

Solfataric Alum Exploitation during the Greco-Roman Period: Some Considerations on its Nature, Enrichment, and Preparation for Market

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Abstract

In the Greco-Roman (G-R) period, alum, the traded commodity, was used extensively by many industries (e.g. textiles, tanning, metals, or as mineral medicinals). It is thought to have travelled from source (the volcanic landscapes of Greece and Italy) to markets, in dedicated amphorae. Alum, the raw material, was made up of a combination of alum group and other minerals, both soluble and insoluble. The two components would have been separated via a cycle of dissolution-evaporation prior to packaging and shipment. But in what shape did alum, the commercial product, travel to market? We present here simple laboratory-based experiments, combined with X-Ray diffraction (XRD) analysis, to demonstrate that alum, the shipped product from these sources, would have been a gel-like material of varying colouration, from clear/off-white to darker shades, depending on level of iron impurities. Aluminium sulfates are highly hygroscopic; travelling as a gel rather than powder, over long-distance sea routes, would have ensured that the product arrived at its destination in a market-approved condition. Travelling as powder would have resulted in water absorption and stickiness.

Introduction

In the Greco-Roman (G-R) period alum, the traded commodity, was used by many and diverse industries (e.g. textiles, tanning, metals, or as mineral medicinals)¹. It was already known in the Mycenaean period as evidenced in Linear B texts.² Alum ‘rock’ was mentioned in Hittite texts³ and by Herodotus.⁴ In the Roman period, Dioscorides⁵ and Pliny⁶ discuss extensively its nature, sources and properties to include its use as a hemostatic. Recently our group demonstrated that it can be active as an antibacterial, as well.⁷

G-R alum is conventionally equated with potassium alum ($\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$). This is a convenient generalisation since a. it refers primarily to the main ingredient in the traded commodity and b. does not take into account either the variety of source materials or the processing they may have undergone prior to shipment to markets. Therefore, when researching the alum industry of the Greco-Roman period it is perhaps best to keep in mind that, in this context, potassium alum is used as a generic name, rather than as a signifier of mineralogical identity.

Alum, the raw material, originated from two volcanic landscapes i.e. Melos, SW Aegean, Greece and the Aeolian Islands, in the Tyrrhenian Sea, Italy (figs.1a/b/c). Today

we know that this is solfataric alum consisting primarily but not exclusively of natural alunogen and/or natural potassium alum as well as a host of other soluble and insoluble alum group minerals (Table 1). This type of raw material would have been extracted and processed quite differently from alunite (rock alum), also known in antiquity and originating from other sources (for example, Egypt) requiring roasting prior to lixiviation (i.e. immersion in water in order to separate the soluble from insoluble components).

In reference to the alum (*alumen*) of Melos, Pliny⁸ discusses three types: *styp-teria phorime* (meaning, abundant), *styp-teria paraphore*, and *melinum*. The former is described as ‘liquid’. Our work so far, on Melos, has matched *melinum* with alunite ($\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$), (in association with quartz and kaolinite), and ‘liquid’ alum (*styp-teria phorime*) with solfataric alum, primarily alunogen ($\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$) with or without potassium alum ($\text{KAl}(\text{SO}_4)_2 \cdot 12(\text{H}_2\text{O})$). It is not clear whether *styp-teria paraphore* was ‘liquid’ or solid. Pliny describes alum as ‘earth exudations’ (*salsugo terrae*), clearly pointing to solfataric alum (see below). Whether the ‘liquid’ alum was liquid (or gel-like) because of processing or because it was liquid in its natural state remains unclear. Nevertheless, travellers to Melos in the 18th century reported seeing alum ‘liquor’ in a cavern in the southeast of the island (*a cavern which distils this aluminous liquor*).⁹



Fig. 1: 1a: Map of the Mediterranean with some well-known localities with solfataric alum (Italy: Ischia, Naples, Lipari, Vulcano; Greece: Melos, Sousaki, Thera, Kos/Nisyros) – 1b: the island of Melos with place names mentioned in the text – 1c: the island of Vulcano with place names mentioned in the text

Mineral	Chemical formula	Colour
Alum-(K)	$KAl(SO_4)_2 \cdot 12H_2O$	White
Alunite	$KAl_3(SO_4)_2(OH)_6$	White
Alunogen	$Al_2(SO_4)_3 \cdot 17H_2O$	White
Anhydrite	$CaSO_4$	Colourless to pale blue
Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$	Colourless to yellow
Halotricite	$FeAl_2(SO_4)_4 \cdot 22H_2O$	Colourless – white
Gypsum	$CaSO_4 \cdot 2H_2O$	Colourless – white
Hydrobasaluminite	$Al_4(SO_4)(OH)_{10} \cdot 12-36H_2O$	White
Millosevichite	$Al_2(SO_4)_3 \cdot 17H_2O$	Red
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$	Grey-white
Pickeringite	$MgAl_2(SO_4)_4 \cdot 22H_2O$	Colourless – white
Steklite	$KAl(SO_4)_2$	Colourless – white
Sulphur	S	Yellow
Tschermigite	$(NH_4)Al(SO_4)_2 \cdot 12H_2O$	Colourless
Tamarugite	$NaAl(SO_4)_2 \cdot 6H_2O$	Colourless
Voltatite	$K_2Fe^{2+}_5Fe^{3+}_3Al(SO_4)_{12} \cdot 18H_2O$	Green to greenish-black

Table 1: Sulphate and aluminium sulfate minerals from Campi Flegrei, Naples and Melos and Vulcano, Aeolian Islands.

The purpose of this short paper is to draw attention to the extraction of solfataric alum in the G-R period to experimentally simulate the dissolution-evaporation cycle underpinning solfataric alum enrichment by using samples of solfataric alum (from the Aeolian island of Vulcano). The laboratory-based experiments aim to provide some insight into how alum might have looked after processing (in colour, hue) and how it would have travelled (as ‘liquid’ or solid). We suggest that alum, the product shipped out from these sources, would most likely have travelled as a gel, rather than a powder. Brief mention is made of the two amphorae, one from Melos and the other from Lipari, thought to have been used for the transport of alum.

Solfataric Alum

Solfataric alum is associated with fumaroles, i.e. vents where ‘steam’, containing gases like carbon monoxide and hydrogen sulphide, is emitted from the earth. A field of fumaroles is called a solfatara. Solfataric alum forms efflorescences, or mineral growths, which are transported to the surface as dissolved sulfate compounds and precipitate near the vent (fig. 2a). They form thick ‘sheets’ of white material that can be removed relatively easily from the walls and ceilings of caverns, contrary to open air vents which can lose these precipitates in the first rain, through dissolution. Today there are several localities across the Mediterranean with variable evidence for solfataric activity (fig. 1a). Solfataras, together with hot springs, on land or under water, and warm soils (c. 60°C) are manifestations of an active geothermal field and by extension, of dormant volcanic activity. Melos has a geothermal field which was strong in the G-R period and most likely until the 18th century.¹⁰ Presently, this field remains strong, although its surface manifestations are wanning. In Melos, the fumaroles that can be visible today occur largely in the southeast part of the island (Kalamos, Aghia Kyriaki, Palaeochori) (fig. 1b); it is there that most of the archaeological evidence for likely Roman alum exploitation is concentrated.¹¹

From the Roman period onwards soluble potassium alum was ‘synthesized’, by roasting insoluble alunite (probably mixed with other minerals as well), and subsequently immersing the roasted ore into vats full of water. Soluble potassium alum would readily dissolve in water, and subsequently collected following evaporation. Archaeological



Fig. 2: 2a: Photo of aluminium salts precipitating out of salt-rich steam and deposited around vents, within the Fyriplaka cavern, SE Melos. These incrustations can be removed easily by hand – 2b: Entrance to the Cave of Alum, Faraglione, Vulcano. Both at the entrance and interior of the cave, there is large variety of white/off-white crystals of various aluminium sulfates forming encrustations of various thickness. Main ‘door’ entrance: 1.6 m high.

evidence for the extraction and processing of alunite-rich rock comes from 7th century CE Lesvos, in the northeastern Aegean.¹² In later periods, rich alunite deposits were worked in Italy, near Rome and in Aegean Turkey.¹³

Regarding the processing of solfataric alum, natural alunogen or potassium alum, Singer quotes the mining expert,¹⁴ Fougereux de Bondaroy who visited the area of the Campi Flegrei near Naples and its associated solfataras, in 1755. The hot soils of the Campi Flegrei were used as an energy source. Fougereux de Bondaroy's illustration (fig. 3a) shows a large tank (c) full of water placed into the hot soils; the alum earth (d) was thrown in and mixed thoroughly to dissolve the soluble salts. The supernatant liquid from the large tank was then removed and deposited into cauldrons (e), which were also embedded in the hot soils. Most of the water would eventually evaporate and the thick layer of pure crystallised alum salt would be removed and packaged.

We have suggested that similar cycles of dissolution-evaporation of natural solfataric alum probably took place in the G-R period in Melos, using the hot soils of the southeastern part of the island (Aghia Kyriaki, fig. 1b), as a heat source. Direct evidence is hard to come by. There is hardly any mineralogical difference in composition, shape, and form between raw materials, intermediate waste and products; furthermore, the installations which could have been in place in the G-R period can only be considered very basic. In the absence of clear archaeological evidence for the processing of the soluble alum group minerals, we have proposed a model for its processing (fig. 3b).

Apart from Melos, another key producer of alum in the G-R period was the Aeolian island of 'Lipari'.¹⁵ We take 'Lipari' to refer either to the island itself or the entire cluster of Aeolian islands, or specifically to the islands of Lipari and neighbouring Vulcano. Today there is relatively limited evidence for fumaroles on Lipari,¹⁶ although in antiquity it might have been quite different. On the other hand, solfataric alum and sulphur were exploited in Vulcano as recently as the late 19th century, probably using methods no different than those practiced in the G-R period.¹⁷

Regarding the geological appearance of alum on Vulcano, alum, sulphur and alunite are present in the Faraglione area and in the crater, La Fossa (fig.1c); kaolin is present in the Faraglione but not in the crater. Vulcanello, in the northern part of the island, is a small island which formed as a result of a volcanic eruption in 180 AD.¹⁸ Faraglione and Vulcanello are characterized almost exclusively by soluble alum salts, slightly soluble sulfates, like gypsum, and insoluble sulfates like alunite and natroalunite (Table 1); there is also native sulphur. Vulcanello is poor in mineralogical variability. The difference in mineralogy between La Fossa and the Faraglione is due to the temperature and composition of the gases as well as chemical modification (not mixing) procedures between different sources.¹⁹ The La Fossa crater is dominated by high temperatures (up to 400°C or higher is common, even close to the surface), Cl-SO₄-rich water, with Boron, Fluorine and metals, deriving from single-step condensation of high enthalpy fluids.²⁰ By contrast, the flat lands to the north, Faraglione, and Vulcanello are characterized by modification of the shallow aquifers by the input of chemical elements and enthalpy

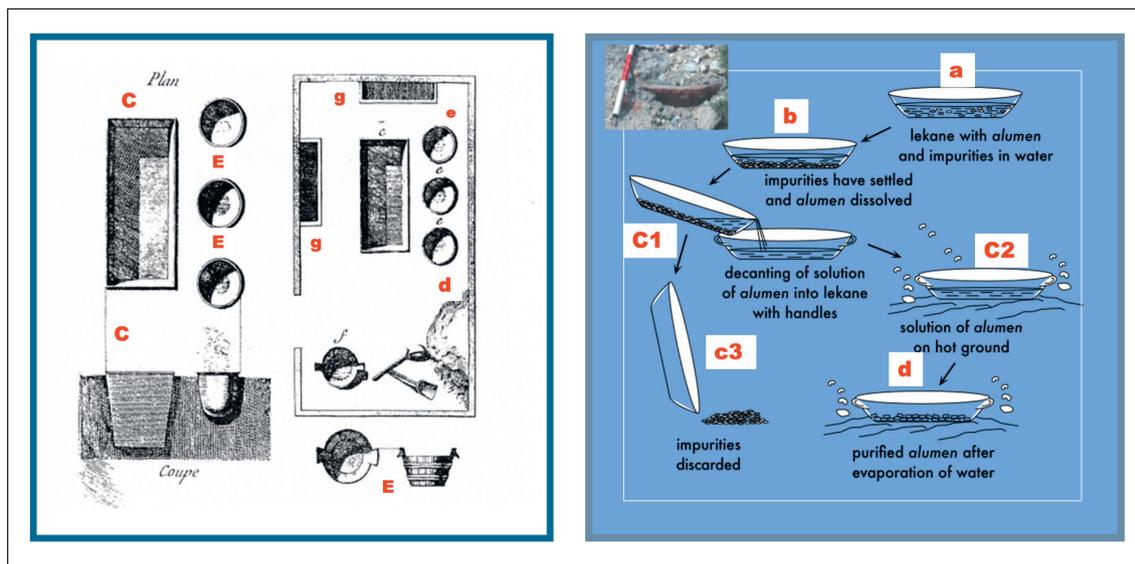


Fig. 3: 3a: Plan of hut at Campi Flegrei, near Naples, after de Fougereux de Bondaroy (18th century)(presented in Singer 1948): a large tank (c), full of water was placed into the hot soils; the alum earth (d) was thrown in it and mixed thoroughly to dissolve the soluble salts. The supernatant liquid from (c) was then removed and deposited into cauldrons (e), which were also embedded in the hot soils. Vats (g) dedicated to other types of minerals, like ammonium chloride, which was also extracted from the same area, at the time – 3b: top left: lekane (shallow wide-open ceramic vessel) likely to have been used in the evaporation of alum salts, embedded within sediments, Aghia Kyriaki, Melos. Main illustration: schematic diagram of the dissolution-evaporation stages within lekane: (a) shows one of these vessels filled with water and salts and embedded in hot soils; (b) non-soluble minerals settle in the bottom while soluble ones are decanted into a new vessel and placed elsewhere on the solfatara; (c) pure alunogen and/or other soluble minerals as well, are collected and packaged.

from the ascending fumarolic vapours, which are separated from the high temperature hydrothermal aquifer.²¹ These steam-heated modified hydrothermal fluids have a considerably lower temperature close to the surface (c. 100°C), which increases to 200°C at a depth of 200 m.²²

The main source of alum on Vulcano's Faraglione area is the Cave of Alum (*Cave di Alume*) (fig. 2b), presently the site of a cavern extensively exploited in the 19th c and overlooking the island's main port. The cavern is not open to the public, but, having acquired permission from the landowner to map its interior we have created a 3D sketchfab model²³ thereof allowing one to 'navigate' its interior. The samples collected from the cavern have a distinct mineralogy consisting entirely of aluminium salts such as alunogen, pickeringite, magnesio-aubertite (a rare mineral which has Vulcano as its type locality) and tamarugite (Table 1). There are currently no active fumaroles within

the cavern, only thick layers of aluminium salts, which make it a unique place to study the environment and mineralogy of this important resource. 19th century documentary records suggest that the products of that mine were processed in ‘workshops’ in its immediate vicinity.²⁴

Experimental Work

For the laboratory-based experiments described in this paper we used one sample, CAVAL 1, deriving from the Cave of Alum, Faraglione, Vulcano (fig. 4a-left). 30 g of CAVAL 1 were placed in a beaker with 100 ml of distilled water. CAVAL 2 (fig. 4b-middle) represents the milky white solute which formed and was allowed to settle and was subsequently filtered, resulting in CAVAL 3a (fig. 4c-right). CAVAL 3b was the coarse-grained residue which was retained by the filter paper. CAVAL 3a was then placed on a hot plate and heated to c. 100°C for 30 minutes. The result was a gelatinous mass (CAVAL 3c, fig. 4d) which was poured out on a plastic boat and allowed to cool.

Further to the above, an additional batch of 30 gr of CAVAL 1 was dissolved in 100 ml of distilled water, resulting in CAVAL 7a, the milky-white solute, and CAVAL 7b, the residue in the beaker. CAVAL 7a3 was the residue retained by the filter paper. CAVAL 7a (milky solute) was then divided in two parts: CAVAL 7a1 was the (re)filtered solute, while CAVAL 7a2 was the unfiltered solute, the same as CAVAL 7a. Both were heated to c. 100°C for 30 minutes. CAVAL 7a2 was removed from the hot plate just before dryness. A gel was formed which upon cooling was poured into another plastic boat. Unlike CAVAL 7a2, CAVAL 7a1 was allowed to evaporate to full dryness, resulting in a gelati-

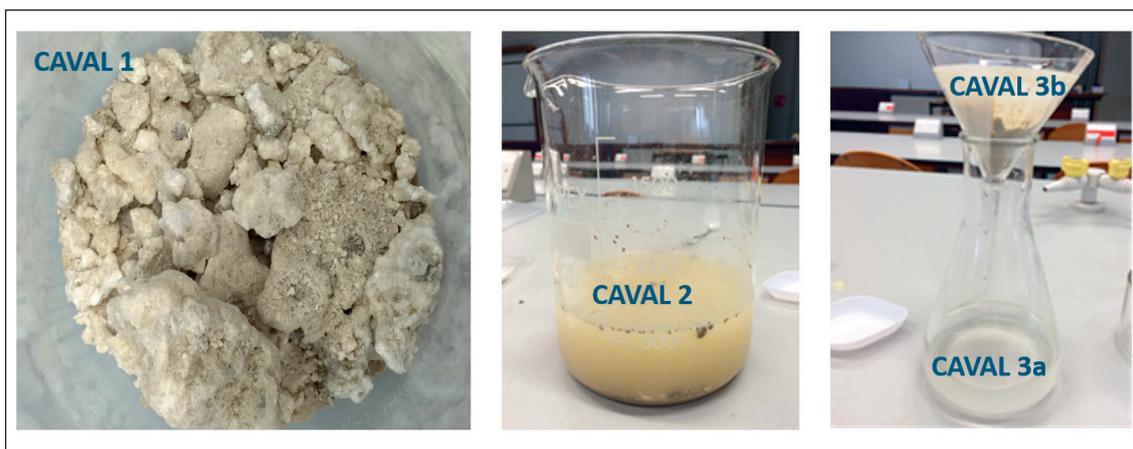


Fig. 4: from left to right: 4a: CAVAL 1, sample of ‘alum’ from Cave of Alum, Faraglione, Vulcano – 4b: CAVAL 2, milky white solute, arising from the dissolution of CAVAL 1 in water – 4c: CAVAL 3a: near-clear solute following filtering: CAVAL 3b: residue retained in the filter paper.

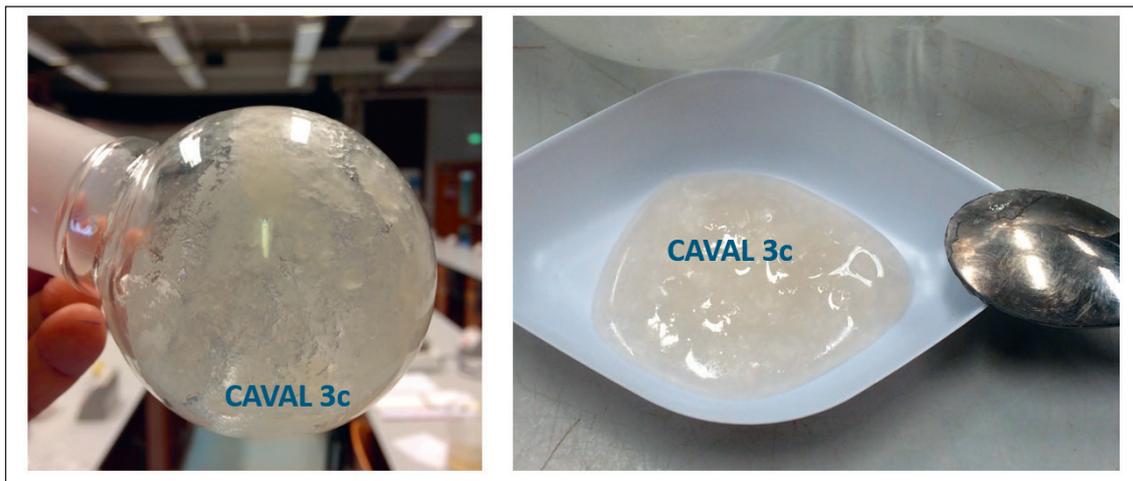


Fig. 4d: CAVAL 3c, a gel-like material, is the product obtained after heating CAVAL 3a at near 100°C, for approximately half an hour; the sample was not allowed to go to complete dryness.

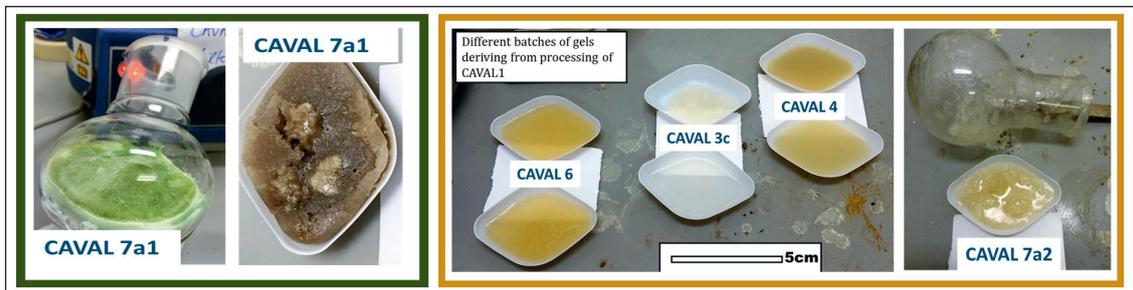


Fig. 5: 5a: green solid mass of CAVAL 7A1 resulting from over heating/heating to dryness. When water was poured in the glass vessel the mixture turned a grey brown, a colour it retained upon cooling – 5b Different batches of processed CAVAL 1 heated but not to dryness resulting in gel-like materials of the compositions shown in Table 2.

nous mass of green colour that adhered to the glass walls (fig. 5a). When 10 ml of water was added to this mass the gel dissolved and the colour of the solution changed from green to dark grey. The colour and gel-like nature of CAVAL 7a2 is shown in fig. 5b together with gels produced from the dissolution-evaporation of other subsamples of CAVAL 1.

X-ray Diffraction Analysis

The mineralogical composition of the Vulcano samples was determined with X-ray diffraction (XRD) at the School of Mineral Resources Engineering, Technical University of Crete, using a Bruker D8 Advance Diffractometer equipped with a Lynx Eye strip silicon detector, and using Ni-filtered CuK α radiation (35 kV, 35 mA). Data were collected in the 2θ range 3–70° 2θ with a step size of 0.02° and counting time of 1 s per strip step (total time 63.6 s per step). The XRD traces were analysed and interpreted with the Diffrac Plus software package from Bruker and the Powder Diffraction File (PDF). The quantitative analysis was performed on random powder samples (side loading mounting) by the Rietveld method using the Autoquan©software package version 2.8.

Results

The results of the XRD analyses are presented in Table 2. A small sub-sample was removed from CAVAL 1 and was analysed by X-ray diffraction (XRD) (fig. 4). The sub-sample contained both hydrous and anhydrous minerals as well as amorphous matter which could exceed 40% (by mass) and some unknown phases constituting 10% (by mass) of the total. The minerals presented here make up the remainder 50% and refer to the crystalline phases. The alum minerals are aluminium sulfates, potassium, sodium or magnesium sulfates or iron aluminium sulfates. There is also the less common magnesium-bearing copper aluminium sulfate (Mg-aubertite).

CAVAL3c and CAVAL7a2, which are enriched subsamples of the original CAVAL 1, are mineralogically different. The latter is rich in alunogen (major) and pickeringite (minor) plus tamarugite (minor), while the reverse is true for CAVAL3c: pickeringite (major) and alunogen and potassium alum (minor). CAVAL3c was filtered before heating but CAVAL7a2 was not; CAVAL3c is characterised by a clear/off-white colour, while CAVAL7a2 has a distinct yellowish tint, suggesting iron-rich phases. However this has not been verified by XRD analysis suggesting levels below the limit of detection.

CAVAL7b and CAVAL7a3 represent residues: the first settled at the bottom of the beaker, the second was retained by the filter paper. In both cases all partly soluble/insoluble minerals (gypsum, anhydrite, natroalunite and jarosite) settled or were retained but some alunogen was 'lost' to the residue.

Unlike CAVAL7a2, CAVAL7a1 was heated to complete dryness, resulting in a bright green-coloured gel attached to the flask wall and which may be associated with the presence of rozenite. To remove it from the flask, water had to be added, in which instance, the gel turned from green to dark grey. It is not clear why there was that colour change.

From the above results we conclude that when different sub-samples of CAVAL 1 underwent enrichment, the resulting product was a gel-like material in all cases. What

<	sample description	Alunogen $Al_2(SO_4)_3 \cdot 17H_2O$	Potassium- alum $KAl(SO_4)_2 \cdot 12H_2O$	Gypsum $CaSO_4 \cdot 2H_2O$	Anhydrite $CaSO_4$	Natrolunite		Tamarugite $NaAl(SO_4)_2 \cdot 6H_2O$	Pickeringite $MgAl_2(SO_4)_4 \cdot 22H_2O$	
						$NaAl_3(SO_4)_3(OH)_6$	$MgSO_4 \cdot 6(H_2O)$		Hexahydrate $MgSO_4 \cdot 6(H_2O)$	Unknown phases
CAVAL 1	original alum' sample	12,5		5,8				14,6		47,3
CAVAL 3C1	filtered solute (3a) after heating at 100C	7,5	4,3							88,2
CAVAL 7A2	unfiltered milky solute = 7a	92,7						1,7		5,6
CAVAL 7A1	filtered milky solute of 7a	14,5	0,7					15,7	17,9	47,4
CAVAL 7A3	insoluble part of CAVAL 1 and similar in composition to 7b	14,5		13,4	2,4	37,4				
CAVAL 7B	insoluble part of CAVAL 1 and similar in composition to 7a3	15,9		56,2		16,4				
CAVAL 1	original alum' sample	Aubertite $CuAl(SO_4)_2Cl \cdot 14H_2O$	Sulphur-a	Jarosite $KFe^{3+}3(OH)_6(SO_4)_2$	Halotrichite $FeAl_2(SO_4)_4 \cdot 22H_2O$	Rozenite $Fe^{2+}SO_4 \cdot 4(H_2O)$	Amorphous			
CAVAL 3C1	filtered solute (3a) after heating at 100C			5,6	9,4	4,8	x			
CAVAL 7A2	unfiltered milky solute = 7a									
CAVAL 7A1	filtered milky solute of 7a			0,8		3				
CAVAL 7A3	insoluble part of CAVAL 1 and similar in composition to 7b		5,5	26,8						
CAVAL 7B	insoluble part of CAVAL 1 and similar in composition to 7a3			11,5						

Table 2: The minerals identified by XRD in the experimental samples. Values in weight percent.

was different was the final colour of the gel, reflecting variation in relative amounts of iron bearing minerals. When traces or indeed larger quantities of iron were present, the resulting gel went from a light yellow (CAVAL 7a2) to deeper yellow-brown as in CAVAL 4 and CAVAL 6 (we have no XRD data for these two samples). We suggest that the colour of gel might have dictated different uses in mordanting i.e. the clear/off white for white cloth, the darker shades for darker cloth.

Pliny alludes to stringent tests (with pomegranate juice) for quality control of commercial alum, implying that even small amounts of iron would be unacceptable to traders and users of alum as a mordant.²⁵ A non-clear/white alum sample, when used as a mordant, would have had an adverse effect on the final colour of the dye particularly for light colours. Separating soluble iron sulfates such as halotrichite from soluble alunogen/potassium alum could not have been straightforward. Nevertheless, Pliny refers to some practice whereby “the part that is collected (from the cavities where it is placed in the winter ...) first is the whiter” pointing to some method of separation involving fractional crystallization.²⁶ Fractional crystallisation, if indeed practiced in antiquity, would have been a very efficient way of dealing with the complex nature of the raw material where even trace amounts of impurities would have had a drastic effect on the quality of the final product, as shown in figs 4 and 5. It is therefore possible that both clear/white alums and ‘tinted’/dark alums were manufactured intentionally. The latter may have been used apart from mordants for darker colours for other industries, like tanning.

Alum Amphorae

It has been claimed that alum travelled in dedicated amphorae: Melos type 1a amphora is thought to have been produced in Melos²⁷; while Richborough 527 was manufactured in Lipari. Neither of them was deemed suitable for foodstuffs.²⁸ The Melian amphora circulated between the end of the first century BC/first century CE until at least the third century CE.

It would be difficult to confirm the above hypotheses. Be that as it may, our experimental simulations have shown that processed alum would have largely travelled as a gelatinous mass in *an* amphora-type container, either exclusively dedicated to it or not. Aluminium sulfates are highly hygroscopic, meaning that they readily attract and hold on to moisture or water molecules from the environment either via absorption or via adsorption. This suggests that if powdered aluminium sulfates, rather than gels of the same, travelled in sealed amphorae over long distance and by sea, on arrival the powdered contents may have agglomerated into a ‘sticky mass’ which would have been difficult to empty. This may have necessitated the breaking of the amphora to recover the contents and perhaps even further treatment of the latter (drying/grinding or other process). By travelling as gels, aluminium sulfates would have travelled safely to their

destinations. Regarding its shelf life, it is expected that the gel would eventually begin to crystallise, with the rate of crystallisation being dependent on levels of moisture and temperature associated with storage. The simple reconstruction experiments described above, combined with XRD analysis of the minerals found within each sub-sample, lead us to the following conclusions:

Conclusions

- In the Greco-Roman period, solfataric alum consisting of a number of soluble and insoluble alum group minerals was perhaps the likely raw material for industries requiring large quantities thereof such as, for example, mordants for textiles or the tanneries. Solfataric alum was relatively easy to extract from fumaroles within caverns, once access into the latter was made possible. Open-air solfataras (outwith caverns), once may have had a temporary cover placed over them so that the deposited salts were not washed away in the first rain.
- The solfataric alum was most likely processed through a dissolution-evaporation cycle for the express purpose of removing insoluble components. This was achieved in an 'eco-friendly' way, namely with the use of the solfataras' hot soils as an energy source. It required no more sophisticated equipment than large ceramic containers embedded into these soils.
- Our simple experimental reconstruction showed that enriched solfataric alum would range from clear/white to tinted yellow to dark brown. A clear or off-white alum batch consisting of minerals like alunogen, potassium alum, or magnesium alum would be appropriate as a mordant of white cloth. Others with a distinct greenish and/or brownish hue consisting of the above but with iron sulfates as well, may have been used for darker colours and/or other industries. Pliny's advice that one should check quality (absence of iron) with some natural reagent, is a reminder of the industry's need for mordants that would not taint the fabric.
- Overheating the enriched alum beyond the evaporation stage appears to have generated new anhydrous phases like hexahydrate, resulting in a significant reduction in the grade of the alum (as per colour) in a mechanism that is not yet clearly understood.
- Finally, it appears that alum transported as a gel in amphorae may have been the best option since it combined a substantially enriched raw material with the reassurance that it would arrive at its destination, unaltered and ready for use. In the archaeological record, how commodities travelled, is normally examined from the perspective of the container and rarely from the perspective of the contents. This brief experimental work shines the light on the latter.

Notes

- ¹ Singer 1948; Borgard et al. 2005.
- ² Firth 2007.
- ³ Levey 1958.
- ⁴ Hdt. 2, 180.
- ⁵ De Materia Medica V.123.
- ⁶ Plin. Nat. Hist. 35, 52.
- ⁷ Photos-Jones et al. 2016.
- ⁸ Plin. Nat. Hist. 35, 52.
- ⁹ Photos-Jones – Hall 2014.
- ¹⁰ Hall et al. 2003a; 2003b; Photos-Jones – Hall 2010.
- ¹¹ Photos-Jones – Hall 2014.
- ¹² Archontidou 2005.
- ¹³ Singer 1948.
- ¹⁴ Singer 1948, 173.
- ¹⁵ Plin. nat. 35, 52.
- ¹⁶ see Cave di Kaolino.
- ¹⁷ Photos-Jones et al. 2018.
- ¹⁸ Harry 2002.
- ¹⁹ Federico et al. 2010; Inguaggiato et al. 2018.
- ²⁰ Garavelli et al. 1997.
- ²¹ Inguaggiato et al. 2018.
- ²² Federico et al. 2010.
- ²³ <<https://sketchfab.com/models/7d9c5bcf95b948ae95091cd36a502d4d>> (last accessed 18th September 2021). We are indebted to Dr Brian Barrett, Geographical and Earth Sciences, Glasgow University, for the preparation of this model, originally presented in Photos-Jones et al. 2017.
- ²⁴ Salvator 1893.
- ²⁵ Plin. nat. 35, 52.
- ²⁶ Hall – Photos-Jones 2009.
- ²⁷ Raptopoulos 2005. <https://archaeologydataservice.ac.uk/archives/view/amphora_ahrb_2005/details.cfm?id=375> (last accessed 18th September 2021).
- ²⁸ Borgard – Cavalier 2003; Borgard 2005.

Image Credits

Fig. 1: after Photos-Jones and Jones 2018, fig. 1 and annotated Google Earth maps, by the authors – Fig. 2: by the authors – Fig. 3a: after Singer 1948, fig. 103.– Fig. 3b: Photos-Jones – Hall 2014, fig. 8.14.– Fig. 4–6: by the authors. – Table 1: adapted and expanded from Photos-Jones et al. 2018. – Table 2: by the authors.

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