfonic **Acid Concentration:** 0.05 M

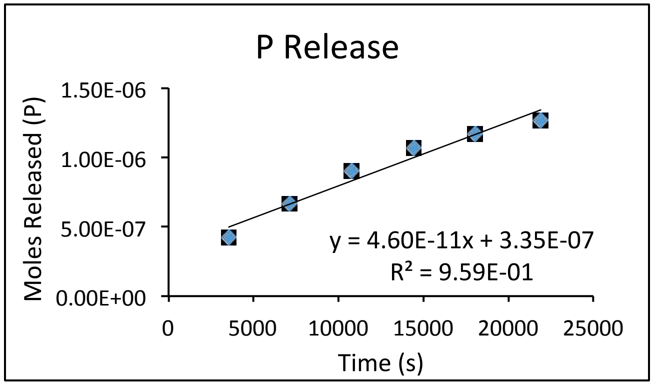
Mineral: Merrillite **Batch ID:** Batch 5 **Specific Surface Area (BET):** 0.0465m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540		4.22E-07	6.71E-07
7140	5.94	6.69E-07	8.43E-07
10800	5.99	9.03E-07	9.00E-07
14460	6.04	1.07E-06	8.92E-07
18060	6.10	1.17E-06	9.91E-07
21900	5.72	1.27E-06	1.12E-06
87000	6.35	2.79E-06	1.49E-06
180180	6.38	2.83E-06	1.65E-06



Ca Regression Statistics		Std. Error
R Square	0.915	4.88E-08
P Regression Statistics		Std. Error
R Square	0.959	7.28E-08



Diss. Rate Ca (K_{diss})	$\boxed{3.152E-10}$	mol min/m^2s
Uncertainty of fit	4.799E-11	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{9.415E-10}$	mol min/m^2s
Uncertainty of fit	9.718E-11	mol min/m^2s

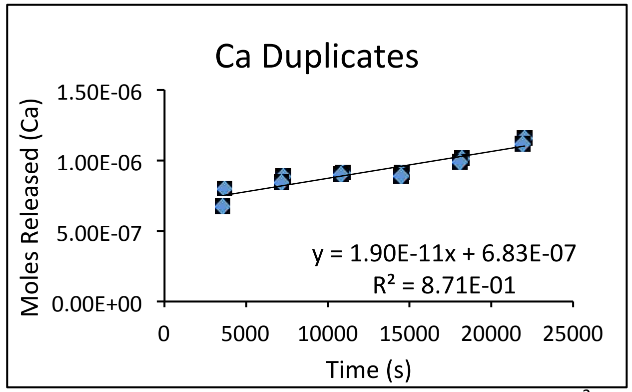
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S12

Organic Acid Duplicates:	Methylsulfonic	**Mineral:**	Merrillite

MES-MER-2

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	3.60E-07	7.98E-07
7260	6.07E-07	8.87E-07
10920	7.24E-07	9.11E-07
14520	7.79E-07	9.14E-07
18180	9.86E-07	1.01E-06
22020	1.13E-06	1.16E-06
87120	2.47E-06	1.43E-06
180360	3.09E-06	1.67E-06

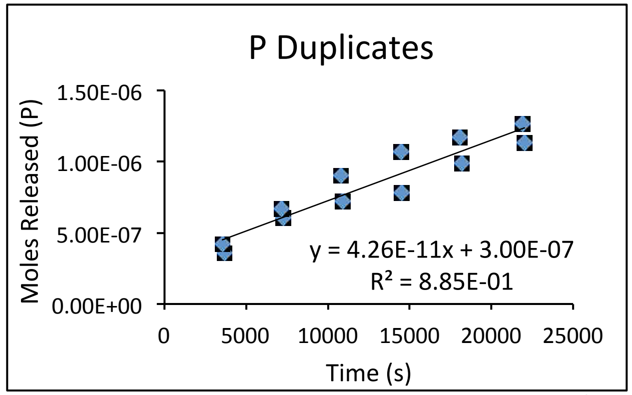


Diss. Rate Ca (K_{diss}) 2.58E-10 mol min/m^2s

Diss. Rate P (K_{diss}) 8.06E-10 mol min/m^2s

MES-MER-D-2

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	4.22E-07	6.71E-07
7140	6.69E-07	8.43E-07
10800	9.03E-07	9.00E-07
14460	1.07E-06	8.92E-07
18060	1.17E-06	9.91E-07
21900	1.27E-06	1.12E-06
87000	2.79E-06	1.49E-06
180180	2.83E-06	1.65E-06



Diss. Rate Ca (K_{diss}) 3.15E-10 mol min/m^2s

Diss. Rate P (K_{diss}) 9.41E-10 mol min/m^2s

Data Sheet S14

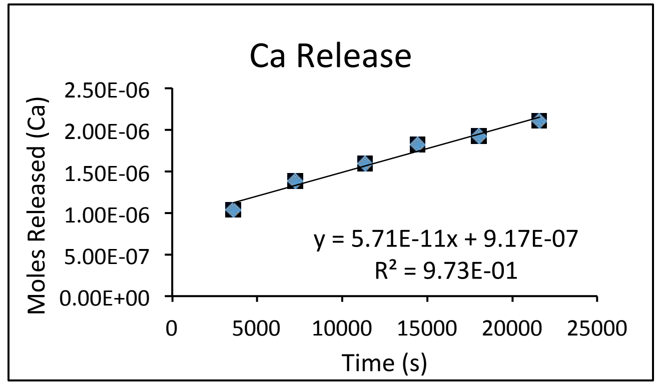
Experiment DI-MER-5

Organic Acid: Inorganic **Acid Concentration:** 0.05 M

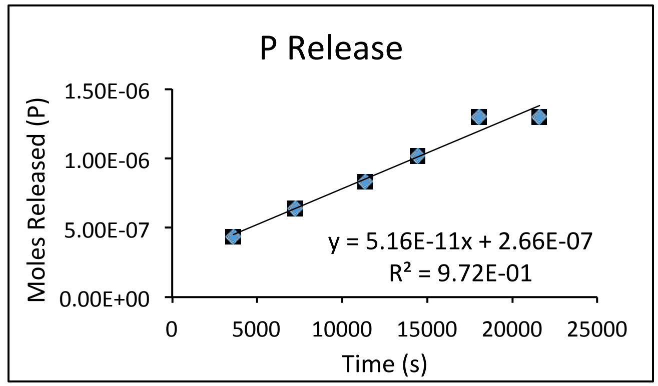
Mineral: Merrillite **Batch ID:** Batch 5 **Specific Surface Area (BET):** 0.0465m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	9.77	4.37E-07	1.04E-06
7260	4.91	6.42E-07	1.38E-06
11340	4.59	8.35E-07	1.59E-06
14460	5.40	1.02E-06	1.82E-06
18060	5.38	1.30E-06	1.92E-06
21600	4.57	1.30E-06	2.10E-06
105660	5.18	2.48E-06	3.39E-06
182760	5.29	2.98E-06	3.70E-06



Ca Regression Statistics		Std. Error
R Square	0.973	7.15E-08
P Regression Statistics		Std. Error
R Square	0.972	6.61E-08



Diss. Rate Ca (K_{diss})	$\boxed{8.611E-10}$	mol min/m^{2}s
Uncertainty of fit	7.179E-11	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{1.056E-09}$	mol min/m^{2}s
Uncertainty of fit	9.011E-11	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S15

Experiment DI-MER-D-5

Organic Acid: Inorganic **Acid Concentration:** 0.05 M

Mineral: Merrillite **Batch ID:** Batch 5 **Specific Surface Area (BET):** 0.0465m^2/g

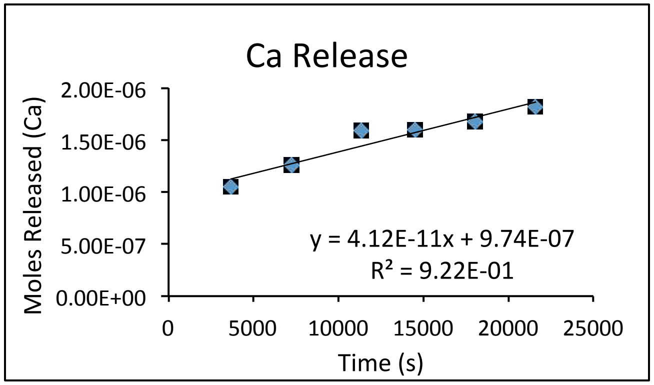
Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00698m^2

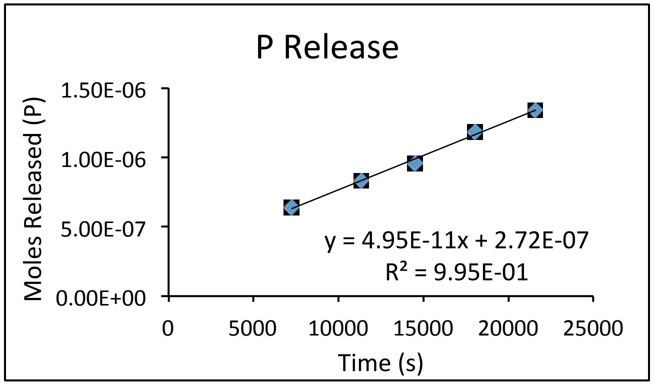
Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	4.72	1.05E-06	1.05E-06
7260	5.83	6.42E-07	1.26E-06
11340	4.70	8.35E-07	1.59E-06
14520	5.30	9.56E-07	1.60E-06
18060	4.94	1.18E-06	1.68E-06
21600	5.47	1.34E-06	1.82E-06
105660	5.48	2.53E-06	3.14E-06
182820	6.29	3.48E-06	3.44E-06

Ca Regression Statistics		Std. Error
R Square	0.922	8.96E-08
P Regression Statistics		**Std. Error**
R Square	0.460	2.05E-07

Diss. Rate Ca (K_{diss})	6.213E-10	mol min/m^2s
Uncertainty of fit	9.022E-11	mol min/m^2s
Diss. Rate P (K_{diss})	1.013E-09	mol min/m^2s
Uncertainty of fit	4.235E-11	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*



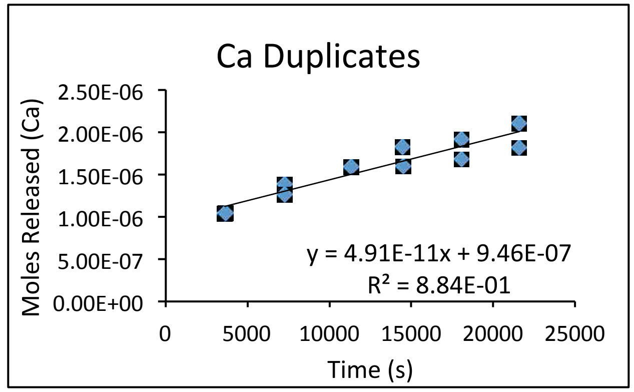


Data Sheet S16

Organic Acid Duplicates:	Inorganic	**Mineral:**	Merrillite

DI-MER-5

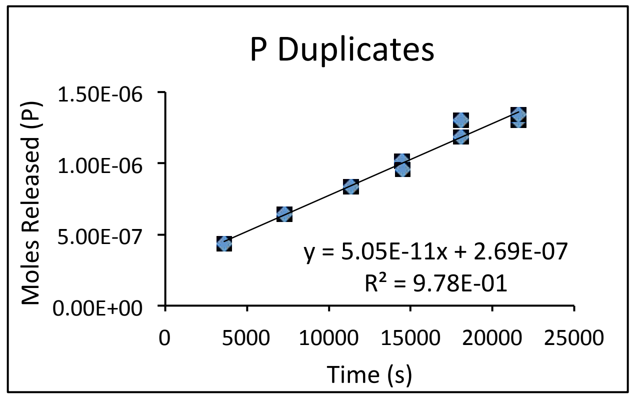
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	4.37E-07	1.04E-06
7260	6.42E-07	1.38E-06
11340	8.35E-07	1.59E-06
14460	1.02E-06	1.82E-06
18060	1.30E-06	1.92E-06
21600	1.30E-06	2.10E-06
105660	2.48E-06	3.39E-06
182760	2.98E-06	3.70E-06



Diss. Rate Ca (K_{diss})	8.61E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.06E-09	mol min/m^{2}s

DI-MER-D-5

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	1.05E-06	1.05E-06
7260	6.42E-07	1.26E-06
11340	8.35E-07	1.59E-06
14520	9.56E-07	1.60E-06
18060	1.18E-06	1.68E-06
21600	1.34E-06	1.82E-06
105660	2.53E-06	3.14E-06
182820	3.48E-06	3.44E-06



Diss. Rate Ca (K_{diss})	6.21E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.01E-09	mol min/m^{2}s

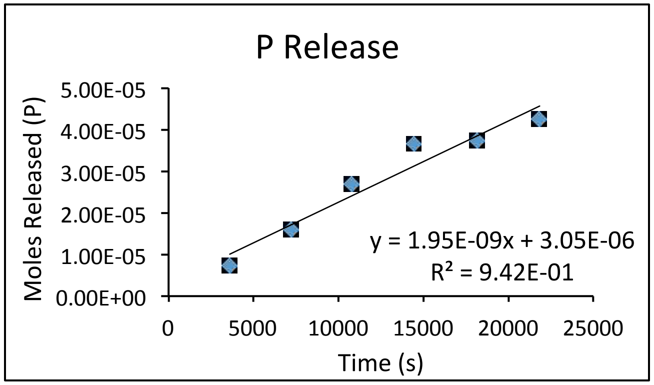
Data Sheet S17

Experiment OXA-MER-2

Organic Acid: Oxalic	**Acid Concentration:** 0.05 M

Mineral: Merrillite	**Batch ID:** Batch 5	**Specific Surface Area (BET):** 0.0465m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00698m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3600	5.47	7.38E-06	N/A
7200	5.48	1.60E-05	N/A
10800	5.50	2.69E-05	N/A
14460	5.53	3.65E-05	N/A
18180	5.57	3.74E-05	N/A
21840	5.61	4.26E-05	N/A
112800	6.70	1.55E-04	N/A
160500	7.09	1.66E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		Std. Error
R Square	0.942	3.69E-06

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	3.991E-08	mol min/m^2s
Uncertainty of fit	4.94E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S18

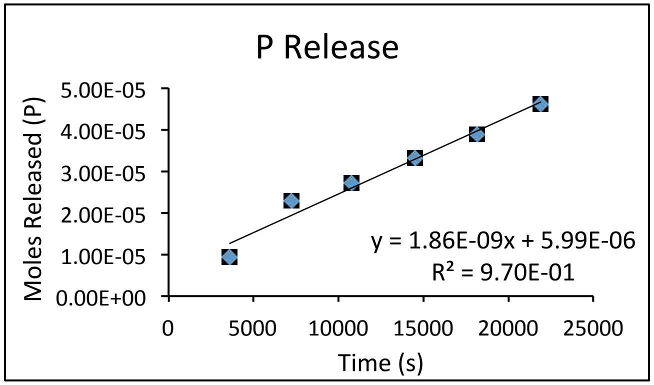
Experiment OXA-MER-D-2

Organic Acid: Oxalic **Acid Concentration:** 0.05 M

Mineral: Merrillite **Batch ID:** Batch 5 **Specific Surface Area (BET):** $0.0465 m^2/g$

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** $0.00698 m^2$

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3600	5.48	9.36E-06	N/A
7260	5.49	2.29E-05	N/A
10800	5.52	2.71E-05	N/A
14520	5.55	3.32E-05	N/A
18180	5.59	3.89E-05	N/A
21900	5.65	4.60E-05	N/A
112800	6.76	2.01E-04	N/A
160560	7.08	1.78E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		Std. Error
R Square	0.970	2.49E-06

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	3.807E-08	mol min/m^2s
Uncertainty of fit	3.33E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S19

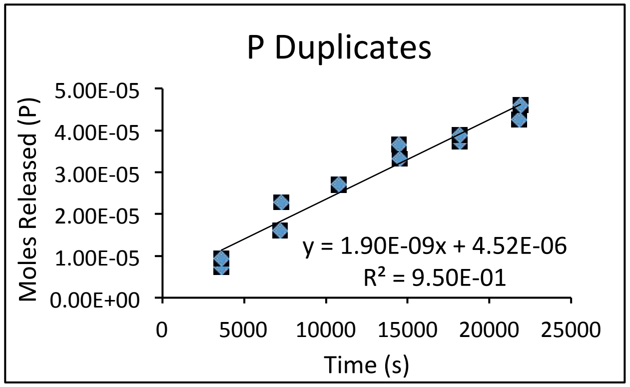
Organic Acid Duplicates:	Oxalic	**Mineral:**	Merrillite

OXA-MER-2

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	7.38E-06	N/A
7200	1.60E-05	N/A
10800	2.69E-05	N/A
14460	3.65E-05	N/A
18180	3.74E-05	N/A
21840	4.26E-05	N/A
112800	1.55E-04	N/A
160500	1.66E-04	N/A

Diss. Rate Ca (K_{diss}) N/A mol min/m^2s

Diss. Rate P (K_{diss}) 3.99E-08 mol min/m^2s



OXA-MER-D-2

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	9.36E-06	N/A
7260	2.29E-05	N/A
10800	2.71E-05	N/A
14520	3.32E-05	N/A
18180	3.89E-05	N/A
21900	4.60E-05	N/A
112800	2.01E-04	N/A
160560	1.78E-04	N/A

Diss. Rate Ca (K_{diss}) N/A mol min/m^2s

Diss. Rate P (K_{diss}) 3.81E-08 mol min/m^2s

Data Sheet S20
Merrillite Blanks

Sample Blank	Final pH	Initial Moles (P)	Final Moles (P)	Initial Moles (Ca)	Final Moles (Ca)
ACE-B-3	5.51	B.D	B.D.	8.10271E-07	6.20917E-07
SUC-B-3	5.54	1.5516E-07	5.772E-08	6.02556E-07	6.52233E-07
MES-B-3	5.46	B.D	8.788E-08	5.00594E-07	9.41646E-07
MEL-B-1	5.73	3.2706E-07	3.2379E-07	1.80646E-06	4.1642E-06
OXA-B-3	5.48	1.26834E-06	2.51206E-06		
DI-B-27	4.69	2.772E-08	2.772E-08	4.0429E-07	5.12142E-07
DI-B-6	5.43	9.468E-08	6.444E-08	5.97874E-07	6.33118E-07
DI-B-7	4.46	1.1088E-07	B.D.	9.41517E-07	7.70159E-07
DI-B-18	6.17	3.2706E-07	2.7801E-07	3.11398E-07	1.45411E-06
DI-B-12	4.52	1.80014E-06	6.05231E-06		

Data Sheet S21

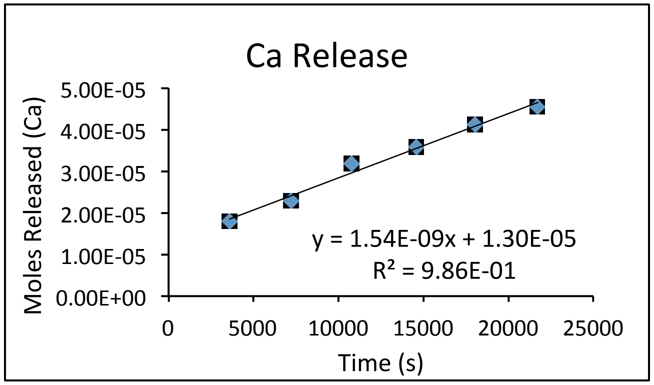
Experiment ACE-WHIT-1

Organic Acid: Acetic | **Acid Concentration:** 0.05 M

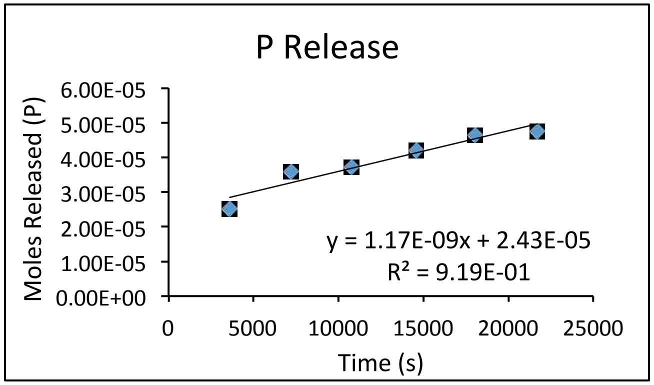
Mineral: Whitlockite | **Batch ID:** Batch 6 | **Specific Surface Area (BET):** 0.0516m^2/g

Initial pH: 5.5 | **Mineral Mass:** 0.1500 g | **Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.51	2.51E-05	1.80E-05
7200	5.52	3.59E-05	2.29E-05
10800	5.52	3.72E-05	3.18E-05
14580	5.53	4.20E-05	3.58E-05
18060	5.53	4.65E-05	4.12E-05
21720	5.53	4.76E-05	4.54E-05
90360	5.57	9.53E-05	8.48E-05
145020	5.57	1.03E-04	9.62E-05



Ca Regression Statistics		Std. Error
R Square	0.992	6.66E-06
P Regression Statistics		Std. Error
R Square	0.919	2.65E-06



Diss. Rate Ca (K_{diss})	$\boxed{2.186E-08}$	mol min/m^{2}s
Uncertainty of fit	6.235E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{2.159E-08}$	mol min/m^{2}s
Uncertainty of fit	3.218E-09	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

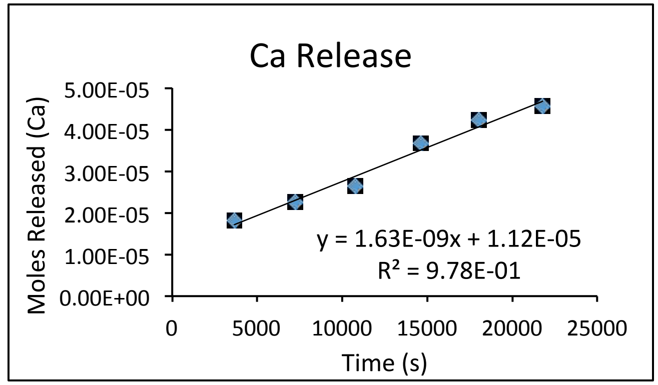
Data Sheet S22

Experiment ACE-WHIT-D-1

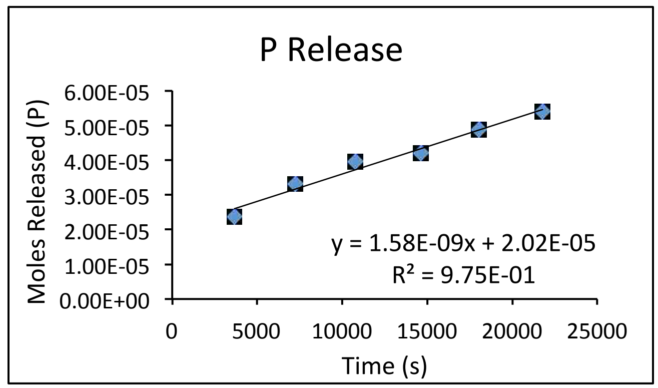
Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.52	2.38E-05	1.82E-05
7260	5.53	3.32E-05	2.26E-05
10800	5.52	3.96E-05	2.64E-05
14640	5.53	4.20E-05	3.67E-05
18060	5.53	4.88E-05	4.23E-05
21780	5.54	5.40E-05	4.57E-05
90360	5.56	9.20E-05	8.96E-05
145020	5.57	1.01E-04	1.00E-04



Ca Regression Statistics		Std. Error
R Square	0.978	1.85E-06
P Regression Statistics		Std. Error
R Square	0.975	1.93E-06



Diss. Rate Ca (K_{diss})	$\boxed{2.314E-08}$	mol min/m^2s
Uncertainty of fit	1.73E-09	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{2.916E-08}$	mol min/m^2s
Uncertainty of fit	2.348E-09	mol min/m^2s

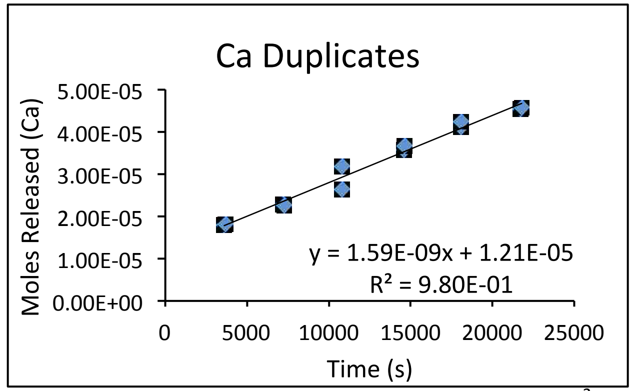
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S23

Organic Acid Duplicates:	Acetic	**Mineral:**	Whitlockite

ACE-WHIT-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	2.51E-05	1.80E-05
7200	3.59E-05	2.29E-05
10800	3.72E-05	3.18E-05
14580	4.20E-05	3.58E-05
18060	4.65E-05	4.12E-05
21720	4.76E-05	4.54E-05
90360	9.53E-05	8.48E-05
145020	1.03E-04	9.62E-05

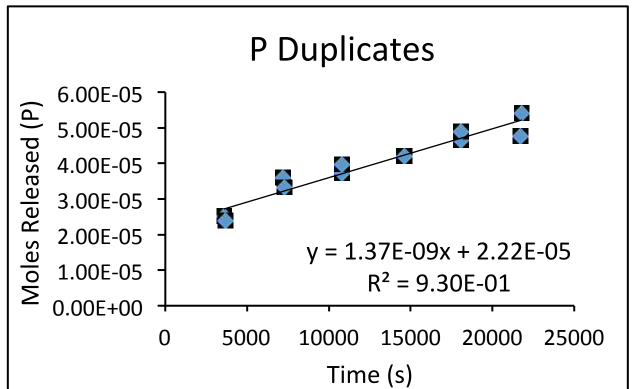


Diss. Rate Ca (K_{diss}) 2.19E-08 mol min/m^2s

Diss. Rate P (K_{diss}) 2.16E-08 mol min/m^2s

ACE-WHIT-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	2.38E-05	1.82E-05
7260	3.32E-05	2.26E-05
10800	3.96E-05	2.64E-05
14640	4.20E-05	3.67E-05
18060	4.88E-05	4.23E-05
21780	5.40E-05	4.57E-05
90360	9.20E-05	8.96E-05
145020	1.01E-04	1.00E-04



Diss. Rate Ca (K_{diss}) 2.31E-08 mol min/m^2s

Diss. Rate P (K_{diss}) 2.92E-08 mol min/m^2s

Data Sheet S24

Experiment SUC-WHIT-1

Organic Acid: Succinic | **Acid Concentration:** 0.05 M

Mineral: Whitlockite | **Batch ID:** Batch 6 | **Specific Surface Area (BET):** $0.0516 m^2/g$

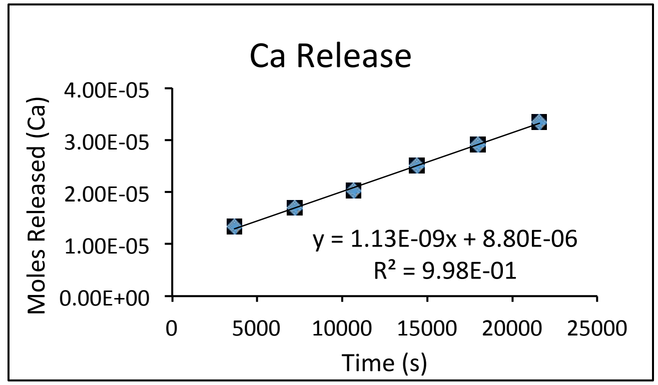
Initial pH: 5.5 | **Mineral Mass:** 0.1500 g | **Total Surface Area (BET):** $0.00774 m^2$

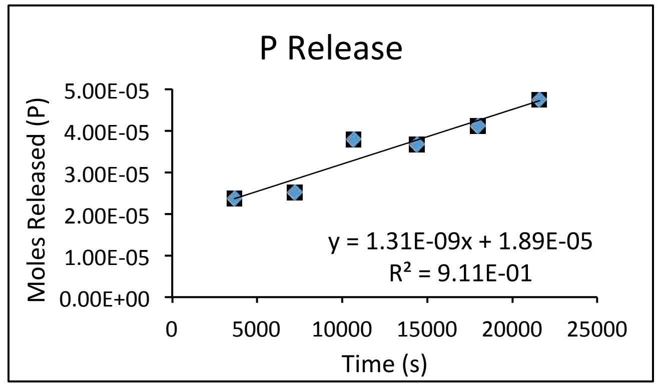
Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.63	2.38E-05	1.34E-05
7200	5.59	2.51E-05	1.69E-05
10680	5.59	3.79E-05	2.03E-05
14400	5.60	3.67E-05	2.50E-05
18000	5.59	4.12E-05	2.92E-05
21600	5.59	4.75E-05	3.35E-05
99900	5.61	9.43E-05	6.77E-05
186900	5.62	1.03E-04	7.57E-05

Ca Regression Statistics		Std. Error
R Square	0.998	3.99E-07
P Regression Statistics		**Std. Error**
R Square	0.911	3.09E-06

Diss. Rate Ca (K_{diss})	1.604E-08	mol min/m^2s
Uncertainty of fit	3.769E-10	mol min/m^2s
Diss. Rate P (K_{diss})	2.418E-08	mol min/m^2s
Uncertainty of fit	3.787E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*





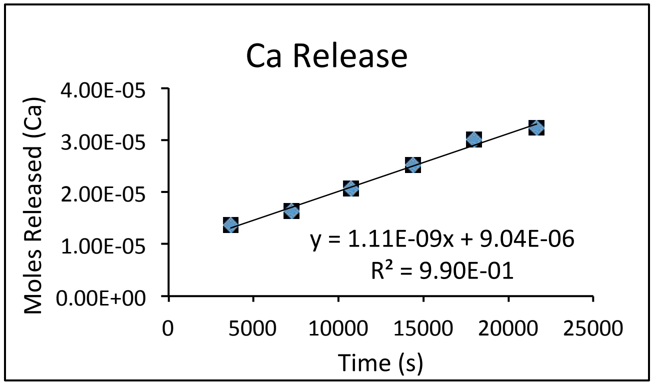
Data Sheet S25

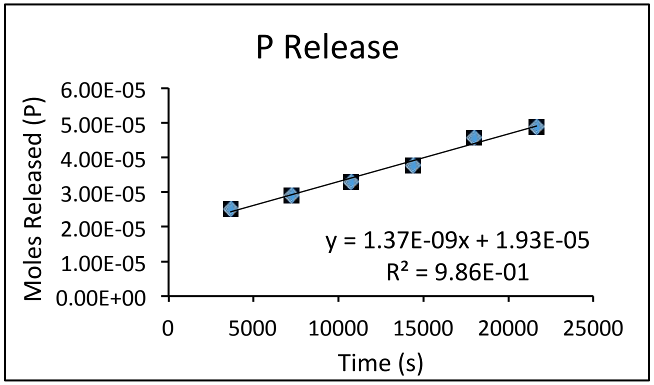
Experiment SUC-WHIT-D-1

Organic Acid: Succinic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.58	2.51E-05	1.36E-05
7260	5.59	2.92E-05	1.63E-05
10740	5.59	3.30E-05	2.06E-05
14400	5.59	3.78E-05	2.52E-05
18000	5.59	4.57E-05	3.02E-05
21660	5.58	4.88E-05	3.23E-05
99900	5.61	9.86E-05	6.65E-05
186960	5.60	1.20E-04	7.94E-05





Ca Regression Statistics		Std. Error
R Square	0.990	8.44E-07
P Regression Statistics		**Std. Error**
R Square	0.986	1.24E-06

Diss. Rate Ca (K_{diss})	$\boxed{1.576E-08}$	mol min/m^2s
Uncertainty of fit	7.965E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{2.529E-08}$	mol min/m^2s
Uncertainty of fit	1.522E-09	mol min/m^2s

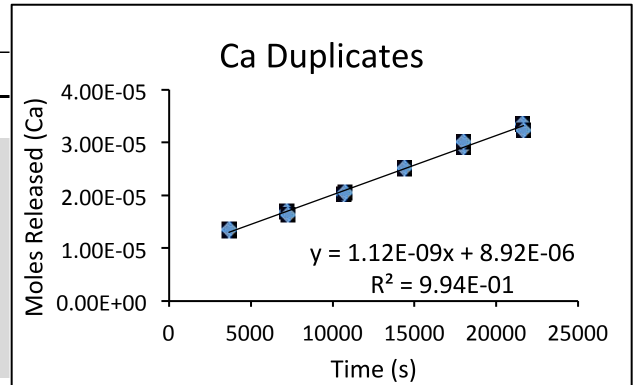
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S26

Organic Acid Duplicates:	Succinic	**Mineral:**	Whitlockite

SUC-WHIT-1

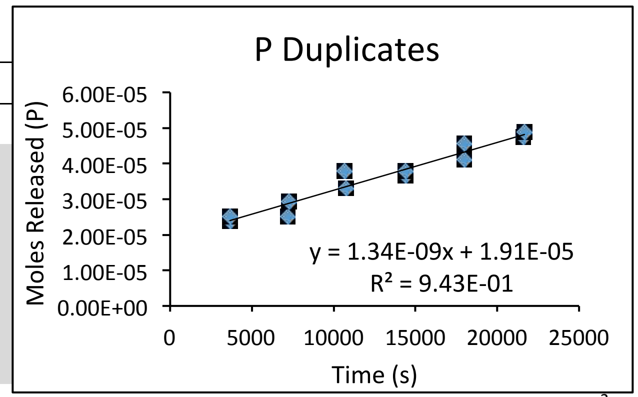
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	2.38E-05	1.34E-05
7200	2.51E-05	1.69E-05
10680	3.79E-05	2.03E-05
14400	3.67E-05	2.50E-05
18000	4.12E-05	2.92E-05
21600	4.75E-05	3.35E-05
99900	9.43E-05	6.77E-05
186900	1.03E-04	7.57E-05



Diss. Rate Ca (K_{diss})	1.60E-08	mol min/m^{2}s
Diss. Rate P (K_{diss})	2.42E-08	mol min/m^{2}s

SUC-WHIT-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	2.51E-05	1.36E-05
7260	2.92E-05	1.63E-05
10740	3.30E-05	2.06E-05
14400	3.78E-05	2.52E-05
18000	4.57E-05	3.02E-05
21660	4.88E-05	3.23E-05
99900	9.86E-05	6.65E-05
186960	1.20E-04	7.94E-05



Diss. Rate Ca (K_{diss})	1.58E-08	mol min/m^{2}s
Diss. Rate P (K_{diss})	2.53E-08	mol min/m^{2}s

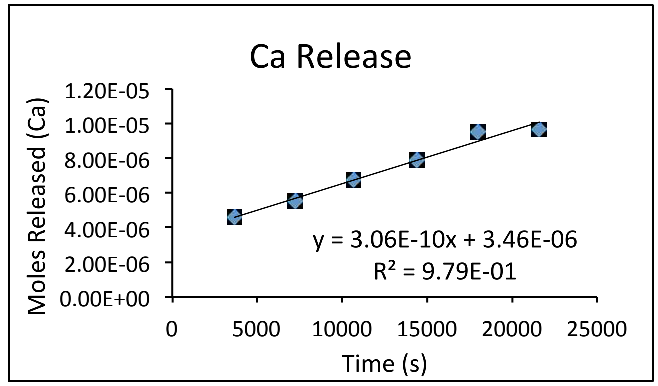
Data Sheet S27

Experiment DI-WHIT-1

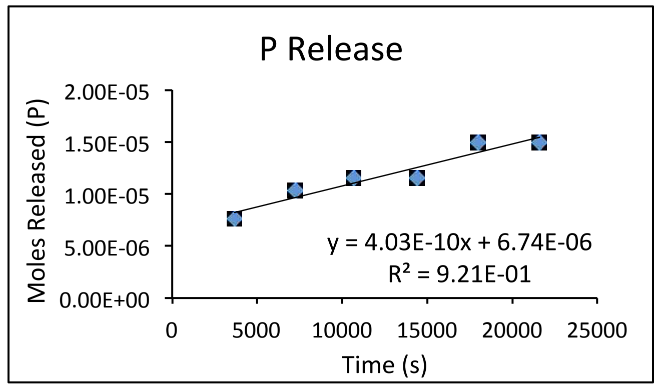
Organic Acid: Inorganic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	6.08	7.60E-06	4.61E-06
7260	5.81	1.03E-05	5.52E-06
10680	6.34	1.16E-05	6.73E-06
14400	6.42	1.16E-05	7.89E-06
18000	6.30	1.49E-05	9.50E-06
21600	6.21	1.49E-05	9.68E-06
99900	6.75	2.66E-05	1.76E-05
186900	6.83	3.38E-05	2.04E-05



Ca Regression Statistics		Std. Error
R Square	0.979	3.39E-07
P Regression Statistics		Std. Error
R Square	0.921	8.89E-07



Diss. Rate Ca (K_{diss})	$\boxed{4.344E-09}$	mol min/m^{2}s
Uncertainty of fit	3.21E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{7.438E-09}$	mol min/m^{2}s
Uncertainty of fit	1.092E-09	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S28

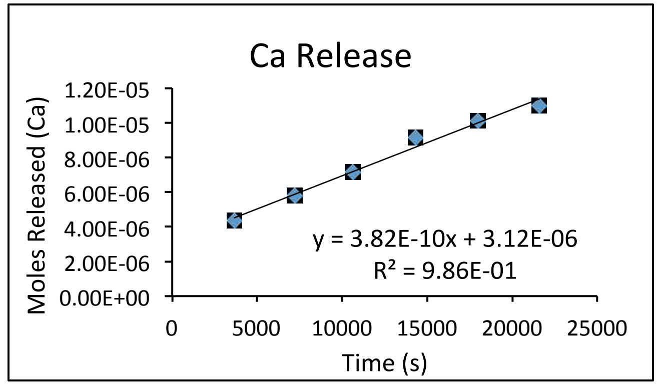
Experiment DI-WHIT-D-1

Organic Acid: Inorganic **Acid Concentration:** 0.05 M

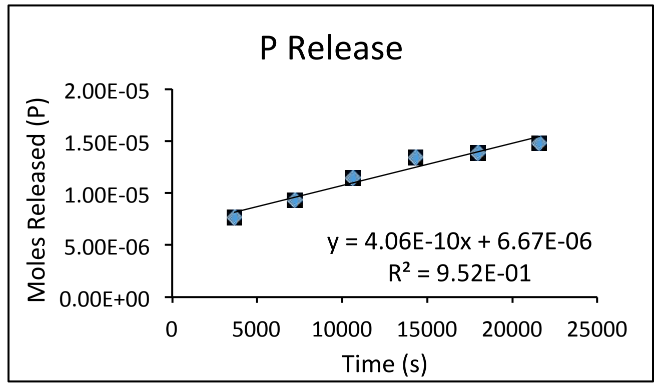
Mineral: Whitlockite **Batch ID:** Batch 6 **Specific Surface Area (BET):** 0.0516m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	6.08	7.68E-06	4.36E-06
7200	6.21	9.35E-06	5.78E-06
10620	6.38	1.15E-05	7.16E-06
14340	6.40	1.34E-05	9.14E-06
18000	6.51	1.39E-05	1.01E-05
21600	6.42	1.48E-05	1.10E-05
99840	6.84	2.45E-05	1.83E-05
186900	6.88	2.48E-05	2.19E-05



Ca Regression Statistics		Std. Error
R Square	0.986	3.44E-07
P Regression Statistics		Std. Error
R Square	0.952	6.83E-07



Diss. Rate Ca (K_{diss})	$\boxed{5.424E-09}$	mol min/m^2s
Uncertainty of fit	3.244E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{7.494E-09}$	mol min/m^2s
Uncertainty of fit	6.447E-10	mol min/m^2s

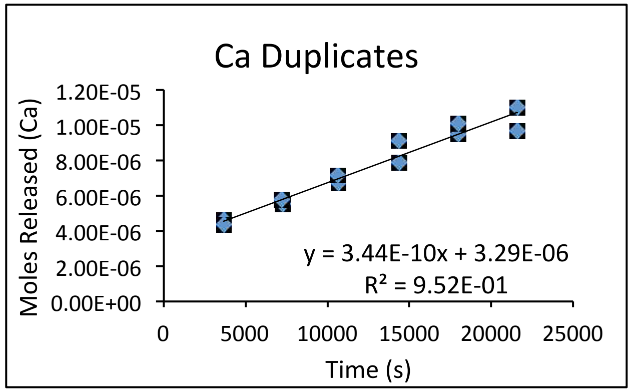
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S29

Organic Acid Duplicates:	Inorganic	**Mineral:**	Whitlockite

DI-WHIT-1

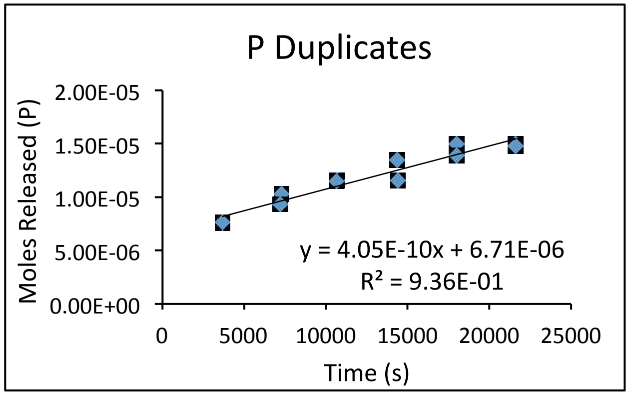
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	7.60E-06	4.61E-06
7260	1.03E-05	5.52E-06
10680	1.16E-05	6.73E-06
14400	1.16E-05	7.89E-06
18000	1.49E-05	9.50E-06
21600	1.49E-05	9.68E-06
99900	2.66E-05	1.76E-05
186900	3.38E-05	2.04E-05



Diss. Rate Ca (K_{diss})	4.34E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	7.44E-09	mol min/m^{2}s

DI-WHIT-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	7.68E-06	4.36E-06
7200	9.35E-06	5.78E-06
10620	1.15E-05	7.16E-06
14340	1.34E-05	9.14E-06
18000	1.39E-05	1.01E-05
21600	1.48E-05	1.10E-05
99840	2.45E-05	1.83E-05
186900	2.48E-05	2.19E-05



Diss. Rate Ca (K_{diss})	5.42E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	7.49E-09	mol min/m^{2}s

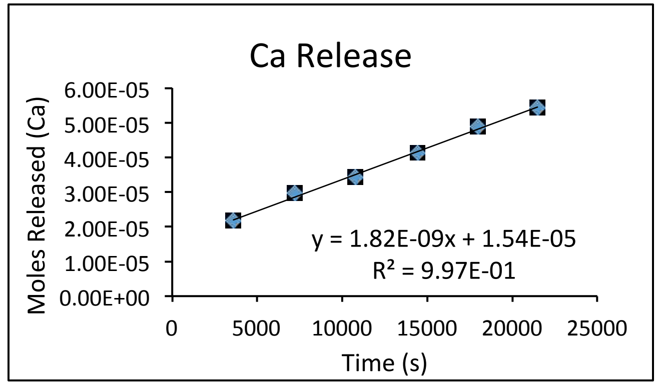
Data Sheet S30

Experiment MEL-WHIT-1

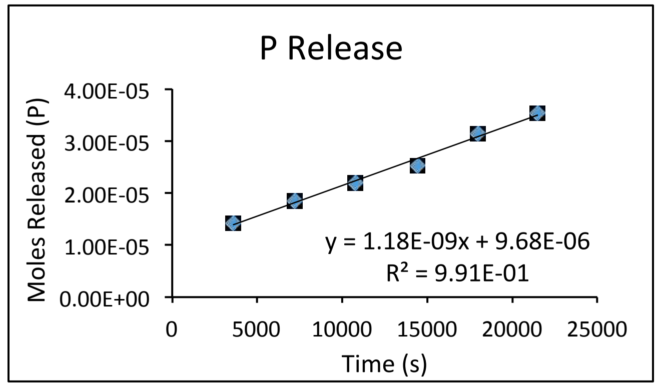
Organic Acid: Mellitic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.61	1.42E-05	2.17E-05
7200	5.61	1.86E-05	2.96E-05
10800	5.61	2.21E-05	3.42E-05
14460	5.63	2.53E-05	4.14E-05
18000	5.64	3.15E-05	4.88E-05
21480	5.66	3.54E-05	5.44E-05
92820	5.69	6.17E-05	9.31E-05
168300	5.57	6.74E-05	9.97E-05



Ca Regression Statistics		Std. Error
R Square	0.997	8.02E-07
P Regression Statistics		Std. Error
R Square	0.991	8.36E-07



Diss. Rate Ca (K_{diss})	$\boxed{2.584E-08}$	mol min/m^{2}s
Uncertainty of fit	7.593E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{2.178E-08}$	mol min/m^{2}s
Uncertainty of fit	1.028E-09	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

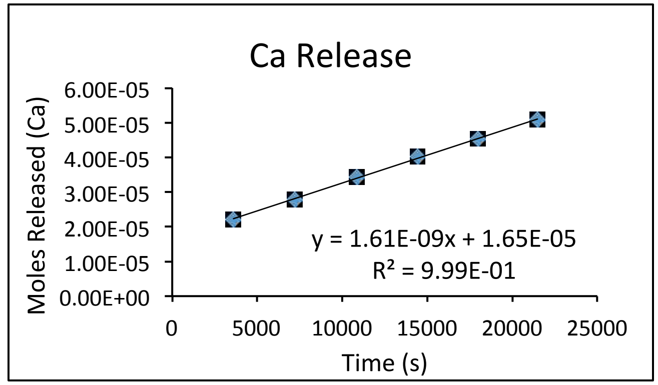
Data Sheet S31

Experiment MEL-WHIT-D-1

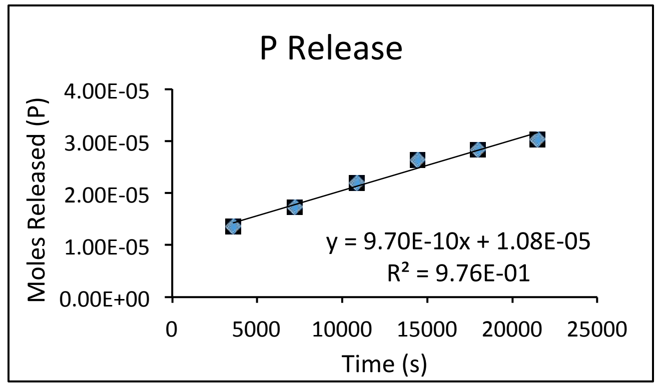
Organic Acid: Mellitic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.61	1.36E-05	2.22E-05
7200	5.58	1.73E-05	2.78E-05
10860	5.60	2.20E-05	3.44E-05
14460	5.60	2.64E-05	4.02E-05
18000	5.64	2.84E-05	4.53E-05
21480	5.60	3.04E-05	5.08E-05
92820	5.66	5.22E-05	8.68E-05
168300	5.56	6.50E-05	9.49E-05



Ca Regression Statistics		Std. Error
R Square	0.999	3.63E-07
P Regression Statistics		Std. Error
R Square	0.976	1.14E-06



Diss. Rate Ca (K_{diss})	$\boxed{2.286E-08}$	mol min/m^2s
Uncertainty of fit	3.434E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{1.79E-08}$	mol min/m^2s
Uncertainty of fit	1.4E-09	mol min/m^2s

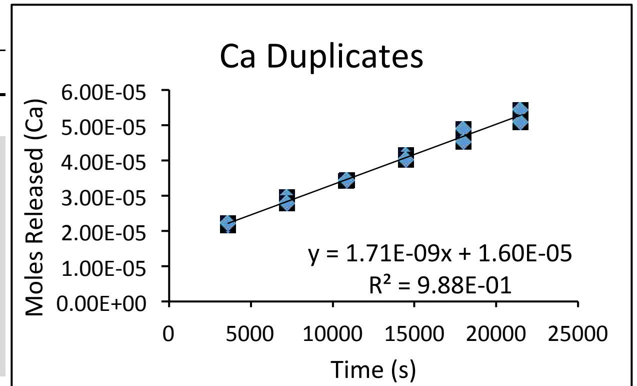
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S32

Organic Acid Duplicates:	Mellitic	**Mineral:**	Whitlockite

MEL-WHIT-1

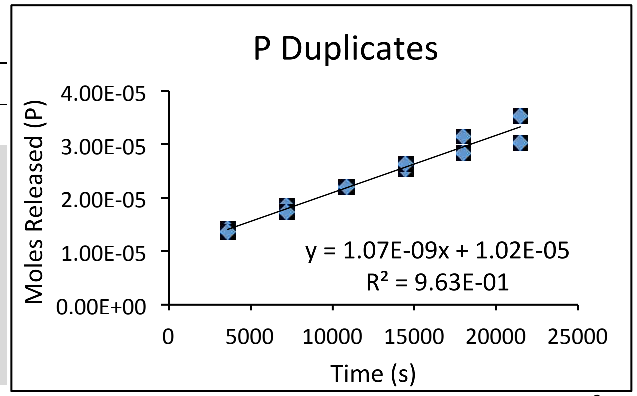
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	1.42E-05	2.17E-05
7200	1.86E-05	2.96E-05
10800	2.21E-05	3.42E-05
14460	2.53E-05	4.14E-05
18000	3.15E-05	4.88E-05
21480	3.54E-05	5.44E-05
92820	6.17E-05	9.31E-05
168300	6.74E-05	9.97E-05



Diss. Rate Ca (K_{diss})	2.58E-08	mol min/m^{2}s
Diss. Rate P (K_{diss})	2.18E-08	mol min/m^{2}s

MEL-WHIT-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	1.36E-05	2.22E-05
7200	1.73E-05	2.78E-05
10860	2.20E-05	3.44E-05
14460	2.64E-05	4.02E-05
18000	2.84E-05	4.53E-05
21480	3.04E-05	5.08E-05
92820	5.22E-05	8.68E-05
168300	6.50E-05	9.49E-05



Diss. Rate Ca (K_{diss})	2.29E-08	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.79E-08	mol min/m^{2}s

Data Sheet S33

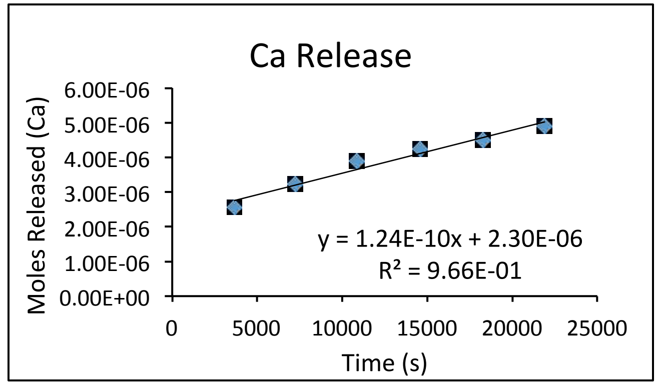
Experiment MES-WHIT-1

Organic Acid: Methylsulfonic | **Acid Concentration:** 0.05 M

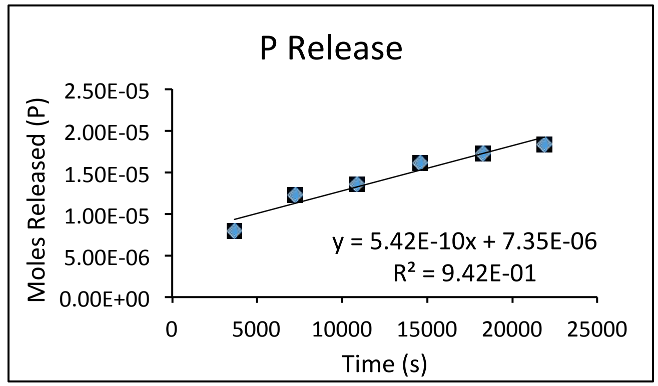
Mineral: Whitlockite | **Batch ID:** Batch 6 | **Specific Surface Area (BET):** 0.0516m^2/g

Initial pH: 5.5 | **Mineral Mass:** 0.1500 g | **Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.79	8.01E-06	2.56E-06
7260	6.14	1.23E-05	3.22E-06
10860	6.15	1.36E-05	3.88E-06
14580	6.30	1.61E-05	4.25E-06
18300	6.78	1.73E-05	4.51E-06
21900	6.33	1.84E-05	4.90E-06
83400	6.66	2.25E-05	8.16E-06
163740	6.80	2.81E-05	9.90E-06



Ca Regression Statistics		Std. Error
R Square	0.966	1.80E-07
P Regression Statistics		Std. Error
R Square	0.942	1.03E-06



Diss. Rate Ca (K_{diss})	1.761E-09	mol min/m^2s
Uncertainty of fit	1.666E-10	mol min/m^2s
Diss. Rate P (K_{diss})	1.000E-08	mol min/m^2s
Uncertainty of fit	1.242E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

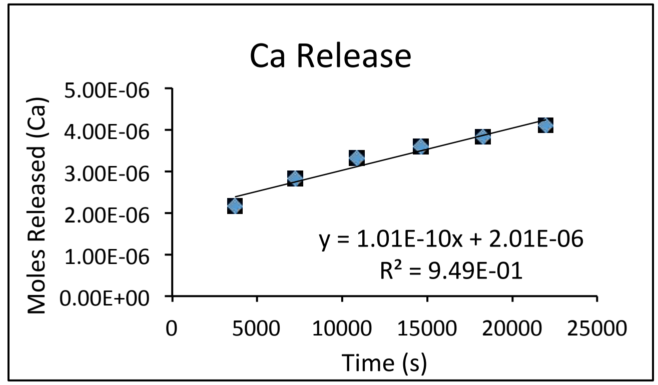
Data Sheet S34

Experiment MES-WHIT-D-1

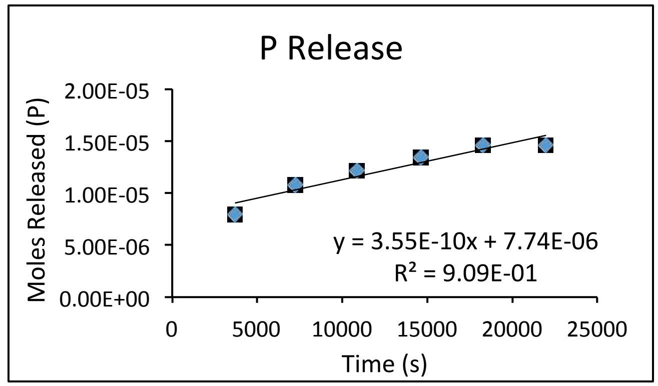
Organic Acid: Methylsulfonic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3720	5.57	8.01E-06	2.17E-06
7260	5.93	1.08E-05	2.82E-06
10860	6.08	1.22E-05	3.32E-06
14640	6.15	1.34E-05	3.60E-06
18300	6.36	1.46E-05	3.82E-06
21960	6.34	1.46E-05	4.11E-06
83460	6.70	2.79E-05	7.54E-06
163800	6.83	2.79E-05	9.57E-06



Ca Regression Statistics		Std. Error
R Square	0.949	1.79E-07
P Regression Statistics		Std. Error
R Square	0.909	8.59E-07



Diss. Rate Ca (K_{diss})	1.434E-09	mol min/m^2s
Uncertainty of fit	1.658E-10	mol min/m^2s
Diss. Rate P (K_{diss})	6.552E-09	mol min/m^2s
Uncertainty of fit	1.036E-09	mol min/m^2s

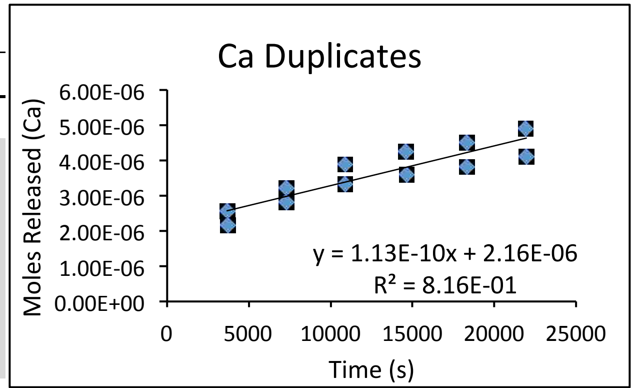
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S35

Organic Acid Duplicates:	Methylsulfonic	**Mineral:**	Whitlockite

MES-WHIT-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	8.01E-06	2.56E-06
7260	1.23E-05	3.22E-06
10860	1.36E-05	3.88E-06
14580	1.61E-05	4.25E-06
18300	1.73E-05	4.51E-06
21900	1.84E-05	4.90E-06
83400	2.25E-05	8.16E-06
163740	2.81E-05	9.90E-06

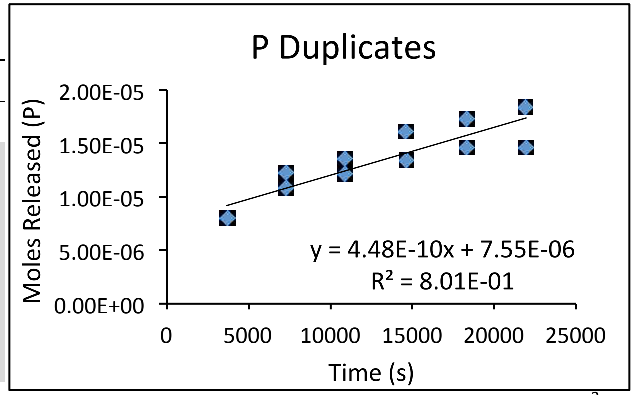


Diss. Rate Ca (K_{diss}) 1.76E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 1.00E-08 mol min/m^{2}s

MES-WHIT-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	8.01E-06	2.17E-06
7260	1.08E-05	2.82E-06
10860	1.22E-05	3.32E-06
14640	1.34E-05	3.60E-06
18300	1.46E-05	3.82E-06
21960	1.46E-05	4.11E-06
83460	2.79E-05	7.54E-06
163800	2.79E-05	9.57E-06



Diss. Rate Ca (K_{diss}) 1.43E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 6.55E-09 mol min/m^{2}s

Data Sheet S36

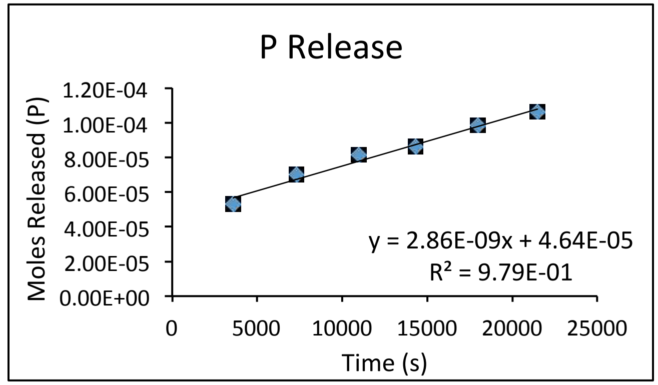
Experiment OXA-WHIT-1

Organic Acid: Oxalic **Acid Concentration:** 0.05 M

Mineral: Whitlockite **Batch ID:** Batch 6 **Specific Surface Area (BET):** $0.0516 m^2/g$

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** $0.00774 m^2$

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3600	5.69	5.29E-05	N/A
7320	5.64	7.00E-05	N/A
10980	5.69	8.14E-05	N/A
14340	5.74	8.62E-05	N/A
18000	5.80	9.84E-05	N/A
21480	5.84	1.06E-04	N/A
90000	6.66	3.55E-04	N/A
175440	7.01	4.71E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		**Std. Error**
R Square	0.979	3.12E-06

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	5.279E-08	mol min/m^2s
Uncertainty of fit	3.85E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

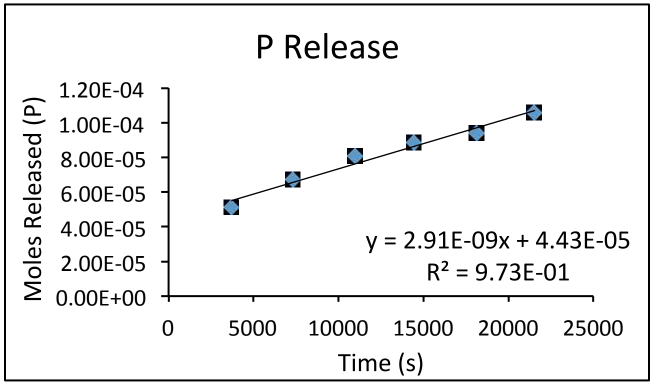
Data Sheet S37

Experiment OXA-WHIT-D-1

Organic Acid: Oxalic	**Acid Concentration:** 0.05 M

Mineral: Whitlockite	**Batch ID:** Batch 6	**Specific Surface Area (BET):** 0.0516m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00774m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3720	5.59	5.11E-05	N/A
7320	5.64	6.70E-05	N/A
10980	5.70	8.07E-05	N/A
14460	5.75	8.84E-05	N/A
18120	5.79	9.41E-05	N/A
21540	5.84	1.06E-04	N/A
90000	6.66	3.61E-04	N/A
175500	7.01	4.12E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		Std. Error
R Square	0.973	3.59E-06

Diss. Rate Ca (K_{diss})	N/A	mol min/m^{2}s
Uncertainty of fit	N/A	mol min/m^{2}s
Diss. Rate P (K_{diss})	5.371E-08	mol min/m^{2}s
Uncertainty of fit	4.43E-09	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S38

Organic Acid Duplicates:	Oxalic	**Mineral:**	Whitlockite

OXA-WHIT-1

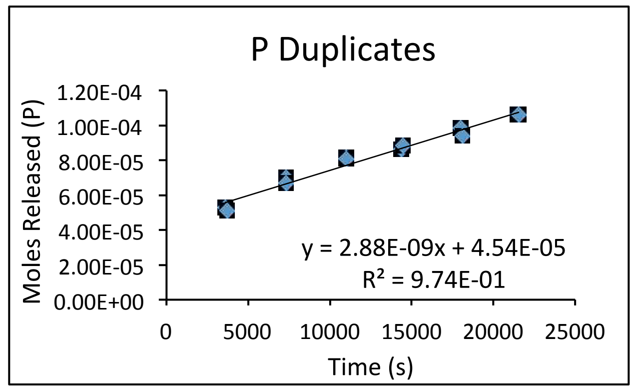
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	5.29E-05	N/A
7320	7.00E-05	N/A
10980	8.14E-05	N/A
14340	8.62E-05	N/A
18000	9.84E-05	N/A
21480	1.06E-04	N/A
90000	3.55E-04	N/A
175440	4.71E-04	N/A

Diss. Rate Ca (K_{diss}) N/A mol min/m^{2}s

Diss. Rate P (K_{diss}) 5.28E-08 mol min/m^{2}s

OXA-WHIT-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	5.11E-05	N/A
7320	6.70E-05	N/A
10980	8.07E-05	N/A
14460	8.84E-05	N/A
18120	9.41E-05	N/A
21540	1.06E-04	N/A
90000	3.61E-04	N/A
175500	4.12E-04	N/A



Diss. Rate Ca (K_{diss}) N/A mol min/m^{2}s

Diss. Rate P (K_{diss}) 5.37E-08 mol min/m^{2}s

Data Sheet S39

Whitlockite Blanks

Sample Blank	Final pH	Initial Moles (P)	Final Moles (P)	Initial Moles (Ca)	Final Moles (Ca)
ACE-B-4	5.53	B.D.	B.D.	4.82901E-07	5.81916E-07
SUC-B-4	5.59	B.D.	B.D.	5.16706E-07	6.41125E-07
MES-B-2	4.81	B.D.	B.D.	3.1616E-07	4.17595E-07
MEL-B-3	5.63	B.D.	B.D.	2.97649E-06	2.29533E-06
OXA-B-2	5.51	5.44345E-07	5.59934E-07		
DI-B-8	5.13	5.121E-07	B.D.	6.6352E-07	5.69374E-07
DI-B-9	5.03	B.D.	B.D.	7.5068E-07	7.81675E-07
DI-B-10	4.71	B.D.	B.D.	4.89237E-07	4.78628E-07
DI-B-20	4.77	B.D.	B.D.	8.15886E-07	4.27861E-07
DI-B-11	5.13	6.78376E-07	6.70928E-07		

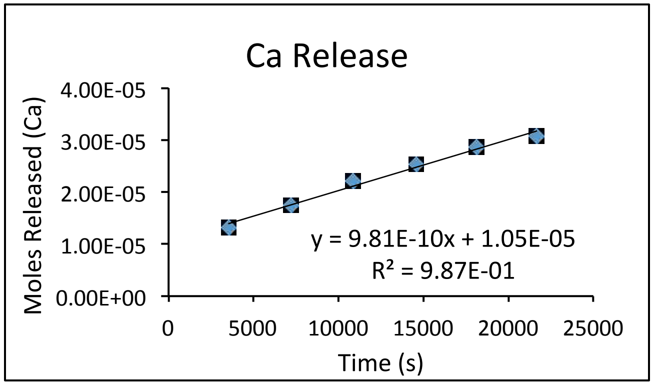
Data Sheet S40

Experiment ACE-CAP-2

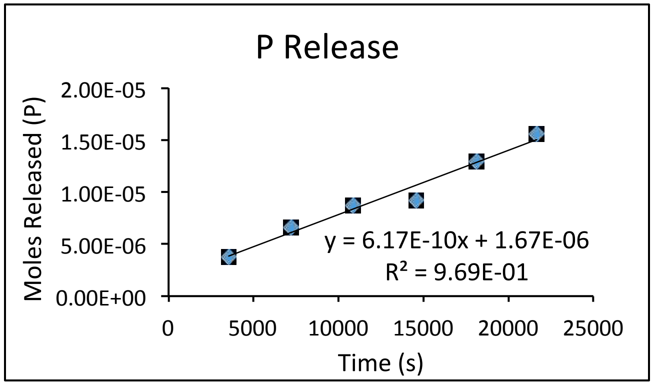
Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Chlorapatite	**Batch ID:** Batch 1512	**Specific Surface Area (BET):** 0.0563m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	5.43	3.79E-06	1.32E-05
7200	5.44	6.60E-06	1.74E-05
10860	5.44	8.72E-06	2.22E-05
14580	5.45	9.22E-06	2.53E-05
18120	5.44	1.30E-05	2.86E-05
21660	5.44	1.56E-05	3.08E-05
94680	5.47	2.25E-05	2.57E-05
337320	5.47	2.77E-05	5.68E-05



Ca Regression Statistics		Std. Error
R Square	0.987	8.66E-07
P Regression Statistics		Std. Error
R Square	0.969	8.32E-07



Diss. Rate Ca (K_{diss})	$\boxed{2.322E-08}$	mol min/m^2s
Uncertainty of fit	1.35E-09	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{2.434E-08}$	mol min/m^2s
Uncertainty of fit	2.161E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

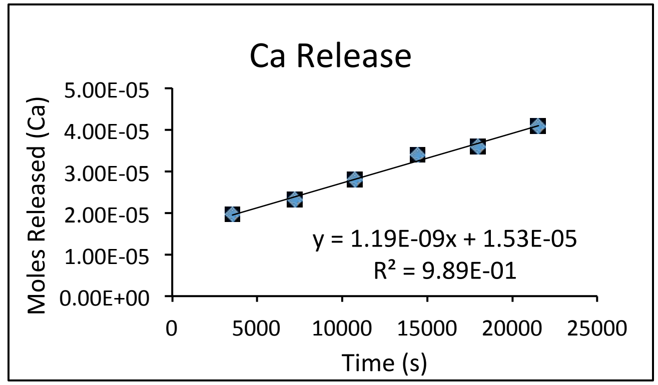
Data Sheet S41

Experiment ACE-CAP-D-2

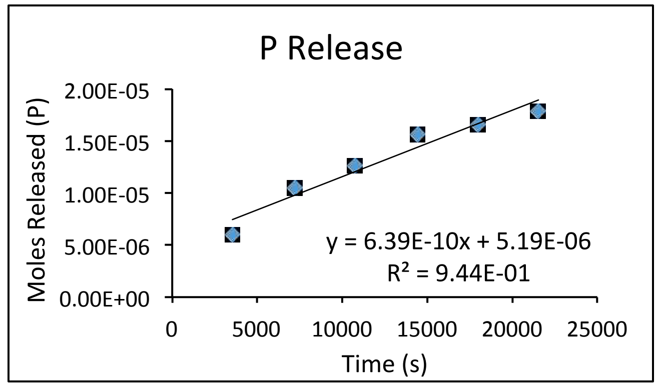
Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Chlorapatite	**Batch ID:** Batch 1512	**Specific Surface Area (BET):** 0.0563m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	5.43	6.04E-06	1.97E-05
7200	5.44	1.05E-05	2.31E-05
10740	5.44	1.27E-05	2.80E-05
14460	5.45	1.56E-05	3.40E-05
18000	5.45	1.66E-05	3.59E-05
21540	5.45	1.79E-05	4.09E-05
94500	5.47	2.56E-05	5.24E-05
337080	5.47	2.82E-05	6.62E-05



Ca Regression Statistics		Std. Error
R Square	0.989	9.32E-07
P Regression Statistics		Std. Error
R Square	0.944	1.18E-06



Diss. Rate Ca (K_{diss})	$\boxed{2.817E-08}$	mol min/m^2s
Uncertainty of fit	1.463E-09	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{2.521E-08}$	mol min/m^2s
Uncertainty of fit	3.075E-09	mol min/m^2s

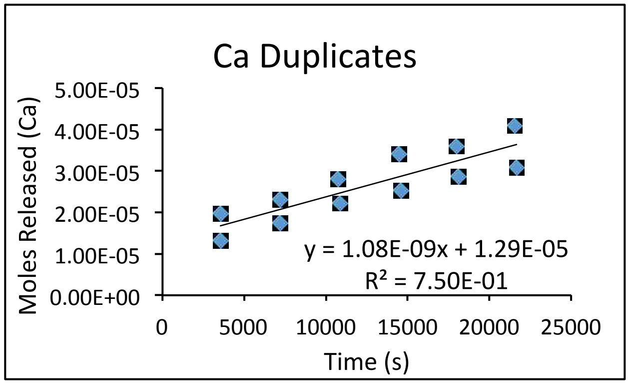
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S42

Organic Acid Duplicates:	Acetic	Mineral:	Chlorapatite

ACE-CAP-2

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	3.79E-06	1.32E-05
7200	6.60E-06	1.74E-05
10860	8.72E-06	2.22E-05
14580	9.22E-06	2.53E-05
18120	1.30E-05	2.86E-05
21660	1.56E-05	3.08E-05
94680	2.25E-05	2.57E-05
337320	2.77E-05	5.68E-05

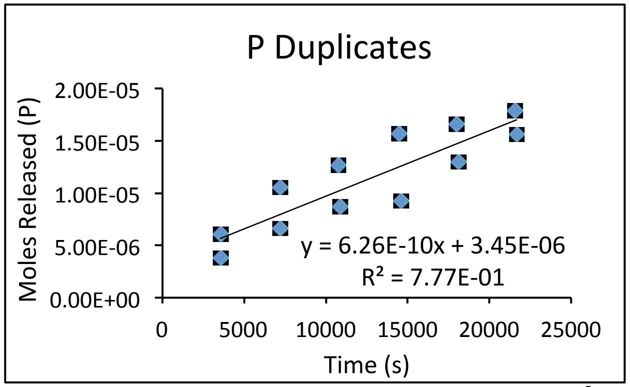


Diss. Rate Ca (K_{diss}) 2.32E-08 mol min/m^2s

Diss. Rate P (K_{diss}) 2.43E-08 mol min/m^2s

ACE-CAP-D-2

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	6.04E-06	1.97E-05
7200	1.05E-05	2.31E-05
10740	1.27E-05	2.80E-05
14460	1.56E-05	3.40E-05
18000	1.66E-05	3.59E-05
21540	1.79E-05	4.09E-05
94500	2.56E-05	5.24E-05
337080	2.82E-05	6.62E-05



Diss. Rate Ca (K_{diss}) 2.82E-08 mol min/m^2s

Diss. Rate P (K_{diss}) 2.52E-08 mol min/m^2s

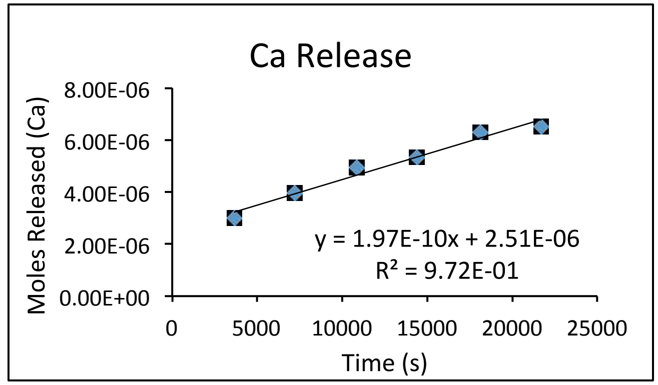
Data Sheet S43

Experiment DI-CAP-1

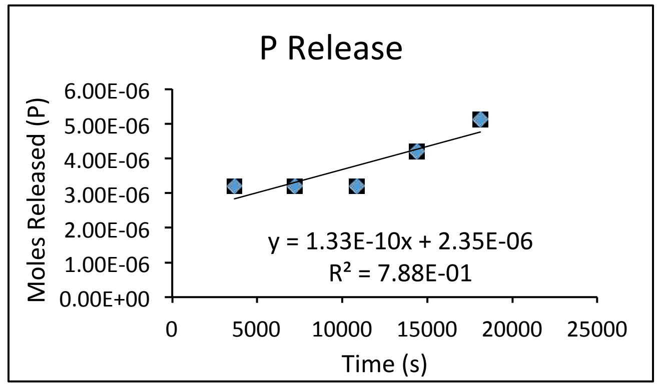
Organic Acid: Inorganic	**Acid Concentration:** 0.05 M

Mineral: Chlorapatite	**Batch ID:** Batch 1512	**Specific Surface Area (BET):** 0.0563m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	6.34	3.21E-06	3.00E-06
7200	6.57	3.21E-06	3.96E-06
10860	6.59	3.21E-06	4.94E-06
14400	6.72	4.20E-06	5.33E-06
18120	6.71	5.12E-06	6.29E-06
21720	6.81	1.34E-04	6.51E-06
91800	6.89	1.67E-05	9.18E-06
174360	6.95	1.82E-05	1.04E-05



Ca Regression Statistics		Std. Error
R Square	0.972	2.55E-07
P Regression Statistics		Std. Error
R Square	0.788	4.56E-07



Diss. Rate Ca (K_{diss})	$\boxed{4.663E-09}$	mol min/m^2s
Uncertainty of fit	3.982E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{5.247E-09}$	mol min/m^2s
Uncertainty of fit	1.576E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S44

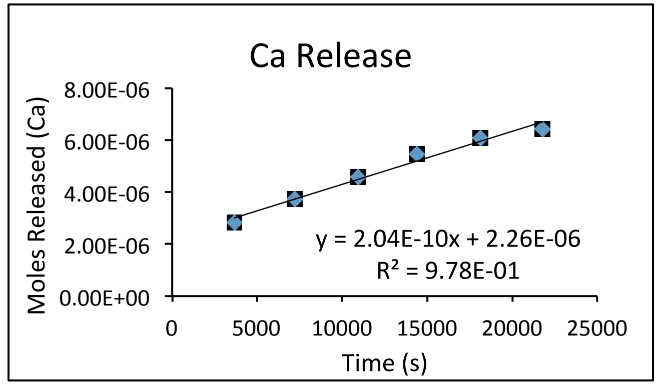
Experiment DI-CAP-D-1

Organic Acid: Inorganic **Acid Concentration:** 0.05 M

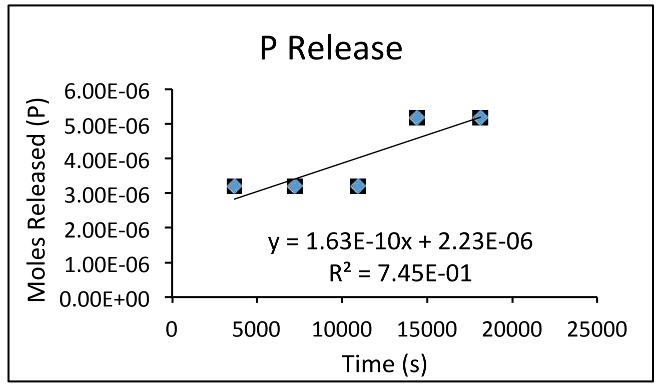
Mineral: Chlorapatite **Batch ID:** Batch 1512 **Specific Surface Area (BET):** 0.0563m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.94	3.21E-06	2.81E-06
7200	6.61	3.21E-06	3.74E-06
10920	6.63	3.21E-06	4.57E-06
14400	6.78	5.18E-06	5.46E-06
18120	6.85	5.18E-06	6.08E-06
21780	6.81	3.54E-05	6.40E-06
91860	7.01	9.74E-06	8.60E-06
174420	7.06	1.12E-05	1.02E-05



Ca Regression Statistics		Std. Error
R Square	0.978	2.33E-07
P Regression Statistics		Std. Error
R Square	0.745	6.30E-07



Diss. Rate Ca (K_{diss})	$\boxed{4.828E-09}$	mol min/m^{2}s
Uncertainty of fit	3.633E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{6.430E-09}$	mol min/m^{2}s
Uncertainty of fit	2.174E-09	mol min/m^{2}s

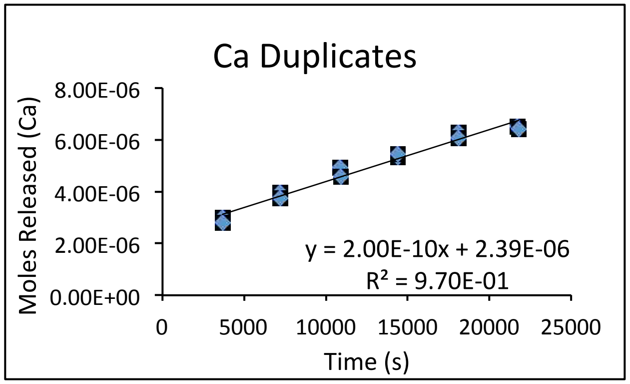
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S45

Organic Acid Duplicates:	Inorganic	**Mineral:**	Chlorapatite

DI-CAP-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	3.21E-06	3.00E-06
7200	3.21E-06	3.96E-06
10860	3.21E-06	4.94E-06
14400	4.20E-06	5.33E-06
18120	5.12E-06	6.29E-06
21720	1.34E-04	6.51E-06
91800	1.67E-05	9.18E-06
174360	1.82E-05	1.04E-05

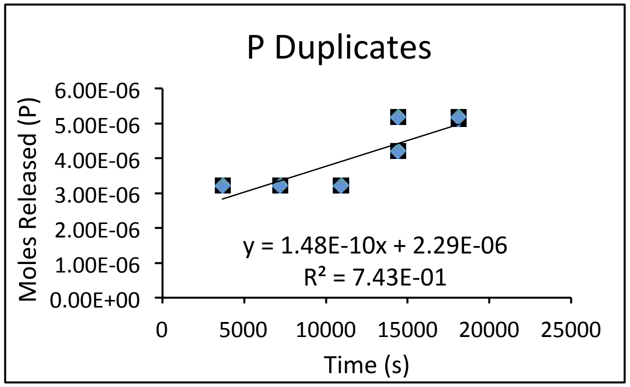


Diss. Rate Ca (K_{diss}) 4.66E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 5.25E-09 mol min/m^{2}s

DI-CAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	3.21E-06	2.81E-06
7200	3.21E-06	3.74E-06
10920	3.21E-06	4.57E-06
14400	5.18E-06	5.46E-06
18120	5.18E-06	6.08E-06
21780	3.54E-05	6.40E-06
91860	9.74E-06	8.60E-06
174420	1.12E-05	1.02E-05



Diss. Rate Ca (K_{diss}) 4.83E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 6.43E-09 mol min/m^{2}s

Data Sheet S46

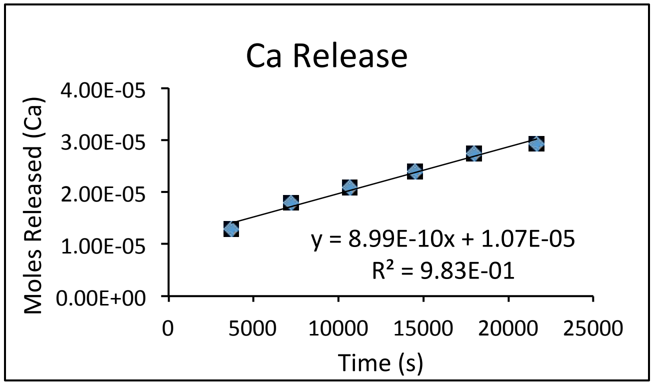
Experiment SUC-CAP-1

Organic Acid: Succinic **Acid Concentration:** 0.05 M

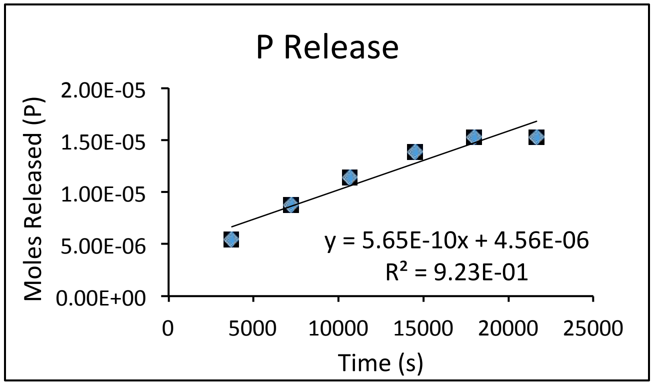
Mineral: Chlorapatite **Batch ID:** Batch 1512 **Specific Surface Area (BET):** 0.0563m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3720	5.53	5.45E-06	1.29E-05
7200	5.55	8.80E-06	1.80E-05
10680	5.51	1.14E-05	2.08E-05
14520	5.51	1.39E-05	2.40E-05
18000	5.61	1.53E-05	2.74E-05
21660	5.58	1.53E-05	2.93E-05
117840	5.61	3.34E-05	5.30E-05
187980	5.59	3.57E-05	5.77E-05



Ca Regression Statistics		Std. Error
R Square	0.983	8.97E-07
P Regression Statistics		Std. Error
R Square	0.923	1.23E-06



Diss. Rate Ca (K_{diss})	2.128E-08	mol min/m^2s
Uncertainty of fit	1.41E-09	mol min/m^2s
Diss. Rate P (K_{diss})	2.225E-08	mol min/m^2s
Uncertainty of fit	3.229E-09	mol min/m^2s

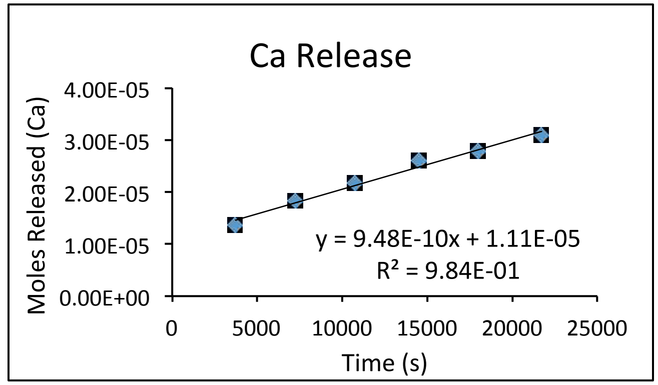
**Shaded data represents initial rate data in supplementary figure*

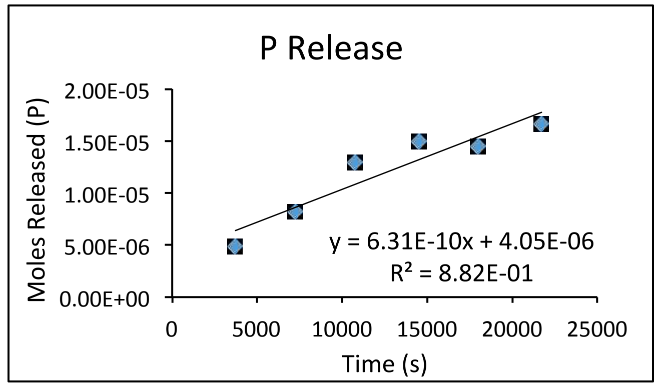
Data Sheet S47
Experiment SUC-CAP-D-1

Organic Acid: Succinic	**Acid Concentration:** 0.05 M

Mineral: Chlorapatite	**Batch ID:** Batch 1512	**Specific Surface Area (BET):** 0.0563m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3720	5.50	4.89E-06	1.36E-05
7260	5.51	8.24E-06	1.83E-05
10740	5.50	1.30E-05	2.17E-05
14520	5.51	1.50E-05	2.60E-05
18000	5.59	1.45E-05	2.78E-05
21720	5.60	1.67E-05	3.09E-05
117900	5.62	3.40E-05	5.59E-05
187980	5.60	3.77E-05	6.05E-05





Ca Regression Statistics		Std. Error
R Square	0.984	9.13E-07
P Regression Statistics		**Std. Error**
R Square	0.882	1.74E-06

Diss. Rate Ca (K_{diss})	2.244E-08	mol min/m^2s
Uncertainty of fit	1.435E-09	mol min/m^2s
Diss. Rate P (K_{diss})	2.489E-08	mol min/m^2s
Uncertainty of fit	4.563E-09	mol min/m^2s

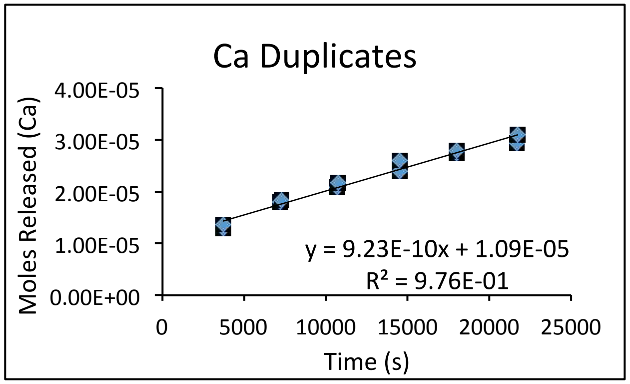
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S48

Organic Acid Duplicates:	Succinic	Mineral:	Chlorapatite

SUC-CAP-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	5.45E-06	1.29E-05
7200	8.80E-06	1.80E-05
10680	1.14E-05	2.08E-05
14520	1.39E-05	2.40E-05
18000	1.53E-05	2.74E-05
21660	1.53E-05	2.93E-05
117840	3.34E-05	5.30E-05
187980	3.57E-05	5.77E-05

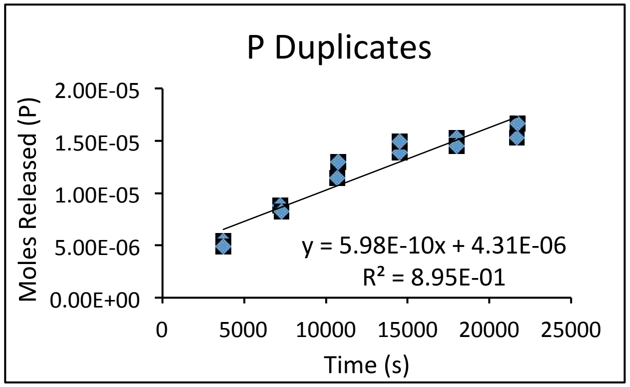


Diss. Rate Ca (K_{diss}) 2.13E-08 mol min/m^{2}s

Diss. Rate P (K_{diss}) 2.22E-08 mol min/m^{2}s

SUC-CAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	4.89E-06	1.36E-05
7260	8.24E-06	1.83E-05
10740	1.30E-05	2.17E-05
14520	1.50E-05	2.60E-05
18000	1.45E-05	2.78E-05
21720	1.67E-05	3.09E-05
117900	3.40E-05	5.59E-05
187980	3.77E-05	6.05E-05



Diss. Rate Ca (K_{diss}) 2.24E-08 mol min/m^{2}s

Diss. Rate P (K_{diss}) 2.49E-08 mol min/m^{2}s

Data Sheet S49

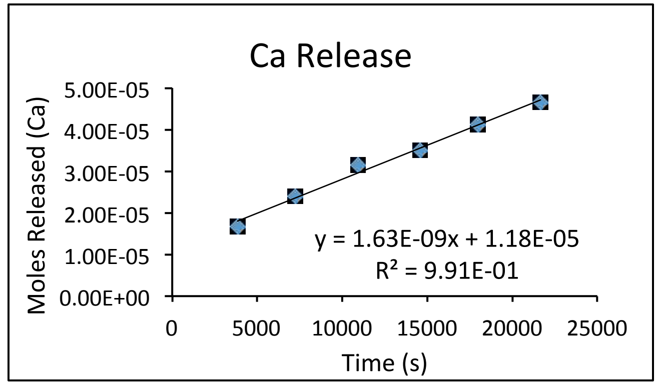
Experiment MEL-CAP-1

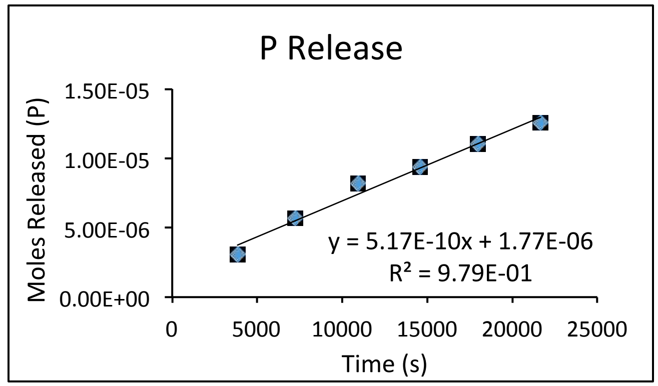
Organic Acid: Mellitic **Acid Concentration:** 0.05 M

Mineral: Chlorapatite **Batch ID:** Batch 1512 **Specific Surface Area (BET):** 0.0563m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3840	5.79	3.08E-06	1.68E-05
7260	5.65	5.72E-06	2.40E-05
10920	5.67	8.22E-06	3.14E-05
14580	5.71	9.39E-06	3.51E-05
18000	5.68	1.10E-05	4.12E-05
21660	5.64	1.26E-05	4.66E-05
82620	5.68	2.79E-05	7.61E-05
184320	5.64	3.93E-05	8.45E-05





Ca Regression Statistics		Std. Error
R Square	0.991	1.19E-06
P Regression Statistics		**Std. Error**
R Square	0.979	5.69E-07

Diss. Rate Ca (K_{diss})	3.858E-08	mol min/m^2s
Uncertainty of fit	1.882E-09	mol min/m^2s
Diss. Rate P (K_{diss})	2.039E-08	mol min/m^2s
Uncertainty of fit	1.502E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

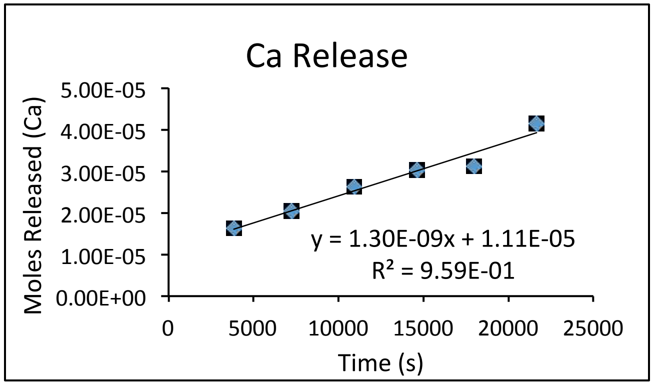
Data Sheet S50

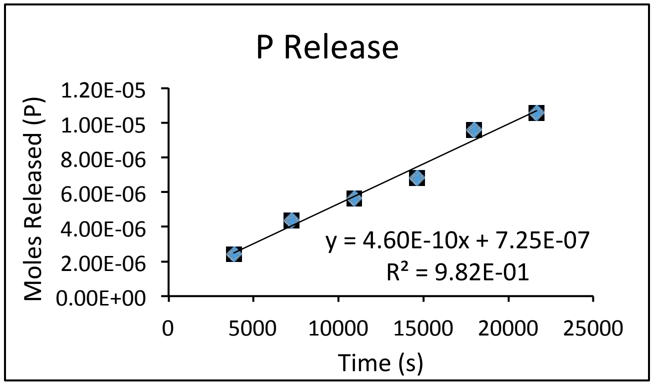
Experiment MEL-CAP-D-1

Organic Acid: Mellitic	**Acid Concentration:** 0.05 M

Mineral: Chlorapatite	**Batch ID:** Batch 1512	**Specific Surface Area (BET):** 0.0563m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3840	5.82	2.42E-06	1.62E-05
7260	5.63	4.40E-06	2.04E-05
10920	5.61	5.65E-06	2.63E-05
14640	5.62	6.82E-06	3.02E-05
18000	5.73	9.57E-06	3.13E-05
21660	5.61	1.06E-05	4.14E-05
82620	5.66	3.78E-05	8.08E-05
184380	5.65	3.74E-05	9.64E-05





Ca Regression Statistics		Std. Error
R Square	0.959	2.02E-06
P Regression Statistics		Std. Error
R Square	0.982	4.65E-07

Diss. Rate Ca (K_{diss})	3.077E-08	mol min/m^{2}s
Uncertainty of fit	3.197E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.815E-08	mol min/m^{2}s
Uncertainty of fit	2.306E-09	mol min/m^{2}s

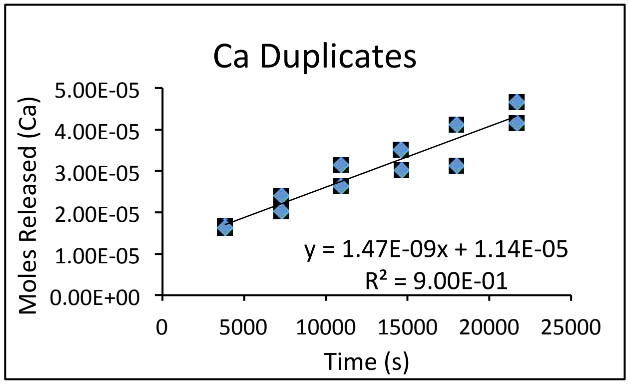
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S51

Organic Acid Duplicates:	Mellitic	**Mineral:**	Chloroapatite

MEL-CAP-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3840	3.08E-06	1.68E-05
7260	5.72E-06	2.40E-05
10920	8.22E-06	3.14E-05
14580	9.39E-06	3.51E-05
18000	1.10E-05	4.12E-05
21660	1.26E-05	4.66E-05
82620	2.79E-05	7.61E-05
184320	3.93E-05	8.45E-05

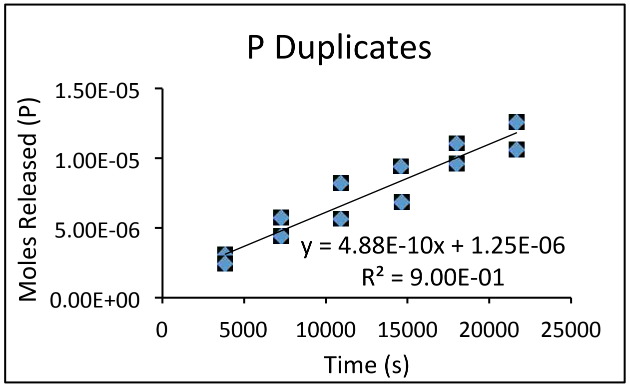


Diss. Rate Ca (K_{diss}) 3.86E-08 mol min/m^{2}s

Diss. Rate P (K_{diss}) 2.04E-08 mol min/m^{2}s

MEL-CAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3840	2.42E-06	1.62E-05
7260	4.40E-06	2.04E-05
10920	5.65E-06	2.63E-05
14640	6.82E-06	3.02E-05
18000	9.57E-06	3.13E-05
21660	1.06E-05	4.14E-05
82620	3.78E-05	8.08E-05
184380	3.74E-05	9.64E-05



Diss. Rate Ca (K_{diss}) 3.08E-08 mol min/m^{2}s

Diss. Rate P (K_{diss}) 1.81E-08 mol min/m^{2}s

Data Sheet S52

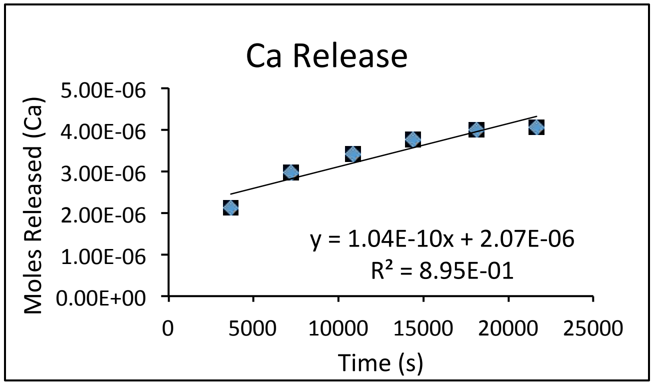
Experiment MES-CAP-1

Organic Acid: Methylsulfonic **Acid Concentration:** 0.05 M

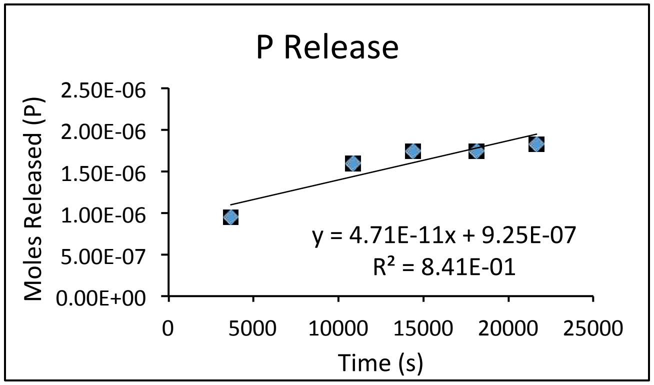
Mineral: Chlorapatite **Batch ID:** Batch 1512 **Specific Surface Area (BET):** 0.0563m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	6.80	9.53E-07	2.12E-06
7200	6.85	6.00E-06	2.96E-06
10860	6.99	1.60E-06	3.41E-06
14400	6.94	1.74E-06	3.76E-06
18120	6.91	1.74E-06	4.00E-06
21660	6.90	1.83E-06	4.05E-06
84840	7.06	2.26E-06	4.75E-06
176700	7.13	2.70E-06	5.17E-06



Ca Regression Statistics		Std. Error
R Square	0.895	2.68E-07
P Regression Statistics		**Std. Error**
R Square	0.841	1.64E-07



Diss. Rate Ca (K_{diss})	$\boxed{2.391E-09}$	mol min/m^{2}s
Uncertainty of fit	4.17E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{1.329E-09}$	mol min/m^{2}s
Uncertainty of fit	2.74E-10	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S53

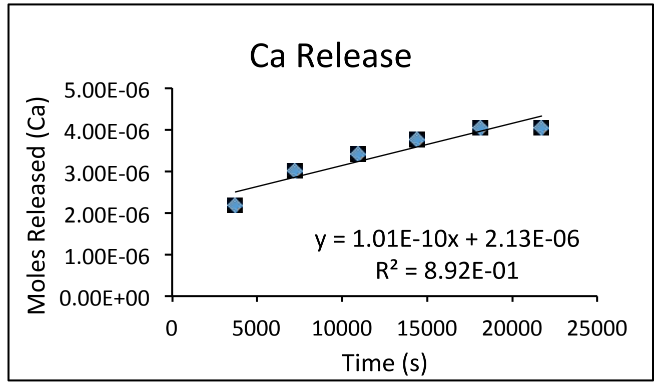
Experiment MES-CAP-D-1

Organic Acid: Methylsulfonic **Acid Concentration:** 0.05 M

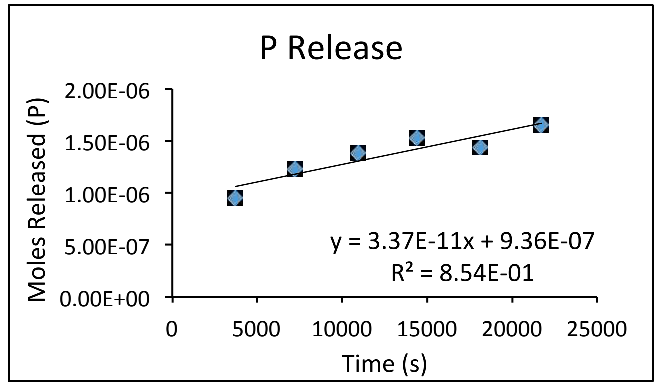
Mineral: Chlorapatite **Batch ID:** Batch 1512 **Specific Surface Area (BET):** $0.0563 m^2/g$

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** $0.00845 m^2$

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3720	6.94	9.53E-07	2.18E-06
7200	7.04	1.23E-06	3.01E-06
10920	6.94	1.38E-06	3.42E-06
14400	7.12	1.53E-06	3.77E-06
18120	7.03	1.44E-06	4.05E-06
21720	7.10	1.65E-06	4.05E-06
84840	7.12	2.17E-06	5.01E-06
176700	7.13	2.64E-06	5.29E-06



Ca Regression Statistics		Std. Error
R Square	0.892	2.66E-07
P Regression Statistics		Std. Error
R Square	0.855	1.05E-07



Diss. Rate Ca (K_{diss})	$\boxed{2.391E-09}$	mol min/m^2s
Uncertainty of fit	4.17E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{1.329E-09}$	mol min/m^2s
Uncertainty of fit	2.74E-10	mol min/m^2s

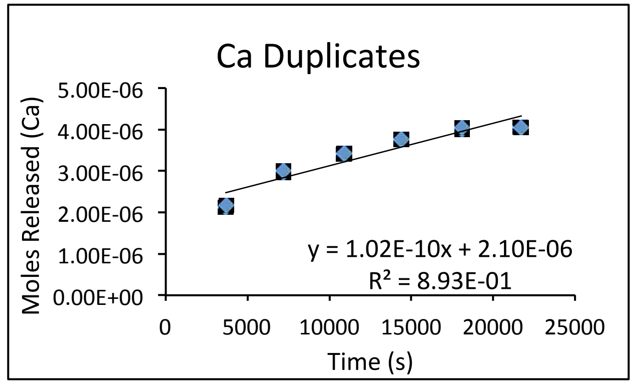
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S54

Organic Acid Duplicates:	Methylsulfonic	**Mineral:**	Chlorapatite

MES-CAP-1

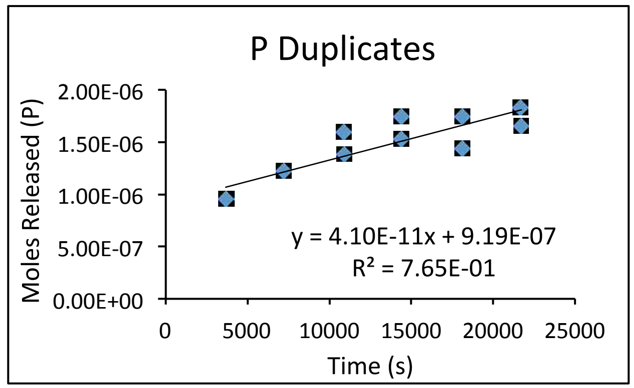
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	9.53E-07	2.12E-06
7200	6.00E-06	2.96E-06
10860	1.60E-06	3.41E-06
14400	1.74E-06	3.76E-06
18120	1.74E-06	4.00E-06
21660	1.83E-06	4.05E-06
84840	2.26E-06	4.75E-06
176700	2.70E-06	5.17E-06



Diss. Rate Ca (K_{diss})	2.39E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.33E-09	mol min/m^{2}s

MES-CAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	9.53E-07	2.18E-06
7200	1.23E-06	3.01E-06
10920	1.38E-06	3.42E-06
14400	1.53E-06	3.77E-06
18120	1.44E-06	4.05E-06
21720	1.65E-06	4.05E-06
84840	2.17E-06	5.01E-06
176700	2.64E-06	5.29E-06



Diss. Rate Ca (K_{diss})	2.39E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.33E-09	mol min/m^{2}s

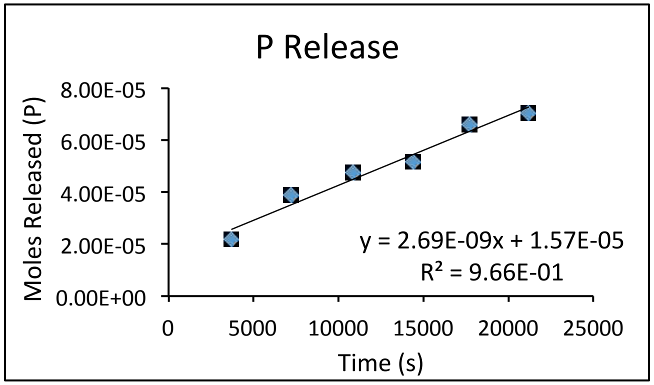
Data Sheet S55

Experiment OXA-CAP-1

Organic Acid: Oxalic	**Acid Concentration:** 0.05 M

Mineral: Chlorapatite	**Batch ID:** Batch 1512	**Specific Surface Area (BET):** 0.0563m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3720	5.72	2.18E-05	N/A
7200	5.65	3.87E-05	N/A
10860	5.75	4.75E-05	N/A
14400	5.75	5.17E-05	N/A
17700	5.83	6.60E-05	N/A
21180	5.92	7.04E-05	N/A
84720	6.69	1.29E-04	N/A
182040	7.09	1.59E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		**Std. Error**
R Square	0.966	3.71E-06

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	1.061E-07	mol min/m^2s
Uncertainty of fit	1.00E-08	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S56

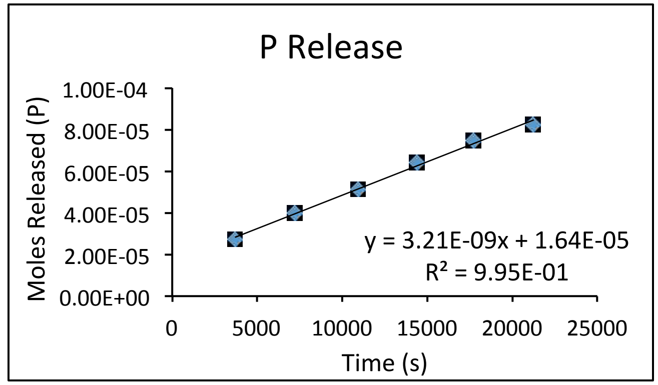
Experiment OXA-CAP-D-1

Organic Acid: Oxalic **Acid Concentration:** 0.05 M

Mineral: Chlorapatite **Batch ID:** Batch 1512 **Specific Surface Area (BET):** 0.0563m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.00845m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3720	5.61	2.72E-05	N/A
7200	5.70	4.00E-05	N/A
10920	5.75	5.14E-05	N/A
14400	5.85	6.42E-05	N/A
17700	5.88	7.47E-05	N/A
21240	6.00	8.25E-05	N/A
84720	6.84	1.55E-04	N/A
182040	7.02	1.66E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		Std. Error
R Square	0.995	1.61E-06

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	8.560E-08	mol min/m^2s
Uncertainty of fit	4.32E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S57

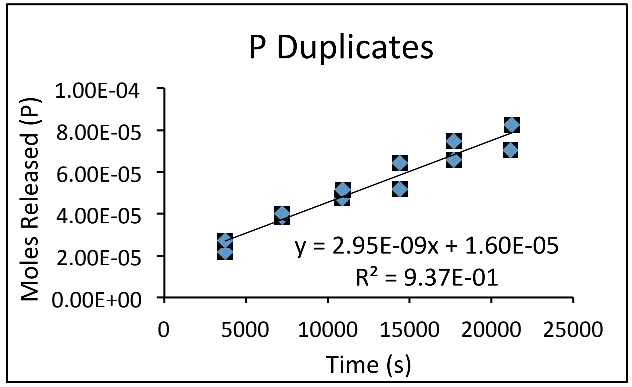
Organic Acid Duplicates:	Oxalic	**Mineral:**	Chlorapatite

OXA-CAP-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	2.18E-05	N/A
7200	3.87E-05	N/A
10860	4.75E-05	N/A
14400	5.17E-05	N/A
17700	6.60E-05	N/A
21180	7.04E-05	N/A
84720	1.29E-04	N/A
182040	1.59E-04	N/A

Diss. Rate Ca (K_{diss}) N/A mol min/m^{2}s

Diss. Rate P (K_{diss}) 1.06E-07 mol min/m^{2}s



OXA-CAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3720	2.72E-05	N/A
7200	4.00E-05	N/A
10920	5.14E-05	N/A
14400	6.42E-05	N/A
17700	7.47E-05	N/A
21240	8.25E-05	N/A
84720	1.55E-04	N/A
182040	1.66E-04	N/A

Diss. Rate Ca (K_{diss}) N/A mol min/m^{2}s

Diss. Rate P (K_{diss}) 8.56E-08 mol min/m^{2}s

Data Sheet S58

Chlorapatite Blanks

Sample Blank	Final pH	Initial Moles (P)	Final Moles (P)	Initial Moles (Ca)	Final Moles (Ca)
ACE-B-6	5.44	B.D.	B.D.	3.6343E-07	4.57221E-07
SUC-B-5	5.51	B.D.	B.D.	5.14697E-07	4.43128E-07
MES-B-4	6.73	1.638E-07	1.7612E-07	3.01439E-07	2.79893E-07
MEL-B-2	5.65	B.D.	B.D.	2.13672E-06	1.37105E-06
OXA-B-5	5.51	1.05622E-06	1.11653E-06		
DI-B-14	6.11	B.D.	B.D.	4.60369E-07	4.93844E-07
DI-B-16	4.94	6.76667E-06	6.77283E-06	3.65281E-07	4.17628E-07
DI-B-17	5.38	B.D.	B.D.	1.9079E-07	4.5577E-07
DI-B-19	5.62	B.D.	B.D.	3.2773E-07	8.37757E-08
DI-B-26	4.97	1.13391E-06	1.07505E-06		

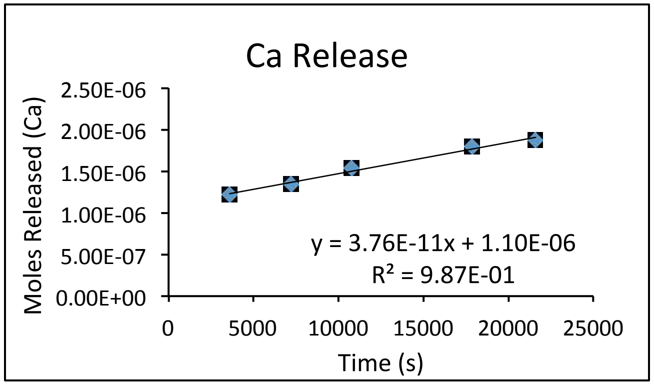
Data Sheet S59

Experiment ACE-FLAP-1

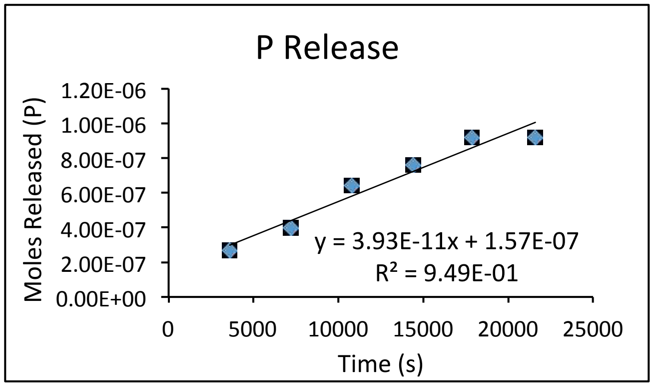
Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.50	2.68E-07	1.22E-06
7200	5.52	3.98E-07	1.34E-06
10800	5.52	6.43E-07	1.54E-06
14400	5.51	7.58E-07	2.07E-06
17880	5.51	9.20E-07	1.80E-06
21600	5.52	9.20E-07	1.87E-06
108960	5.52	1.58E-06	2.47E-06
180180	5.53	1.62E-06	2.80E-06



Ca Regression Statistics		Std. Error
R Square	0.987	3.75E-08
P Regression Statistics		**Std. Error**
R Square	0.949	6.83E-08



Diss. Rate Ca (K_{diss})	$\boxed{1.562E-09}$	mol min/m^2s
Uncertainty of fit	1.048E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{2.721E-09}$	mol min/m^2s
Uncertainty of fit	3.15E-10	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

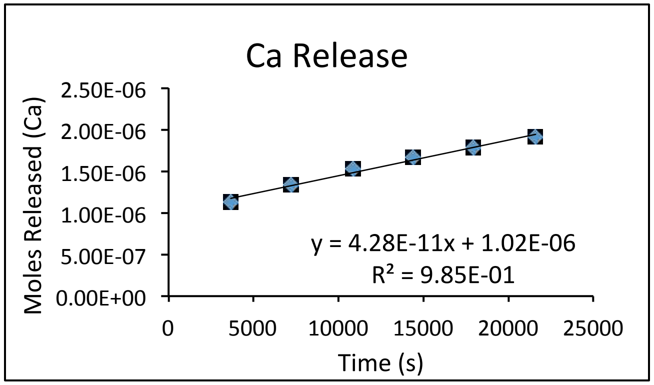
Data Sheet S60

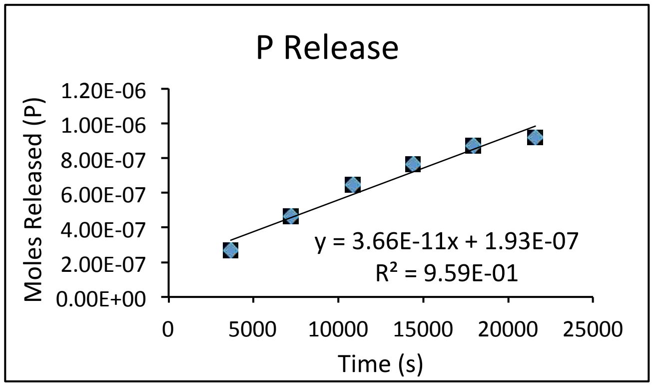
Experiment ACE-FLAP-D-1

Organic Acid: Acetic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3660	5.50	2.68E-07	1.13E-06
7200	5.51	4.63E-07	1.34E-06
10860	5.51	6.46E-07	1.53E-06
14400	5.52	7.61E-07	1.67E-06
17940	5.53	8.69E-07	1.78E-06
21600	5.53	9.20E-07	1.91E-06
108960	5.52	1.53E-06	2.36E-06
180180	5.53	1.61E-06	2.61E-06





Ca Regression Statistics		Std. Error
R Square	0.985	3.91E-08
P Regression Statistics		**Std. Error**
R Square	0.959	5.65E-08

Diss. Rate Ca (K_{diss})	1.778E-09	mol min/m^{2}s
Uncertainty of fit	1.084E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	2.534E-09	mol min/m^{2}s
Uncertainty of fit	2.608E-10	mol min/m^{2}s

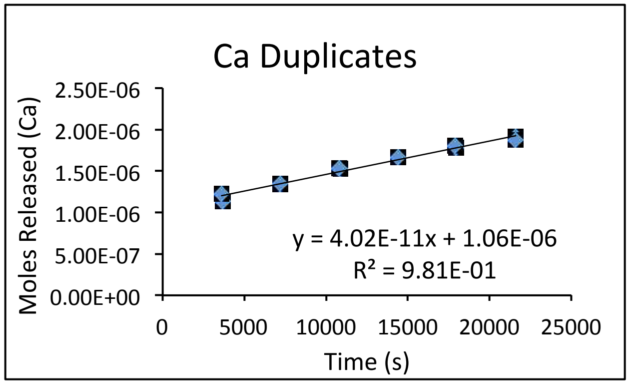
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S61

Organic Acid Duplicates:	Acetic	**Mineral:**	Fluorapatite

ACE-FLAP-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	2.68E-07	1.22E-06
7200	3.98E-07	1.34E-06
10800	6.43E-07	1.54E-06
14400	7.58E-07	2.07E-06
17880	9.20E-07	1.80E-06
21600	9.20E-07	1.87E-06
108960	1.58E-06	2.47E-06
180180	1.62E-06	2.80E-06

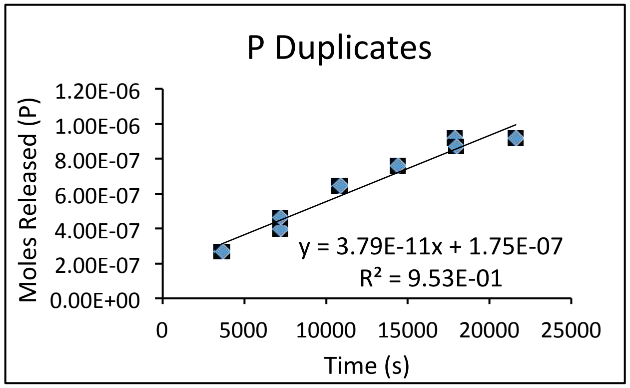


Diss. Rate Ca (K_{diss}) 1.56E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 2.72E-09 mol min/m^{2}s

ACE-FLAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3660	2.68E-07	1.13E-06
7200	4.63E-07	1.34E-06
10860	6.46E-07	1.53E-06
14400	7.61E-07	1.67E-06
17940	8.69E-07	1.78E-06
21600	9.20E-07	1.91E-06
108960	1.53E-06	2.36E-06
180180	1.61E-06	2.61E-06



Diss. Rate Ca (K_{diss}) 1.78E-09 mol min/m^{2}s

Diss. Rate P (K_{diss}) 2.53E-09 mol min/m^{2}s

Data Sheet S62

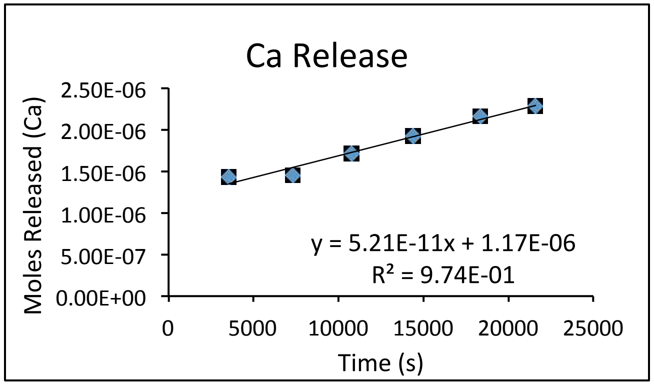
Experiment SUC-FLAP-1

Organic Acid: Succinic **Acid Concentration:** 0.05 M

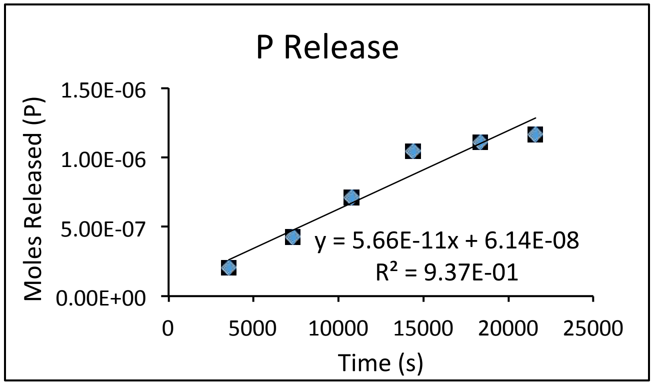
Mineral: Fluorapatite **Batch ID:** Durango **Specific Surface Area (BET):** 0.0321m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	5.56	2.04E-07	1.43E-06
7320	5.56	4.30E-07	1.45E-06
10800	5.58	7.13E-07	1.71E-06
14400	5.57	1.05E-06	1.92E-06
18360	5.59	1.11E-06	2.16E-06
21600	5.56	1.17E-06	2.28E-06
122820	5.57	2.47E-06	3.38E-06
178980	5.57	2.52E-06	3.70E-06



Ca Regression Statistics		Std. Error
R Square	0.974	6.52E-08
P Regression Statistics		Std. Error
R Square	0.937	1.11E-07



Diss. Rate Ca (K_{diss})	$\boxed{2.164E-09}$	mol min/m^{2}s
Uncertainty of fit	1.785E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{3.918E-09}$	mol min/m^{2}s
Uncertainty of fit	5.08E-10	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

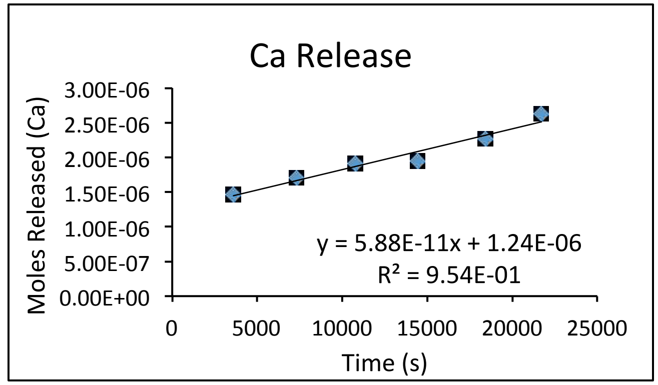
Data Sheet S63

Experiment SUC-FLAP-D-1

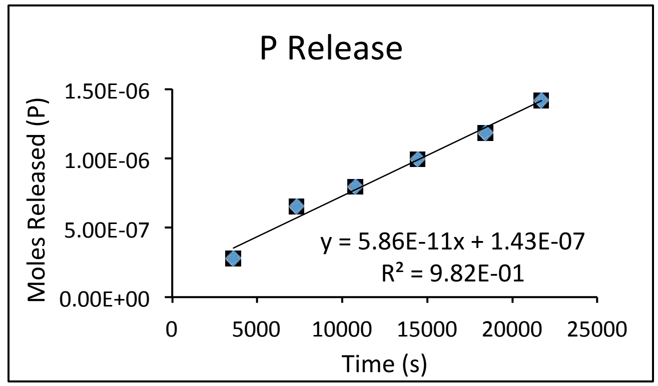
Organic Acid: Succinic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.57	2.80E-07	1.47E-06
7320	5.58	6.55E-07	1.70E-06
10800	5.56	7.97E-07	1.91E-06
14460	5.55	9.97E-07	1.94E-06
18420	5.57	1.18E-06	2.26E-06
21720	5.58	1.42E-06	2.62E-06
122940	5.57	2.56E-06	3.55E-06
179100	5.55	3.06E-06	3.71E-06



Ca Regression Statistics		Std. Error
R Square	0.954	9.82E-08
P Regression Statistics		Std. Error
R Square	0.982	5.98E-08



Diss. Rate Ca (K_{diss})	$\boxed{2.442E-09}$	mol min/m^2s
Uncertainty of fit	2.676E-10	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{4.057E-09}$	mol min/m^2s
Uncertainty of fit	2.717E-10	mol min/m^2s

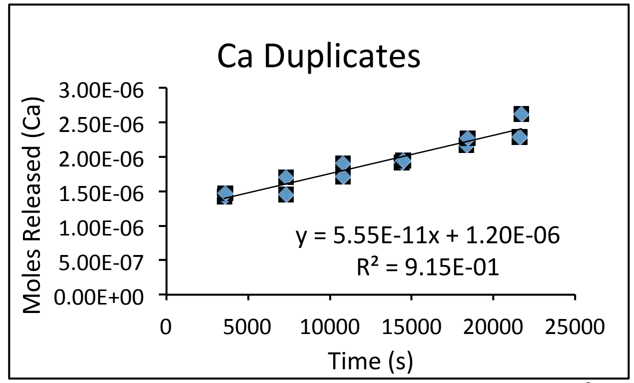
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S64

Organic Acid Duplicates:	Succinic	**Mineral:**	Fluorapatite

SUC-FLAP-1

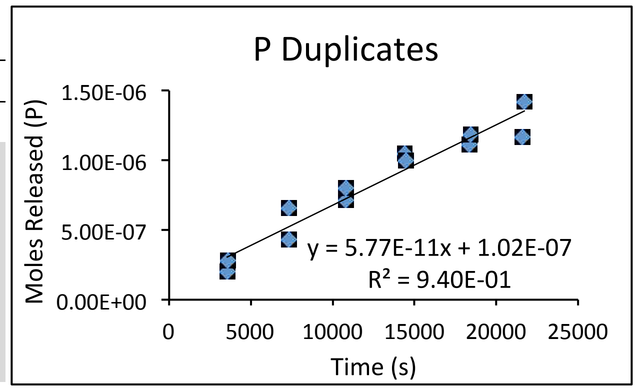
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	2.04E-07	1.43E-06
7320	4.30E-07	1.45E-06
10800	7.13E-07	1.71E-06
14400	1.05E-06	1.92E-06
18360	1.11E-06	2.16E-06
21600	1.17E-06	2.28E-06
122820	2.47E-06	3.38E-06
178980	2.52E-06	3.70E-06



Diss. Rate Ca (K_{diss})	2.16E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	3.92E-09	mol min/m^{2}s

SUC-FLAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	2.80E-07	1.47E-06
7320	6.55E-07	1.70E-06
10800	7.97E-07	1.91E-06
14460	9.97E-07	1.94E-06
18420	1.18E-06	2.26E-06
21720	1.42E-06	2.62E-06
122940	2.56E-06	3.55E-06
179100	3.06E-06	3.71E-06



Diss. Rate Ca (K_{diss})	2.44E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	4.06E-09	mol min/m^{2}s

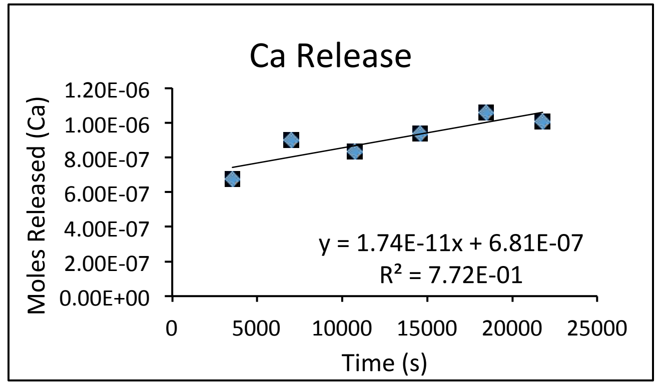
Data Sheet S65

Experiment MES-FLAP-1

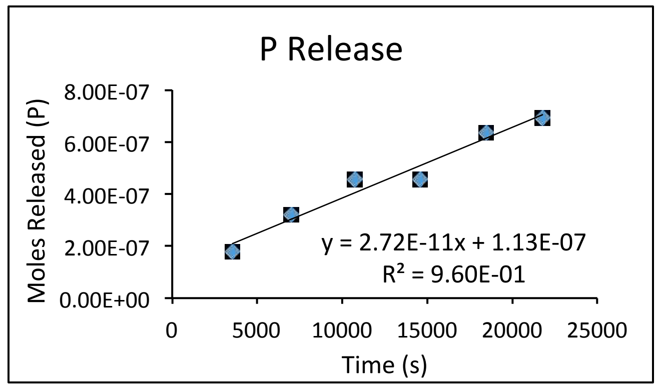
Organic Acid: Methylsulfonic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** $0.0321 m^2/g$
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** $0.004815 m^2$

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	6.16	1.79E-07	6.74E-07
7020	5.02	3.22E-07	9.01E-07
10740	5.16	4.58E-07	8.32E-07
14580	5.10	4.58E-07	9.37E-07
18480	4.83	6.38E-07	1.06E-06
21780	4.90	6.93E-07	1.01E-06
88260	4.91	1.06E-06	1.22E-06
163500	5.02	1.10E-06	1.31E-06



Ca Regression Statistics		Std. Error
R Square	0.772	7.32E-08
P Regression Statistics		Std. Error
R Square	0.960	4.29E-08



Diss. Rate Ca (K_{diss})	7.227E-10	$mol\ min/m^2s$
Uncertainty of fit	1.965E-10	$mol\ min/m^2s$
Diss. Rate P (K_{diss})	1.883E-09	$mol\ min/m^2s$
Uncertainty of fit	1.918E-10	$mol\ min/m^2s$

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S66

Experiment MES-FLAP-D-1

Organic Acid: Methylsulfonic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3540	5.10	1.07E-07	7.15E-07
7020	5.18	3.94E-07	8.38E-07
10800	5.15	3.94E-07	8.50E-07
14580	4.88	5.86E-07	8.97E-07
18540	4.87	5.86E-07	9.77E-07
21780	4.80	6.97E-07	1.02E-06
88260	4.84	1.01E-06	1.30E-06
163560	4.99	1.10E-06	1.30E-06

Ca Regression Statistics		Std. Error
R Square	0.954	2.63E-08
P Regression Statistics		Std. Error
R Square	0.886	7.93E-08

Diss. Rate Ca (K_{diss})	6.438E-10	mol min/m^2s
Uncertainty of fit	7.051E-11	mol min/m^2s
Diss. Rate P (K_{diss})	1.980E-09	mol min/m^2s
Uncertainty of fit	3.544E-10	mol min/m^2s

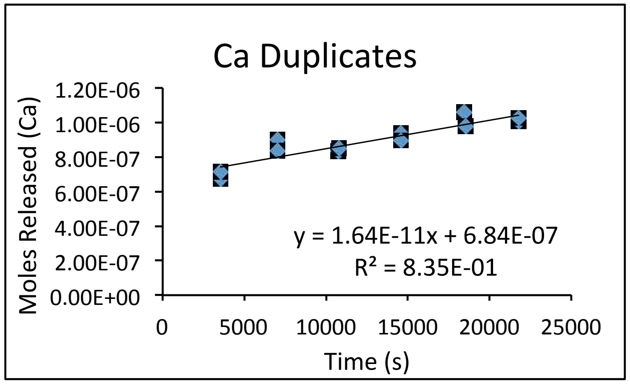
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S67

Organic Acid Duplicates:	Methylsulfonic	**Mineral:**	Fluorapatite

MES-FLAP-1

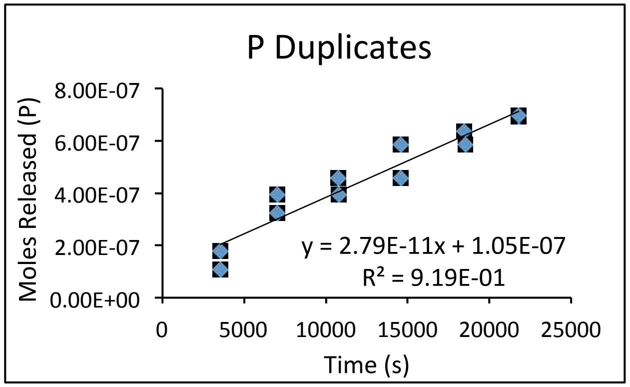
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	1.79E-07	6.74E-07
7020	3.22E-07	9.01E-07
10740	4.58E-07	8.32E-07
14580	4.58E-07	9.37E-07
18480	6.38E-07	1.06E-06
21780	6.93E-07	1.01E-06
88260	1.06E-06	1.22E-06
163500	1.10E-06	1.31E-06



Diss. Rate Ca (K_{diss})	7.23E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.88E-09	mol min/m^{2}s

MES-FLAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3540	1.07E-07	7.15E-07
7020	3.94E-07	8.38E-07
10800	3.94E-07	8.50E-07
14580	5.86E-07	8.97E-07
18540	5.86E-07	9.77E-07
21780	6.97E-07	1.02E-06
88260	1.01E-06	1.30E-06
163560	1.10E-06	1.30E-06



Diss. Rate Ca (K_{diss})	6.44E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.98E-09	mol min/m^{2}s

Data Sheet S68

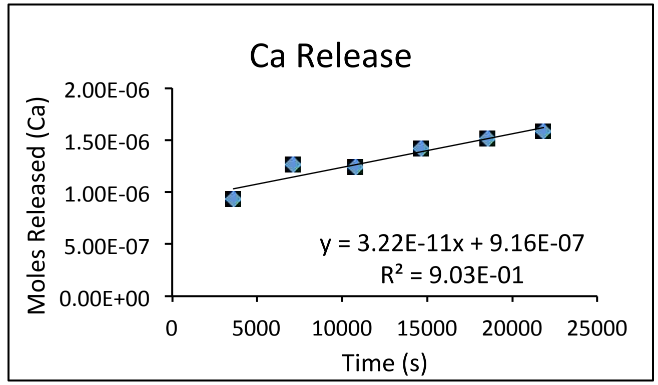
Experiment DI-FLAP-1

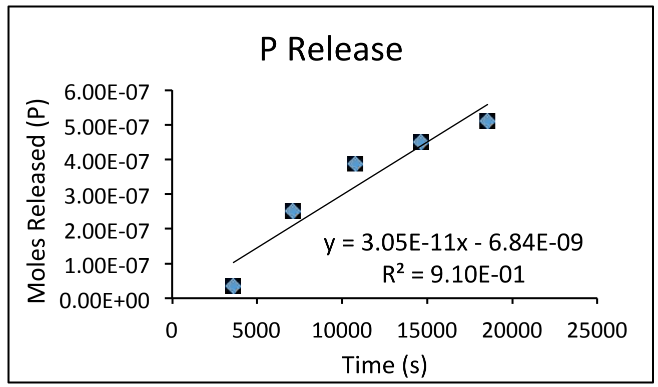
Organic Acid: Inorganic **Acid Concentration:** 0.05 M

Mineral: Fluorapatite **Batch ID:** Durango **Specific Surface Area (BET):** 0.0321m^2/g

Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.12	3.51E-08	9.37E-07
7080	5.20	2.51E-07	1.26E-06
10800	5.10	3.86E-07	1.24E-06
14640	4.96	4.50E-07	1.42E-06
18540	4.64	5.10E-07	1.52E-06
21840	4.76	4.54E-07	1.58E-06
88320	5.14	8.69E-07	2.09E-06
163560	5.00	9.17E-07	2.43E-06





Ca Regression Statistics		Std. Error
R Square	0.903	8.15E-08

P Regression Statistics		Std. Error
R Square	0.910	6.55E-08

Diss. Rate Ca (K_{diss})	1.337E-09	mol min/m^{2}s
Uncertainty of fit	2.189E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	2.111E-09	mol min/m^{2}s
Uncertainty of fit	3.827E-10	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

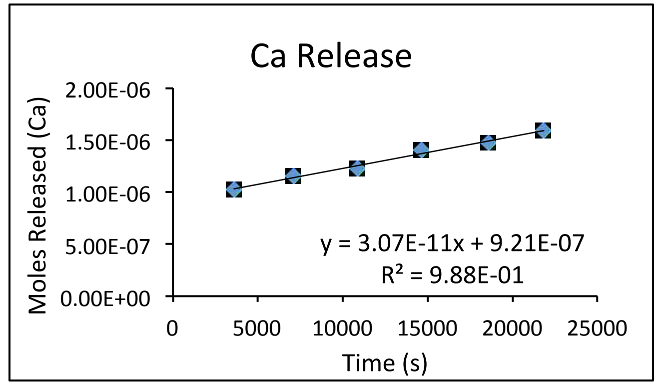
Data Sheet S69

Experiment DI-FLAP-D-1

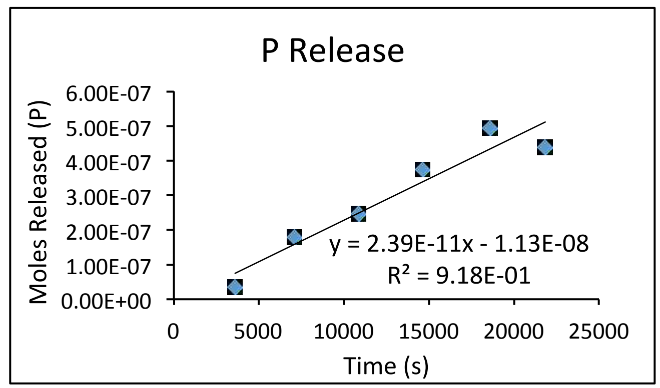
Organic Acid: Inorganic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	4.85	3.51E-08	1.02E-06
7080	4.73	1.79E-07	1.16E-06
10860	4.97	2.47E-07	1.23E-06
14640	5.21	3.74E-07	1.41E-06
18600	4.77	4.94E-07	1.47E-06
21840	4.76	4.38E-07	1.59E-06
88320	4.82	7.49E-07	2.06E-06
163620	5.02	9.41E-07	2.31E-06



Ca Regression Statistics		Std. Error
R Square	0.988	2.62E-08
P Regression Statistics		Std. Error
R Square	0.918	5.53E-08



Diss. Rate Ca (K_{diss})	$\boxed{1.275E-09}$	mol min/m^2s
Uncertainty of fit	7.029E-11	mol min/m^2s
Diss. Rate P (K_{diss})	$\boxed{1.655E-09}$	mol min/m^2s
Uncertainty of fit	2.472E-10	mol min/m^2s

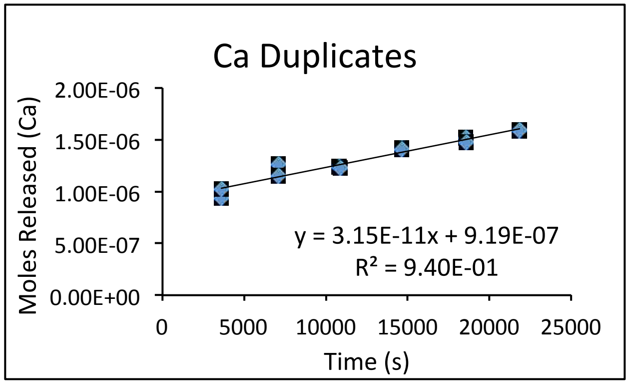
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S70

Organic Acid Duplicates:	Inorganic	**Mineral:**	Fluorapatite

DI-FLAP-1

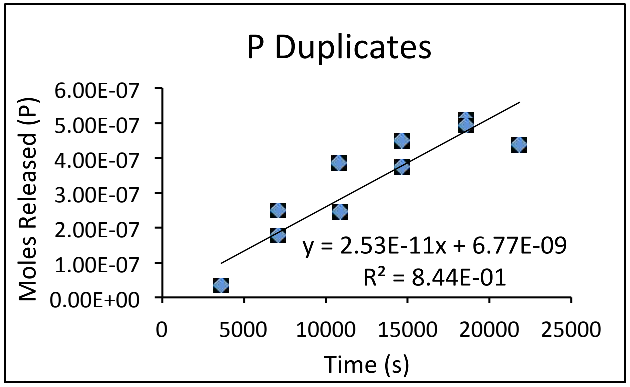
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	3.51E-08	9.37E-07
7080	2.51E-07	1.26E-06
10800	3.86E-07	1.24E-06
14640	4.50E-07	1.42E-06
18540	5.10E-07	1.52E-06
21840	4.54E-07	1.58E-06
88320	8.69E-07	2.09E-06
163560	9.17E-07	2.43E-06



Diss. Rate Ca (K_{diss})	1.34E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	2.11E-09	mol min/m^{2}s

DI-FLAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	3.51E-08	1.02E-06
7080	1.79E-07	1.16E-06
10860	2.47E-07	1.23E-06
14640	3.74E-07	1.41E-06
18600	4.94E-07	1.47E-06
21840	4.38E-07	1.59E-06
88320	7.49E-07	2.06E-06
163620	9.41E-07	2.31E-06



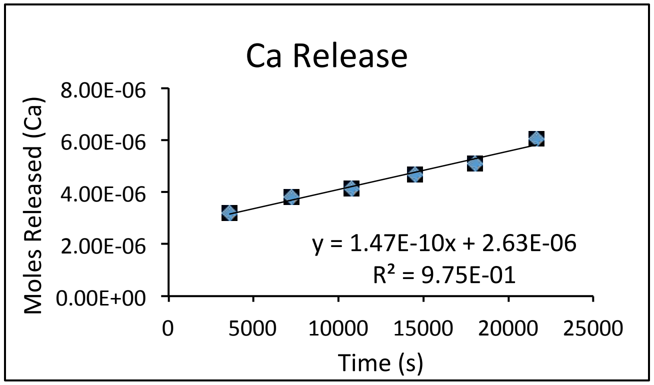
Diss. Rate Ca (K_{diss})	1.28E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	1.65E-09	mol min/m^{2}s

Data Sheet S71
Experiment MEL-FLAP-1

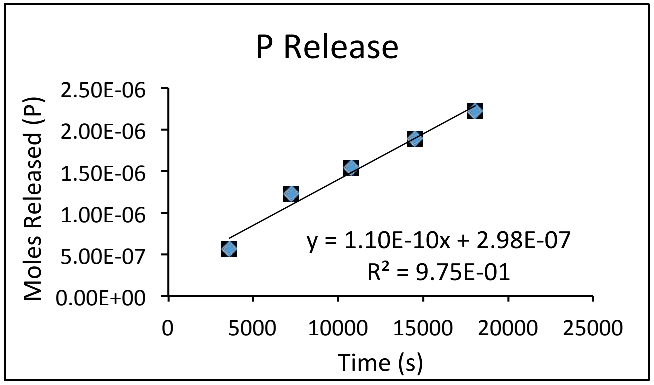
Organic Acid: Mellitic **Acid Concentration:** 0.05 M

Mineral: Fluorapatite **Batch ID:** Durango **Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5 **Mineral Mass:** 0.1500 g **Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.64	5.68E-07	3.19E-06
7260	5.66	1.23E-06	3.82E-06
10800	5.66	1.54E-06	4.13E-06
14520	5.69	1.89E-06	4.67E-06
18060	5.70	2.22E-06	5.08E-06
21660	5.65	2.58E-06	6.05E-06
115200	5.76	5.59E-06	9.65E-06
182400	5.71	9.82E-06	1.19E-05



Ca Regression Statistics		Std. Error
R Square	0.975	1.79E-07
P Regression Statistics		Std. Error
R Square	0.983	1.05E-07



Diss. Rate Ca (K_{diss})	$\boxed{6.106E-09}$	mol min/m^{2}s
Uncertainty of fit	4.912E-10	mol min/m^{2}s
Diss. Rate P (K_{diss})	$\boxed{7.338E-09}$	mol min/m^{2}s
Uncertainty of fit	4.829E-10	mol min/m^{2}s

**Shaded data represents initial rate data in supplementary figure*

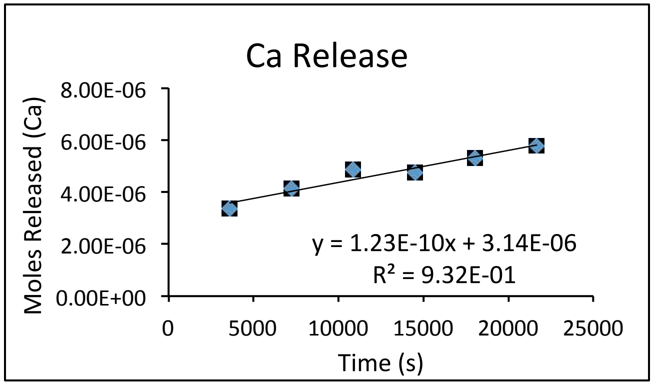
Data Sheet S72

Experiment MEL-FLAP-D-1

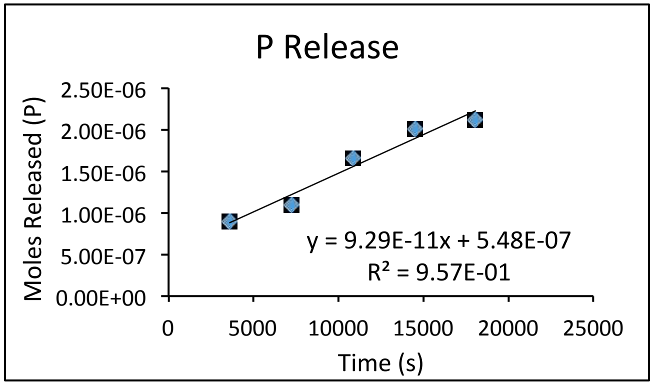
Organic Acid: Mellitic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	B.D.
3600	5.60	8.98E-07	3.35E-06
7260	5.66	1.10E-06	4.12E-06
10860	5.58	1.66E-06	4.88E-06
14520	5.65	2.01E-06	4.75E-06
18060	5.65	2.12E-06	5.31E-06
21660	5.62	2.69E-06	5.78E-06
115200	5.67	6.03E-06	1.06E-05
182400	5.63	8.49E-06	1.26E-05



Ca Regression Statistics		Std. Error
R Square	0.932	2.52E-07
P Regression Statistics		Std. Error
R Square	0.974	1.20E-07



Diss. Rate Ca (K_{diss})	5.109E-09	mol min/m^2s
Uncertainty of fit	6.933E-10	mol min/m^2s
Diss. Rate P (K_{diss})	6.771E-09	mol min/m^2s
Uncertainty of fit	5.515E-10	mol min/m^2s

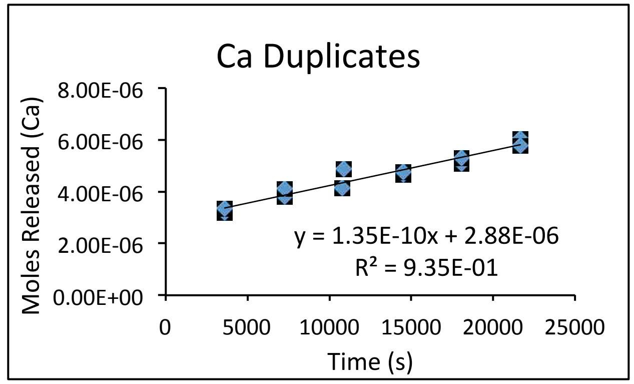
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S73

Organic Acid Duplicates:	Mellitic	Mineral:	Fluorapatite

MEL-FLAP-1

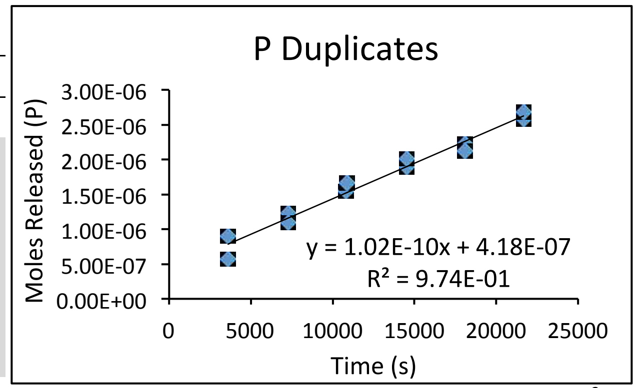
Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	5.68E-07	3.19E-06
7260	1.23E-06	3.82E-06
10800	1.54E-06	4.13E-06
14520	1.89E-06	4.67E-06
18060	2.22E-06	5.08E-06
21660	2.58E-06	6.05E-06
115200	5.59E-06	9.65E-06
182400	9.82E-06	1.19E-05



Diss. Rate Ca (K_{diss})	6.11E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	7.34E-09	mol min/m^{2}s

MEL-FLAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)
0	B.D.	B.D.
3600	8.98E-07	3.35E-06
7260	1.10E-06	4.12E-06
10860	1.66E-06	4.88E-06
14520	2.01E-06	4.75E-06
18060	2.12E-06	5.31E-06
21660	2.69E-06	5.78E-06
115200	6.03E-06	1.06E-05
182400	8.49E-06	1.26E-05



Diss. Rate Ca (K_{diss})	5.11E-09	mol min/m^{2}s
Diss. Rate P (K_{diss})	6.77E-09	mol min/m^{2}s

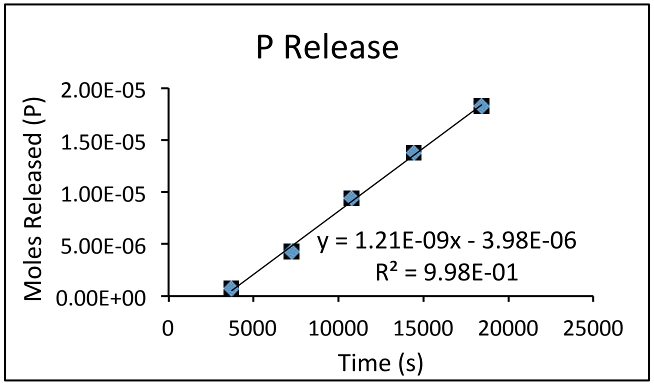
Data Sheet S74

Experiment OXA-FLAP-1

Organic Acid: Oxalic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3720	5.48	7.28E-07	N/A
7260	5.49	4.32E-06	N/A
10800	5.49	9.42E-06	N/A
14460	5.50	1.37E-05	N/A
18420	5.51	1.82E-05	N/A
21900	5.50	9.12E-05	N/A
85080	5.78	9.92E-05	N/A
182220	6.13	1.28E-04	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		**Std. Error**
R Square	0.998	3.79E-07

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	8.377E-08	mol min/m^2s
Uncertainty of fit	2.268E-09	mol min/m^2s

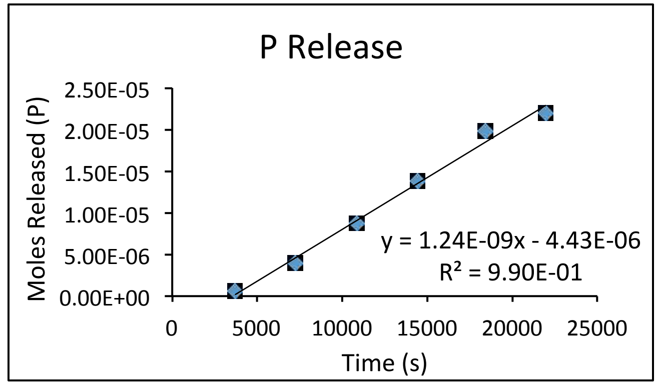
**Shaded data represents initial rate data in supplementary figure*

Data Sheet S75
Experiment OXA-FLAP-D-1

Organic Acid: Oxalic	**Acid Concentration:** 0.05 M

Mineral: Fluorapatite	**Batch ID:** Durango	**Specific Surface Area (BET):** 0.0321m^2/g
Initial pH: 5.5	**Mineral Mass:** 0.1500 g	**Total Surface Area (BET):** 0.004815m^2

Time (s)	pH	Moles Released (P)	Moles Released (Ca)
0	5.5	B.D.	N/A
3720	5.47	5.84E-07	N/A
7260	5.47	3.96E-06	N/A
10860	5.48	8.72E-06	N/A
14460	5.50	1.38E-05	N/A
18420	5.49	1.98E-05	N/A
21960	5.51	2.19E-05	N/A
85080	5.80	6.42E-05	N/A
182160	6.16	8.00E-05	N/A



Ca Regression Statistics		Std. Error
R Square	N/A	N/A
P Regression Statistics		Std. Error
R Square	0.990	9.36E-07

Diss. Rate Ca (K_{diss})	N/A	mol min/m^2s
Uncertainty of fit	N/A	mol min/m^2s
Diss. Rate P (K_{diss})	8.584E-08	mol min/m^2s
Uncertainty of fit	4.226E-09	mol min/m^2s

**Shaded data represents initial rate data in supplementary figure*

Data Sheet S76

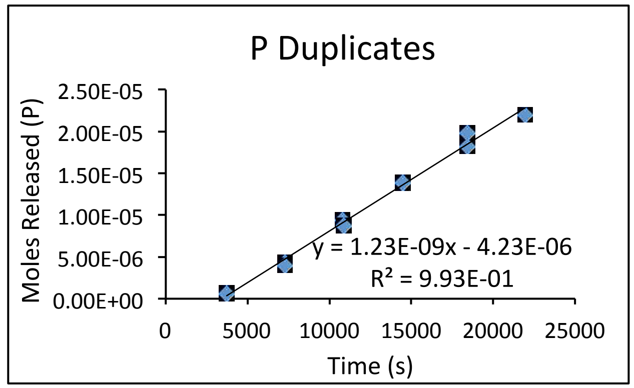
Organic Acid Duplicates:	Oxalic	**Mineral:**	Fluorapatite

OXA-FLAP-1

Time (s)	Moles Released (P)	Moles Released (Ca)			
0	B.D.	B.D.			
3720	7.28E-07	N/A			
7260	4.32E-06	N/A			
10800	9.42E-06	N/A			
14460	1.37E-05	N/A			
18420	1.82E-05	N/A			
21900	9.12E-05	N/A			
85080	9.92E-05	N/A	*Diss. Rate Ca (K_{diss})*	N/A	mol min/m^{2}s
182220	1.28E-04	N/A	*Diss. Rate P (K_{diss})*	8.38E-08	mol min/m^{2}s

OXA-FLAP-D-1

Time (s)	Moles Released (P)	Moles Released (Ca)			
0	B.D.	B.D.			
3720	5.84E-07	N/A			
7260	3.96E-06	N/A			
10860	8.72E-06	N/A			
14460	1.38E-05	N/A			
18420	1.98E-05	N/A			
21960	2.19E-05	N/A			
85080	6.42E-05	N/A	*Diss. Rate Ca (K_{diss})*	N/A	mol min/m^{2}s
182160	8.00E-05	N/A	*Diss. Rate P (K_{diss})*	8.58E-08	mol min/m^{2}s

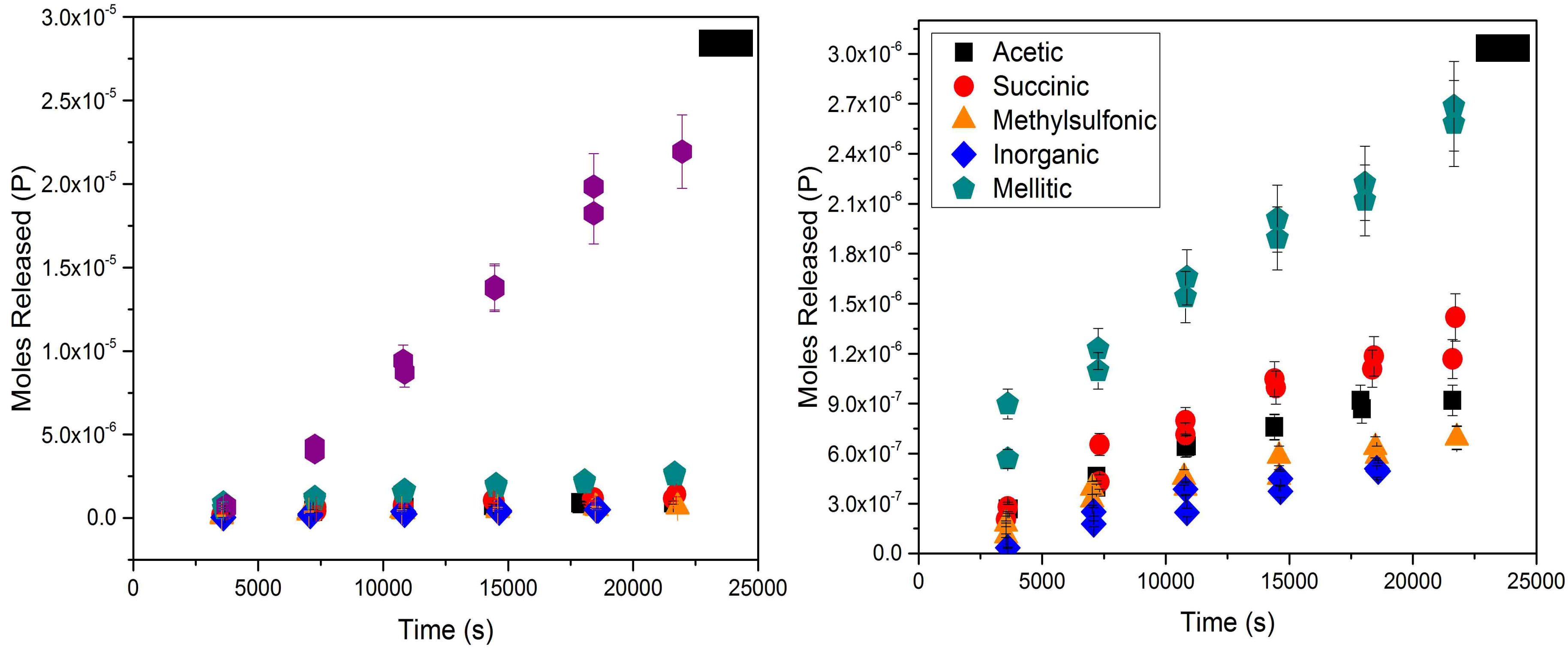


Data Sheet S77

Fluorapatite Blanks

Mineral: None	**Batch ID:** N/A	**Specific Surface Area (BET):** N/A
Initial pH: 5.5	**Mineral Mass:** 0.000 g	**Total Surface Area (BET):** N/A

Sample Blank	Final pH	Initial Moles (P)	Final Moles (P)	Initial Moles (Ca)	Final Moles (Ca)
ACE-B-7	5.51	B.D.	B.D.	4.86E-07	5.67E-07
DI-B-27	5.04	B.D.	B.D.	3.87E-07	5.12E-07
SUC-B-6	5.55	B.D.	B.D.	5.24E-07	6.36E-07
DI-B-22	5.26	B.D.	B.D.	4.99E-07	5.26E-07
MES-B-5	4.63	B.D.	B.D.	6.22E-07	6.66E-06
DI-B-23	4.66	B.D.	B.D.	5.47E-07	6.23E-07
MEL-B-4	5.61	B.D.	B.D.	2.43E-06	2.50E-06
DI-B-24	6.07	B.D.	B.D.	8.09E-07	7.57E-07
OXA-B-4	5.44	B.D.	B.D.	n.d.	n.d.
DI-B-25	4.89	B.D.	3.42E-05	n.d.	n.d.



[redacted]

Moles released of phosphate in the presence of fluorapatite (A) with oxalic acid and (B) without oxalic acid. (B) shows the order of enhanced release of phosphate from the fluorapatite surface for the other four acids over the inorganic control. While mellitic acid enhances the release of phosphate from fluorapatite drastically, acetic acid, succinic acid, and methylsulfonic acid, only slightly enhance the release of phosphate.

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Curriculum Vitae

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EDUCATION

University of Nevada, Las Vegas, (UNLV) Las Vegas, NV
Master's Degree (Geoscience) 2014 – 2017

Midwestern State University, (MSU) Wichita Falls, Texas
Bachelor's of Science (Geology, Minor: Chemistry) 2010 –2014

TEACHING EXPERIENCE

University of Nevada, Las Vegas, NV
Head Teaching Assistant, GEOL 101 2016
Coordination of teaching assistants, students, laboratory preparations, organization, teaching, and grading
Graduate Teaching Assistant – GEOL 101 2014 – 2015
Organization, teaching and grading of introductory geology labs

Midwestern State University, Wichita Falls, Texas
Teaching Assistant, Life/Earth Science Laboratory 2011 – 2014
Integrated biology and geology labs
Teaching Assistant – Physical Science Laboratory 2011 – 2014
Integrated physics and chemistry labs
Chemistry Tutor 2012 – 2014
Undergraduate tutor for introductory, general, and organic chemistry

OTHER WORK EXPERIENCE

Precision Machine Works Inc, Tacoma, Washington
Aerospace Document Control 2009 -2012
Computer based work: Microsoft Office, docLink and Visual.

RESEARCH EXPERIENCE

University of Nevada, Las Vegas
Planetary Geochemistry 2014 - Present
Master's Thesis: Phosphate Release: The effect of prebiotic organic compounds on dissolution rates of merrillite, whitlockite, chlorapatite, and fluorapatite

Midwestern State University,
Geochemical Research Spring 2014
Collection and analysis of samples from the Wichita Mountains

LEADERSHIP

Guest Lecturer, Mineralogy, UNLV	May 2015
AAPG Vice President (MSU Student Chapter)	2013 – 2014
SGE Secretary (Geologic Honor Society – MSU Chapter)	2013 – 2014
American Chemical Society Public Relations (MSU Chapter)	2013 – 2014
American Chemical Society President (MSU Chapter)	2012 – 2013
1, 2, 3 Science (First grade science development/implementation)	2009 – 2010

AWARDS

Geosymposium 3rd place – Graduate Oral Presentation, UNLV	April 2016
Geosymposium 3rd place – Graduate Poster Presentation, UNLV	April 2016
GPSA Research Forum, Oral Presentation, 1st place, UNLV	March 2016
GPSA Research Funding, UNLV	Spring 2016
Geosymposium 1st place – Graduate Oral Presentations, UNLV	April 2015
GPSA Research Forum, Poster Presentation Honorable Mention, UNLV	March 2015
GPSA Travel Funding, Conference travel, UNLV	Spring 2015
Welsh Scholarship, MSU	2011 – 2012
Geology Academic Scholarship, MSU	2011 – 2012
Geology Outstanding Freshman Award, MSU	Spring 2011
Yale Science and Engineering Award, Most Outstanding Exhibit	Spring 2009
First Place Washington State Science Fair, Physics Category	Spring 2009

VOLUNTEER EXPERIENCE

Walter Bracken STEAM Academy Career Fair	Jan 2016
Walter Bracken STEAM Academy K-12 Experiences	Spring 2015
American Chemical Society – Boys and Girls Club Chemistry Carnival	2011 – 2013
American Chemical Society – Bowie Junior High Science Night	2011, 2012
Girl Scout Troop Helper	2010 – 2011
Girl Scout Silver Award Recipient	2006 – 2007
Girl Scout community service award	

MEMBERSHIP

Girl Scout Member	1999 – 2010
Lifetime Girl Scout Member	Beginning June 2010
American Chemical Society Member	2011 –2014
Geological Society of America Member	2013 – Present

INSTRUMENTATION EXPERIENCE

Instruments used during master's

Flame atomic absorption (AA) spectrometry (Thermo Scientific iCE 3000 Series)
Thermo Scientific Genesys 10S UV-Vis spectrometer
Agilent 7700x ICP-MS
JEOL SEM model JSM-5610 (Oxford ISIS EDS)

Lawrence Berkeley National Lab, Berkeley, CA (Advanced Light Source)

Beamlines 10.3.2 (Laue diffraction), 12.3.2 (Microdiffraction)

Argonne National Lab, Chicago, IL (Advanced Photon Source)

Beamlines 13-ID-E (GSECARS), 13-ID-D (Diffraction, XAFS, XANES)

ABSTRACTS/CONFERENCE PRESENTATIONS

C.L. Bartlett, E.M. Hausrath, C.T. Adcock (2016) Phosphate release: The effect of prebiotic organic compounds on dissolution of Mars-relevant minerals, 47th Lunar and Planetary Science Conference, Houston, TX.

C.L. Bartlett, E.M. Hausrath, C.T. Adcock (2016) Phosphate Release: The effect of prebiotic organic compounds on nutrient release from Mars-relevant minerals, UNLV Department of Geoscience Geosymposium, Las Vegas, NV.

Z. Harrold, E. Hausrath, O. Tschauner, A. Garcia, A. Murray, J. Raymond, **C. Bartlett** (2016) Snow algae-microbe- mineral interactions and implications for snow algae growth, American Geophysical Union Conference, San Francisco, CA.

Z. R. Harrold, E. M. Hausrath, **C. L. Bartlett**, A. H. Garcia, O. Tschauner, A. E. Murray, J. Raymond (2016) Bioavailability of mineral-bound Iron to a snow algae community and implications for life in extreme environments, 47th Lunar and Planetary Science Conference, Houston, TX.

E.M. Hausrath, Z. Harrold, A.E. Murray, O. Tschauner, A.H. Garcia, **C.L. Bartlett** and J. Raymond (2016) Interactions of snow algae, microorganisms and minerals in snowy Mars-analog environments provide potential elemental and mineralogical biosignatures, Biosignature Preservation and Detection in Mars-Analog Environments Conference, Lake Tahoe, NV.

C.L. Bartlett, E.M. Hausrath, C.T. Adcock (2015) Phosphate release: The effect of prebiotic organic compounds on dissolution of Mars-relevant phosphate minerals, 46th Lunar and Planetary Science Conference, Houston, TX.

E. M. Hausrath, **C. L. Bartlett**, and C.T. Adcock (2015) Abundant mobile phosphate in potentially habitable early environments on Mars, Astrobiology Science Conference, Chicago, IL.

C.L. Bartlett, E.M. Hausrath, C.T. Adcock (2015) Phosphate Release: The effect of prebiotic organic compounds on dissolution of Mars-relevant phosphate minerals, UNLV Department of Geoscience Geosymposium, Las Vegas, NV.

E.M. Hausrath, **C. L. Bartlett**, C.T. Adcock (2015) Abundant phosphate mobility in potentially habitable early environments on Mars, Nevada NASA EPSCoR and Space Grant Consortium, Las Vegas, NV.

E.M. Hausrath, **C.L. Bartlett**, A.H. Garcia, O. Tschauner, A.E. Murray, J.A. Raymond (2015) Interactions between snow-adapted organisms, minerals and snow in a Mars-analog environment, and implications for the possible formation of biosignatures, American Geophysical Union Conference, San Francisco, CA.