Pottery production in salt workshops: petrographic and XRF analyses of pottery from Nueva Esperanza, El Salvador

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ABSTRACT
Crystallized salt can be extracted by boiling brine in pottery over fire. This technique was implemented in many ancient civilizations throughout the world and is used even today. We identified the raw materials and technological aspects of potteries used in salt workshops from the Early Classic period (AD 250–550) of Nueva Esperanza (Pacific coast of El Salvador) by subjecting 19 samples to a petrographic analysis and wavelength-dispersive X-ray fluorescence. Previous research suggests salt pots were local, but decorated pots were transported from inland communities through markets. However, all 19 samples were made from similar main raw materials, indicating that a variety of techniques and processes were used to manufacture different types of potteries in the associated salt workshops. In sum, this study’s approach should enhance understanding of ancient salt workshops, particularly regarding related pottery production systems and the nature of trade.

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1. Introduction
1.1. Research background and goals
Salt is an indispensable component for human life. Thus, humans have been developing and specializing in methods for extracting the substance across Asia, Africa, Europe, and the Americas for thousands of years (e.g. Antonites 2016; Kawashima 2015; McKillop 2019; Weller 2015; Yankowski 2019). This includes the evaporation method, which has remained common globally. More specifically, salt extraction can be accomplished by boiling brine in pottery containers over open fire (e.g. Andrews 1983; Dillon, Pope, and Love 1988; McKillop 2002, 2019; Reina and Monaghan 1981; Williams 2003). In the worldwide salt research context, specialized potteries used to boil brine are commonly known as salt pots, or briquetage, which are generally found in jar or bowl form. These potteries are also friable and of a standardized rim diameter. Archaeological and ethnographic studies from areas across the globe (including Mesoamerica) have shown that many of these salt pots were typically discarded after use, thus accumulating to form mounds over time (Brigand and Weller 2015; McKillop 2019; Parsons 2001; Watson and McKillop 2019; Williams 2003). Various studies have also focused on Mesoamerican salt pots to describe their unique features, including variations in form, size, and surface treatment (e.g. McKillop 2019; Parsons 2001; Williams 2003). Despite many such variations, few archaeologists (McKillop 2019) have used scientific methods or technological interventions to study the raw materials and production technologies used to manufacture salt pots.
Most studies on pottery involving petrographic and/or other archaeometric analyses have focused on highly decorated samples to identify potential imports/exports while elucidating the mechanisms of regional interaction (e.g. Halperin and Bishop 2016; Ting et al. 2015). In this regard, recent studies have shown it is beneficial to target simple utilitarian vessels through joint approaches involving petrographic and archaeometric analysis, thus enhancing understanding of clay outcrops, clay recipes, manufacturing techniques, cultural behaviors, and community practices (e.g. Casale et al. 2020; Donner et al. 2019; Lawrence, Fitzpatrick, and Giovas 2021; Stienaers et al. 2020). However, related focus on ancient salt practices around the world is still lacking, despite salt pots being clearly specialized from a functional standpoint and integrally related to ancient subsistence economies.

A previous petrographic analysis indicated salt pots found in Late Classic site Paynes Creek, Belize, were made in local salt workshops but that other non-salt pots were manufactured in different geological locations and thus obtained through the market system (McKillop 2019, 132). Given the geographical diversity and technological variation associated with salt pottery production, however, it is possible potters working in salt workshops manufactured different types of pottery, including highly decorated potteries. Although many ancient Mesoamerica-related scholarly sources recognize salt’s social, political, economic, and symbolic importance (e.g. McKillop 2008, 2019; Sharer and Traxler 2005; Williams 2003), only limited archaeological research into other regions and periods in Mesoamerican history has been conducted. This study, therefore, aimed to achieve a better understanding of the ancient pottery industry and economy pertaining to Mesoamerican salt workers, which is still under scholarly consideration. We thus conducted petrographic and wavelength-dispersive X-ray fluorescence (WD-XRF) analyses on samples collected from an Early Classic period (AD 250–550) salt workshop in Nueva Esperanza, located on El Salvador’s Pacific coast.

There were two main research goals. The first was to identify the raw materials and technological aspects of potteries used in ancient salt workshops, including both the fine and coarse-ware types, the latter of which were used as salt pots for boiling brine. The second was to examine the pottery production organization and trade based on evidence from salt workshops. As such, this study conducted a petrographic analysis and WD-XRF, both of which are useful for understanding the topics introduced above but have not been broadly applied in academic investigations into ancient salt workshops. Although we found slight differences in the Nueva Esperanza samples, our results also showed high similarity in the main mineral composition of the raw materials in all samples, which suggests that these were extracted from similar geological environments. With access to similar raw material, it thus appears that potters in salt workshops could implement different procedures and techniques. Further, salt makers in Mesoamerica were not only focused on salt production and its contingent activities (McKillop 2019, 115) but may have also manufactured slipped and decorated potteries, which were probably used as serving vessels, offering vessels for burial or ritual activities, or products intended for market. Continued research into different regions of Mesoamerican salt workshops should further clarify issues such as pottery production techniques, social organizations of salt workshops, local economies, and trade practices. Such evidence is highly important for future scholarly debate.

1.2. Site description and geological setting

Nueva Esperanza is located on the eastern side of the Lower Lempa River Delta in El Salvador, which consists of Quaternary sedimentary deposits (Figure 1a and 1b). The Lempa River Delta comprised a mangrove area, lagoon area, Jiquilisco Bay, and the San Juan del Gozo Peninsula. The Berlin-Chinameca volcanic area is situated approximately 20–25 km north of the site. Based on litho-stratigraphic formation classifications (Lexa et al. 2011; Wiesemann 1975), the area consists of the Cuscatlán Formation (Quaternary silicic volcanic rocks) and San Salvador Formation (Quaternary intermediate and mafic volcanic rocks). Additionally, two older formations run along the Upper Lempa River (Figure 1b), including the Balsamo Formation (Upper Mocene/Pliocene intermediate and mafic volcanic rocks) and the Morazán Formation (Oligocene/Miocene silicic volcanic and intrusive rock).

Sites located close to seawater sources are suitable for making salt. Andrews (1983) pioneering research on Mesoamerican salt production reported evidence of pre-Hispanic salt industries in the Lempa River Delta, although he did not conduct any excavations himself. In fact, the current study’s lead author conducted the first systematic excavations targeted at pre-Hispanic salt production in the Lempa River Delta in 2007, 2012, and 2014, thus demonstrating that Nueva Esperanza was a pre-Hispanic salt workshop. It was abruptly abandoned after a massive discharge of the Ilopango volcano known as the Tierra Blanca Joven (TBJ) eruption (situated approximately 55 km west of the site) (Ichikawa 2011, 2015). Stratigraphic location under the TBJ tephra and identifiable ceramic style indicate that Nueva Esperanza dates to AD 250–550, falling into the Early Classic period of the Mesoamerican chronology.
Our archaeological and geomorphological investigations around the Lower Lempa River Delta and Jiquilisco Bay revealed that the present environmental setting was formed after the TBJ eruption. At that time, Nueva Esperanza and surrounding areas were buried by a layer of primary tephra 20–30 cm thick, followed by a secondary tephra deposit 1.5–2 m thick, which may have come from the Lempa River’s successive floods. While we also identified at least four possible pre-Hispanic salt workshops (i.e. Espíritu Santo, Isla Peleada, Tiesterero, and Puerto Parada) on small islands situated within the mangrove ecosystem in the interior of Jiquilisco Bay (evidenced by high concentrations of briquetage), we found no archaeological sites, nor was there any such evidence from the primary tephra layer found on the sandbar enclosing the bay in the south, referred to as the San Juan del Gozo Peninsula (Figure 1a). Notably, the peninsula itself was also formed through sedimentary processes following the TBJ eruption. Given this, the past coastal environmental setting was markedly different from today’s local environment.

The Early Classic period is largely a mystery in the study context due to both a lack of information and the difficulty of dating the TBJ eruption. Further, our archaeological survey showed no highly visible monumental architectures to indicate the existence of regional centers in the Lower Lempa River Delta.
Before the TBJ eruption, however, several regional centers with monumental architectures had already been established in distant areas between the Late/Terminal Preclassic and Early Classic periods, including Chalchuapa, El Cambio, and Quelepa (Figure 1a). Although salt production can be traced to the Preclassic period along the Pacific coasts of both Mexico and Guatemala (Nance 1992), salt workshops were likely developed along El Salvador’s Pacific coast in conjunction with the emergence and development of pre-Hispanic inland centers, which lacked nearby salt resources.

The contextual and artifactual similarities between Nueva Esperanza and other Mesoamerican salt workshops (e.g. Andrews 1983; McKillop 2002, 2019; Nance 1992; Williams 2003) suggest Nueva Esperanza’s inhabitants were producing salt through the labor-intensive process of boiling brine in pots over fire (Ichikawa 2011). Our on-site investigations revealed low, long earthen mounds measuring at least 2 m in height and 70 m in length comprising densely deposited fragments and friable potsherds in association with abundant amounts of charcoal (Ichikawa 2015). As these mounds were situated near the coastal area, it is assumed they resulted from a brine enrichment process involving seawater (Watson and McKillop 2019). Fragmented potsherds accounted for more than 90% of the total ceramic collection found at the site. These artifacts contained attributes that many previous studies have observed among potsherds found at salt workshops in other locations (e.g. Andrews 1983; Dillon, Pope, and Love 1988; McKillop 2019; Nance 1992; Parsons 2001; Williams 2003), including (1) unslipped porous surfaces, (2) evidence of heating from repeated or high-frequency use, (3) interiors that were slightly smoother than the exteriors, and (4) standard rim diameters (an average of 16 cm in Nueva Esperanza). The scarcity of animal bones, marine resources, grinding stones, figurines, and other artifacts also indicate that Nueva Esperanza was a specialized salt-producing locality. However, the remains of seven individuals, including males and females ranging in age from infancy to adulthood, were unearthed in association with offering artifacts (Herrera Reyes, Morita, and Ichikawa 2015; Ichikawa 2015). Although there is currently no clear evidence of residential architecture at Nueva Esperanza (e.g. pit holes or low platforms made from earth or stone), it is still possible that salt makers lived at or nearby the workshop area.

2. Materials and methods

2.1. Materials

In this study, we investigated a total of 19 artifacts recovered from the 2014 field season, all excavated from the section of the earthen mound formed as a result of the brine enrichment process. Well-controlled stratigraphic data are available for these materials (Figure 2). During the stratigraphic excavation process, 3,932 potsherds were recovered, mainly consisting of two distinct paste types classified by visual analysis: coarse-ware (3,627, 92.2%) and fine-ware (296, 7.8%). Of these, we analyzed 16 potsherds (Figure 3; Table 1). All 16 samples were found in layers with high material concentrations (i.e. Layers 23, 30,
and 31; see Figure 2). The sample’s size was constrained by the limited availability of diagnostic sherds within the material assemblage. First, there were a small number of rim sherds, which is the part preferred for petrographic analysis (Quinn 2013, 21). As mentioned, because of their nature, salt pots (i.e. coarse-ware potsherds) are found highly fragmented. Thus, there were 107 coarse-ware-type rim sherds whose form could be classified and rim diameter measured. Second, there were only 61 fine-ware-type rim sherds, and because of small fragments and high erosion, diagnostic features like form and decoration could be identified for only half of these.

Nine coarse-ware types featured attributes common among specialized potteries used to boil brine, as follows. The paste is coarse, has relatively high porosity, and is mainly reddish-brown (2.5 YR 5/4) to pale red (7.5 R 6/3) in color. Grain size is fairly large with abundant mineral inclusions. These nine analyzed samples were selected from different layers with high material concentrations, specifically based on wall shape, including (a) convergent, (b) divergent, and (c) direct. The sample also included seven fine-ware types, which were analyzed to determine whether they were produced using different clay recipes and techniques. Although fine-ware-type paste color tends to be similar to that of the coarse-ware type, it is more compact, meaning smaller grain size and fewer inclusions, and sometimes they have a dark or gray core. Fine-ware types were grouped into three subtypes according to stylistic features: (1) Orange slipped ceramic with Usulután decoration, which is a diagnostic ceramic type broadly distributed across southeastern Mesoamerica (Goralski 2008); if

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**Table 1. Sample descriptions.**

| No. | Material | Ware Type | Vessel Form | Slip | Decoration | Layer |
|-----|----------|-----------|-------------|------|------------|-------|
| 1   | Potsherd | Coarse    | Type B      | -    | -          | 22 (7.5 YR 3/1) |
| 2   | Potsherd | Coarse    | Type A      | -    | -          | 22 (7.5 YR 3/1) |
| 3   | Potsherd | Coarse    | Type C      | -    | -          | 22 (7.5 YR 3/1) |
| 4   | Potsherd | Fine      | Jar         | Black-brown | -          | 22 (7.5 YR 3/1) |
| 5   | Potsherd | Fine      | Bowl        | Orange on cream | Usulután and red paint | 22 (7.5 YR 3/1) |
| 6   | Potsherd | Fine      | Bowl        | Orange on cream | Groove | 22 (7.5 YR 3/1) |
| 7   | Potsherd | Coarse    | Type A      | -    | -          | 30 (10 YR 3/2) |
| 8   | Potsherd | Coarse    | Type B      | -    | -          | 30 (10 YR 3/2) |
| 9   | Potsherd | Coarse    | Type C      | -    | -          | 30 (10 YR 3/2) |
| 10  | Potsherd | Fine      | Bowl        | Orange | Usulután | 30 (10 YR 3/2) |
| 11  | Potsherd | Fine      | Bowl        | Orange | - | 30 (10 YR 3/2) |
| 12  | Potsherd | Coarse    | Type A      | -    | -          | 31 (10 YR 2/3) |
| 13  | Potsherd | Coarse    | Type B      | -    | -          | 31 (10 YR 2/3) |
| 14  | Potsherd | Coarse    | Type C      | -    | -          | 31 (10 YR 2/3) |
| 15  | Potsherd | Fine      | Bowl        | Orange on cream | Usulután | 31 (10 YR 2/3) |
| 16  | Potsherd | Fine      | Bowl        | Red | - | 31 (10 YR 2/3) |
| 17  | ACL      | -         | -           | -    | -          | 22 (7.5 YR 3/1) |
| 18  | ACL      | -         | -           | -    | -          | 30 (10 YR 3/2) |
| 19  | ACL      | -         | -           | -    | -          | 31 (10 YR 2/3) |

*Type A is convergent body, Type B is divergent body, Type C is direct body. 
*ACL is amorphous clay lumps.
imported potteries were, in fact, included in the ceramic assemblages, this Usulután ceramic would be a candidate. (2) Orange- or red-slipped ceramic but without Usulután decorations: artifacts of this type feature similar characteristics except for the absence of Usulután decorations and were probably used as serving vessels. (3) Black-brown ceramic: this is the only type with the jar form in ceramic collections and was probably used as storage or cooking vessels. The surface is very smooth, slipped slightly, and dark brown in color (10YR 3/2).

The three amorphous clay lumps (ACLs) were included for comparative purposes. It is often assumed that ACLs are broken parts of cylinders, sockets, spacers, bases, or other salt-making debris that cannot be typed (Sills and McKillop 2018, 465). As there is no clear evidence of cylinders, sockets, or spacers at Nueva Esperanza, the investigated ACLs may be remains of clay stoves or kilns. In total, 128 ACLs were recovered during the 2014 field season, found in layers with high material concentrations. Their color is mainly light red (7.5R 6/8) with fewer identifiable white inclusions than the potsherds.

2.2. Methods

This study implemented two approaches to identify the raw materials and technological differences/similarities between the different salt workshop pottery types. First, we conducted a petrographic analysis of thin sections using a Meiji Techno ML-9000. Subsequent observations were made through a polarizing microscope after cutting the specimens parallel to their vertical axes, impregnating them with epoxy resin, and mounting each on a glass slide using petroxy 154. Each section was finished by hand until a thickness of 30 µm was reached. Grains were counted via the point-counting method, setting grids measuring 0.1 mm per unit for the eyepiece, and counting grains over 30 µm diameter until 300 grains were reached under ×100 magnification (Middleton, Freestone, and Leese 1985). Subsequently, each fabric group was described in detail based on a descriptive method adapted from Whitbread (1995) and Quinn (2013).

Second, the samples’ chemical compositions were investigated via WD-XRF using a tabletop Rigaku ZSX-100e. After removing their surface layers, each sample was powdered in a stainless-steel mill and agate mortar. In preparation for the analysis, fusion beads were duplicated using 0.402 g of powdered specimen in a fusion with 4.0 g lithium tetraborate at 1/10 dilution. The values of major and minor elements (SiO₂, TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, CaO, Na₂O, K₂O, P₂O₅) and trace elements (Ba, Cr, Nb, Ni, Rb, Sr, V, Y, Zn, Zr, Cu) were calculated using the fundamental parameter method in the ZSX software. Major and minor oxide concentrations were indicated as percentages, while those of other trace elements were presented as parts-per-million (ppm). All resulting WD-XRF data were analyzed through principal component analysis (PCA) using MATLAB. Static analyses were conducted using base-10 logarithm concentrations while compensating for magnitude differences, thus enabling the identification of distinct groups for each sample. It should be noted that Y was excluded from the PCA because it was detected at extremely low concentrations, and P₂O₅ was omitted because it can be highly influenced by the post-depositional process (Freestone, Meeks, and Middleton 1985).

3. Results

3.1. Petrographic analysis

All 19 samples were divided into four main compositional groups (Nueva Esperanza A, B, C, and D). Group Nueva Esperanza C was subdivided into C-1 and C-2 to differentiate inclusions of volcanic tuff and glass. All samples contained high quantities of quartz, plagioclase, and K-feldspar, indicating they were largely composed of volcanic rocks (Figure 4; Tables 2 and 3). Hypabyssal rock and volcanic tuff and glass were also included in the matrix, thus indicating the geological influence of several rock types in all Nueva Esperanza samples. Interpretation of the observed inclusion size within the matrix suggests that no samples contained an intentional inclusion of particular raw materials. However, the fine-ware samples, particularly the slipped samples, contained many more fine particles than coarse-ware samples. These differences may have resulted from technological controls, such as those implemented during raw material selection and preparation involving crushing, grinding, sieving, and kneading.

3.1.1. Nueva Esperanza A

This fine-ware-type group (sample Nos. 5, 6, 11, and 15) is characterized by a large quantity of volcanic rock and less hypabyssal rock. Grain size is 0.15–0.8 mm, with poorly sorted inclusion distribution. Plagioclase is the main mineralogical component; quartz, K-feldspar, and pyroxene are also observed. The clay matrix is orange-brown to dark reddish-brown, optically inactive, and vitrified or weakly vitrified.

3.1.2. Nueva Esperanza B

This fine-ware-type group (sample Nos. 4, 10, and 16) is characterized by higher quantities of hypabyssal rock and volcanic tuff and glass than the other groups. Grain size is 0.15–0.60 mm, and inclusion distribution is poorly or moderately sorted. As in Group Nueva Esperanza A, this group is composed largely of
Nueva Esperanza A (Sample No.6 fine-ware type with Usulutan decoration)

Nueva Esperanza B (Sample No.10 fine-ware type with Usulutan decoration)

Nueva Esperanza C-1 (Sample No.1 coarse-ware type)

Nueva Esperanza C-2 (Sample No.3 coarse-ware type)

Nueva Esperanza D (Sample No.18 Amorphous clay lump)

Figure 4. Thin-section photomicrographs of samples from Nueva Esperanza taken via plane-polarized light (PPL) and cross-polarized light (XP) qz: quartz; pl: plagioclase; ho: amphibole; opx: orthopyroxene; cpx: clinopyroxene; tu: tuff; vo: volcanic rock; hyp: hypabyssal rock.
plagioclase, but volcanic tuff and glass and hypabyssal rock are more frequent than in Group Nueva Esperanza A, and samples also contain quartz, K-feldspar, and pyroxene. The clay matrix is dark reddish-brown, optically inactive, and vitrified or weakly vitrified.

3.1.3. Nueva Esperanza C-1
Plagioclase, quartz, K-feldspar, and hypabyssal rock are the most common inclusions. Samples (Nos. 1, 2, 7, 12, and 13) corresponding to this group are coarse-ware types. Grain size is mainly 0.15–0.7 mm, with several measuring 0.9–1.2 mm, and inclusion distribution is moderately sorted. The voids are composed mainly of macro-elongate vughs and meso-planar voids, which are larger than in other samples. The clay matrix is orange-brown to dark reddish-brown; it is optically active and weakly inactive. There are no signs of vitrification.

3.1.4. Nueva Esperanza C-2
The main mineralogical characteristics are similar to C-1 but distinguished by inclusions, although in small quantities, of volcanic tuff and glass. All samples (Nos. 3, 8, 9, and 14) are coarse-ware types. Grain size is 0.2–0.8 mm, with a few grains measuring 0.9–1.2 mm. While the volcanic glass grain size is under 0.2 mm, that of volcanic tuff is 0.2–1.1 mm. Inclusion distribution is moderately sorted. The clay matrix is orange-brown to dark reddish-brown, optically active, and weakly inactive. There are weak signs of vitrification.

3.1.5. Nueva Esperanza D
This group is characterized by volcanic rock, particularly a higher quantity of K-feldspar, hypabyssal rock, and less inclusion of volcanic tuff and glass than the other groups. Only ACLs (Nos. 17, 18, and 19) belong to this group. The grain size is 0.15–0.5 mm. Inclusion distribution is poorly sorted. The clay matrix is orange-brown to dark reddish-brown and optically active. There is no sign of vitrification.

3.1.6. WD-XRF analysis
Tables 4 and 5 show WD-XRF analysis results. As shown in Figure 5, PCA analysis results were roughly consistent with those from the petrographic analysis. PC1 (50%) indicates three broad clusters among the investigated samples; The first is Group 1 (plotted from −0.6 to −0.4 in Figure 5), which consists of fine-ware potsherds (Nos. 5, 6, 11, and 15) featuring high levels of Cu and V; of these, three (5, 6, and 15) feature orange slip with Usulután decorations. Group 2 (plotted around 0 ± 0.2 in Figure 6) consists of all coarse-ware potsherds and two fine-ware potsherds (Nos. 4 and 10), all of which contain higher amounts of hypabyssal rock than those in the other groups. Further, samples in this group contained slightly higher levels of both MgO and MnO. Group 3 (plotted from 0.4–0.6 in Figure 6) consists of all ACLs (Nos. 17–19) and one red-slipped potsherd (No. 16), which feature orange slip with Usulután decorations. Group 2 (plotted around 0 ± 0.2 in Figure 6) consists of all coarse-ware potsherds and two fine-ware potsherds (Nos. 4 and 10), all of which contain higher amounts of hypabyssal rock than those in the other groups. Further, samples in this group contained slightly higher levels of both MgO and MnO. Group 3 (plotted from 0.4–0.6 in Figure 6) consists of all ACLs (Nos. 17–19) and one red-slipped potsherd (No. 16), which feature high amounts of K$_2$O that clearly distinguish them from those in other groups.

As the main compositional elements in soil, the ratios of SiO$_2$ and Al$_2$O$_3$ suggest that the artifacts were manufactured with a mixture of clay bodies and other inclusions. Group 1 was characterized by lower amounts of SiO$_2$ and higher amounts of Al$_2$O$_3$, meaning the bodies contained greater amounts of clay than those in other groups (Figure 6: right). However, Groups 2 and 3 had higher amounts of SiO$_2$ and lower amounts of Al$_2$O$_3$, indicating a greater amount of inclusions and less clay. Group 3 was also characterized by high quantities of K$_2$O, indicating the raw materials used to make those artifacts

### Table 2. Mineral composition proportions revealed via petrographic analysis.

| No. | qz | pl | K-fel | bt | lm | mv | hb | opx | cpx | ol | cm | vg/tu | vo | plu | hyp |
|-----|----|----|-------|----|----|----|----|-----|-----|----|----|-------|----|-----|-----|
| 1   | 35 | 145| 5     | 0  | 19 | 0  | 1  | 3   | 1   | 3  | 9  | 8     | 31 | 2   | 0   |
| 2   | 43 | 134| 19    | 0  | 14 | 0  | 0  | 3   | 1   | 9  | 10 | 23    | 1  | 43  |
| 3   | 35 | 109| 39    | 3  | 13 | 0  | 0  | 0   | 0   | 4  | 10 | 43    | 0  | 44  |
| 4   | 47 | 97 | 23    | 1  | 11 | 0  | 1  | 3   | 2   | 5  | 45 | 33    | 0  | 32  |
| 5   | 18 | 164| 24    | 0  | 14 | 0  | 3  | 5   | 9   | 0  | 25 | 33    | 0  | 3   |
| 6   | 33 | 123| 20    | 0  | 58 | 0  | 5  | 5   | 5   | 1  | 37 | 11    | 0  | 6   |
| 7   | 52 | 109| 50    | 1  | 5  | 0  | 1  | 1   | 3   | 0  | 23 | 16    | 0  | 37  |
| 8   | 42 | 111| 37    | 1  | 7  | 0  | 0  | 1   | 1   | 0  | 27 | 22    | 2  | 49  |
| 9   | 54 | 105| 38    | 0  | 9  | 0  | 0  | 1   | 0   | 0  | 0  | 2     | 18 | 43  |
| 10  | 31 | 88 | 71    | 0  | 19 | 0  | 0  | 1   | 0   | 0  | 6   | 39    | 17 | 0   |
| 11  | 15 | 145| 23    | 0  | 9  | 0  | 0  | 12  | 4   | 0  | 6   | 13    | 70 | 0   |
| 12  | 20 | 133| 35    | 0  | 5  | 0  | 1  | 5   | 6   | 0  | 2   | 10    | 35 | 2   |
| 13  | 23 | 132| 38    | 0  | 4  | 0  | 1  | 1   | 1   | 0  | 5   | 30    | 0  | 66  |
| 14  | 34 | 123| 40    | 0  | 7  | 0  | 3  | 3   | 2   | 0  | 2   | 10    | 9  | 2   |
| 15  | 20 | 152| 44    | 0  | 8  | 0  | 0  | 1   | 2   | 0  | 2   | 23    | 47 | 1   |
| 16  | 51 | 113| 42    | 2  | 10 | 0  | 1  | 1   | 6   | 0  | 5   | 15    | 18 | 1   |
| 17  | 67 | 64 | 106   | 2  | 19 | 0  | 1  | 0   | 4   | 0  | 33  | 2     | 1   | 0   |
| 18  | 42 | 95 | 79    | 1  | 23 | 1  | 1  | 1   | 0   | 0  | 36  | 3     | 10  | 0   |
| 19  | 59 | 97 | 81    | 4  | 16 | 0  | 0  | 1   | 0   | 0  | 25  | 5     | 9   | 0   |

Notes: qz: quartz; pl: plagioclase; K-fel: K-feldspar; bt: biotite; lm: limonite; mv: muscovite; hb: hornblende; opx: orthopyroxene; cpx: clinopyroxene; ol: olivine; cm: colored minerals; vg/tu: volcanic glass/tuff; vo: volcanic rock; plu: plutonic rock; hyp: hypabyssal rock
Table 3. Petrographic analysis summary.

| Group                  | Nueva Esperanza A                                         | Nueva Esperanza B                                           | Nueva Esperanza C-1                                        | Nueva Esperanza C-2                                        | Nueva Esperanza D                                        |
|------------------------|-----------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|
| Samples Matrix         | Nos. 5, 6, 11, 15 mm Orange-brown to dark reddish-brown, optically inactive, vitrified or weakly vitrified. | Nos. 4, 10, 16 mm Orange-brown to dark reddish-brown, optically inactive, vitrified or weakly vitrified. | Nos. 1, 2, 7, 12, 13 Orange-brown to dark reddish-brown, optically active, weakly inactive. | Nos. 3, 8, 9, 14 Orange-brown to dark reddish-brown, optically active, weakly inactive, weakly vitrified. | Nos. 17, 18, 19 Orange-brown to dark reddish-brown, optically active. |
| Void                   | 3–5%, consisting mainly of meso-elongate vugs and meso-planar voids. Moderate alignment of voids to margins of section. No. 11, consisting mainly of macro-elongate vugs and channels and macro-planar voids. Weak alignment of voids to margins of section. | 3–5%, consisting mainly of meso-elongate voids. Moderate alignment of voids to margins of section. No. 4, consisting mainly of meso-planar voids. Weak alignment of voids to margins of section. | 5–15%, consisting mainly of macro-elongate vugs voids and meso-planar voids. Moderate alignment of voids to margins of section. No. 12, 35%, consisting mainly of macro-elongate vugs and channels. Moderate alignment of voids to margins of section. | 7–10%, consisting mainly of macro-elongate vugs voids and meso-planar voids. Moderate alignment of voids to margins of section. No. 14, 5%, consisting mainly of meso-vugs, channels and meso-planar voids. Moderate alignment of voids to margins of section. | 3%, consisting mainly of meso-vugs. No alignment of voids to margins of section. |
| General inclusion size | Significantly variation, poorly sorted (No. 5 is weakly sorted), 0.15–0.8 mm, few 0.8–1.1 mm. No. 11, bimodal, 0.1–0.65 mm, few 0.7–1.1 mm | Poorly or moderately sorted, 0.15–0.6 mm, few 0.8–1.0 mm | Moderately sorted (No. 13, poorly sorted), 0.15–0.7 mm, few 0.9–1.2 mm | Moderately sorted, 0.2–0.8 mm, few 0.9–1.2 mm | Poorly sorted, 0.15–0.5 mm |
| Hypabyssal rock fragments | Rare weathered rock, sub-angular or sub-around (0.2–0.7 mm) | Dominant weathered rock sub-angular or sub-around rock (0.1–0.4 mm) | Dominant weathered plutonic rock, sub-angular or sub-around rock (0.3–0.75 mm) | Dominant weathered rock, sub-angular or sub-around rock (0.3–0.8 mm), few 0.9–1.2 mm | Frequent weathered rock, sub-angular or sub-around rock, 0.2–0.4 mm |
| Volcanic rock          | Dominant, sub-angular or sub-around rock (0.1–0.75 mm, some 0.7–1.1 mm), basalt and andesite. | Dominant, sub-angular or sub-around rock (0.15–0.65 mm), basalt and andesite. | Dominant, sub-angular or sub-around rock (0.25–1.1 mm), basalt and andesite. | Dominant, sub-angular or sub-around rock (0.25–1.1 mm), basalt and andesite. | Rare, sub-angular or sub-around rock (0.1–0.3 mm), basalt and andesite. |
| Tuff                   | n/a Frequent tuff (0.2–0.8 mm) and volcanic grass (0.1–0.2 mm) | n/a Frequent tuff (0.2–1.1 mm) and volcanic grass (0.1–0.2 mm) | n/a Frequent tuff (0.2–1.1 mm) and volcanic grass (0.1–0.2 mm) | n/a Frequent tuff (0.2–1.1 mm) and volcanic grass (0.1–0.3 mm) | n/a Frequent tuff (0.2–1.1 mm) and volcanic grass (0.1–0.3 mm) |
| Plagioclase            | Frequent plagioclase, angular and sub-angular, 0.1–0.6 mm, several 1.1 mm | Frequent plagioclase, angular and sub-angular, 0.1–0.5 mm | Frequent plagioclase, angular, and vugs to angular, 0.2–0.7 mm | Frequent plagioclase, angular, and sub-angular, 0.25–0.85 mm | Frequent plagioclase, angular, and sub-angular, 0.15–0.5 mm |
| Quartz                 | Angular and sub-angular, 0.1–0.6 mm | Angular and sub-angular, 0.1–0.45 mm, few >1.0 mm | Angular and sub-angular, 0.2–0.85 mm | Angular and sub-angular, 0.2–0.8 mm | Angular and sub-angular, 0.1–0.5 mm |
| K-feldspar             | Rare K-feldspar, sub-angular, 0.1–0.8 mm | Rare K-feldspar, sub-angular, 0.1–0.7 mm | Rare K-feldspar, sub-angular, 0.2–0.8 mm, few 1.0–1.1 mm | Rare K-feldspar, sub-angular, 0.2–0.7 mm | Common K-feldspar, sub-angular, sub-around, 0.1–0.25 mm |
| Pyroxene               | Orthopyroxene (0.1–0.45 mm) and clinopyroxene (0.1–0.6 mm) | Orthopyroxene (0.1–0.7 mm), No. 16, rare orthopyroxene (<0.2 mm) | Orthopyroxene (0.1–0.45 mm) and clinopyroxene (0.1–0.4 mm) | Orthopyroxene (0.1–0.45 mm) and clinopyroxene (0.2–0.3 mm) | Rare orthopyroxene (0.1–0.4 mm) and clinopyroxene (0.1–0.2 mm) |
| Mica                   | No. 6, rare biotite, <0.5 mm | Rare biotite, <0.4 mm | Rare biotite, <0.5 mm | Rare biotite, <0.3 mm | Rare biotite, <0.3 mm |
| Amphibole              | No. 5, rare hornblende, 0.15 mm | Rare hornblende, 0.1–0.4 mm | Rare hornblende, 0.1–0.3 mm | Rare hornblende, 0.1–0.3 mm | No. 18, rare biotite, <0.2 mm |

contained greater amounts of quartz and K-feldspar than those in the other groups (Figure 6: left).

4. Discussion

In this study, we conducted petrographic and WD-XRF analyses to identify the characteristics of the raw materials and technological aspects of the examined potteries, focusing on elucidating the pottery production organization and trade practice based on evidence from the Early Classic salt workshop at Nueva Esperanza, El Salvador.

The high similarity of mineral composition among samples seen in the petrographic analysis is important. Although it is still difficult to identify specific outcrop locations, this similarity suggests that the raw pottery materials in this study were extracted from similar geological environments, presumably near the salt workshop. While a previous study indicated salt workers imported non-salt pots from inland sites through an exchange network (McKillop 2019, 132), the data produced in this study suggest potters manufactured different types of potteries in the salt workshops using similar local materials rather
than importing items from distant areas. Identifying specific outcrop locations is problematic because of the site’s location in the Quaternary sediment deposit. The Lempa River, El Salvador’s largest river, passes through different geological areas, meaning different sediment types flow downstream and are deposited in the Lower Lempa River Delta. Nevertheless, as evident from the geological map of the study area (Figure 1b), basalt, andesite, and feldspar (the samples’ main mineralogical components) were available from nearby locations. Hypabyssal and plutonic rock such as biotite and granite may have also been contained in the soil. Archaeological and ethnographical data suggest the Nueva Esperanza ACLs are assumed to be remains of clay stoves or kilns (Parsons 2001; Reina and Monaghan 1981; Williams 2003). Further, previous studies indicate the clay sources used to obtain materials for these facilities were generally located close to the workshops; that is, the ACLs raw material could be from areas close to the site. Further, the area’s geological formation is complex; the ACLs’ high amount of feldspar may come from local geological variation. Although this high level could be due to technological processes, such as crushing, sieving, grinding, kneading, or firing, such processes are unlikely in this case because K-feldspar is not susceptible to weathering and the small inclusion size would make it difficult to intentionally remove or add K-feldspar. Further, if the K-feldspar were included deliberately, there would likely be clearer differences in K-feldspar amounts among the samples. As the K-feldspar is found in certain quantities in all samples, it is most likely that the composition is naturally present. Additional support for this possibility comes from previous ethnographic and archaeological studies, which show salt pots were manufactured from raw materials extracted from nearby local sites (e.g. McKillop 2019, 132; Parsons 2001, 257; Yankowski 2019, 145). Generally, salt pots were discarded after boiling the brine and extracting the crystalized salt, resulting in accumulations that eventually created the aforementioned earthen mounds (McKillop 2019; Williams 2003). Given both the nature of use and large recovered

| No. | Na₂O | MgO | Al₂O₃ | SiO₂ | P₂O₅ | K₂O | CaO | TiO₂ | MnO | Fe₂O₃ |
|-----|------|-----|-------|------|------|-----|-----|------|-----|------|
| 1   | 2.7  | 2.3 | 18.2  | 59.6 | 0.2  | 1.3 | 2.9 | 1.0  | 0.3 | 11.1 |
| 2   | 2.6  | 1.9 | 18.3  | 60.0 | 0.3  | 1.4 | 2.8 | 1.0  | 0.3 | 11.2 |
| 3   | 2.4  | 2.2 | 19.1  | 59.8 | 0.4  | 1.6 | 2.6 | 1.0  | 0.3 | 10.0 |
| 4   | 2.4  | 2.1 | 19.3  | 58.7 | 0.3  | 1.8 | 2.6 | 1.1  | 0.3 | 11.4 |
| 5   | 1.9  | 2.3 | 23.2  | 51.2 | 0.3  | 0.7 | 4.0 | 0.7  | 0.3 | 14.0 |
| 6   | 1.9  | 1.4 | 25.9  | 49.2 | 0.5  | 1.0 | 2.1 | 1.4  | 0.2 | 16.1 |
| 7   | 3.1  | 4.6 | 15.8  | 61.0 | 0.2  | 1.8 | 3.0 | 0.9  | 0.2 | 9.9  |
| 8   | 2.4  | 3.7 | 18.0  | 59.4 | 0.1  | 1.9 | 2.8 | 0.9  | 0.2 | 10.2 |
| 9   | 2.6  | 1.8 | 18.7  | 60.2 | 0.1  | 1.7 | 2.9 | 1.1  | 0.2 | 10.5 |
| 10  | 2.3  | 3.3 | 23.7  | 49.1 | 0.2  | 0.8 | 4.2 | 1.2  | 0.3 | 14.5 |
| 11  | 3.0  | 3.5 | 18.2  | 58.0 | 0.1  | 1.5 | 2.6 | 1.0  | 0.4 | 11.5 |
| 12  | 3.3  | 3.1 | 18.1  | 59.8 | 0.1  | 1.3 | 3.0 | 1.0  | 0.4 | 9.6  |
| 13  | 3.0  | 3.6 | 17.7  | 59.0 | 0.1  | 1.6 | 2.8 | 0.9  | 0.3 | 10.8 |
| 14  | 1.8  | 2.6 | 24.2  | 49.3 | 0.1  | 0.6 | 4.1 | 1.3  | 0.2 | 15.5 |
| 15  | 2.4  | 2.2 | 18.9  | 60.6 | 0.1  | 1.8 | 2.2 | 1.0  | 0.2 | 10.3 |
| 16  | 3.3  | 2.7 | 17.1  | 62.6 | 0.2  | 2.5 | 2.6 | 0.8  | 0.2 | 7.7  |
| 17  | 2.8  | 2.1 | 18.1  | 62.4 | 0.1  | 2.1 | 2.3 | 1.0  | 0.2 | 8.6  |
| 18  | 3.3  | 2.6 | 17.9  | 61.2 | 0.1  | 2.1 | 2.5 | 0.9  | 0.1 | 8.8  |

Table 4. Major and minor elements found in Nueva Esperanza samples based on WD-XRF (wt.%).

Table 5. Trace elements found in Nueva Esperanza samples based on WD-XRF (ppm).
quantities, coarse-ware type (i.e. salt pots) must have been manufactured locally.

Although the investigated samples were made from similar raw materials, there were some obvious technological differences based on manufacturing process-related evidence. Importantly, this study elucidated the technological features of the coarse-ware type, which have been overlooked by many ancient ceramic studies (Rice 2009, 137). The petrographic data suggest the clay used for the coarse-ware type was less refined when compared to the materials used for the fine-ware type and was also fired at lower temperatures for shorter periods. This resulted in a friable and porous coarse-ware type. Thin vessels with non-porous compositions are considered ideal for boiling brine, as they feature similar properties to efficient cooking pots (Kawashima 2015; Weller 2015, 72; Yankowski 2019, 135). Although further research is needed to formally make the claim, various differences in recovered salt pots’ quality suggest different degrees of specialization and/or varied labor organizations in the salt workshops. During the Classic period, salt production was managed at the household level, where contingent multicrafting activities related to salt production were also conducted, including pottery making, facility and canoe construction, and firewood chopping to create fuel for boiling brine in pots (McKillop 2019, 115–132). Given this wide variety of tasks, salt pots may have strictly been made to fulfill the minimum required functions.

The analyzed fine-ware potteries provide interesting data about the manufacturing processes and organization in the salt workshops. PCA indicated that fine-ware potteries petrographically categorized as Nueva Esperanza A (Nos. 5, 6, 11, and 15) were manufactured using slightly different raw materials than other pottery samples and the ACLs. Interestingly, the PCA results also showed that Nueva Esperanza B fine-ware potsherds (Nos. 4, 10, and 16) overlapped with the Nueva Esperanza C (coarse-ware) and D (ACLs) samples that contained raw materials that could be extracted near the workshop. Although this sample is small and the possibility that items were imported from other regions cannot be discarded, the significant overlap supports the idea that three fine-ware potteries (including those with Usulután decorations) were manufactured from local raw materials similar to those for the coarse-ware potteries and ACLs but using different production techniques and processes. WD-XRF analysis showed that, although from a different period, Late/Terminal Preclassic Usulután style vessels from Chalchuapa are clearly different from the Nueva Esperanza samples (Supplemental data 1), indicating fine-ware potteries in Nueva Esperanza did not come from western El Salvador’s most influential center. Further, although an entirely different geographical area, research has shown salt workshops from Albuquerque in the Philippines were used to manufacture 15 different types of pots (Yankowski 2019, 145). In this regard, it is possible potteries from the Nueva Esperanza salt workshops used a variety of techniques and processes to create different types of pots from similar main materials while still devoting substantial amounts of time to other
contingent activities related to the salt-making process.

5. Conclusions

This study identified the characteristics of raw materials and technologies used to manufacture salt pots and other potteries in salt workshops, focusing on pottery production systems and the nature of trade. One potential limitation, however, is that these preliminary findings are based on a small sample of artifacts from a single site. Additional research is needed to verify broader regional variations in clay sources as well as technological differences between ancient Mesoamerican salt makers. Nevertheless, this exploratory study of Nueva Esperanza produced insightful information concerning Mesoamerican salt workshops. Specifically, our petrographic and WD-XRF analyses resulted in important data pertaining to pottery production in the above context, including raw material selection, production techniques, workshop organization, and trade practices, which were not fully clarified in previous related studies.

Salt is an archaeologically invisible material. However, as a critical commodity, it played important roles in the rise and fall of many ancient societies (McKillop 2019; Salie 2015; Vogel 2010; Williams 2003). Thus, salt pots have been archaeologically and ethnographically recognized globally. Nevertheless, few studies have subjected these types of artifacts to extensive analyses (Yankowski 2008), nor have many previous researchers made comparisons beyond the slipped and decorated pottery types, which are usually the target for detailed analysis. As McKillop previously highlighted (2019, 139–143), different processes were likely used to create salt-making potteries in the household, workshop, and at the regional level. In sum, this exploratory study showed petrographic and WD-XRF analyses on potteries from salt workshops. Specifi- cally, our petrographic and WD-XRF analyses resulted in important data pertaining to pottery production in the above context, including raw material selection, production techniques, workshop organization, and trade practices, which were not fully clarified in previous related studies.

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Disclosure statement

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Data availability statement

Excavated materials are available from the Dirección de Arqueología, Dirección Nacional del Patrimonio Cultural, Ministerio de Cultura, El Salvador. All digital and analysis data were generated by the authors and are available for research purposes by contacting the corresponding author.

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References

Andrews, Anthony P. 1983. Maya Salt Production and Trade. Tucson: The University of Arizona Press.

Antonites, Alexander. 2016. “The Organization of Salt Production in Early First Millennium CE South Africa.” Journal of Anthropological Archaeology 44: 31–42. doi:10.1016/j.jaa.2016.08.001.

Brigand, Robin, and Olivier Weller. 2015. The Archaeology of Salt, Approaching an Invisible Past. Leiden: Sidestone Press.

Casale, Simone, Natalia Donner, Dennis Braekmans, and Alexander Geurds. 2020. “Geochemical and Petrographic Assessment of Clay Outcrops and Archaeological Ceramics from the Pre-Hispanic Site of Aguas Buenas (cal 400–1250 CE), Central Nicaragua.” Microchemical Journal 156: 104829. doi:10.1016/j.microc.2020.104829.

Dillon, Brian, Kevin Pope, and Michael Love. 1988. “An Ancient Extractive Industry: Maya Saltmaking at Salinas de las Nueve Cerros, Guatemala.” Journal of New World Archaeology 7 (2/3): 37–107.
