Inferring provenance, manufacturing technique, and firing temperatures of the Monagrillo ware (3520–1300 cal BC), Panama's first pottery

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Abstract - Monagrillo (3520–1300 cal BC) is Panama's oldest pottery. Archaeologists assumed it was a low-fired expedient ware made with any available clay. We studied 1) clay sources (thin sections; DTA; shrinkage, porosity, and plasticity tests), 2) manufacturing techniques (xeroradiography; thin sections; visual inspection), and 3) firing temperature (SEM-EDS; porosity tests). We identified two clay types, one restricted to the Pacific coast, one widely distributed. Vessels were made by layering slabs and occasionally lumps. Rim- and lip-finishing is variable. Firing temperature (>800–950°C) is relatively high for open firing. Porosity is quite low. These aspects indicate that Monagrillo is not an experimental or expedient ware.

1. Monagrillo, Panama's first pottery

In the Americas, the earliest known pottery becomes progressively younger along the Central American isthmus and into Mexico. Therefore, some archaeologists have reasonably assumed that diffusion was the primary mechanism for the dispersal of ceramics northwards from South America (Ford 1969; Fonseca Zamora 1997; Meggers 1997). Others have argued that independent invention is as plausible an explanation, as there are geographical gaps in the distribution of the earliest known wares in Central and Mesoamerica which differ stylistically and technologically from each other and from contemporary South American wares (Cooke 1995; 2005; Hoopes 1995). Clark and Gosser (1995) propose that invention was 'dependent' – i.e., that people adopted the technology from other groups but manipulated style and function for their own purposes.

The Monagrillo ware (Willey and McGimsey 1954) is the earliest known pottery in Panama. It was produced between 2600 and 1200 BC (3520–1300 cal BC) over an area of 5600 km^2 in the central part of the country, between Parita Bay on the Pacific coast and the Coclé del Norte drainage in the Caribbean foothills (Fig. 1; Cooke 1995, Fig. 14.1; Griggs 2005). It has not been reported elsewhere in Panama. It appears stratified directly above Preceramic layers at two rock-shelters (Cueva de los Ladrones (Cl1) and the Aguadulce Shelter (Ag13)). This fact supports the hypothesis that it was the first pottery made in central Panama.

Current evaluations suggest that the Monagrillo pottery is typologically coherent, showing little evidence for diachronic change during its long period of manufacture. Vessel shapes are limited to bowls and restricted collarless vessels (Cooke 1995, Fig. 14.2). No handles, lugs, or feet have been found. Decoration consists of red- painted bands and daubs, and rare incised decoration using lines and volutes. Towards the end of the tradition, short collars are added to jars, and the variety of incised, impressed and modelled motifs increases. These developments, however, are poorly dated (Cooke 1995, Fig. 14.3; Cooke and Sánchez-Herrera 2004).

Previous assessments of Monagrillo pottery have relied on comparing data obtained from visual (usually non-instrumental) inspection of manufacturing processes, intuitive typological studies and regional site surveys supported by radiocarbon chronologies. Our study of the Monagrillo ware uses rigorous analytical methods derived from materials science and geology, focusing on the production process, with particular attention to raw material selection and firing temperatures.

2. Subsistence economy, settlement patterns and social interactions of the Monagrillo potters

Data about the subsistence economy, settlement patterns, and social interactions of the Monagrillo potters have been provided by (1) archaeological surveys (Cooke and Ranere 1992),

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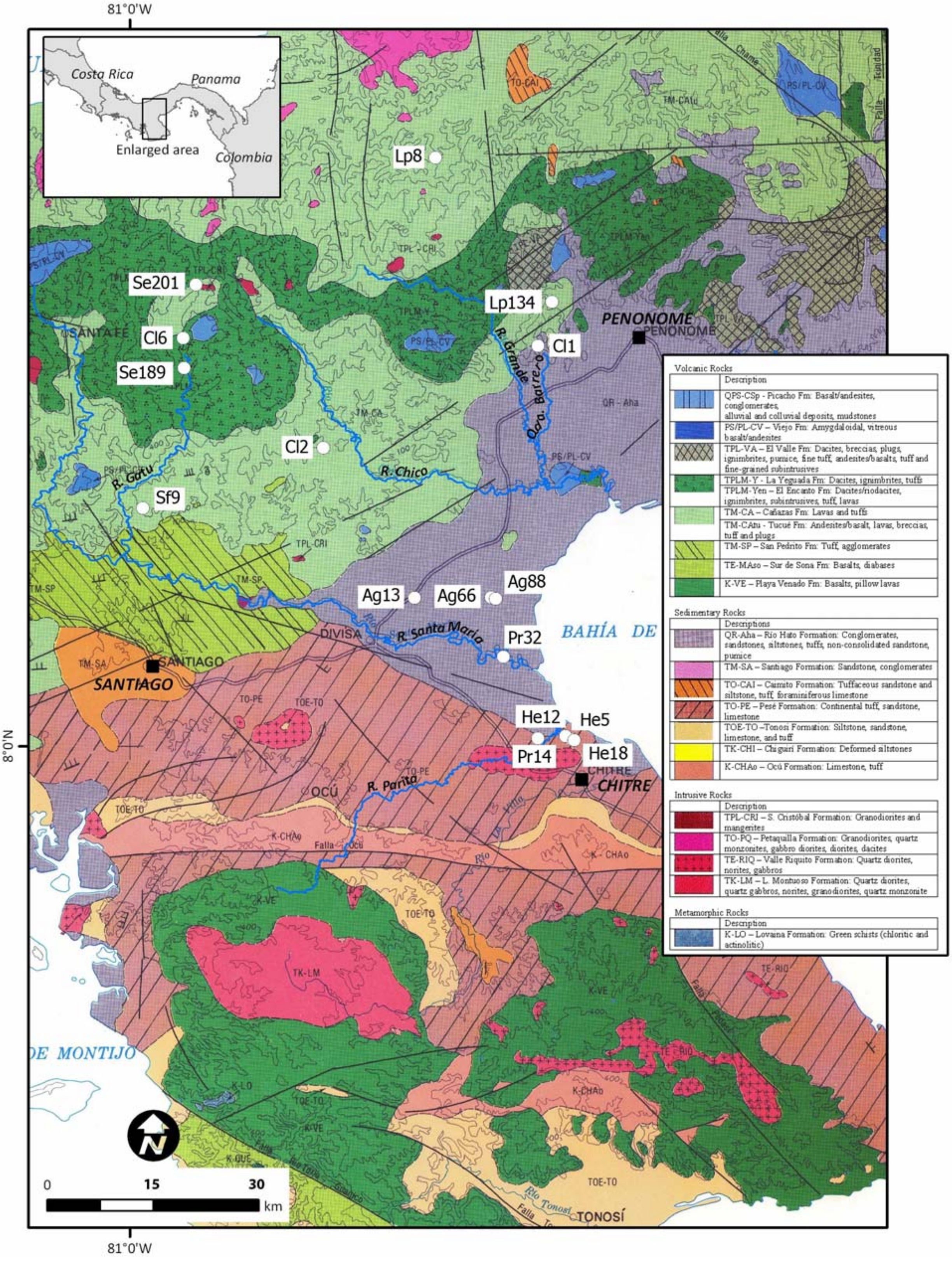

Figure 1. Geological map of Panama with Monagrillo sites The map, modified from del Giudice and Recchi (1969), was produced with the assistance of Natalia Hoyos.

(2) excavations at stratified sites (Willey and McGimsey 1954; Bird and Cooke 1978; Ranere and Hansell 1978; Cooke 1984), (3) archaeobotany (Dickau 2005, 2010; Piperno and Pearsall 1998; Perry *et al.* 2007), (4) zooarchaeology (Hansell 1979; Carvajal Contreras and Hansell 2008; Cooke and Jiménez 2008; Cooke *et al.* 2008), (5) geomorphology (Clary *et al.* 1984), and (6) vegetation history derived from a lake sediment record at Laguna La Yeguada, located within the Monagrillo pottery production zone (Piperno and Pearsall 1998; Piperno 2006).

Like their Preceramic predecessors in central Panama, Monagrillo potters were farmers who by 3500 cal BC had cleared extensive tracts of forest on the Pacific watershed for planting early forms of New World staple crops, e.g., maize (*Zea mays),* manioc (*Manihot esculenta)*, sweet potatoes (*Ipomoea batatas)*, squash (*Cucurbita* spp.) and peppers (*Capsicum* spp.). They were not hunter-gatherers and 'incipient' agriculturalists bound to the marine littoral – as formerly believed (Willey 1971). However, the degree and duration of sedentism at individual sites, and the seasonality of their occupations, are difficult to gauge from the existing record.

On the Pacific watershed of Panama under present-day climatic conditions, rain-fed farming is only possible between May and December. Domestic refuse at the largest Monagrillo site (Zapotal [Pr32]) covers ca. 1 ha. This site, located near prime agricultural soils, produced a large number of plant-processing tools. The remains of a small dwelling were also found here. It is likely that it was a village (Cooke and Ranere 1992; Perry *et al.* 2007). Ag13 and Cl1 – two rock-shelters located 18 and 25 km from the present-day shore of Parita Bay – were probably occupied for long periods at a time (i.e., during the farming season). Game was regularly brought back to each site. Shellfish, crabs, and fish from the marine littoral, also regularly consumed, would have been obtained by making trips to the coast or through exchange. Palm nuts were processed intensively at the Ag13. The primary species – the Neotropical oil palm, *Elaeis oleifera* – requires swampy habitats, and is most productive in rainy season months. The processing of palm fruits (*Atallea alenii*) and balsam seeds (*Humirastrum diguense*) is in evidence at the only Monagrillo site known on the Caribbean watershed: Calaveras (Lp8). This shelter's inhabitants consumed maize and may well have lived year round in this perennially humid habitat.

Hansell's (1979) preliminary growth-ring study of marine shells found in middens at the Monagrillo (He5) type site suggests that this settlement, dated between 2400 and 1300 BC (2800–1400 cal BC) and located then on the active marine shore of Parita Bay, was occupied mostly in the dry season (non-farming) months by people who spent the rest of the year elsewhere. Fishing in in-shore marine habitats was an important activity here and at Pr32. The high number of small shoaling fish in the middens, e.g, thread-herrings (*Opithonema* spp.), small jacks (*Carangidae* spp.), and sea catfish (*Ariidae* spp.), suggests the use of gill-nets and/or inter-tidal weirs. Inland-coast seasonal transhumance is still practised in this region in the dry season. He5 and Pr32 may have provided the inland shelters with dried and salted fish – another practice that persists in the region (Zohar and Cooke 1997). Smaller rock-shelters in the foothills and mountains where Monagrillo pottery is scarce are likely to have been occupied intermittently or irregularly as hunting-and-gathering camps or as rest stations on paths.

These data allow us to infer that Monagrillo communities interacted regularly, exchanging or transporting foodstuffs and other produce from many different habitats in an environmentally heterogeneous interaction zone. It can be assumed that pottery was one of these products.

The primary goal of this study is to use a detailed examination of the production processes and circulation of the Monagrillo pottery in order to improve knowledge about residential and interactive behaviour and pottery use before the appearance of those better -known regional societies that archaeologists consider to be chiefdoms with well-defined social classes and extensive trade connections (e.g., Linares, 1977; Helms, 1979; Drennan 1996; Isaza-Aizuprúa, 2007; Haller, 2008).

3. Materials and methods

Sample inventory

Analyses were conducted on 110 Monagrillo sherds obtained through excavations conducted at sites in four environmental zones, and also on 12 raw clay samples collected near Cl1 and He5. Sample details are provided in Table 1.

Table 1. Inventory of Monagrillo sherd samples (samples for each analysis were chosen from this inventory).

Environmental Zone	Site	River Drainage	Abbrev.	Number of sherds	Number of clay samples
Pacific Coast	Monagrillo	Parita	He5	30	3
	Zapotal	Santa María	Pr32	20	
	La Mula-Sarigua	Parita	Pr14	3	
Pacific Plains	Aguadulce	Santa María	Ag13	20	
Pacific Foothills	Cueva de los Ladrones	Grande	Cl1	31	9
	Carabalí	Santa María	Sf9	2	
Caribbean Foothills	Calaveras	Coclé del Norte	Lp8	4	

Pottery provenance

In order to ascertain the locations where Monagrillo pottery was made, we studied the physical properties of archaeological sherds and raw clays deemed suitable for pottery production according to the results of Iizuka and Vandiver (2006). The mineralogical analysis used petrography (He5, 9 sherds and 2 modern clay samples; Pr32, 5 sherds; Pr14, 3 sherds; Ag13, 4 sherds; Sf9, 2 sherds; Cl1, 7 sherds and 4 modern clay samples). The manufacturing techniques of archaeological sherds were identified using visual and petrographic analysis in conjunction with xeroradiography.

Physical clay properties including shrinkage, plasticity, and porosity were tested using three samples of clays gathered from He5 and nine clay samples from Cl1. The plasticity test was carried out by determining the minimum radius of curvature that could be made with 1 cm diameter coils of hydrated clay before the clay began to crack. For the shrinkage test, we measured the linear drying shrinkage comparing wet and dry states for three days. The porosity test was conducted by firing the clays in 100°C increments from 500°C to 800°C using a rapid ramp and 15 minute soak sequentially at each temperature. After each firing, the sample was weighed and then boiled in distilled water for 1 hour. The samples then sat in water for 24 hours before reweighing. The percentage of increased weight was directly related to the amount of water taken up by the pores of the ceramic. This method is useful for measuring open porosity, but does not work for closed porosity.

The composition of the ceramics and raw clay samples was determined using a variety of techniques. Because illitic and smectitic clays have very distinctive thermal decomposition characteristics, differential thermal analysis (DTA) on one sample from Cl1 and one sample from He5 provides a good indication of the clay type (Mackenzie 1970). Petrographic examination of the sherds and sample clays fired to 750°C for 15 minutes in an electric furnace was useful for identifying the mineral constituents of the ceramics. The mineral determinations were compared to the geological map of Central Panama. Based on mineralogy and morphology, we were able to identify both intentionally added temper and natural inclusions present in the clays. Natural mineral inclusions tend to be rounded, well integrated with the clay matrix, and often weathered. Intentionally added inclusions are often angular and have fresh (non-weathered) minerals, including feldspars.

Pottery manufacturing techniques

Detailed visual analyses allowed us to identify butt and bevel joints, cracks, thickened body parts, and indentations. Petrography and xeroradiography were used to examine elongation and direction of pores, and ultimately identify manufacturing lines in the sherds.

Firing temperature

Microstructural changes in pottery occur with the progressive sintering and vitrification of the clay matrix due to increased temperature (Tite and Maniatis 1975; Kingery 1987; Tite 1995, 37). Original firing temperatures were estimated by examining the microstructural features of sherds using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) on a Hitachi S-2460. Archaeological sherds were reheated at 100°C increments, and the original microstructure was compared to the reheated specimens. The point at which the microstructure changes marks the upper boundary of the original firing temperature range. A requisite of this experiment is that the sherd composition undergoes no changes during burial. For example, additions of soluble salts can cause changes to the thermo-physical properties of a pottery sample, e.g., melting at a lower temperature. In order to meet this requirement, the sherds selected for this experiment were screened so that no salts were present on their surfaces. EDS measurements ensured that the composition of the examined area was representative of the clay and not nearby mineral inclusions or salt accretions. Sherd fragments were imaged at x10,000 magnification. In addition to the microstructural analysis, the porosity of Monagrillo sherds was measured and compared to the porosity of clays fired at 100°C intervals, as described above.

4. Results

Geological setting and the provenance of Monagrillo pottery

A principal objective of this study is to relate petrographic thin sections of Monagrillo pottery to the extremely complex geology of Central Panama. Ongoing research by others (e.g., geologists of the Smithsonian Tropical Research Institute Geology Program; Wörner *et al.* 2009) is rapidly modifying the current knowledge of regional geology. The following summary highlights salient features that should enable us to differentiate clay sources across the region.

The clearest petrographic differences – and therefore the ones most relevant to identifying the sources of clays used in the Monagrillo pottery – exist between the geologically older Azuero Peninsula to the south and the younger Cordillera Central to the north (Fig. 1). The Azuero Peninsula is itself divided into four zones: (1) the *Azuero Plateau*, which contains the oldest rocks in Western Panama, e.g., Mesozoic pillow basalts, diabase, and occasional gabbroic intrusives (Okaya and Ben-Avraham 1987, 794; Buchs *et al.* 2010), (2) the *Ocú Formation* (Fig. 1, K-CHAo) including Late Cretaceous formations of deep ocean hemipelagic limestones, (3) *Proto-Arc* igneous rocks including basaltic to basaltic trachyandesitic lava flows and Late Cretaceous dykes (Buchs *et al.* 2010, 20, 23, 28), and (4) the mature arc of the *Azuero Arc Group*, which includes igneous rocks with felsic intrusives and mafic to felsic volcanic rocks of Late Cretaceous-Middle Eocene age (del Giudice and Recchi 1969; Fig. 1, TK-LM, K-VE; Buchs *et al.* 2010, 22–4).

Ceramics which used clays and geological tempering materials from the *Proto-Arc* and *Azuero Arc* should be distinguishable using petrography. The subophitic, intersertal and porphyritic igneous rocks of the *Proto-Arc* contain minerals such as clinopyroxene, plagioclase, orthopyroxene, amphibole, alkali-feldspar, and glass (Buchs *et al.* 2010, 20, 24). On the other hand, the *Azuero Arc* outcrops contain granodiorites with zircon and amphibole minerals. While the lavas have inter-granular to porphyritic texture, the porphyritic rocks contain zoned plagioclase, alkali-feldspar, greenish clinopyroxene, amphibole, and quartz (Buchs *et al.* 2010, 21). The rocks of these zones can also be distinguished geochemically (Buchs *et al.* 2010, 16).

The Cordillera Central consists mostly of Miocene and Pleistocene-Holocene rocks (de Boer *et al.* 1988, 278; Lissinna 2005, 51–2, 73; Wörner *et al.* 2009, 192). The subduction-related calc-alkaline volcanism from the Late Tertiary comprises: (1) the *Cañazas group* (Fig. 1, TM-CA) containing basaltic to andesitic lavas and tuffs, (2) the *La Yeguada Formation* (Fig. 1, TPLM-Y) containing dacitic to rhyolitic volcanic rocks, and (3) the *El Valle Formation* (Fig. 1, TPL-VA) containing dacitic lavas, breccias, ignimbrites, tuffs, and some basalts/andesites (Lissinna 2005, 51). In the Cordillera Central, eruptions occurring between the El Barú Volcano in the west and the El Valle Volcano in the east resulted in the presence of orthopyroxene phenocrysts, amphibole, and clino-pyroxene, but at El Valle, *not olivine*. In addition, K_2O values relative to SiO_2 decrease eastwards from El Barú to El Valle (de Boer *et al.* 1988, 280–1). The numerous recent eruptions – up to about 13,000 years ago (Bush and Colinvaux 1990; Defant et al. 1991; Knutsen 2010) – complicate ceramic sourcing by petrography within the Cordillera Central. We believe, however, that combining petrography with geochemistry could potentially be effective.

Rivers deposit sediments from entire drainages. Therefore, the mineral signatures of clays obtained in the lower stretches of rivers will reflect the basal geology from nearby areas and from farther upstream, where different kinds of rocks may be found. The River Parita rises in the mountains of the Azuero Peninsula. Thus, we predict that Monagrillo pottery produced at He5 and Pr14, in the lower stretches of this river, will contain clays derived from *igneous intrusive* and *sedimentary* rocks found along the course of the river. On the other hand, pottery made near Cl1 in the River Grande drainage is likely to use materials derived from the Cordillera Central, where igneous *extrusive* rocks predominate.

To sum up, the geology of the production zone of Monagrillo pottery is sufficiently differentiated to enable us to distinguish pottery made with raw materials from either the Azuero Peninsula or the Cordillera Central. As our study progresses, it is likely that we will be able to identify the provenance of some clays and tempers within these two areas. Sites located along the lower stretches of rivers on the Pacific side will provide greater challenges because of the mixed geological signatures of the alluvial zone.

Petrographic analysis

The results of our petrographic analyses of Monagrillo sherds (Iizuka, 2013) show that some sherds contain only natural mineral inclusions, while others have both natural *and* added inclusions. The added inclusions are mono-mineralic cracked igneous intrusive rocks or monomineralic angular sands from a similar geological context. He5 sherds are classified into six types, Pr32 sherds into two types, Pr14 sherds into three types, Ag13 sherds into three types, Sf9 sherds into two types, CL1 sherds into four types, and Lp8 sherds into one type. In addition, raw clays collected near He5 and Cl1 were classified into two types. We grouped together the pottery paste types with the same mineralogical characteristics, regardless of site provenance. These groupings are summarised in Table 2.

Group 1 consists of clays with extrusive felsic natural inclusions and intentionally added temper of cracked intrusive igneous felsic rock or monomineralic angular sand with igneous felsic rock constituency. Pottery types belonging to Group 1 are found at six sites (He5, Sf9, Pr32, Ag13, Cl1 and Lp8) located near the Parita, Santa María, Grande, and Coclé del Norte rivers. The next most frequent type (Group 2) includes clays whose natural inclusions are igneous felsic extrusive and intermediate extrusive rock fragments. Igneous felsic intrusive cracked rock fragments or monomineralic angular sand with igneous felsic constituency have been added as temper. Sherds with these characteristics were found at five sites (He5, Pr32, Ag13, Sf9 and Pr14) located near the Parita and Santa María rivers. They were not identified at sites in other drainages, Cl1 along the Grande river, or Lp8 along the Coclé del Norte river.

Granitic rock natural inclusions in clays were only found at He5 and Pr32, which are both located near the Pacific coast, in the Parita and Santa María drainages, respectively. However, He5 granitic clays (Groups 9, 10, 11) have granitic rocks as the major natural inclusions, whereas Pr32 clays (Group 5) have granite in addition to igneous extrusive felsic and intermediate rocks as the natural inclusions. Some He5 granitic clays (He5-Type 1 and 2) contain tourmaline, a distinctive mineral which was not found at Pr32. One He5-Type 1 sherd has a sandstone inclusion.

To sum up, our petrographic analyses revealed that all river drainages in which Monagrillo sites are found produced sherds with clays derived from igneous felsic extrusive rocks, regardless of whether mineral temper was added intentionally to the clay. Raw clay samples gathered from both Cl1 and He5 (and fired to 750°C) contained clay with similar igneous felsic extrusive rock inclusions. Archae-ological sherds found at He5 were the only ones that had granitic rock-based clays, indicating a local origin. A combination of both felsic and intermediate igneous extrusive rock fragments was only present in sherds from sites in the Santa María drainage basin, including He5, located by the Parita river but close to the mouth of the Santa María river. None of the Cl1 sherds contained intermediate extrusive rock inclusions.

We do not know whether the absence of intermediate extrusive rock inclusions in the Cl1 clays is due to: (1) the weathering away of previously existing potassium-rich feldspars in intermediate extrusive rocks in the clays; or (2) people gathering clays from areas where there were no intermediate extrusive rocks, although the vicinity of Cl1 can geologically contain these rock types. At this point, it is difficult to conclude whether the discrepancy between the geology surrounding Cl1 and Lp8 and the ceramic pastes of the sherds from these sites – that is, the likely presence of intermediate extrusive rocks in the area, with the pottery not containing intermediate extrusive rock inclusions – is due to the movement of pottery or the movement of raw materials into these regions, or to the preferential selection of weathered clays that are local to these sites. Bulk compositional analyses of the ceramic pastes and raw materials using a portable X-ray fluorescence (XRF) unit, inductively coupled plasma mass spectrometry (ICP-MS), and electron probe micro-analysis (EPMA) may allow us to distinguish between these regions chemically.

Table 2. Pottery groups according to added inclusions and clay types.

Added inclusion types and clay types	
Group 1	[Igneous felsic intrusive temper] + [igneous extrusive felsic natural inclusions] Lp8-Type 1, Cl1-Type 1, Sf9-Type 1, Pr32-Type 1, He5-Type 7, Ag13-Type 3, He5-Type 3
Group 2	[Igneous felsic intrusive temper] + [igneous intermediate extrusive + felsic extrusive natural inclusions] He5-Type 5, Pr32-Type 1, Ag13-Type 2, Sf9-Type 2, Pr14-Type 2
Group 3	[Igneous felsic intrusive temper] + [igneous felsic extrusive + mafic natural inclusions] He5-Type 6
Group 4	[Igneous intermediate intrusive temper] + [igneous felsic extrusive natural inclusions] Cl1-Type 2, Cl1-Type 3
Group 5	[Igneous intermediate intrusive temper] + [igneous felsic extrusive + igneous intermediate extrusive natural inclusions + igneous felsic intrusive natural inclusions] Pr32-Type 2
Group 6	[Igneous intermediate intrusive temper] + [igneous felsic extrusive + intermediate extrusive + mafic extrusive natural inclusions] Pr14-Type 1
Group 7	[Cracked igneous mafic intrusive rock temper or sand] + [igneous felsic extrusive natural inclusions] Pr14-Type 3
Group 8	[Igneous mafic intrusive temper] +[igneous felsic extrusive + intermediate extrusive and/or mafic extrusive natural inclusions] Ag13-Type 1 ((?) extrusive inclusions are heavily weathered)
Group 9	[Natural inclusions with granitic rock fragments with tourmaline and minor amounts of igneous extrusive rocks and sedimentary sandstone without added inclusions in clay] He5-Type 1
Group 10	[Natural inclusions with granitic rock fragments with tourmaline and minor amounts of igneous extrusive rocks without added inclusions in clay] He5-Type 2
Group 11	[Natural inclusions with granitic rock fragments without tourmaline and with minor amounts of igneous felsic extrusive rocks without added inclusions] He5-Type 4
Group 12	[Clays with major inclusions that are igneous felsic extrusive rocks] – He5-Clay 1, Cl1-Clay 1, Cl1-Type 4 – Clays (excluding added inclusions) of Lp8-Type 1, CL1-Type 1, SF9-Type 1, Pr32-Type 1, He5-Type 7, Ag13-Type 3, Cl1-Type 2, Cl1-Type 3, Pr14-Type 3, Ag13-Type1
Group 13	[Clays with igneous felsic extrusive and intermediate extrusive rock inclusions] – He5-Clay 2 – Clays (excluding added inclusions) of He5-Type 5, Pr32-Type 1, Ag13-Type 2, Sf9-Type 2, Pr32-Type 2, Ag13-Type 1 (?)
Group 14	[Clays with biotite and felsic extrusive rock inclusions] Cl1-Clay 2

Manufacturing technique

Iizuka and Vandiver's (2006) clay suitability test for pottery production of clays collected near Cl1 and He5 indicated that, at Cl1, clays have to be carefully selected, while at He5, clays are workable and can be readily used for pottery production. DTA showed that both areas contained illitic clays.

Visual inspection, xeroradiography, and petrography showed that most Monagrillo sherds were constructed by overlapping slabs of clay. However, a few sherds at Pr32 (n=5) and Ag13 (n=3) combined slabs at their seams with small clay lumps. Lips and rims are finished in many different ways. Some have lips folded on top of slabs or consist of two clay pieces attached to a slab. The radiography in Figure 2 (top image) shows elongated pores in sherd Cl1-45-F13, indicating joints in the ceramic fabric. The bottom image in Figure 2 shows the thin section of He5-76-F1, with elongated pores aligned parallel to the vessel surface.

Porosity test

The porosities of clays suitable for pottery production (5 samples) were all above 27% (the minimum porosity was 26.84% [He5-DO-1, fired at 800°C]). On the other hand, the porosity of Monagrillo pottery (8 samples) ranged between 26.19% (He5-63-F12) and 9.77% (Cl1-3-F120). The porosities of the archaeological sherds were much lower than porosities obtained for the clay samples collected near Cl1 and He5 after they were fired to 800°C. We interpret this characteristic to signify that all archaeological sherds must have been fired above 800°C if the clays were gathered locally.

Firing temperature

The re-firing experiments corroborate the conclusion reached from the porosity tests. The results of our microstructural study using SEM-EDS (Fig. 3) are the following:

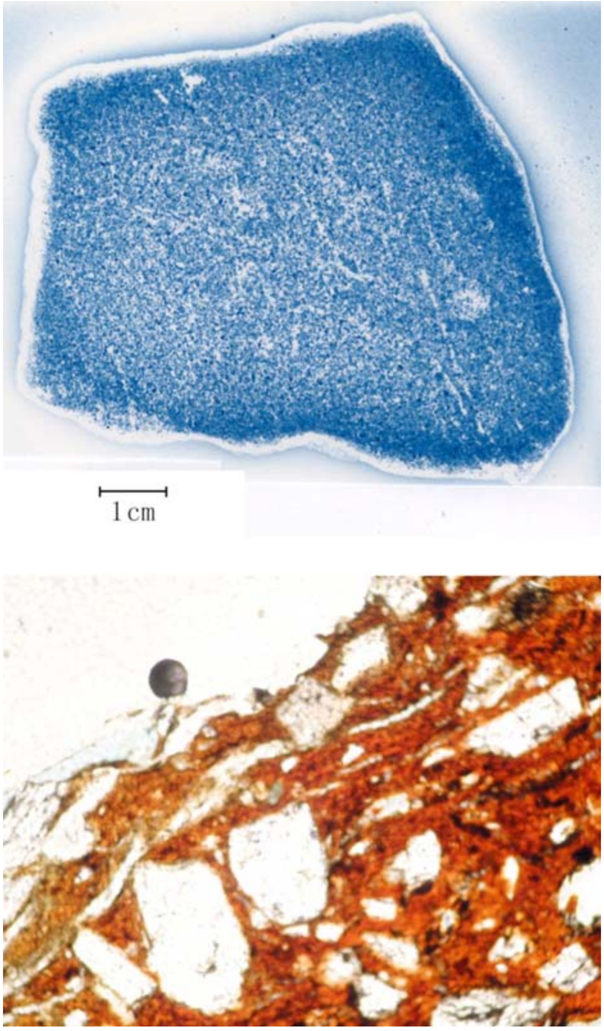

Figure 2. (top) Radiograph of a Monagirllo sherd (Cl1-45-F13) from xeroradiography. The radiograph shows locations and alignment of pores, indicators of joints created during manufacturing. (bottom) Image of a ceramic thin section under plane polarized light. The thin section shows alignment of elongated pores parallel to the vessel align with the left margin.

Cl1-3-F137
Microstructure remains unchanged up to 900°C. Slight rounding of clay particles becomes visible at 1000°C and continues up to 1100°C. We conclude that the firing temperature was slightly lower than 1000°C, probably 950°C.

Cl1-45-F26
No change occurs in this re-fired sherd up to 900°C, but a drastic change takes place at 1000°C. We infer that the original firing temperature was a little over 900°C. Figure 3 shows the SEM-EDS images and data of Cl1-45-F26.

He5-63-F12
The microstructural analysis of this re-fired sherd revealed that there is no detectable change between 500°C and 800°C. Some rounding of the pores in the clay matrix and smoothing of the pore walls is visible at 900°C. A similar sintering stage continues at 1000°C. A major microstructural change occurs at 1100°C as the sherd deforms plastically, losing its original shape. We infer that this vessel was originally fired at approximately 850°C.

He5-76-F1
The clay matrix of this sherd shows intensified rounding of the pore edges at 900°C as compared to the images taken at 800°C. We infer a firing temperature slightly above 800°C, although, unlike for He5-63-F12, microstructural changes at 1000°C are more pronounced.

5. Conclusions

Raw material selection

Archaeologists have assumed that Monagrillo pottery was crude and expedient, made with any available local clay, and fired at low temperatures (500°C). This opinion was not based on instrumental or microscopic analyses (Cooke and Ranere 1992; Cooke 1995). A petrographer (Hill 2002) who analysed 20 samples sent to him by John Griggs from four sites (He5, Ag13, Cl1, and Lp8) deduced that local clays were used and that no temper was added. However, in contradiction to Hill's (2002) results, our study suggests that a temper of freshly cracked monomineralic coarse rocks or angular monomineralic sands were added to some Monagrillo vessels. In the future, we plan to compare the petrography and geochemistry of the intentionally added mineral temper with those of rocks gathered from zones of igneous intrusive rocks in Central Panama.

Geological studies of Central Panama show that the Azuero Peninsula and isthmus proper have different formation histories. Azuero is older than the Cordillera Central. Our project analysed Monagrillo sherds obtained from seven sites located in four distinct drainages (Coclé del Norte, Grande, Santa María, and Parita) and in four different environmental zones (Pacific coast, Pacific plains, Pacific foothills, and Caribbean foothills). Our results to date suggest that, mineralogically, the most ubiquitous pottery fabric (from six sites) incorporates natural inclusions of igneous felsic extrusive rock and temper of igneous felsic intrusive rocks. This type is found at sites from every major river drainage. Sites located in the Santa María and Parita drainage basins (He5, Pr32, Ag13, Sf9, Pr14) all have pottery with igneous felsic intrusive characteristics, and clays based on igneous extrusive felsic *and* intermediate rocks. However, this fabric type was not found in Cl1 or Lp8, located in the Grande and Coclé del Norte drainages, respectively. Geochemical analyses are necessary to further classify the above clay types. Pottery made with clay containing natural granitic inclusions that appear to contain tourmaline were only found at He5. In addition, a sherd with sandstone inclusion was only found at He5. He5 is located on the coast of the Azuero Peninsula, at the mouth of the Parita River and near the La Villa River, both of which receive alluvial deposits from igneous intrusive and sedimentary (limestone and sandstone) host rocks. This suggests that the pottery found at He5 likely has a local signature that is distinct from that of the pottery found in Cl1 and Lp8.

Manufacturing technique

Willey and McGimsey (1954) proposed that Monagrillo vessels were made using the coil building technique.

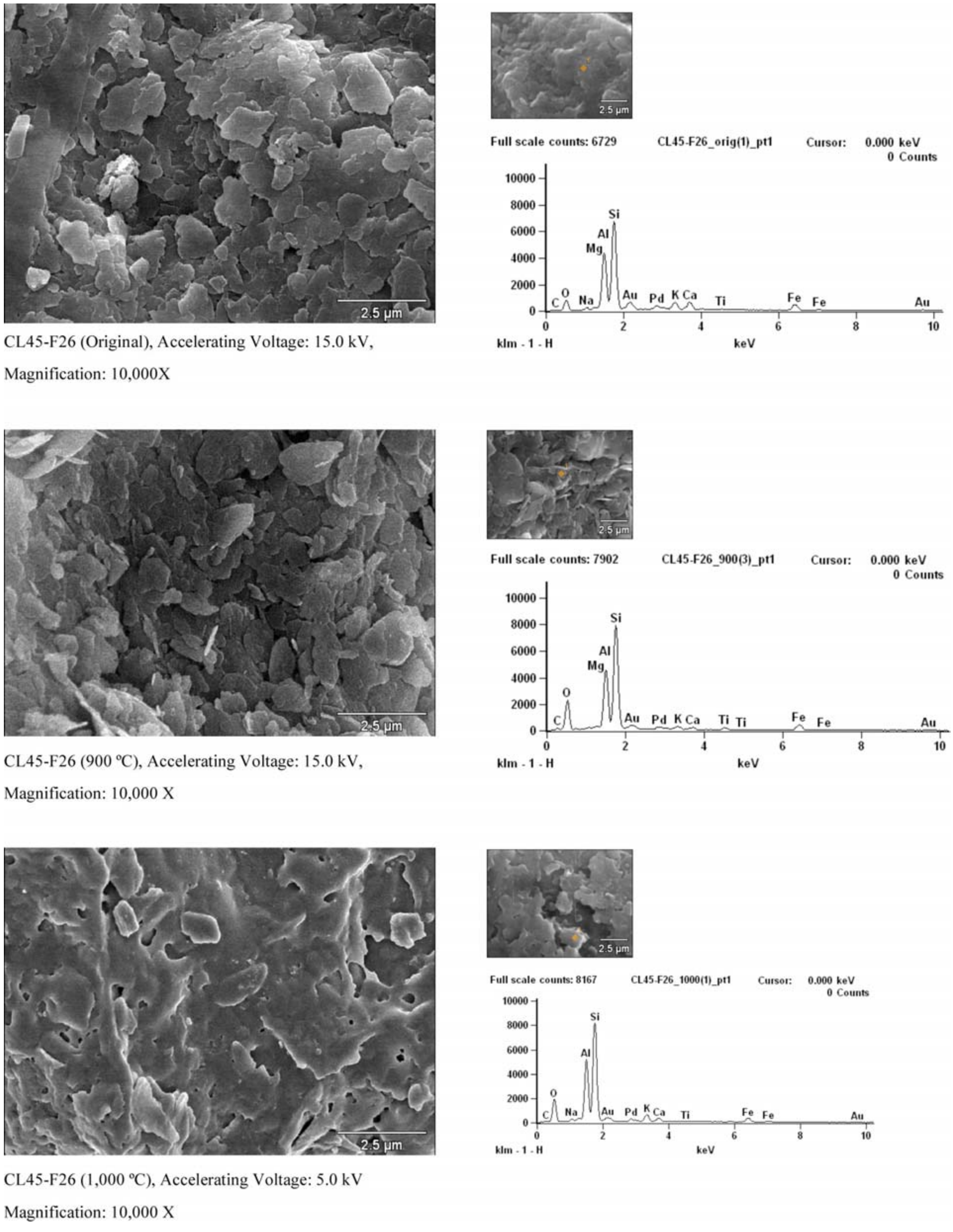

Figure 3. SEM examination of sherd CL45-F26 after refiring experiments. The ceramic microstructure remains uchanged at 900°C but appears more sintered at 1000°C, indicating an original firing temperature between those two thresholds.

Our research indicates that most Monagrillo pottery did not resort to this technique, but rather used layered slabs. Some vessel bodies from Pr32 and Ag13 were made by combining slabs and small lumps of clay. In general terms, there is very little variation in the techniques employed for building vessels. The finishing of rims and lips exhibits the greatest variability.

Porosity

Our porosity tests suggest that the porosity index of Monagrillo vessels was always lower than that of clays gathered near Cl1 and He5, fired at 100°C intervals between 500°C and 800°C. This means that if potters from these sites gathered nearby clays and fired them, they would have fired the pottery above 800°C to reach the porosity of the archaeological sherds.

Firing temperatures

It has been proposed that Monagrillo pottery was crude and fired at very low temperatures (Cooke and Ranere 1992; Cooke 1995). Although our sample size is still small, our results contradict this hypothesis, indicating that pottery from Cl1 and He5 was fired at 950°C and between 800°C and 850°C, respectively. Experimental and ethno-archaeological studies suggest that temperatures attained with the open firing method normally range between 500 and 900°C (Tite 1995), and occasionally reach 950°C (Gosselain 1992) to 1000°C (Colton 1953; Shepard 1980; Rye 1981). Thus, it is likely that the Monagrillo pottery was fired at the higher end of the open firing temperature range. We thus conclude that Monagrillo pottery is more expertly made than it was previously suggested.

Regional interpretations

Mobility of the Monagrillo population

The techniques we have employed so far have only identified two clay types within the samples of Monagrillo sherds: (1) clays with mostly granitic rock-based natural inclusions that contain tourmaline, and (2) clays with natural inclusions that consist of igneous extrusive rocks. The fact that the former is found only at He5 suggests that some of the pottery used by this site's inhabitants used nearby sources of raw materials. Since the second clay type is so ubiquitous, we cannot identify its precise provenance. The granitic-based ceramic paste with tourmaline has not yet been found outside He5. Therefore, it is reasonable to infer that Monagrillo people did not carry or exchange locally made pottery far from this site. It is hoped that further investigations will enable us to identify additional evidence for local production, and thus improve our ability to determine how Monagrillo pottery was circulating.

Manufacturing methods

Despite previous arguments to the contrary, this study has shown that the manufacturing methods of the Monagrillo ware were relatively homogenous. Regardless of the archaeological sites from which they originated, all of the sherds were produced in similar ways, using layered slabs or slabs joined with lumps of clay. Firing temperatures were relatively uniform for the entire collection and clustered at the upper range of temperatures attainable by open-firing. The main difference in manufacturing methods seen with this collection is that some ceramics show additions of mineral temper, while others contain only natural temper. Such skill and attentiveness reflect a well-established and carefully performed craft.

We propose that the Monagrillo potters prioritised impermeability and resistance to breakage. High firing temperatures enhanced their vessels' suitability for holding liquids and for being transported over long distances. Vessels whose primary functions are serving, cooking, and storage can perform these functions even if they are fired at low temperatures (500–800°C). However, the addition of temper does increase thermal shock resistance and therefore optimality for cooking.

Future directions

Our research has shed new light on the Monagrillo pottery of the Central American isthmus, providing support for the argument that this was not an experimental or hastily produced ware. Raw materials were carefully selected, and vessels were manufactured to fit specific performance criteria. This interpretation contradicts the previously held notion that the Monagrillo ware was crude and roughly made. Future research will address the outstanding issue of trace element compositional differences in Monagrillo pottery, focusing on identifying additional meaningful geochemical signatures of clays and firing tempers across the entire production zone.

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