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Curricular Materials on the Chemistry of Pottery, Including Thermodynamic Calculations for Redox Reactions in the 3-Stage Firing Process of Athenian Black- and Red-Figure Vases Produced from the Sixth–Fourth Centuries BCE

Christopher R. Vyhnal*

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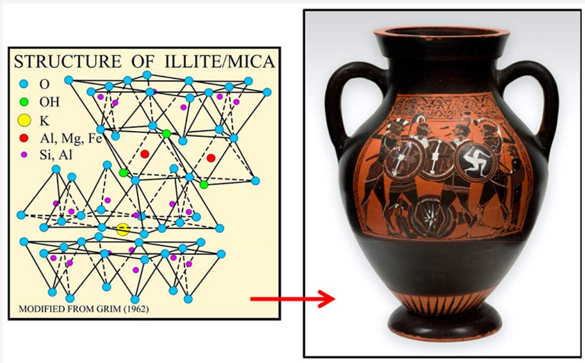
ABSTRACT: In place of a traditional Advanced Placement Chemistry class at the high school where I teach, I have recently developed and implemented a year-long, interdisciplinary curriculum that presents typical inorganic chemistry topics in the context of their relevant applications in archeology, art history, studio art, and the investigation, authentication, restoration, and conservation of cultural heritage materials. One of the units in the new course explores the chemistry of pottery and includes curricular materials presented in three lessons and described here: (1) an introductory slideshow and a problem set that has students complete general stoichiometric and gas law calculations and examine SiO_2 specific gravity data, refractive index data, and phase diagrams related to chemical reactions that dehydrate kaolinite clay and temperature changes that produce SiO_2 phase transformations during firing, (2) a laboratory exercise that has students create their own pinch pots and coil pots and measure mass changes resulting from water lost during drying and bisque firing, and (3) a slideshow, web-based video resources, and case study that allow students to explore in detail the technically sophisticated, 3-stage (oxidizing–reducing–oxidizing, hereafter "ORO") firing process that was used to create aesthetically elegant, Athenian black- and red-figure vases starting in the sixth century BCE, and to conduct thermodynamic calculations to verify the plausibility of several dehydration and redox reactions that are thought to have produced characteristically colored minerals that have been observed both in ancient pots and in modern reproductions. These curricular materials represent a novel way to stimulate and engage students in the application of their chemistry skills and content knowledge in an interdisciplinary context and are suitable for use by teachers of general chemistry or interdisciplinary science and art classes in high schools, colleges, and universities.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Curriculum, Interdisciplinary/Multidisciplinary, Analogies/Transfer,*
Applications of Chemistry, Gravimetric Analysis, Phases/Phase Transitions/Diagrams, Solid State Chemistry, Thermodynamics

■ INTRODUCTION

This paper is one of several published thus far[1,2] that describe new classroom activities designed as part of an innovative course that represents a pedagogical shift away from a traditional, Advanced Placement Chemistry high school class and toward a more interdisciplinary, project-based curriculum that explores conventional inorganic chemistry concepts in the context of their applications in archeology, art history, studio art, and the investigation, authentication, restoration, and conservation of cultural heritage materials. The goals of this curricular and pedagogical change are to (1) attract and enroll students who might not otherwise see themselves as "advanced science students" by presenting the material in a unifying, humanistic, and artistic theme; (2) engage students more deeply in the study of scientific principles by applying them in novel, useful, and interesting ways, thereby stimulating students' curiosity and sense of wonder while enhancing their skills and retention of chemical concepts; and (3) expand students' views of why the study of chemistry is a meaningful and purposeful enterprise.

Numerous papers published in this *Journal* have explored various aspects of the chemistry or analysis of pottery for instructional purposes. Denio reviewed the origin, composition, properties, and firing of clay[3] and redox reactions in glazes.[4]

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Manche[5] and Rogers[6] discussed the thermoluminescence technique for dating pottery and identifying forgeries, respectively, and Hill and others[7] described the application of scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) to the analysis of archeological materials, including pottery sherds and ceramic tiles. Harper and others[8] included gas chromatography−mass spectrometry (GC−MS) analysis of lipid residues absorbed in pottery sherds as part of a college course that attracts students from specializations in chemistry, biochemistry, anthropology, and museum studies. Festa and others[9] likewise described chemical characterization of the contents of an Egyptian sealed alabaster vase using multiple analytical techniques as part of a course for master's degree students in applied chemistry for cultural heritage. Robinson[10] presented the descriptive chemistry and pre-Columbian history of technology from natural resources, including pottery, as part of a high school chemistry curriculum.

Indeed, the useful role of chemistry in informing archeological studies has long been recognized.[11−13] The application of chemical analytical methods in modern archeological studies of ancient materials ("chemical archeology") including pottery sherds is increasingly common and involves, for example, the characterization of the following:

(1) bulk chemical composition by X-ray fluorescence spectrometry (XRF) or inductively coupled plasma mass spectrometry (ICP-MS)
(2) mineralogic composition by polarized light microscopy (PLM), X-ray diffraction spectrometry (XRD), or Fourier transform infrared spectroscopy (FTIR)
(3) isotopic composition by thermal ionization mass spectrometry (TIMS)
(4) chemical/textural features and surface phenomena via PLM or electron microprobe (EMP) analysis or SEM-EDS with elemental mapping
(5) chemical composition of absorbed or contained organic components by gas chromatography−mass spectrometry (GC−MS).

In such studies, the chemical information obtained from archeological pottery may reveal details regarding the following:

(1) the provenance of clay body source materials
(2) the preproduction trade of raw material goods
(3) the technical methods utilized in pottery production (for example, firing temperatures and atmospheric conditions in the kiln or the chemical composition/mineralogical characterization of decorative slips and their application techniques)
(4) the postproduction trade of finished pottery vessels and/or their contents
(5) the technological transfer between different pottery workshops
(6) the changes over time in any of the above features

For examples of such studies, see the review in Zumbulyadis[14] or recent chemical archeology investigations of ancient pottery[15−21] and the source terrains for clays[13,22] and tempering additives.

Given this backdrop, it is clear there are ample opportunities for teachers and students to explore chemical concepts in the applied context of pottery. This paper presents a few classroom activities developed in this theme as part of The Thacher School's new, interdisciplinary, second-year chemistry course for high school students, *Advanced Chemistry: Applications in Archaeology and Art*, in the hope that other teachers may find them useful in their own classrooms and laboratories.

■ CURRICULAR MATERIALS

Lesson 1: Introduction to the Chemistry of Pottery (Slideshow and Problem Set)

What is the origin of kaolinite clay, and what is its chemical composition and crystalline structure? How does the crystalline structure of kaolinite clay allow it to be formed into pots which then retain their shape? Why does clay pottery need to be fully dried before firing? What are the chemical and physical changes that kaolinite clay undergoes during firing in a kiln? What are some flaws that may occur during the firing of common pottery glazes and how might they be avoided? The pottery unit in the new course begins with a slideshow (20−30 min) that presents information on pottery source materials and the changes they undergo during firing in a kiln. The production of kaolinite clay via geological, physical, and chemical weathering is discussed with images that illustrate the effects of volumetric expansion of water as it freezes in the cracks of granitic outcrops (also known as "freeze−thaw"

Figure 1. Example of "freeze−thaw" weathering or "frost wedging" in granitic rocks of the Sierra Nevada mountains in California. Cracks in the outcrop in the upper left portion of the photograph accept moisture which is subjected to freeze−thaw cycles over geologic time scales. In the cracks, expansion of moisture as it freezes to ice gradually wedges the rocks apart, eventually separating boulders (lower right) which subsequently are carried downslope and subjected to additional physical weathering which reduces the particle sizes from boulders to cobbles to pebbles to sands, silts, and clays. The increase in the surface area to volume ratio of particles as particle size decreases facilitates chemical weathering.

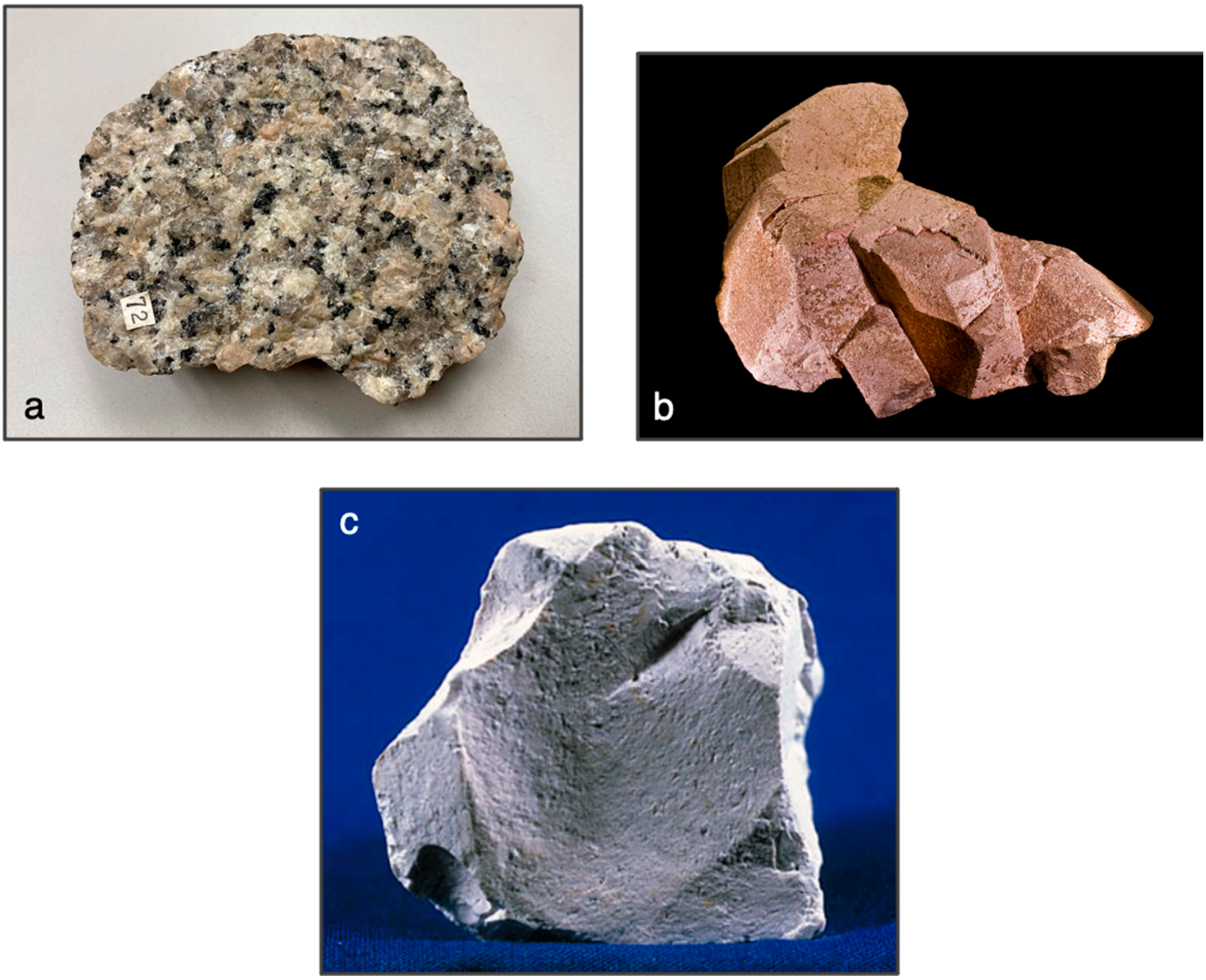

Figure 2. (a) Biotite granite hand sample from St. Cloud, Minnesota. Photo credit: B. Domangue.[27] (b) Orthoclase hand sample from Minas Gerais, Southeast Region, Brazil. Photo credit: Didier Descouens.[28] (c) Kaolinite hand sample, locality unknown. Photo credit: United States Geological Survey.[29]

weathering or "frost wedging") with the corresponding production of isolated boulders which are subsequently reduced in size to cobbles, pebbles, sands, silts, and clays by collisions during downslope transport (Figure 1), thereby facilitating chemical weathering. Images of (1) granitic rock, (2) orthoclase (a potassium feldspar), one of the major, rock-forming minerals in granite, and (3) kaolinite, the chemical alteration product of orthoclase, are also shown (Figure 2). The chemical reaction of orthoclase to kaolinite, the primary clay mineral in ceramics production, is also presented:

$$\begin{aligned} &2KAlSi_3O_8(\text{s, orthoclase}) + 2H_2O(\text{l}) \\ &\quad \rightarrow Al_2Si_2O_5(OH)_4(\text{s, kaolinite}) \\ &\qquad + K_2SiO_3(\text{aq, potassium silicate}) + 3SiO_2(\text{s, quartz}) \end{aligned} \tag{1}$$

The crystal structure of kaolinite, a "1:1 clay mineral", is displayed[23] (Figure 3) and described as consisting of alternating siloxane layers of hexagonally arranged silicate tetrahedra (or "T layers") and gibbsite-like layers of aluminum octahedrally coordinated to 4 hydroxide units and 2 oxygen atoms (or "O layers").[24] The significance of water-filled interlayer sites and the corresponding role of hydrogen bonding on the clay's plasticity and ability to hold its shape[25] are also addressed.

The slideshow continues with an illustration and discussion of the progressive chemical and physical (or "phase") changes that occur during firing and cooling of pottery, using a kiln firing chart[26] as a guide. Important chemical reactions include the conversion of kaolinite to metakaolin near 500 °C

$$\begin{aligned} &Al_2Si_2O_5(OH)_4(\text{s, kaolinite}) \\ &\quad \rightarrow Al_2O_3{\cdot}2SiO_2(\text{s, metakaolin}) + 2H_2O(\text{l}) \end{aligned} \tag{2}$$

and the conversion of metakaolin to mullite near 1050 °C

$$\begin{aligned} &3(Al_2O_3{\cdot}2SiO_2)(\text{s, metakaolin}) \\ &\quad \rightarrow 3Al_2O_3{\cdot}2SiO_2(\text{s, mullite}) + 4SiO_2(\text{s, quartz}) \end{aligned} \tag{3}$$

A relevant phase diagram for SiO_2 is also shown (Figure 4) and used as a vehicle for students to better understand the corresponding phase changes in SiO_2 that occur during the firing and cooling of pottery. The associated reading[25] and problem set (see the Supporting Information for questions and an answer

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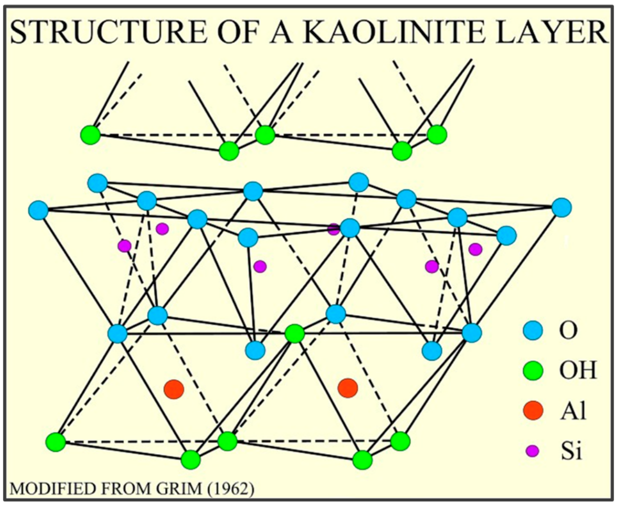

Figure 3. Crystal structure of kaolinite[23] (modified from Grim, 1962[30]), the most common clay mineral in fired ceramics, has a "1:1 clay mineral" structure consisting of alternating siloxane layers of hexagonally arranged silicate tetrahedra (or "T layers") and gibbsite-like layers of aluminum (or "O layers") octahedrally coordinated to 4 hydroxide units and 2 oxygen atoms.

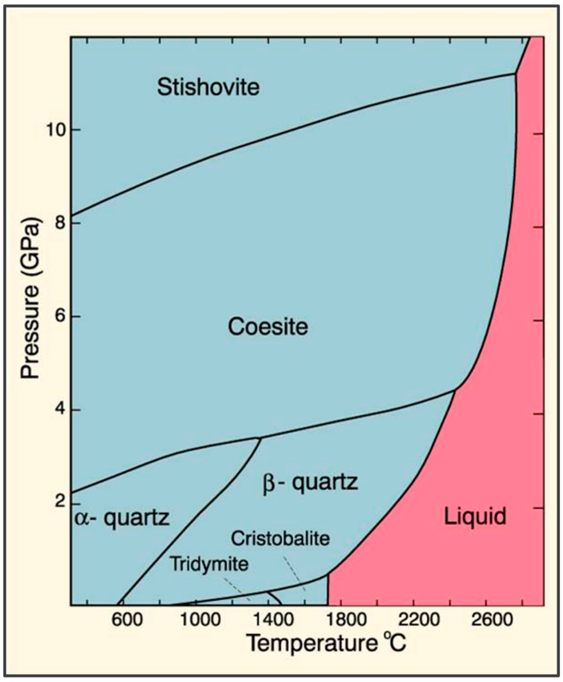

Figure 4. SiO_2 phase diagram from Winter CC 4.0[31] showing the pressure−temperature (P−T) stability regions of the most common SiO_2 polymorphs. The SiO_2 phases that are stable during the firing of pottery lie very near the x-axis at 1 atm pressure.

key) are assigned as homework and prompt students to understand and explain why the chemical structure of kaolinite clay and hydrogen bonding between its layers make the material particularly well-suited for shaping into pottery. The students then conduct stoichiometric calculations related to the chemical reaction that forms kaolinite from orthoclase. They also conduct an ideal gas law calculation to determine the volumetric expansion of liquid water at room temperature and atmospheric pressure upon its conversion to vapor at 100 °C and atmospheric pressure and are asked to explain the significance of the calculation with respect to the firing of pottery. Students are also prompted to calculate the theoretical mass percentage of "chemical water" lost during the reaction of kaolinite to metakaolin near 500 °C (a value to which the students will refer when they later conduct their own measurements of water lost during the firing of pots that they make themselves). The silica phase diagram is also utilized as a reference for questions that prompt students to understand and explain which SiO_2 polymorphs are expected to form during the firing and cooling of pottery, which phases are *not* expected to form (and why), and what factors might account for any differences between observed SiO_2 polymorphs in actual pottery firing experiments and theoretical expectations based on the SiO_2 phase diagram. Students also are provided with specific gravity and refractive index data for SiO_2 polymorphs and related phases (see ref 32 and sources cited therein) and asked to generate a mathematical model of their relationship and then reflect on and explain the model results in terms of the physics of light and the kinetic molecular theory of matter. Several final questions prompt students to explore two common chemical glazes, "whiting" ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), and conduct stoichiometric calculations of the expected mass loss on ignition (LOI) due to their thermal decomposition during firing. Students are asked to explain where the lost mass goes and how they might modify glaze application and firing protocols to prevent the glazes from "clouding up with microbubbles".

Lesson 2: Making Pottery and Measuring Water Loss (Laboratory Exercise)

How much water does wet clay lose during drying? How much "chemical water" does dried clay lose during firing? How does the latter figure compare to theoretical calculations from lesson 1? The second lesson in the unit is a laboratory exercise that has students get their hands dirty (literally) by hand-forming their own pottery and measuring mass changes due to water loss during drying and bisque firing to cone 08 (near 950 °C)[26] in the school's pottery kiln. For simplicity and time's sake, we chose to make basic pinch pots[33] and coil pots[34] during a single lab period (about 70 min) using Soldate 60 clay purchased from a ceramics supplier.[35] Mass measurements of the pots were then recorded using a gram balance a total of four times:

(1) immediately after hand-forming the pots
(2) 6 days later after drying the pots to "leather" hardness under 3 mil plastic sheeting
(3) after another 3 days, just prior to bisque firing the pots
(4) after bisque firing the pots

Results are summarized in Table 1. The percentage of mass loss at each stage was calculated and compared, and students were asked to reflect on and explain their results. As can be seen in the table, results for the percentage of water lost during drying were slightly larger and less consistent for the coil pots than for pinch pots; this is attributed to the fact that students added varying amounts of wet clay slip to smooth the pottery surface between coils. Chemical water loss during firing, as measured from the dried, prefired mass of both the pinch and coil pots, was quite consistent at 7.9 ± 0.4%, and notably less than the 14% value the students calculated in the problem set from lesson 1. This is attributed to the fact that the Soldate 60 clay body the students used to make their pots is not pure kaolinite but includes about 6 wt % of a tempering additive that did not release water or other volatile components during firing in the kiln. Future iterations of this laboratory activity will also incorporate the addition of whiting or dolomite glaze during a

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Table 1. Gravimetric Measurements of Water Loss During Drying and Firing of Pottery

Date: Sample	11/25/20 Fresh Mass (g)	12/1/20 'Leather' Mass (g)	12/4/20 Pre-Fire Mass (g)	12/8/20 Post-Fire Mass (g)	12/1/20 'Leather' % Lost (%)	12/4/20 Pre-Fire % Lost (%)	12/8/20 Post-Fire % Lost (%)
Pinch Pots							
Sample 1	308	291	253	234	5.5%	17.9%	7.5%
Sample 2	290	279	241	221	3.8%	16.9%	8.3%
Sample 3	276	261	227	208	5.4%	17.8%	8.4%
Sample 4	294	278	241	223	5.4%	18.0%	7.5%
Sample 5	297	273	244	225	8.1%	17.8%	7.8%
Sample 6	296	280	243	224	5.4%	17.9%	7.8%
Sample 7	320	304	264	242	5.0%	17.5%	8.3%
				Average	**5.6%**	**17.7%**	**7.9%**
				1σ	**1.4%**	**0.4%**	**0.4%**
Coil Pots							
Sample 1	490	406	380	350	17.1%	22.4%	7.9%
Sample 2	344	327	282	259	4.9%	18.0%	8.2%
Sample 3	397	375	319	296	5.5%	19.6%	7.2%
Sample 4	175	153	134	123	12.6%	23.4%	8.2%
Sample 5	638	583	517	476	8.6%	19.0%	7.9%
Sample 6	304	271	240	222	10.9%	21.1%	7.5%
Sample 7	262	254	211	194	3.1%	19.5%	8.1%
				Average	**9.9%**	**20.6%**	**7.8%**
				1σ	**4.6%**	**2.1%**	**0.4%**

subsequent lab period and a second firing for students to record the glaze LOI for comparison with the theoretical calculations they conducted in lesson 1 and experimental results from other sources.[36] Diffuse reflectance spectroscopy and quantitative colorimetry[1,2] of the pots might also be incorporated in future iterations of the lab activity in order to quantitatively assess color changes in the clay during drying and bisque firing.

Lesson 3: Athenian Black- and Red-Figure Vases (Case Study with Slideshow and Video Resources, Focus Questions and Problem Set)

How were aesthetically elegant, Athenian black- and red-figure vases dating from the sixth−fourth century BCE produced? How can our modern analytical methods and our theoretical understanding of chemical principles inform our understanding of these ancient but still technologically sophisticated pottery production methods? Numerous recent, analytical investigations of both ancient, Athenian black- and red-figure vases and modern, laboratory, and commercial reproductions have shed considerable light on the source materials and technologically sophisticated, multi-stage firing process that were used to create these impressive works of art some two and a half millennia ago (see, for example, refs 37−41 and this recent and thorough review, ref 42, which summarizes the results of prior investigations and details practical experience gained from some 800 replication experiments conducted over a 20 year span).

The lesson begins with a slideshow (20−30 min) that presents students with examples of older, black-figure pottery, younger, red-figure pottery, and "bilingual" examples of pottery decorated using both techniques (Figure 5). Chemical and structural differences between illite, an important clay mineral in the production of Athenian black- and red-figure pottery, described as a "2:1 clay mineral" composed of an octahedral alumina layer ("O layer") sandwiched between two silica tetrahedral silica layers ("T layers")[43] (Figure 6), and kaolinite clays are also presented and discussed. Several excellent videos (∼25 min total run time), that describe the source materials and their chemistry,[44] detail the black-figure[45] and red-figure[46] decorative techniques and discuss the 3-stage ORO "iron-reduction" firing protocol[47] used in the production of ancient Athenian vases are included as part of the presentation. Next, balanced chemical equations for dehydration and redox reactions that produce the observed, color-contributing minerals (hematite, magnetite, wüstite, and hercynite) during 3-stage, ORO firing are presented.

During stage 1 firing to temperatures between 900 and 950 °C in a fully vented kiln and therefore under oxidizing conditions,[42] goethite (yellow), naturally present in the clay body and slip as a weathering product of illite, is dehydrated to form hematite (red):

$$2FeO(OH)(s,\ goethite) \rightarrow Fe_2O_3(s,\ hematite) + H_2O(l) \quad (4)$$

During stage 2 firing, additional fuel is added to the kiln, and the kiln vents are closed, resulting in incomplete combustion of the fuel, the production of carbon monoxide, a reducing atmosphere, and a lower firing temperature (optimally between 800 and 830 °C).[42] This results in the conversion of red hematite (present both in the clay body and in the specially selected and prepared, gray, illite slip used to paint portions of the pot) to magnetite, wüstite, and hercynite, which are all either black or dark gray minerals:

$$3Fe_2O_3(s,\ hematite) + CO(g) \rightarrow 2Fe_3O_4(s,\ magnetite) + CO_2(g) \quad (5)$$

$$Fe_2O_3(s,\ hematite) + CO(g) \rightarrow 2FeO(s,\ wüstite) + CO_2(g) \quad (6)$$

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Figure 5. Examples of ancient Athenian, black- and red-figure pottery made using the 3-stage ORO firing process. (a) Artist unknown, *Belly-Amphora (Storage Jar)*, ~550−540 BCE, The Art Institute of Chicago (the reverse side of the same pot is shown in the graphical abstract).[52] (b) Attributed to the Phiale Painter, *Terracotta Lekythos (Oil Flask)*, ~440 BCE, The Metropolitan Museum of Art, New York.[53] "Bilingual" pottery was made by utilizing both the black-figure and red-figure decorative techniques on opposite sides of the same pot, sometimes painted by different artists.

$$\mathrm{FeO(s,\ w\ddot{u}stite) + Al_2O_3(s,\ from\ clays)} \rightarrow \mathrm{FeAl_2O_4(s,\ hercynite)} \quad (7)$$

During stage 2 firing, in areas of the pot painted with the illite slip, the characteristic "Black Glass-ceramic" (BGc)[42] is sintered, effectively sealing the black and dark gray, Fe^{2+}-bearing minerals produced from any future exposure to oxygen and thereby preventing their subsequent chemical reaction. At this point, the kiln is again vented to reestablish an oxidizing atmosphere, and the temperature is increased once again to between 900 and 950 °C. In areas of the pot *not* painted with the illite slip (and which therefore remain porous), the additional exposure to oxygen causes any black and gray, Fe^{2+}-bearing minerals formed during stage 2 firing to react with available oxygen and revert to red hematite during stage 3 firing:

$$\mathrm{4Fe_3O_4(s,\ magnetite) + O_2(g) \rightarrow 6Fe_2O_3(s,\ hematite)} \quad (8)$$

$$\mathrm{4FeO(s,\ w\ddot{u}stite) + O_2(g) \rightarrow 2Fe_2O_3(s,\ hematite)} \quad (9)$$

$$\mathrm{4FeAl_2O_4(s,\ hercynite) + O_2(g)} \rightarrow \mathrm{2Fe_2O_3(s,\ hematite) + 4Al_2O_3(s)} \quad (10)$$

The slideshow concludes by presenting the chemical composition of the characteristic BGc, the optimal clay particle size and annealing temperature required to make it,[40] and a map showing the purported illite clay source areas utilized from the Panakton plateau, the Mt. Parnes region, and Laurium in Greece.[41]

Students are then shown an excellent, recorded video (~25 min) of a panel discussion organized by the Getty Conservation Institute[48] on the detailed analysis of Athenian black- and red-figure pottery. A series of focus questions about the recorded panel discussion have been compiled for use either as a homework assignment or as teacher prompts to facilitate a class discussion (see Supporting Information for questions and answers). The final exercise in the unit is a problem set in which students are provided with thermodynamic data[49−51] for the phases present in reactions 4−10 and asked to calculate the enthalpy, entropy, and Gibbs free energy changes for chemical reactions that produce the observed phases to verify the thermodynamic plausibility of the balanced, chemical equations thought to produce the characteristically colored minerals in Athenian black- and red-figure pottery (see Supporting Information for questions and answers).

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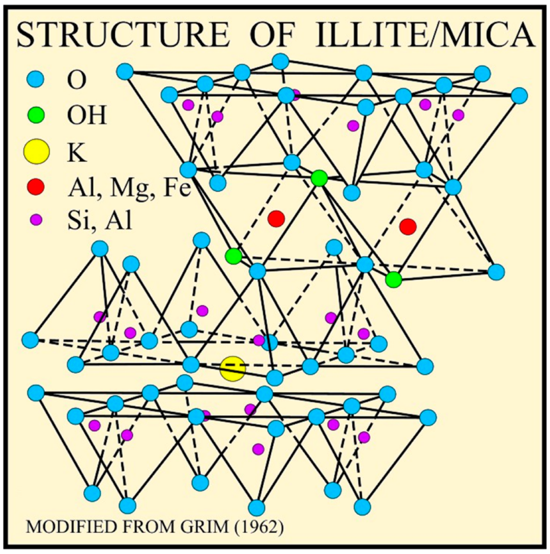

Figure 6. Crystal structure of illite[43] (modified from Grim, 1962[30]), an important constituent in the production of Athenian black- and red-figure pottery, is described as a "2:1 clay mineral" composed of an octahedral alumina layer ("O layer") sandwiched between two silica tetrahedral silica layers ("T layers").

CONCLUSIONS AND FUTURE WORK

The three lessons described herein present chemical concepts that are traditionally taught in introductory or general chemistry classes: hydrogen bonding, molecular geometry, crystalline structure, reaction stoichiometry calculations, mass−volume conversions utilizing the density equation, ideal gas law calculations, phase diagrams, specific gravity, data modeling using linear regressions, kinetic−molecular theory, oxidation−reduction reactions, and thermodynamic calculations. Here, they are presented in a unifying and applied context that is, based on my experience offering the class this past year, more interesting and meaningful for students. Additional material that may not necessarily be covered in a traditional introductory or general chemistry class (analytical chemical methods) is readily available via the numerous analytical studies that have been published on Athenian black- and red-figure pottery (and other types of pottery). Indeed, one of my additional goals in revamping The Thacher School's advanced chemistry curriculum was to introduce students to reading, discussing, understanding, and interpreting primary source science publications, and they are provided with numerous opportunities to do so in the new curriculum described here and in prior publications.[1,2] For example, during the winter term of the course, which focuses on chemical archeology, the students read scientific papers on (1) the chemical and mineralogical composition of pottery sherds with implications for the provenance of clay body source materials, the trade network for raw material goods, and the production methods used to make pottery that was buried by the 79 CE eruption of Mt. Vesuvius at Pompeii;[54,55] (2) the chemical composition of Roman Imperial coins as reflecting attempts to standardize ancient smelting and minting operations across the Roman empire starting with the reign of Augustus (23−20 BCE);[56] and (3) the chemical composition of ancient Egyptian glass beads as indicating the use of smelting byproducts (metallurgical slags) as coloring agents in the production of early glasses.[57]

Feedback from students on the pedagogical shift and case studies approach in the new course has been very positive. Comments from several students who took the new class this past year include the following:

"I have loved the case studies and have found them to be very fascinating."

"This interdisciplinary course has increased my interest in STEM 10-fold. I am someone who considers themselves a humanities person, however, this class has made me enjoy science."

"It is one of the most unique Thacher classes I've ever taken, because not only does it combine topics that I thought did not relate to each other (chemistry and art), but it also let me see how science can be applied to the greater world and in everyday situations. You do not need to be a chemistry genius nor an art connoisseur to enjoy and get the most out of the class, which was one of my fears going into it. It made me excited to learn science in a way I never thought I would be."

The new course also represents a shift in the primary modes of assessment away from more traditional quizzes and tests and toward more collaborative and project-based work (oral and video presentations prepared in small groups, collaboratively generated infographics, etc.). In future iterations of the course, I hope to incorporate more summative assessments (quizzes) in order to evaluate students' retention of chemical concepts more objectively. That said, my school is committed to fostering the kinds of changes in curriculum, pedagogy, and assessment described here, and the rich and rewarding teaching and learning experience in the new course this past year has thoroughly convinced me of the merits of this approach.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00953.

Introduction to pottery chemistry worksheet and key (PDF, DOCX)

Measuring mass loss of pottery during drying and firing (PDF, DOCX)

Introduction to the redox chemistry of Athenian Pottery and key (PDF, DOCX)

Thermodynamics of redox reactions in Athenian pottery and key (PDF, DOCX)

AUTHOR INFORMATION

Corresponding Author

Christopher R. Vyhnal − *Science Department Chair, Philip Bard Chair for Excellence in Science Teaching, The Thacher School, Ojai, California 93023, United States;* orcid.org/0000-0002-0184-8754; Email: cvyhnal@thacher.org

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.1c00953

Notes

The author declares no competing financial interest.

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