Scanning Electron Microscopy (SEM) Analysis of STA stoneware

Alasdair Chi, PhD candidate, History Program, Nanyang Technological University

Overview of Important Oxides in Ceramics

Bodies

Silicon oxide (SiO_2), which is the most abundant element in paste formula, is excluded from the statistical analyses. Aluminium oxide (Al_2O_3) permits clay pastes to tolerate more extreme kiln conditions, and high proportions correlate with stoneware and porcelain formula.

Given that aluminium oxides are the second-most abundant in clay formulae, the Al_2O_3/SiO_2 ratio (no units) is representative of the bulk properties of the clay and serves as a useful baseline / x-axis to compare other minor elements.

Whilst Al_2O_3 improves the quality of stoneware and porcelain clay, iron oxide (Fe_2O_3) is generally seen as doing the opposite, with excessive amounts leading to premature melting of ceramic vessels at high temperatures, necessitating manual removal.

Conversely, potassium oxide (K_2O) generally has a positive effect on the clay in the kiln during firing, permitting tolerance to the higher temperature and longer firing durations, both typical of stoneware and porcelain. This is often added to clay via minerals.

Glazes

Ceramic glazes contain several components: the chief ones being fluxing agents (oxides which permit the mixture to melt into glass) and colorants/opacifiers (oxides which contribute to the tint and hue of the glaze). There are also oxides which are present in glazes as by-products of the fluxing agents' extraction.

The two most common fluxing agents seen in glazes are calcium oxide (K_2O), and less often, potassium oxide (K_2O). As with Al_2O_3/SiO_2, the ratio between the two can be used as a quick benchmark of a glaze formula.

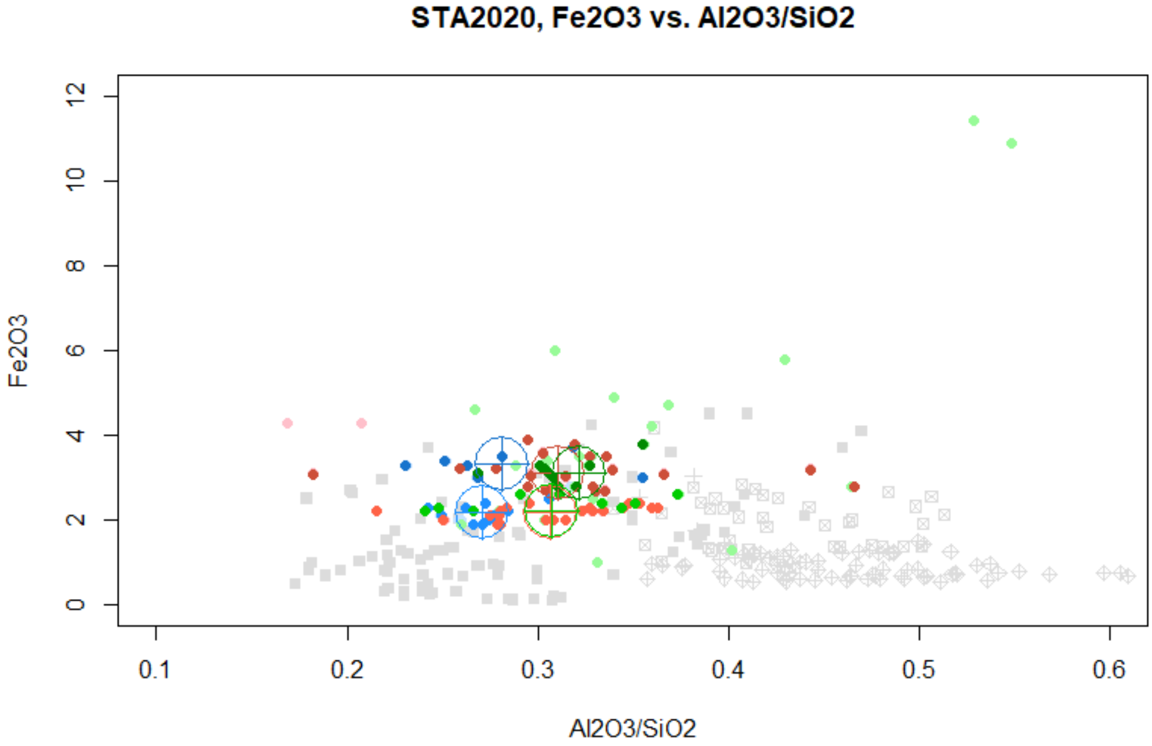
Iron oxide (Fe_2O_3) fulfils the role of a colorant; its oxidation state also influences the color of the glaze. The other common colorant used in the 14th century is manganese oxide (MnO_2), which is more frequently seen in Ming Dynasty and later porcelains.

Calcium can be extracted either from limestone, which does not contain significant amounts of magnesium oxide (MgO) and phosphorous oxide (P_2O_5), or from organic ash, which contains MgO and P_2O_5. Plotting these oxides against CaO to determine the linearity of their relationship will point towards which source was used.

STA 2020

<u>Bodies</u>

Iron oxide (Fe_2O_3) vs. Al_2O_3/SiO_2

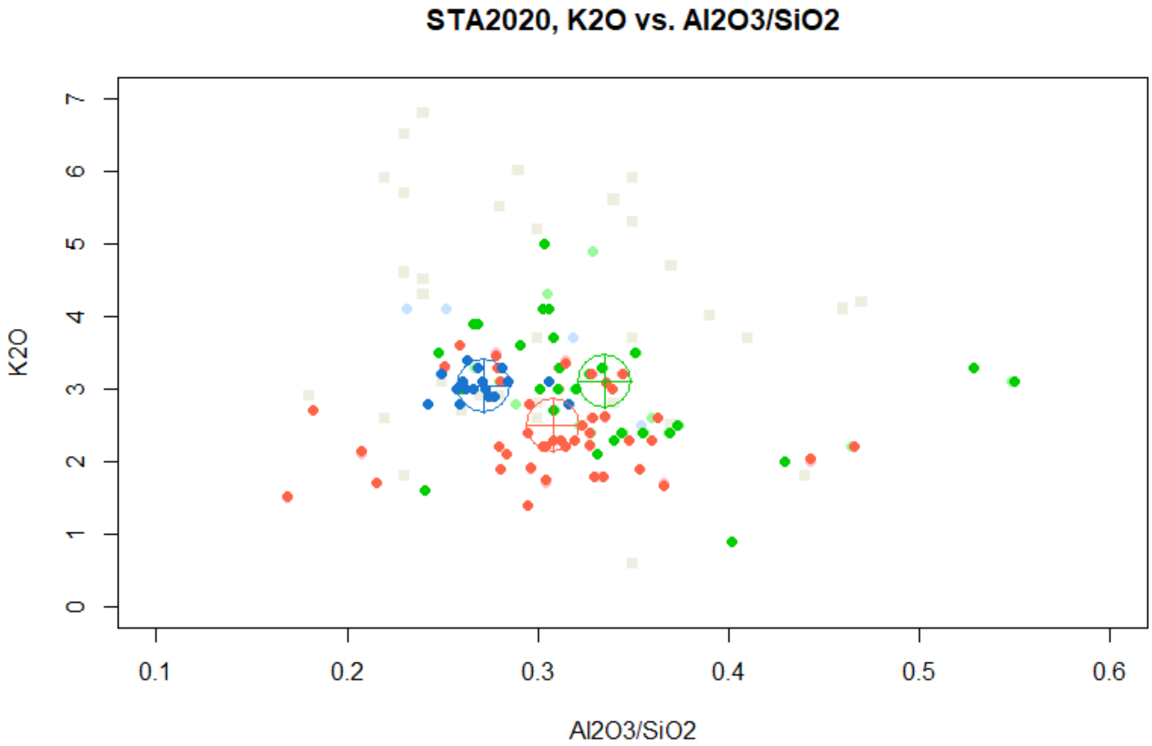


	Main body	Outliers	Means
Buff ware	●	●	⊕
Brittle ware	●	●	⊕
Mercury jar	●	●	⊕
Chinese ceramics	■	◇⊠	n/a

While the reported Fe_2O_3% vs. Al_2O_3/SiO_2 values in the STA2020 sample are largely compatible with the figures seen in STA2017 (see Chi 2017), there is one trend visible in the STA2020 sample which was not present in STA2017: namely the existence of high-iron and low-iron groups across all three major categories, suggesting at least two different production centers or two different recipes at the same kilns for mercury jars, brittle stoneware, and buff stoneware.

The Al_2O_3/SiO_2 ratios of brittle and buff ware are statistically indistinct and may reflect similar formulae. Mercury jar, however, are notably depleted in Al_2O_3 relative to both brittle and buff stoneware (as well as more tightly concentrated in terms of variance), which is consistent with phenomena observed in STA2017 suggesting a coalescing of mercury jar manufacture – minus the complicating factor of the high-iron category existing.

Potassium oxide (K_2O) vs. Al_2O_3/SiO_2



	Main body	Outliers	Means
Buff ware	●	●	⊕
Brittle ware	●	●	⊕
Mercury jar	●	●	⊕
Chinese ceramics	■	◇⊠	n/a

There is no major deviation from the STA2017 results in terms of this plot (see Chi 2017), although the presence of some high-K_2O buff sherds in the STA2020 corpus have raised its mean to above that of the STA2017 sherds. As with STA2017, both mercury jars and brittle ware are elevated in K_2O relative to buff ware, with those high-K_2O buff sherds being the exception.

While less clear than in STA2017, this nevertheless still supports the hypothesis that mercury jar can be meaningfully distinguished from the other two main categories (and that brittle and buff ware are distinct from each other).

	Mercury Jar	**Brittle**	**Buff**
Al_2O_3	Low	High	High
Fe_2O_3	*Both*	*Both*	*Both*
K_2O	High	High	Low

The values seen in the STA2020 corpus, as with the STA2017 sherds are much closer to those seen in Jingdezhen porcelain than Longquan porcelains despite their Fe_2O_3%

affinity, with Longquan ware K_2O% being much higher than anything in the corpus, tending towards 6% as opposed to the ~2-3% values seen here.

As with the STA2017 corpus, I am nevertheless still inclining towards a production sequence more similar to Longquan kilns than the Jingdezhen *chaine operatoire*, just with less K_2O%, as adding potassium is less intensive than removing iron with regard to the formation of these stoneware clays. The Dehua kilns are once again totally excluded as their K_2O% is much higher and Fe_2O_3% is much lower than anything in the STA2020 corpus.

Aluminium oxide

Category	Al_2O_3%	Category	Al_2O_3%	Category	Al_2O_3%
Mercury jar	**19.9 ± 1.1**	**Brittle ware**	**21.7 ± 2.0**	**Buff ware**	**22.3 ± 1.7**
STA-MER-UA	20.4 ± 2.3	STA-BRI-GA	21.8 ± 1.4	STA-BUF-GA	23.1 ± 1.4
STA-MER-UB	19.9 ± 0.3	STA-BRI-GB	23.2 ± 1.2	STA-BUF-GB	22.3 ± 1.4
		STA-BRI-GBH	*27.5*	*STA-BUF-67*	*16.8*
STA-MER-UC	19.1 ± 1.0	*STA-BRI-GC*	*22.4*	*STA-BUF-GC*	*23.5 ± 1.8*
				STA-BUF-57	*14.0*
STA-MER-UD	19.3 ± 0.1	*STA-BRI-GD*	*21.2*	*STA-BUF-GD*	*20.8*
STA-MER-113	*22.2*				
		STA-BRI-SE	21.7 ± 2.0	STA-BUF-SE	23.8 ± 4.7
		STA-BRI-SF	*24.0*	*STA-BUF-SF*	
		STA-BRI-SG	*19.0*	STA-BUF-UG	21.5 ± 1.3
		STA-BRI-UH	20.3 ± 1.9	STA-BUF-UH	22.5 ± 1.6
		STA-BRI-118	27.5		
		STA-BRI-UJ	20.1 ± 1.2	STA-BUF-UJ	14.4 ± 1.7
		STA-BRI-UK	24.0 ± 24	*STA-BUF-UK*	*20.4*
		STA-BRI-UL	22.5		
		STA-BRI-42	*27.1*		

Categories

```
> summary(aov(Al ~ Type, data= AlCombined))
            Df Sum Sq Mean Sq F value   Pr(>F)    
Type         2  57.68  28.839   9.983 0.000166 ***
Residuals   65 187.77   2.889                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
> with(AlCombined, pairwise.t.test(x=Al, g=Type, p.adjust="none"))

        Pairwise comparisons using t tests with pooled SD 

data:  Al and Type
```

```
            Brittle Buff
Buff        0.3231  -
MercuryJar  0.0015  9.6e-05
```

Mercury jar are distinct from brittle and buff stoneware, having less Al_2O_3 overall.

Fabric Groups

Mercury Jar: No fabric groups are distinct from each other.

```
> summary(aov(Al ~ FabricGroup, data= mercuryjarsTrimmed))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  2   3.76   1.881    0.67  0.528
Residuals   14  39.33   2.810
> with(mercuryjarsTrimmed, pairwise.t.test(x=K, g=FabricGroup, p.adjust="n
one"))

        Pairwise comparisons using t tests with pooled SD

data:  K and FabricGroup

           STA-MER-UA STA-MER-UB
STA-MER-UB 0.24       -
STA-MER-UC 0.17       0.66

P value adjustment method: none
```

Brittle stoneware: No fabric groups are distinct from each other, except GB from UJ and possibly UH.

```
> summary(aov(Al ~ FabricGroup, data= brittleTrimmed[Al < 25,]))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  5  32.71   6.542    1.07  0.415
Residuals   15  91.72   6.114
5 observations deleted due to missingness

> with(brittleTrimmed[Al < 25,], pairwise.t.test(x=Al, g=FabricGroup, p.ad
just="none"))

        Pairwise comparisons using t tests with pooled SD

data:  Al and FabricGroup

           STA-BRI-GA STA-BRI-GB STA-BRI-UH STA-BRI-UJ STA-BRI-UK
STA-BRI-GB 0.437      -          -          -          -
STA-BRI-UH 0.694      0.054      -          -          -
STA-BRI-UJ 0.557      0.031      1.000      -          -
STA-BRI-UK 0.557      1.000      0.097      0.065      -
STA-BRI-UL 1.000      1.000      0.530      0.419      1.000

P value adjustment method: holm
```

Buff stoneware: Only BUF-UG and BUF-UH are distinct, with -UG at 21.5% and -UH at 22.5%.

```
> summary(aov(Al ~ FabricGroup, data= buffTrimmed[FabricGroup != "STA-BUF-
GC" & Al > 17 & Al < 26,]))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  4  11.71   2.927   1.437  0.252
Residuals   24  48.88   2.037
```

```
> with(buffTrimmed[FabricGroup != "STA-BUF-GC" & Al > 17 & Al < 25.5,], pa
irwise.t.test(x=Fe, g=FabricGroup, p.adjust="none"))

        Pairwise comparisons using t tests with pooled SD

data:  Fe and FabricGroup

           STA-BUF-GA STA-BUF-GB STA-BUF-SE STA-BUF-UG
STA-BUF-GB 0.612      -          -          -
STA-BUF-SE 0.678      1.000      -          -
STA-BUF-UG 0.279      0.096      0.201      -
STA-BUF-UH 0.319      0.675      0.745      0.012

P value adjustment method: none
```

Comparison with STA 2017

Mercury jar: there is no statistically significant difference between mean STA2017 and STA2020 Al_2O_3% values.

```
> var.test(mercuryjarsTrimmedAl$Al, mercuryjarsSTA$Al)

        F test to compare two variances

data:  mercuryjarsTrimmedAl$Al and mercuryjarsSTA$Al
F = 1.5012, num df = 14, denom df = 30, p-value = 0.3411
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.6421656 4.1019487
sample estimates:
ratio of variances
          1.501238
```

```
> t.test(mercuryjarsTrimmedAl$Al, mercuryjarsSTA$Al, equal.var=T)

        Welch Two Sample t-test

data:  mercuryjarsTrimmedAl$Al and mercuryjarsSTA$Al
t = 0.4529, df = 23.347, p-value = 0.6548
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.5265257  0.8220096
sample estimates:
mean of x mean of y
 19.90000  19.75226
```

Brittle ware: there is no statistically significant difference between mean STA2017 and STA2020 Al_2O_3% values.

```
> var.test(brittleTrimmedAl$Al, brittleSTATrimmedAl$Al)

        F test to compare two variances

data:  brittleTrimmedAl$Al and brittleSTATrimmedAl$Al
F = 1.3044, num df = 23, denom df = 70, p-value = 0.3946
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.7010345 2.7278950
sample estimates:
ratio of variances
          1.304374

> t.test(brittleTrimmedAl$Al, brittleSTATrimmedAl$Al, equal.var=TRUE)

        Welch Two Sample t-test

data:  brittleTrimmedAl$Al and brittleSTATrimmedAl$Al
t = 1.3768, df = 35.678, p-value = 0.1772
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.2876007  1.5022720
sample estimates:
mean of x mean of y
 21.72917  21.12183
```

Buff ware: While the mean values are statistically indistinct, the variance of the STA2017 buff stoneware is larger than that of the STA2020 sample by a statistically significant amount (63%).

```
> var.test(buffTrimmedAl$Al, buffSTATrimmedAl$Al)

        F test to compare two variances

data:  buffTrimmedAl$Al and buffSTATrimmedAl$Al
F = 0.3601, num df = 30, denom df = 75, p-value = 0.002582
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.2040390 0.6882254
sample estimates:
ratio of variances
         0.3601004

> t.test(buffTrimmedAl$Al, buffSTATrimmedAl$Al, equal.var=F)

        Welch Two Sample t-test

data:  buffTrimmedAl$Al and buffSTATrimmedAl$Al
t = -0.85367, df = 90.175, p-value = 0.3956
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -1.1167177  0.4454444
sample estimates:
mean of x mean of y
 22.23226  22.56789
```

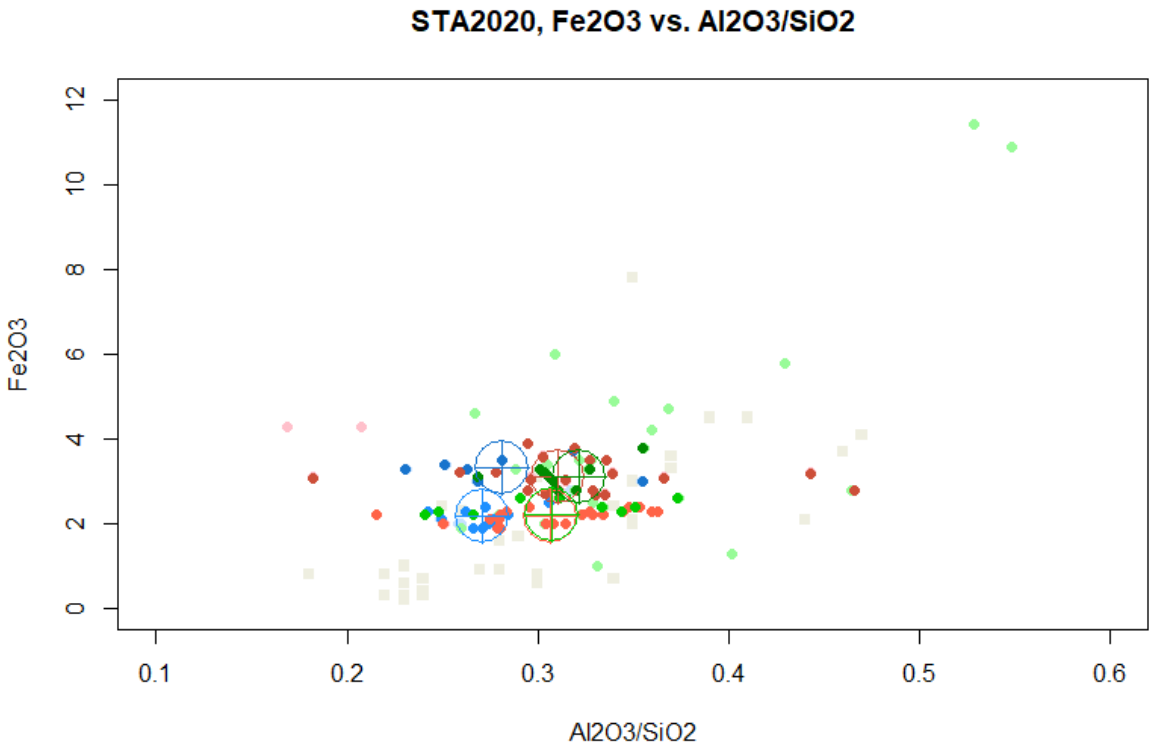
Iron oxide

Category	Fe_2O_3%	Category	Fe_2O_3%	Category	Fe_2O_3%
Mercury jar (high)	**3.3 ± 0.3**	**Brittle ware (high)**	**3.3 ± 0.3**	**Buff ware (high)**	**3.1 ± 0.4**
Mercury jar (low)	**2.2 ± 0.2**	**Brittle ware (low)**	**2.4 ± 0.5**	**Buff ware (low)**	**2.2 ± 0.1**
STA-MER-UA	3.0 ± 0.6	STA-BRI-GA	2.2 ± 0.9	STA-BUF-GA	2.5 ± 0.4
STA-MER-UB	2.5 ± 0.7	STA-BRI-GB	2.6 ± 0.2	STA-BUF-GB	2.6 ± 0.2
		STA-BRI-GBH	11.2 ± 0.4		
STA-MER-UC	2.1 ± 0.2	*STA-BRI-GC*	*3.5*	STA-BUF-GC	3.0 ± 0.8
STA-MER-UD	2.2 ± 0.4	*STA-BRI-GD*	*3.4*	*STA-BUF-GD*	*3.8*
		STA-BRI-SE	2.9 ± 0.6	STA-BUF-SE	2.9 ± 0.5
		STA-BRI-SF	*4.2*	*STA-BUF-SF*	*2.4 ± 0.5*
		STA-BRI-SG	*4.6*	STA-BUF-UG	2.2 ± 0.3
		STA-BRI-UH	2.6 ± 0.8	STA-BUF-UH	2.9 ± 0.4
		STA-BRI-UJ	2.7 ± 0.6	STA-BUF-UJ	4.2 ±<0.1
		STA-BRI-UK	*2.3*	*STA-BUF-UK*	3.1
		STA-BRI-UL	*5.1*		

Categories

```
> summary(aov(Fe ~ Type, data= FeCombined))
            Df Sum Sq Mean Sq F value Pr(>F)
Type         5 14.005  2.8009   39.12 <2e-16 ***
Residuals   56  4.009  0.0716
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> with(FeCombined, pairwise.t.test(x=Fe, g=Type, p.adjust="holm"))

                 Pairwise comparisons using t tests with pooled SD

data:  Fe and Type

                  Brittle-HighFe Brittle-LowFe Buff-HighFe Buff-LowFe MercuryJar-Hi
ghFe
Brittle-LowFe     1.6e-07        -             -           -          -
Buff-HighFe       1.00           2.5e-08       -           -          -
Buff-LowFe        1.3e-13        0.22          < 2e-16     -          -
MercuryJar-HighFe 0.71           1.6e-08       0.35        6.7e-14    -
MercuryJar-LowFe  2.8e-11        0.30          8.9e-13     1.00       5.2e-12

P value adjustment method: holm
```

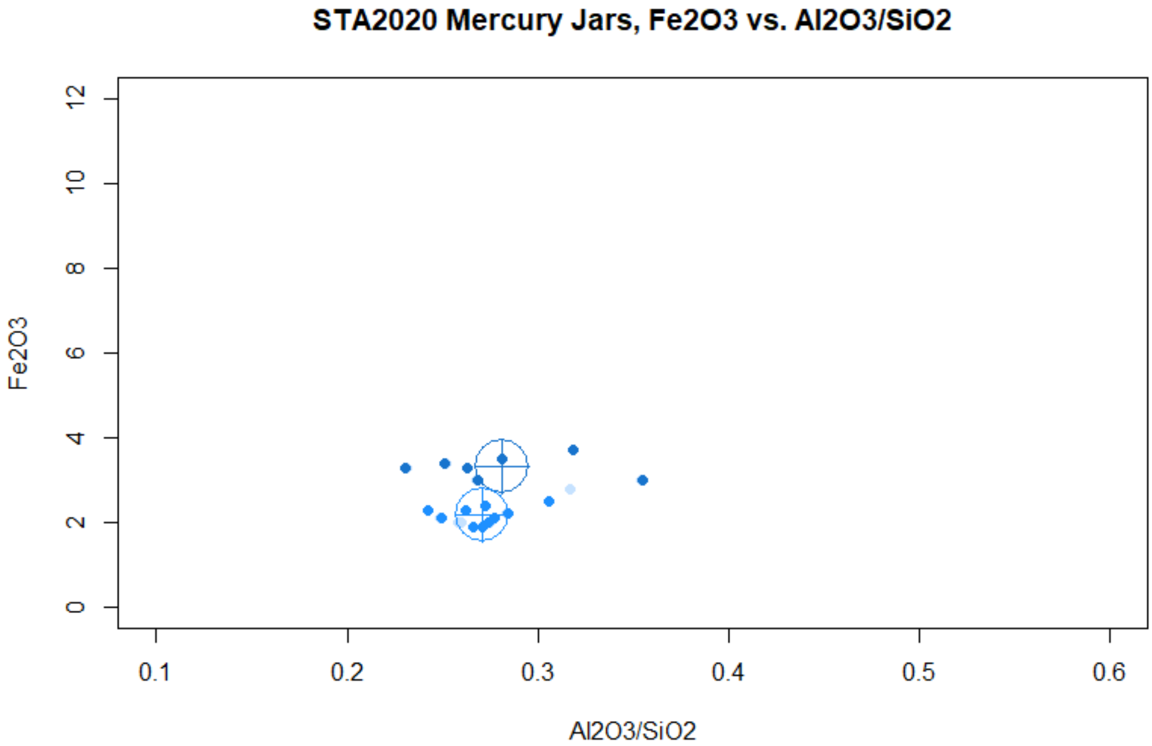
All three categories, even putting aside outliers, are divided into statistically distinct Fe_2O_3-elevated and Fe_2O_3-depleted groups; all low groups are statistically indistinct from each other and all high groups are statistically indistinct.



	Main body	Outliers	Means
Buff ware	●	●	⊕
Brittle ware	●	●	⊕
Mercury jars	●	●	⊕
Chinese ceramics	■	◇⊠	n/a

Fabric Groups

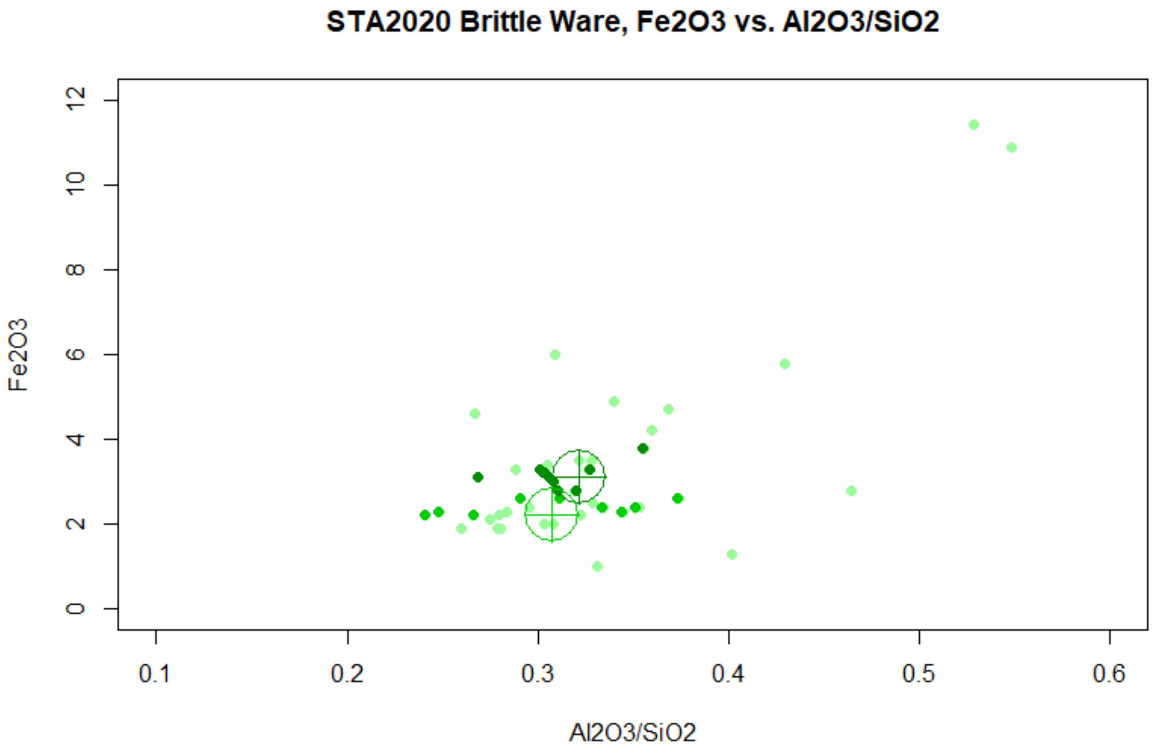
Mercury Jar




```
> summary(aov(Fe ~ FabricGroup, data= mercuryjarsTrimmed))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  2  1.782  0.8912   2.849 0.0916 .
Residuals   14  4.379  0.3128
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
> with(mercuryjarsTrimmed, pairwise.t.test(x=Fe, g=FabricGroup, p.adjust="
none"))

        Pairwise comparisons using t tests with pooled SD

data:  Fe and FabricGroup
           STA-MER-UA STA-MER-UB
STA-MER-UB 0.123      -
STA-MER-UC 0.046      0.413

P value adjustment method: none
```

STA-MER-UC has a barely statistically significant Fe_2O_3% depletion relative to the other two groups.

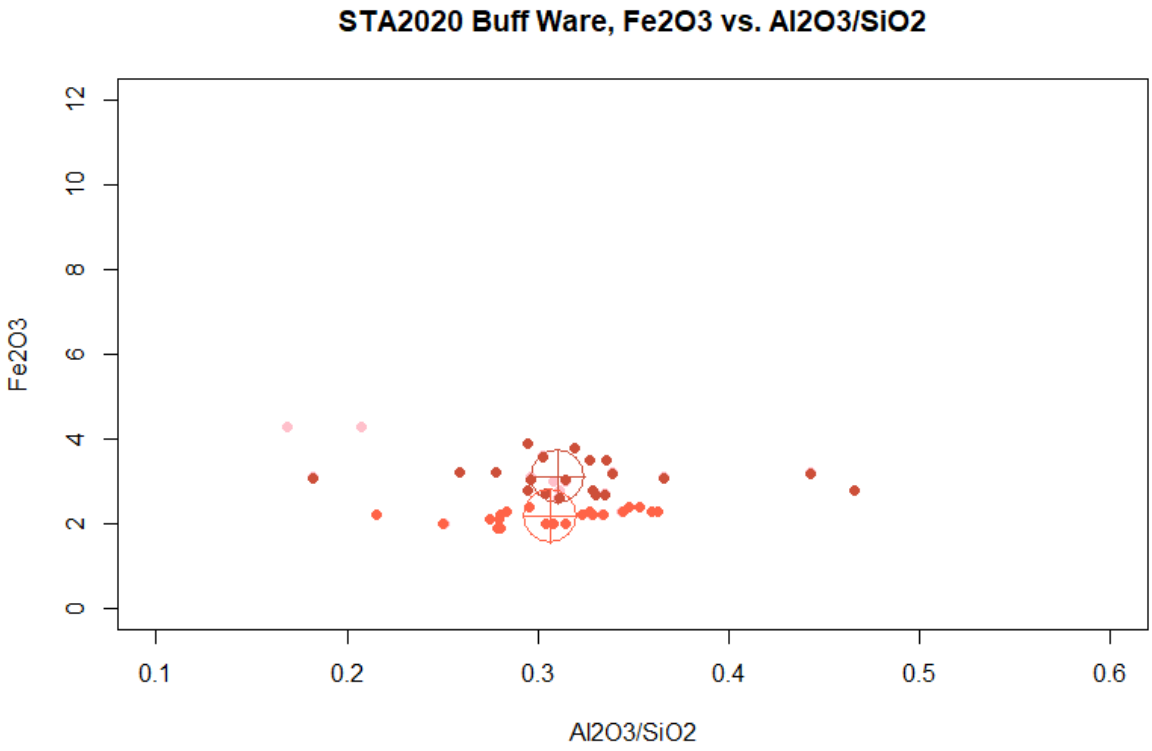
Brittle Stoneware




```
> summary(aov(Fe ~ FabricGroup, data= brittleTrimmed[brittleTrimmed$Fabric
Group != "STA-BRI-UK",]))
            Df Sum Sq Mean Sq F value   Pr(>F)    
FabricGroup  5 143.20  28.640   48.86 1.71e-09 ***
Residuals   17   9.96   0.586                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> with(brittleTrimmed[brittleTrimmed$FabricGroup != "STA-BRI-UK",], pairwi
se.t.test(x=Fe, g=FabricGroup, p.adjust="holm"))

        Pairwise comparisons using t tests with pooled SD 

data:  Fe and FabricGroup 

           STA-BRI-GA STA-BRI-GB STA-BRI-UH STA-BRI-UJ
STA-BRI-GB 1.00000    -          -          -         
STA-BRI-UH 1.00000    1.00000    -          -         
STA-BRI-UJ 1.00000    1.00000    1.00000    -         
STA-BRI-UL 0.00016    0.00197    0.00063    0.00074   

P value adjustment method: holm
```

STA-BRI-GB has a subset which is significantly higher in Fe_2O_3 than all other groups; STA-BRI-UL is also significantly higher in Fe_2O_3 than all other groups.

Buff Stoneware




```
> summary(aov(Fe ~ FabricGroup, data= buffTrimmed[buffTrimmed$FabricGroup
!= "STA-BUF=SE",]))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  5  2.575  0.5151   2.035  0.104
Residuals   28  7.088  0.2532

> with(buffTrimmed[buffTrimmed$FabricGroup != "STA-BUF=SE",], pairwise.t.t
est(x=Fe, g=FabricGroup, p.adjust="none"))

        Pairwise comparisons using t tests with pooled SD

data:  Fe and FabricGroup

           STA-BUF-GA STA-BUF-GB STA-BUF-GC STA-BUF-SE STA-BUF-UG
STA-BUF-GB 0.627      -          -          -          -
STA-BUF-GC 0.211      0.417      -          -          -
STA-BUF-SE 0.405      0.699      0.688      -          -
STA-BUF-UG 0.366      0.140      0.027      0.079      -
STA-BUF-UH 0.339      0.688      0.578      0.942      0.020

P value adjustment method: none
```

STA-BUF-UG is significantly depleted in iron oxide relative to the high-Fe groups of -GC and -UH; however, these are not significantly enriched relative to the rest of the buff corpus.

Comparison with STA 2017

Mercury Jar

The Fe_2O_3-high group among the STA2020 mercury jar is statistically distinct from the STA2017 sample mercury jar.

```
> var.test(mercuryjarsTrimmedLow$Fe,mercuryjarsSTA$Fe)

        F test to compare two variances

data:  mercuryjarsTrimmedLow$Fe and mercuryjarsSTA$Fe
F = 0.34741, num df = 9, denom df = 30, p-value = 0.09844
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.1349383 1.2369343
sample estimates:
ratio of variances
         0.3474134

> t.test(mercuryjarsTrimmedLow$Fe, mercuryjarsSTA$Fe, equal.var=T)

        Welch Two Sample t-test

data:  mercuryjarsTrimmedLow$Fe and mercuryjarsSTA$Fe
t = 0.78186, df = 26.594, p-value = 0.4412
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.1148809  0.2561713
sample estimates:
mean of x mean of y
 2.170000  2.099355
```

There is no statistically significant difference between mean STA2017 and STA2020 Fe_2O_3% values with regard to the Fe_2O_3-low group among the mercury jar.

Brittle Stoneware

```
> var.test(brittleTrimmedFeHigh$Fe, brittleSTATrimmedFe$Fe)

        F test to compare two variances

data:  brittleTrimmedFeHigh$Fe and brittleSTATrimmedFe$Fe
F = 0.11577, num df = 9, denom df = 62, p-value = 0.001603
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.04975261 0.39891463
sample estimates:
ratio of variances
          0.115774

> t.test(brittleTrimmedFeHigh$Fe, brittleSTATrimmedFe$Fe, equal.var=F)

        Welch Two Sample t-test

data:  brittleTrimmedFeHigh$Fe and brittleSTATrimmedFe$Fe
t = 0.70974, df = 39.75, p-value = 0.482
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.1836450  0.3823751
sample estimates:
mean of x mean of y
```

```
 3.160000  3.060635
```

There is no statistically significant difference between mean STA2017 and STA2020 Fe_2O_3% values with regard to the Fe_2O_3-high group amongst the brittle ware, although the variance in the STA2017 corpus is significantly higher.

```
> var.test(brittleTrimmedFeLow$Fe, brittleSTATrimmedFe$Fe)

        F test to compare two variances

data:  brittleTrimmedFeLow$Fe and brittleSTATrimmedFe$Fe
F = 0.038514, num df = 8, denom df = 62, p-value = 4.925e-05
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.01601871 0.14561332
sample estimates:
ratio of variances
        0.03851351

> t.test(brittleTrimmedFeLow$Fe, brittleSTATrimmedFe$Fe, equal.var=F)

        Welch Two Sample t-test

data:  brittleTrimmedFeLow$Fe and brittleSTATrimmedFe$Fe
t = -5.5073, df = 63.927, p-value = 6.928e-07
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.9002799 -0.4209900
sample estimates:
mean of x mean of y
 2.400000  3.060635
```

The Fe_2O_3-low group among the brittle ware is statistically distinct from the STA2017 sample brittle stoneware.

Buff ware

```
> var.test(buffTrimmedFeHigh$Fe, buffSTATrimmedFe1$Fe)

        F test to compare two variances

data:  buffTrimmedFe$Fe[buffTrimmedFe$Fe > 2.5] and buffSTATrimmedFe1$Fe
F = 0.70829, num df = 14, denom df = 52, p-value = 0.4879
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.3326275 1.8648337
sample estimates:
ratio of variances
         0.7082939

> t.test(buffTrimmedFeHigh$Fe, buffSTATrimmedFe1$Fe, equal.var=T)

        Welch Two Sample t-test

data:  buffTrimmedFe$Fe[buffTrimmedFe$Fe > 2.5] and buffSTATrimmedFe1$Fe
t = 7.0632, df = 26.293, p-value = 1.578e-07
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 0.5552694 1.0107684
sample estimates:
mean of x mean of y
 3.120000  2.336981
```

The Fe_2O_3-high group amongst the buff ware is statistically distinct from the STA2017 sample buff ware.

```
> var.test(buffTrimmedFeLow$Fe, buffSTATrimmedFe1$Fe)

        F test to compare two variances

data:  buffTrimmedFe$Fe[buffTrimmedFe$Fe < 2.5] and buffSTATrimmedFe1$Fe
F = 0.15618, num df = 16, denom df = 52, p-value = 0.0001931
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.07545694 0.38518722
sample estimates:
ratio of variances
         0.1561848

> t.test(buffTrimmedFeLow$Fe, buffSTATrimmedFe1$Fe, equal.var=F)

        Welch Two Sample t-test

data:  buffTrimmedFe$Fe[buffTrimmedFe$Fe < 2.5] and buffSTATrimmedFe1$Fe
t = -2.1408, df = 64.934, p-value = 0.03605
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.29888402 -0.01037236
sample estimates:
mean of x mean of y
 2.182353  2.336981
```

There is a statistically significant difference between mean STA2017 and STA2020 Fe_2O_3% values with regard to the Fe_2O_3-high buff ware group, on the magnitude of 0.15%.

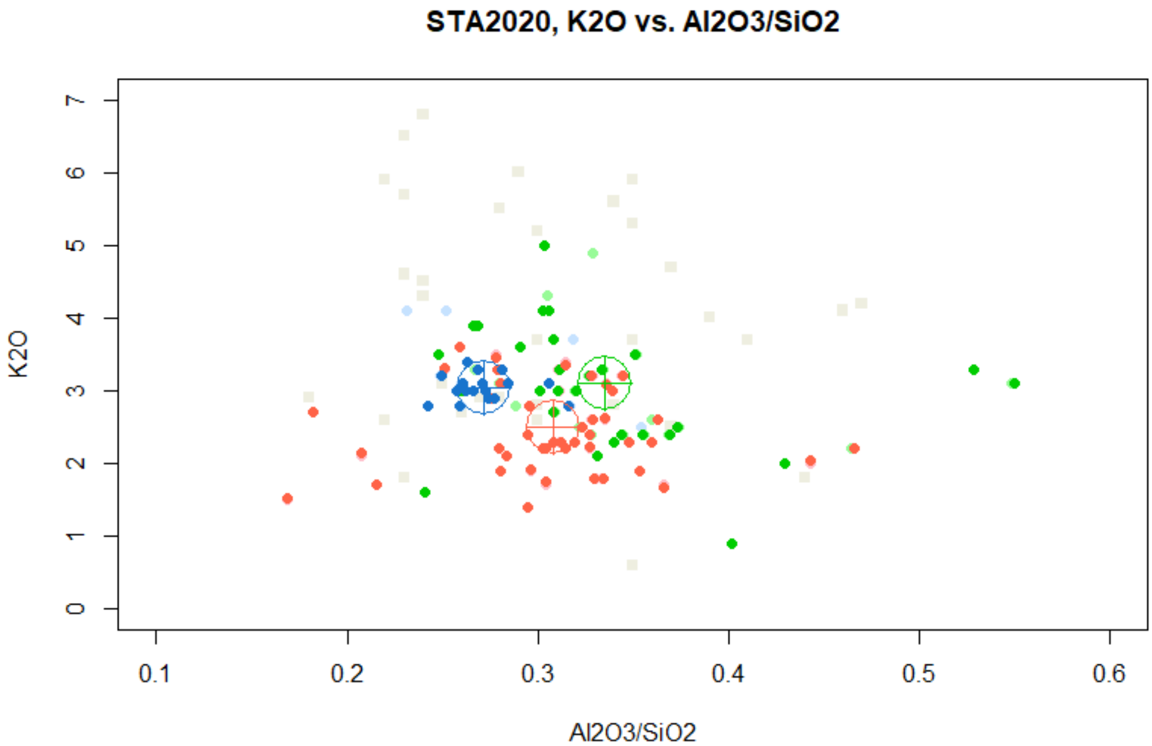
Potassium oxide

Category	K_2O%	Category	K_2O%	Category	K_2O%
Mercury jar	**3.0 ± 0.2**	**Brittle ware**	**3.0 ± 0.9**	**Buff ware**	**2.4 ± 0.6**
STA-MER-UA	3.4 ± 0.6	STA-BRI-GA	3.5 ± 0.3	STA-BUF-GA	2.3 ± 0.5
STA-MER-UB	3.1 ± 0.2	STA-BRI-GB	3.1 ± 0.4	STA-BUF-GB	2.3 ± 0.5
STA-MER-UC	3.0 ± 0.2	*STA-BRI-GC*	*2.6*	STA-BUF-GC	2.5 ± 0.2
STA-MER-UD	2.9 ± 0.2	*STA-BRI-GD*	*4.3*	*STA-BUF-GD*	*2.4*
		STA-BRI-SE	3.8 ± 1.5	STA-BUF-SE	2.9 ± 0.8
		STA-BRI-SF	*2.6*	STA-BUF-SF	3.0 ± 0.5
		STA-BRI-SG	*3.3*		
		STA-BRI-UH	2.8 ± 1.5	STA-BUF-UH	2.4 ± 0.8
		STA-BRI-UJ	3.5 ± 0.4	STA-BUF-UJ	1.8 ± 0.4
		STA-BRI-UK	2.3 ±<0.1	*STA-BUF-UK*	1.9
		STA-BRI-UL	2.3 ± 0.1		

Categories

```
> with(KCombined, pairwise.t.test(x=K, g=Type, p.adjust="holm"))

        Pairwise comparisons using t tests with pooled SD

data:   K and Type

           Brittle Buff
Buff       0.00054 -
MercuryJar 0.92426 0.00191

P value adjustment method: holm
```

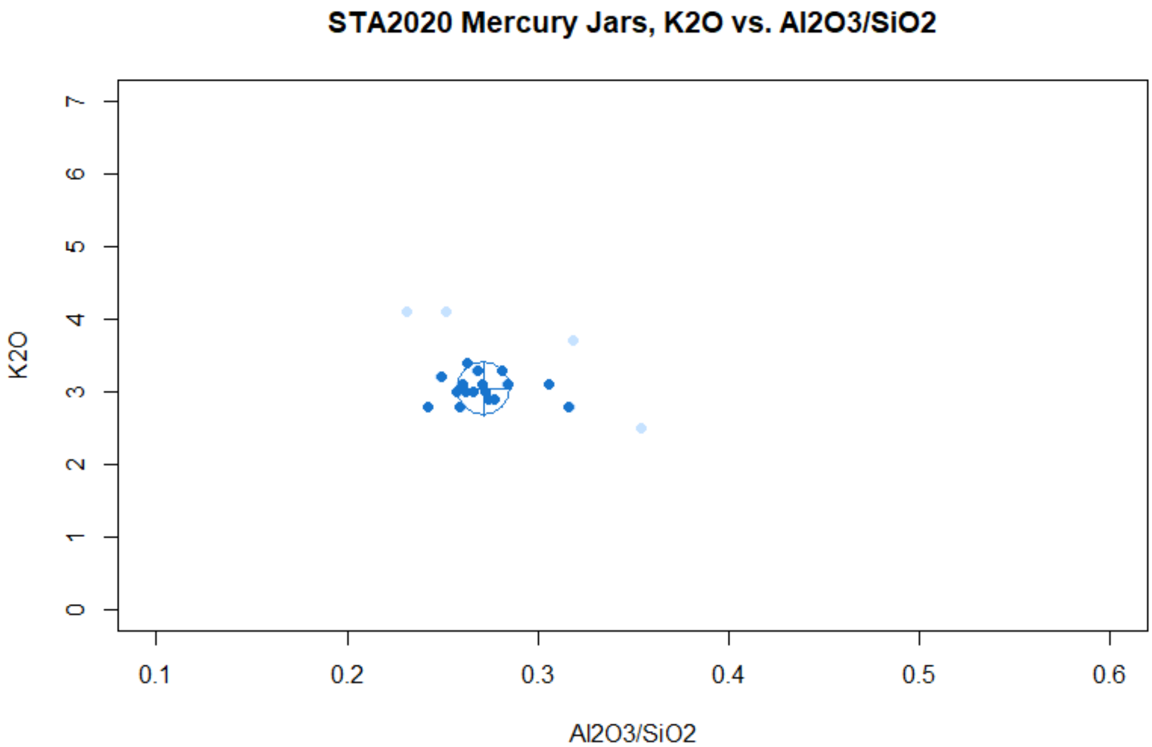
Both mercury jar and brittle stoneware are elevated in K_2O relative to buff stoneware in a statistically significant fashion, but are indistinguishable from each other.



	Main body	Outliers	Means
Buff ware	●	●	⊕
Brittle ware	●	●	⊕
Mercury jars	●	●	⊕
Chinese ceramics	■	◇⊠	n/a

Fabric Groups

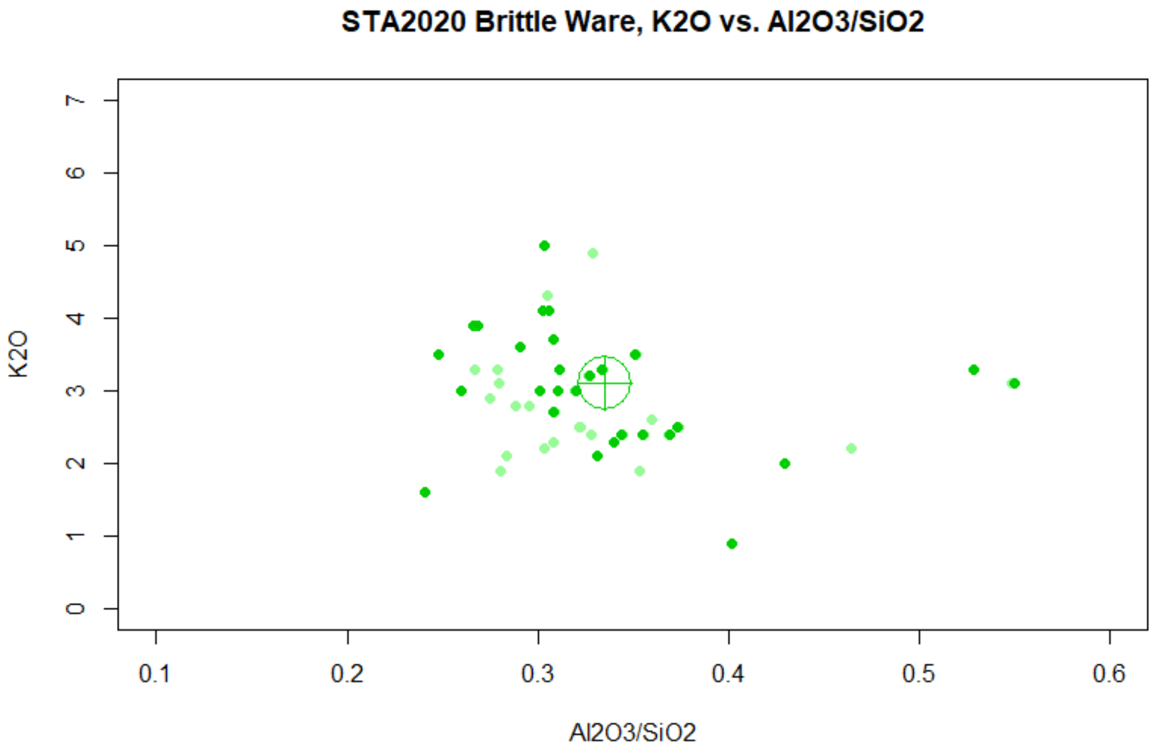
Mercury Jar




```
> summary(aov(K ~ FabricGroup, data= mercuryjars))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  3 0.7232  0.2411   1.633  0.219
Residuals   17 2.5092  0.1476
> with(mercuryjars, pairwise.t.test(x=K, g=FabricGroup, p.adjust="none"))

        Pairwise comparisons using t tests with pooled SD

data:  K and FabricGroup

           STA-MER-UA STA-MER-UB STA-MER-UC
STA-MER-UB 0.203      -          -
STA-MER-UC 0.135      0.630      -
STA-MER-UD 0.073      0.490      0.889

P value adjustment method: none
```

STA-MER-UD almost has a statistically significant K_2O% depletion relative to STA-MER-UA.

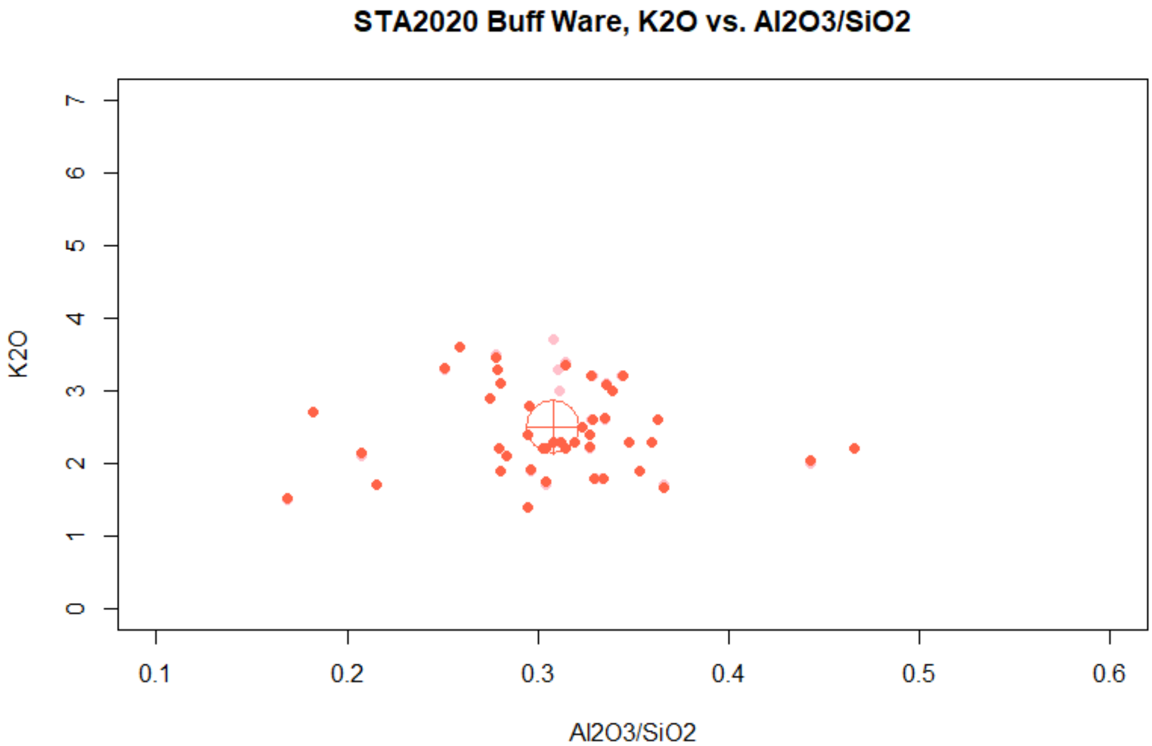
Brittle Stoneware




```
> summary(aov(K ~ FabricGroup, data= brittleTrimmedK1))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  5  5.069  1.0138   1.361  0.282
Residuals   19 14.150  0.7447


> with(brittleTrimmedK1, pairwise.t.test(x=K, g=FabricGroup, p.adjust="non
e"))

        Pairwise comparisons using t tests with pooled SD

data:  K and FabricGroup

           STA-BRI-GA STA-BRI-GB STA-BRI-UH STA-BRI-UJ STA-BRI-UK
STA-BRI-GB 0.419      -          -          -          -
STA-BRI-UH 0.138      0.515      -          -          -
STA-BRI-UJ 0.948      0.491      0.187      -          -
STA-BRI-UK 0.114      0.328      0.622      0.140      -
STA-BRI-UL 0.038      0.194      0.481      0.058      0.944

P value adjustment method: none
```

STA-BRI-UL has a statistically significant depletion of K_2O relative to BRI-GA and possibly -UJ.

Buff Stoneware




```
> summary(aov(K ~ FabricGroup, data= buffTrimmed))
            Df Sum Sq Mean Sq F value Pr(>F)
FabricGroup  5  0.793  0.1586    0.43  0.824
Residuals   28 10.336  0.3692

> with(buffTrimmed, pairwise.t.test(x=K, g=FabricGroup, p.adjust="none"))

        Pairwise comparisons using t tests with pooled SD

data:  K and FabricGroup

           STA-BUF-GA STA-BUF-GB STA-BUF-GC STA-BUF-SE STA-BUF-UG
STA-BUF-GB 0.69       -          -          -          -
STA-BUF-GC 0.62       0.90       -          -          -
STA-BUF-SE 0.18       0.33       0.43       -          -
STA-BUF-UG 0.64       0.98       0.87       0.24       -
STA-BUF-UH 0.76       0.87       0.77       0.22       0.85

P value adjustment method: none
```

No fabric groups are statistically distinct from each other.

Bibliography

Alasdair Chi. **A framework for the study of 'mercury jars' and other stoneware from the Temasek period of Singapore, alongside 12th–14th century stoneware from Kota Cina, Sumatra**. 2017. M.Sc. diss., University of Oxford.