

Intentional Clay-mixing in the Production of Traditional and Ancient Ceramics and its Identification in Thin Section

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Abstract

Ethnographic and historical accounts have indicated that traditional potters intentionally mix two or more sources of clay in order to prepare composite pastes for pottery production. It has long been assumed that a such practice also took place in the past, but detecting evidence for clay mixing in ancient ceramic sherds has proved challenging due to thorough blending, as well as the existence of natural heterogeneity within clay sources. Very few detailed studies on clay mixing exist within the fields of ceramic petrography and ancient pottery technology, and both diagnostic criteria and descriptive terminology are therefore poorly defined. The present paper attempts to fill this gap in our knowledge by reviewing the methods of clay mixing from ethnographic sources as well as archaeologists attempts to identify it in thin section. By studying naturally heterogeneous clay under the polarising light microscope and experimentally mixing pastes according to the various methods reported ethnographically, the study attempts to identify possible lines of evidence with which to detect intentional clay mixing in ancient ceramics. These are then applied to archaeological ceramic sherds from a range of periods and geographic regions. The study reaffirms the difficulties in identifying intentional mixing, which can result in a diverse set of compositional and microstructural phenomena that may also occur naturally, and proposes additional criteria with which to distinguish these two processes. It also highlights the overlap between clay mixing and the technological practice of adding non-plastic temper to the clay body.

Keywords

Ceramics; Chaîne opératoire; Paste preparation; Clay mixing; Thin-section ceramic petrography; Ethnography; Experimental archaeology

1. Introduction

Potters rarely manufacture ceramics with naturally occurring raw clay direct from the ground. Instead, they manipulate and process it in several ways in order to achieve a clay ‘paste’ or ‘body’ that is suited to the particular pottery vessel or other ceramic object that they wish to produce (Rye 1981, p. 19; Rice 1987, p. 118–119; Roux 2019, p. 30–40). The exact clay preparation methods applied by individual potters and workshops vary widely, but can be broken down into three types of actions: the processing of individual raw material components (drying, grinding, winnowing, sieving, settling, levigation), the combination of

different ingredients (tempering, clay mixing), and methods of hydration and homogenisation (wetting, ageing, souring, working) (Quinn 2013, p. 154–174).

Tempering and clay mixing are two important and frequently applied means of altering the physical properties of the clay paste by introducing additives to it. Though some overlap exists between the concepts of tempering and clay mixing (Rice 1987, p. 119), the term ‘temper’ is often used in archaeological studies of ceramics to describe loose aplastic particulate material such as mineral grains, crushed ceramics pieces or ‘grog’, shell, bone and chopped plant matter that was intentionally added by potters. Clay mixing on the other hand is the premeditated mixture of two or more clay sources in a wet, moist or dry powdered state.

Potters temper and mix different clay sources in order to improve its physical behaviour at various stages in the production process and wider life cycle of a ceramic object. This includes the stickiness or ‘plasticity’ of the clay paste during forming, its degree of shrinkage during drying and firing, and the strength, toughness, thermal shock resistance and thermal conductivity of the finished artefact when in use (Rice 1987, p. 58–67, 228–230; Müller 2016; Roux 2019, p. 36–38). Certain paste preparation methods may also have symbolic meaning that is not easily explained in terms of material properties or vessel function (e.g. Chapman 2000, p. 54; Gosselain and Smith 2005; Quinn and Burton 2009, p. 288).

Given the diversity in paste preparation methods used in traditional pottery production and the wide range of criteria that govern actions such as tempering and clay mixing, their detection in ancient pottery provides archaeologists with insights into the skills, know-how, beliefs and craft traditions of ancient potters (e.g. Amicone et al. 2020), as well the ways in which production was organised (e.g. Quinn et al. 2017). Evidence for specific technological practices can be sought at the macroscopic scale on the surfaces or a fresh break of sherds, as well as at a microscopic and atomic scale using scientific techniques. One of the principal tools used to study the raw materials and paste preparation of ancient pottery and other ceramics is thin section ceramic petrography (Whitbread 1995; Reedy 2008; Quinn 2013). By examining the mineralogical composition and microstructure of the inclusions, matrix and voids of ceramic ‘fabrics’ at high magnification down the optical microscope, it is possible to detect subtle evidence for many of the steps involved in their production sequence or *chaîne opératoire* (Roux 2019, p. 1–4) that is not visible to the naked eye. For example, a range of textural and compositional criteria can be used to distinguish between naturally occurring inclusions and intentionally added temper material (Quinn 2013, p. 156–169). By detecting temper, analysts can understand the various ingredients involved in the preparation of ceramic pastes, interpret their raw material sources and therefore seek the production locations or ‘provenance’ of transported pottery.

Despite its not uncommon use in traditional pottery production, recognising the practice of clay mixing in ancient sherds remains problematic. As potters usually mix clay sources that differ in their composition, texture and optical appearance, the incomplete blending of two or more types of clay on a microscopic scale can leave visible heterogeneity in ceramics in thin section (Woods 1982; Whitbread 1995, p. 392; Quinn 2013, p. 168, 170–172). However, streaks, swirls and laminations of two or more clay types can also occur in pottery made from

naturally heterogeneous clay that has not been sufficiently homogenised. In addition, it has been claimed that traditional potters can mix two or more clay sources to an extent that no traces of the component parts are visible under the microscope in thin section (e.g. Matson 1972; Vaughan 1995, p. 116). Potters mix clay in both a dry and a moist state in varying proportions and they use a range of methods to blend them into a single paste. This means that not all intentionally mixed pastes are likely to look the same, which makes it difficult to distinguish them from fabrics containing natural phenomena deriving from the clay source itself.

In order to shed much needed light on the topic of intentional clay mixing during pottery production and its recognition in thin section, the present paper takes an experimental approach. Experimental archaeology can be used to bridge ethnographic analogues and the production technology practiced in the past (Harry 2010). It examines the reliability and accuracy of archaeological interpretations of material culture (Skibo 1992, p. 18). Despite the application of experimental archaeology to the reconstruction of other technological steps in the pottery manufacturing sequence in thin section, such as tempering and forming (e.g. Whitbread 1986, 1996; Cuomo di Caprio and Vaughan 1993; Thér 2016), very few studies have been conducted on the intentional blending of two or more clay sources. Following a detailed review of the methods used to mix clay in traditional pottery production and the efforts of archaeologists to identify it in ancient ceramics, the paper outlines a set of experiments that apply these in a controlled manner to create mixed ceramic pastes of several types. These specimens are analysed in detail in thin section in order to test the microstructural and compositional criteria proposed by previous authors and detect additional phenomena related to whether the clay sources were mixed in a dry state, a moist state or a combination of the two. Finally, the characteristics observed in the intentionally mixed experimental ceramics are compared to thin sections of prehistoric and historic pottery that is known to be or suspected to have been mixed. Finally, the study proposes new terminology for the description of argillaceous features in ceramics under the microscope and considers the overlap between the related practices of clay mixing and tempering.

2. Clay Mixing in Traditional Pottery Manufacture

The intentional mixing of two or more clay sources has been recorded in a significant number of ethnographic studies of traditional pottery production across the globe, including in the Aegean (Bettina 2019; Blitzer 1984; Hampe and Winter 1962, 1965; Hein et al. 2004; Jones 1986; Matson 1972; Vaughan 1995; Voyatzoglou 1974, 1984), Cyprus (Jones 1986; London 1989), the Andes (Tschopik 1950; Sillar 1988, 2000, p. 56–57), the Amazon (DeBoer and Lathrap 1979), Mesoamerica (Arnold 1971, 2000; Lackey 1978; Maggetti et al. 1984), sub-Saharan Africa (Arthur 2000; Barbour 1989; Brown 1972; Dietler and Herbich 1989; Fowler 2008; Gill 1981; Gosselain and Smith 2005; Smith 2000; Soper 1989; Tobert 1984), India (Roux 2019, p. 38–39), South Asia (Beaudry et al. 1987; Rye and Evans 1976, p. 20) and the Philippines (London 1991; Neupert 2000; Yankowski 2008). These reveal the wide variety of methods used in the process of clay mixing in terms of the number and type of clay sources, their proportions, moisture content, grain size and the methods and tools used to blend them.

Potters typically collect clay in a dry state, or they leave moist clay to dry first before pounding or grinding it to a powder that is then refined in some way before use. This common step in pottery production is also applied in many cases to the preparation of one or more clay sources prior to intentional mixing. For example, Voyatzoglou (1984) and Hein et al. (2004) report that the potters of Thrapsano, Crete pounded and sieved two kinds of dried clay, fine grey Neogene age material and a coarser red more recent alluvial clay deposit. By sieving, cleaning or winnowing, potters remove larger particles from a clay source that could otherwise interfere with the manufacture of the ceramic object (Quinn 2013, p. 154–156).

Numerous studies have reported the mixing of two clay sources in a dry powdered state prior to hydration (Blitzer 1984; Hein et al. 2004; Lackey 1978; London 1989; Rye and Evans 1976, p. 20; Sillar 1988; 2000, p. 57; Tobert 1984; Tschopik 1950; Voyatzoglou 1974; 1984). Dry loose clay is easy to mix as the fine light grains intersperse with relatively low force. Powdering dry clay also renders it more amenable to the uptake of water during hydration, potentially resulting in a more homogeneous clay mass.

Not all potters grind dry clay before mixing (Tobert 1984; Tschopik 1950). Instead they place lumps of both clay sources in a mortar or other grinding surface and pound these simultaneously, gradually mixing them in the process, as in the Aymara of Peru, where Tschopik (1950) reported that purple and red clay was blended, before being hydrated and subsequently and tempered with sand. In Araypallpa, Peru, Sillar (1988; 2000, p. 56) observed that Andean potters simultaneously ground and mixed red clay and white clay, whilst adding water, rather than after the process. This might be expected to be a less efficient means of blending due to the execution of several processes at once.

The mixing of two or more sources of moist or wet clay has also been reported in traditional pottery production (Brown 1972; Maggetti et al. 1984). Potters either procure clay in a moist state, or more commonly hydrate dry, powdered clay before mixing. The amount of water added to one or both of the clay sources is likely to determine the effort required to blend the mixture. Clay sources with only a modest amount of water (e.g. Brown 1972), referred to here as ‘moist’, will need to be vigorously worked by hand, foot or mechanically, whereas if excess water is added to clay to form a ‘wet’ slurry or slip (e.g. Maggetti et al. 1984), then this can be mixed much easily by stirring (Rye 1981, p. 19). The drawback with this latter approach to mixing two wet clay sources is that the liquid mixture cannot be used until it has lost much of its water through air drying.

Potters are also known to add dry powdered clay to wet or moist clay to prepare a paste (Arnold 1971; Matson 1972). On the Yucatan Peninsula, Ticul, Arnold (1971) reported that potters soaked one clay type in water and mixed another dry source into it. The dry clay was thought to act as non-plastic material, reducing the plasticity of the ‘base clay’. Matson (1972) observed that potters in Petriadhes near Messinia, Greece soaked red clay to form a slurry, to which dry pulverised white clay was added in approximately equal proportions. The mixture was then wet sieved and aged. Matson (1972) examined a sample of the fired paste via thin-section petrography, but no visible evidence of clay-mixing was identified.

In most of the cases mentioned above, potters blended two separate clay sources. However, it is not unknown for three (Hampe and Winter 1962; Tobert 1984; Bettina 2019), four or even as many as five clay sources to be mixed (Jones 1986, p. 873). Traditional potters may also add separate particulate temper material to intentionally mixed clay pastes (Tobert 1984; Tschopik 1950).

3. Previous Archaeological and Experimental Studies on Clay Mixing

The practice of clay mixing in ancient ceramic production is often inferred from the study of archaeological sherds in thin section (e.g. Amicone and Quinn 2015; Bourriau et al. 2000; Day 1989; Myer 1984; Stilborg 1997, p. 241; Vince and Tomber 2005). In most cases it has been inferred from the presence of colour, textural or compositional heterogeneity in ceramic fabrics, particularly the existence of clay-rich features such as bodies, streaks and laminations of two or more clay types. For example, Day and Kilikoglou (2001, fig. 47, p. 116) observed streaks within the clay matrix of pottery from Late Minoan Kommos, Crete in thin section and concluded that these were produced by mixing light coloured calcareous clay with red non-calcareous clay. Similarly, Michelaki et al. (2015, p. 813) reported in thin sections of Neolithic pottery from Calabria "lenses within the clay matrix with inclusions in higher frequency and similar orientation that are distinguishable from the adjacent areas", which could have resulted from the intentional mixing of two different clay sources. These sorts of features can be subtle and deformed, with merging boundaries, as well as more distinct and equant shaped with sharper margins, suggesting that they had variable plasticity and moisture. Well-defined rounded clay pellets or lumps with sharp boundaries have been attributed to clay mixing in several studies, including Medieval English floor tiles by Quinn (2013, p. 214) and Late Bronze Age transport jars from Crete by Day et al. (2011).

The presence of inclusions with polymodal or skewed unimodal grain size distributions has been proposed by Whitbread (1995, p. 392–393) as a criterion that could be used to interpret intentional clay mixing, as unprocessed naturally occurring clay is commonly unimodal. He also suggested that strong differences in the composition of inclusions present in a single fabric might be caused by the intentional blending of two or more clay sources from distinctive geological sources. This situation has been interpreted by Riley (1981) in coarse wares from Late Bronze Age Thebes, Greece, where the presence of low-grade metamorphic inclusions and abundant foraminifera microfossils were interpreted as being the result of intentional mixing by the potter. The existence of microfossil inclusions of species of different types, ages or environmental tolerances has been used to interpret intentional clay mixing (Jansma 1977; Matiskainen and Alhonen 1984; Stilborg 1997, p. 241), though this situation can also result from the use of alluvial clay deposits that contain sedimentary material eroded from several sources (e.g. Quinn et al. 1998).

Very few of these studies have been supported by the analysis of either raw material samples or experimental replication. Previous clay mixing experiments are surprisingly rare and limited in nature, but have nevertheless demonstrated some of the possible microstructures that can be left by blending two clay sources (e.g. Myer 1984; Quinn 2013, fig. 6.21, p. 170). The analysis of present day or historic ceramics, known to have been made with a mixed clay paste, are also few in number. Hurley (2009) analysed materials from an eighteenth-century

pottery industry in South Yorkshire, England, where written records reported the practice of clay mixing. Some of these sherds exhibit both laminations and bodies that are reminiscent of that seen in prehistoric material and experiments (Quinn 2013, fig. 6.21, p. 170).

Woods (1982, p. 15) sounded a warning about attributing clay streaks to intentional mixing because “most clay deposits contain clays of different colour and these may be difficult to disperse and mix thoroughly into another clay”. Indeed, the use of variegated or ‘variecoloured’ clay (Michelaki et al. 2015) has been interpreted from the existence of heterogeneity in the clay matrix of archaeological thin sections, for example by Cootes and Quinn (2017, fig. 5, p. 10) in Bronze Age pottery from the Peak District National Park, England. The decision as to whether clay-rich streaks, swirls and bodies in ceramics are natural or intentional seems to be influenced by the type of ceramic object in question and thus the likelihood of potters mixing two or more clay sources to produce a composite paste. For example, clay pellets of light-coloured silty sediment and darker more clay-rich material were recorded in thin sections of the Terracotta Army sculptures in China by Quinn et al. (2017, fig. 3, p. 970) and tentatively ascribed to intentional mixing. However, these also occurred in the paste of ‘rammed earth’ that was used to build the walls of Emperor Qin Shihuang’s mausoleum, in which the statues are located. In this case, it seemed less probable that several thousand tonnes of clay would have been carefully blended for such a purpose. Examples of extreme heterogeneity in brick, furnace linings and other coarse ceramic building materials (CBM) that have been interpreted as the incomplete homogenisation of variegated sedimentary clay include Quinn (2013, fig. 3.5, p. 43, fig. 4.23, p. 96).

Despite the observation of microscopic heterogeneity in ancient ceramics from many geographic regions and archaeological periods and the interpretation of this as remnants of either intentional or natural mixing, very few clear criteria have been proposed to distinguish between these two possible causes. Experimental replication has not yet been sufficiently deployed to tackle this problem, nor have sufficient analyses taken place of modern or historic materials that are known to have been made with a mixed clay paste.

4. Methodology

The present study applies an experimental approach in an attempt to define microscopic criteria for distinguishing intentional clay-mixing from natural heterogeneity. Intentionally mixed clay pastes have been created in the laboratory (Table 1), replicating the various methods recorded in the ethnographic studies above. The experimental pastes have been analysed in thin section under the microscope and the observed textual characteristics in the intentionally mixed samples have been compared with those in naturally heterogeneous clay samples (Table 1), as well as archaeological specimens.

Four types of samples were analysed: 1. Unprocessed naturally heterogeneous clay; 2. Homogenised naturally heterogeneous clay; 3. Intentionally mixed pastes containing two types of studio clay; 4. Intentionally mixed pastes containing two types of natural clay (Table 1). Five samples of naturally variegated, well-bedded clay were procured from an outcrop of the Eocene Lambeth Group at Lower Upnor on the River Medway in Kent, England (Gallois and Edmunds 1965, p. 54) (Figure 1). Since the colour of clay is heavily

influenced by its mineralogical composition (Valanciene et al. 2010), the variegation in the Lambeth Group clay was taken to indicate the presence of compositional heterogeneity. These samples were studied both in their raw state as well as after homogenisation (Table 1). One of the samples, collected in a moist plastic state, was homogenised by hand kneading until no variegation was visible to the naked eye. The other four, which consisted of dry clay lumps, were ground to fine granules and powder using a pestle and mortar, homogenised until they had a uniform colour and then hydrated until moist. The ground dry clay granules had a maximum diameter of c. 5 mm.

Fine, commercially available red-firing terracotta and buff-coloured ball clay were mixed to form experimental clay pastes (Table 1). These two visually distinct clay sources were combined in a dry powdered state, in a moist plastic state and by blending one source of dry clay to the other in a moist state. They were mixed in proportions of 1:1 by volume and homogenised by hand until there were no visual remnants of either clay source. The terracotta was acquired in a moist state, whilst the ball clay was came in a dry fine powdered state. This meant drying and grinding the former with a pestle and mortar to obtain powder, and wetting the latter to make it moist and plastic. The pastes mixed by combining two moist clay sources were blended for two different lengths of time to examine the effect this had on homogenisation.

Two types of visually and compositionally different homogeneous natural clay were also obtained and mixed in the same combinations as the studio clay (Table 1). The sampled sources were the Eocene London Clay from Minster on the Isle of Sheppey and the Cretaceous Gault Clay from Folkestone, both in Kent, England (Gallois and Edmunds 1965, p. 49 and 79) (Figure 1). Both had to be ground and powdered for use in a dry state and hydrated to render this moist and plastic. The experiments did not include the mixing of clay as a wet slurry.

The homogenised and experimentally mixed studio and natural clay sources were formed into small test tiles or 'briquettes'. These were allowed to dry and then fired in an electric kiln at a maximum temperature of 750°C for one hour under an oxidising atmosphere, along with the unprocessed variegated natural clay samples. Standard 30µm thin sections were prepared from the 24 specimens using the standard procedure for archaeological ceramics, including resin impregnation (Quinn 2013, p. 3–33). These were studied visually under the polarising light microscope at magnifications of x25-400 in plane polarised light (PPL) and crossed-polars (XP). The nature of the natural heterogeneity of the variegated clay was examined and compared to the homogenised specimens of the same material. The degree and nature of heterogeneity in the various natural and studio clay mixes was recorded and the samples were compared to one another. Notes were made of the shape, size and abundance of features such as streaks, swirls, laminations, lenses, pellets and clay lumps (Table 2), as well as the nature of their boundaries and degree of concordance with the rest of the fabric (Whitbread 1986, table 1, p. 80). Finally, these were compared to thin sections of archaeological ceramics with heterogeneous clay-rich features from various archaeological periods and parts of the world, as well as the findings of previous studies, including those reviewed above.

5. Results

In thin section the unprocessed naturally heterogeneous clay samples revealed the existence of significant compositional variation. This took the form of differences in the colour and optical density (Whitbread 1986, table 1, p. 80) of the clay matrix, as well as variation in the abundance, texture and types of clasts/inclusions (Figure 2A and B). Despite the existence of distinct bedding in the Eocene Lambeth Group clay in the field (Figure 1), these layers were not clearly visible in most of the 75x25 mm thin sections of the five samples taken across the outcrop. The variation was instead more gradational, patchy or seemingly random. Plastic and aplastic bodies of one clay composition were present in small numbers and may have resulted from the natural disturbance of the clay deposit on the face of the outcrop.

After working, the variegated clay samples were more homogeneous in thin section, but retained some of their original intrinsic variability. The samples homogenised in a moist state exhibit streaks of clay with a different colour and/or inclusion size, mostly short and discontinuous, with diffuse boundaries, as well as some laminations (Figure 2C and D). The degree of deformation of these features varied, as did the widths of the laminations. Equant lenses were occasionally identified in the samples, as was the uneven distribution of coarser inclusions. The variegated clay homogenised in a dry state revealed different features. Equant or slightly elongate clay lumps of different shapes and sizes with sharp to more diffuse boundaries are common (Figure 2E and F). These are likely to be grains of ground up clay that were not sufficiently hydrated during to render them plastic. They vary in their colour and internal texture depending on what part of the original variegated clay source they derived from. Some larger lumps contain internal variation deriving from the original clay. Streaks were rarely identified in the variegated clay samples homogenised in a dry state.

More-or-less equant clay lumps with sharp to diffuse boundaries are also visible in the thin sections of clay pastes produced by the intentional mixing two different studio and natural clay sources in a dry powdered state. The sample made by dry mixing the two studio clay types contains lumps of red terracotta that did not sufficiently hydrate (Figure 3A), whereas no such features deriving from the more finely powdered ball clay were detected, suggesting that it was fully blended. The admixture of dry powdered London Clay and Gault Clay left behind clay lumps of both clay types (Figure 3B). Less common plastic features such as lenses, streaks and laminations are also present in the dry mixed clay pastes (Figure 3C). The streaks were relatively fine and smooth with very few abrupt twists.

Streaks and laminations were commonly observed in the experimental pastes formed by the mixing of two different studio or natural clay sources in a moist plastic state. These features tend to be thin and continuous with clear to diffuse boundaries (Figure 3D and E). The widths of layers both within and between laminations is relatively uniform. The samples that were blended for a longer period of time were more thoroughly homogenised in thin section and contain only subtle less continuous streaks and laminations with merging boundaries (Figure 3F).

Most pastes produced by mixing dry clay of one type with moist clay of another contained clay lumps and lenses of the dry clay source (Figure 3G and H) and only rare plastic features

were present the samples. An exception is the mix of moist terracotta with dry, pulverised ball clay which exhibited a homogenised fabric without unmixed ball clay features.

The abundance of streaks, swirls, laminations, lenses, pellets and clay lumps in the various experimentally mixed sample types is summarised in Table 3.

6. Discussion

The absence of clear streaks and laminations in the thin sections of unprocessed clay obtained from the naturally variegated material suggests that the variation seen in the deposit occur at scale greater than that seen down the microscope. While the sampled material is by no means indicative of all heterogeneous variegated clay, the outcrop was heavily bedded with distinct layers (Figure 1) and the analysed samples were selected at several places across these. Streaks and laminations were instead more characteristic of the intentionally homogenised clay samples and those made from the mixture of two clay types than the unprocessed variegated natural clay. Variation in the abundance, size and composition of sand and silt-sized grains and the colour of the clay fraction does occur across the field samples, but this is more gradational when seen under the microscope. In addition, significant less ordered heterogeneity exists, including patches of iron-staining and argillaceous bodies (Figure 2A and B). The latter, which could feasibly be mistaken for those seen in the homogenised variegated clay and intentionally mixed samples, may have formed by erosion at the outcrop and processes of bioturbation.

Despite efforts to homogenise the variegated field samples to the point that they appeared uniform to the naked eye, they still contained microscopic heterogeneity in thin section under the microscope. This means that it is feasible that ancient ceramics displaying heterogeneous clay pastes could have been made from naturally variegated clay that was not completely homogenised. Such an explanation has been proposed for ceramic bricks by Quinn (2013, fig. 3.5, p. 43, fig. 7.1, p. 214) (Figure 4A) based on the premise that the paste for these coarse ceramic building units may not have needed to be well mixed. Interestingly, the microstructures seen in these examples bear close resemblance to those in some of the homogenised variegated clay in this study (compare Figure 2C and 4A). The types of clay-rich features encountered in the blended variegated material appear to be strongly dependent on its degree of hydration prior to homogenisation, with the moist clay samples containing plastic streaks, laminations and semi-plastic lenses and the dry powdered samples resulting in more aplastic clay lumps and other bodies. With this in mind, the deformed plastic features seen in Bronze Age pottery by Cootes and Quinn (2017, fig. 5, p. 10) (Figure 4B), which matched that of a nearby naturally variegated clay source, might be taken to imply that the raw materials for this vessel were collected and used in a moist rather than a dry state.

The results of the experiments indicate that pastes prepared by the intentional mixing of two clay sources can result in similar compositional and microstructural phenomena to incompletely homogenised naturally variegated clay. These include streaks, swirls, laminations, lenses and clay lumps. These terms and the features that they refer to, are defined and illustrated in Table 2. As with the homogenisation of variegated clay, the moisture content of the mixed clay sources has strong influence on type of features left

behind. Mixing two moist clay sources left plastic streaks, laminations and lenses in the experiments, whereas mixing two dry clay sources or one dry and one moist clay source, resulted in a greater proportion of aplastic clay lumps and other bodies. This distinction is due to the fact that not all of the dry clay particles sufficiently hydrated, and therefore remained as solid inclusions, whereas the moist plastic clay formed less distinct plastic features. The likelihood of the dry clay particles hydrating appears to be related to their grain size, with the finer powdered ball clay leaving much less clay lumps than the coarser ground up terracotta. It is also likely to be influenced by the amount of water added to the mix in the case of dry-dry mixing, or already present in one of the clay sources in either moist-dry or wet-dry mixing. The degree of moisture is also likely to affect the ease with which two hydrated clay sources can be homogenised, with a wet-wet mix being easier to mix than a moist-moist mix. Two additional variables that influence homogenisation are the amount of time spent working the paste and/or the method used (i.e. hand kneading, foot trampling, pug mill).

The range of argillaceous features seen in thin section in the intentionally mixed clay pastes seem to match those seen in other rare experiments, as well as the occasional petrographic analysis of ethnographic and historical ceramics that were known to be mixed. Clay mixing experiments by Myer (1984, p. 61-62) resulted in “terra rossa lumps...suspended within the more uniform matrix” (Jones 1986, p. 818), whereas experimentally moist-moist mixed paste featured in Quinn (2013, fig. 6.21, p. 170) (Figure 4C) produced conspicuous plastic laminations. Eighteenth century vernacular tableware analysed by Hurley (2009) from a workshop in South Yorkshire, England that was known to have mixed clay (Kenworthy 1928, p. 72), an example of which is illustrated in Quinn (2013, fig. 6.22, p. 170) (Figure 4D), exhibits similar fine laminations parallel to the margins of the sherds as well as semi-plastic concordant lenses of one of the clay sources, which seems to have been mixed in a dry state. Vaughan (1995, p. 116) reports that ceramics made by the potters of Siphnos, Greece were so well mixed that it was impossible to detect evidence for this process in thin section. In this case, it is perhaps likely that one or more of the clay sources was wet and the mix was well worked so that the components completely blended. Specimens of ceramics made by a modern potter from Rhodes, Greece that mixes clay (Bettina 2019) were also found to be devoid of plastic or aplastic argillaceous features in thin section (Figure 4E).

Given the strong overlap between the compositional and microstructural phenomena prepared by mixing two clay sources and homogenising naturally variegated clay, it is likely to be difficult to distinguish between these two processes in archaeological material in thin section. This concurs with the findings and suspicions of previous authors including Woods (1982) and Quinn (2013). Nevertheless, the experiments presented here offer some tentative criteria that might be used in this endeavour. These include the ‘band widths’ (Table 1) of streaks and laminations, which appear to be finer and more uniform in intentionally moist-moist mixed pastes than in blended heterogeneous clay. This idea is supported by the experiment of Quinn (2013, fig. 6.21, p. 170) (Figure 4C) and the findings of Hurley (2009) (Figure 4D), and might therefore be applied in future studies. Ceramics made from the intentional mixing of two compositionally very different homogeneous clay sources, such as “the ‘classic’ mix of terra Rossa and pale calcareous clay” used in traditional pottery production in the Aegean (Jones 1986, p. 782), if not completely blended, might be expected to leave distinct features

interpretable as each of these two materials. On the other hand, the more gradational variation in seen in naturally heterogeneous clay, is likely to result in a more complex pattern once blended. Notwithstanding the intentional mixing of naturally heterogeneous clay, either with another different heterogeneous or homogeneous source, it seems more likely that clay lumps with internal heterogeneity, where present, are the result of incomplete homogenisation of variegated clay in a dry state.

Turning to the published examples of heterogeneity within archaeological ceramics discussed above, in addition to the clearly mixed examples reported in Hurley (2009), a good candidate for intentional clay mixing is the Medieval tile from England illustrated by Quinn (2013, fig. 7.2, p. 214) (Figure 4E). Here, aplastic clay lumps of two distinct sources, dark fine clay-rich clay and lighter-coloured, coarser inclusion rich material, can be clearly seen, surrounded by a homogenised plastic clay matrix that is clearly recognisable in terms of its colour and composition as the complete mixture of these two ingredients. This suggests that the paste of this archaeological sample was prepared by mixing two dry powdered clay sources, which were not completely hydrated. Similarly, the presence of distinct clay-rich and more silty equant features in the paste used to manufacture the statues of the Terracotta Army, might imply that this were also prepared using a dry-dry clay mix (Quinn et al. 2017, fig. 3, p. 970) (Figure 4F). The frequent spherical, rounded red clay pellets reported by Day et al. (2011, fig. 4e, g and h, p. 525) in Late Bronze Age transport jars from Crete (Figure 4G) seem to be poorly hydrated remnants of powdered red clay that was intentionally added to a lighter coloured calcareous plastic source, as in the experiment of Myer (1984). Whether occasional bodies or streaks of one clay type within a ceramic thin section are the result of intentional clay mixing is hard to tell, especially where they occur only in one or two samples from a larger fabric (e.g. Michelaki et al. 2015, p. 813). The 'representativeness' of standard 25x50mm or 25x75mm thin sections with respect to the paste of a complete pot or sherd (Quinn 2013, p. 23), means that uncommon inclusions or other features may not always be encountered. However, it is perhaps best to take a cautious approach when interpreting heterogeneity and use the evidence available within multiple thin sections made from the same paste recipe.

Clay lumps of the type seen in thin section in the experiments can occur in ceramic pastes that were not intentionally dry-dry or moist-moist mixed, or not made from incompletely homogenised dry variegated natural clay. They can be left behind by the use of dry powdered clay of which not all particles were hydrated due to their size and/or the addition of insufficient water (Quinn 2013, p. 171, figures 6.25 and 6.26, p. 172; Quinn and Burton 2009, figure 8, p. 284) (Figure 4H). They are also likely to be left by the addition of ground clay particles to plastic clay of the same type (e.g. Druc 2000; Smith 2000). In both cases, these features will have a similar colour and composition to the surrounding clay matrix, which formed from the hydration of the same clay material, whereas in dry-dry and wet-dry mixing they will not. In addition, in dry-dry mixing, it should be possible to see clay lumps of both clay types.

The clay lumps and lenses encountered in this investigation fall within the definition of the term 'argillaceous inclusions' used by various authors (e.g. Whitbread 1989, 1995; Cuomo di Caprio and Vaughan 1993; Quinn 2013), meaning that they are clay-rich. However, there are

numerous other types of clay-rich inclusions of very different origins, including fired clay temper or 'grog' and intrinsic or added mudstone rock fragments. Whitbread (1986) documented the nature of these phenomena and proposed criteria that can be used to distinguish between them, and Cuomo di Caprio and Vaughan (1993) focused on the distinctive characteristics of grog in thin section. The plastic streaks and laminations seen in the experimental samples on the other hand might, are not argillaceous inclusions as they exhibit merging boundaries and therefore blend into the surrounding fabric. The terms 'textural concentration features' (Whitbread 1995, p. 386) or just 'textural features' (Quinn 2013, p. 91, 93) have been used for these. However, the word 'textural' is not necessarily appropriate given that it refers to grain size, and therefore inclusions. 'Clay concentration features', a term used for the description of soil thin sections by Kemp (1985, p. 32) might more appropriate, despite the fact that they can contain material other than clay (Whitbread 1995, p. 386) and some can have less clay within them than the surrounding fabric.

Determining whether an argillaceous feature is plastic inclusion, a plastic clay concentration feature or an aplastic lump or fragment of poorly hydrated clay is likely to be subjective in some cases, given the variation in the degree of hydration, plasticity, blending and deformation seen in the features in the experiments above, as well as in archaeological specimens. This may pose issues during the petrographic characterisation or description of ceramic fabrics in thin section, as clay-rich inclusions and concentration features are treated differently. The former, as inclusions, should be described along with the other particles >10 microns in size (Quinn 2013, p. 91) and the latter are either documented along with the clay matrix section (Quinn 2013, p. 91-94) or in a separate entry on textural concentration features (Whitbread 1995, p. 386). Unfortunately, there is no obvious solution to this problem and a decision needs to be made by the analyst based on the nature of the inclusions boundaries, including the presence of ring voids, its internal microstructure, its degree of concordance with the surrounding fabric (Whitbread 1986, table 1, p. 80).

Another area of overlap is the distinction between clay mixing and temper. If temper can be defined as the "intentional addition of aplastic particulate matter to a clay paste" (Quinn 2013, p. 156), then the admixture of dry clay powder to another moist or wet source might fall into this. Temper is often added by potters to reduce the plasticity of the paste by increasing the proportion of aplastic material within it. The mixture of dry powdered clay can serve this purpose, particularly where the particles are large and/or are not sufficiently hydrated and remain as clay lumps. Indeed, the term 'clay temper' has been used in the literature to describe this process (Shepard 1964; Weaver 1963). As most clay sources contain intrinsic inclusions, the mixture of a coarse and/or inclusion-rich clay source with a finer and/or inclusion poor clay source can have a similar affect to the addition of temper by modifying the proportion of plastic to aplastic material. Plasticity is the most often cited motivation for traditional potters to mix different types of clay (Arnold 1971; Fowler 2008; Hein et al. 2004; Lister and Lister 1987, 257; London 1991; Reedy 2008, 150; Smith 2000) and the instances of lighter-coloured siltier clay mixed with darker more clay-rich material (Figure 4E) may suggest that this was also the case in the past. Perhaps in recognition of this, some authors use the term 'temper' to mean anything mixed into to clay, including both plastic and aplastic material (e.g. Rye 1976, p. 109).

Care should be taken when studying ceramics in thin section to distinguish between heterogeneity within the clay paste used to manufacture a sample and compositional variability that formed at a later date. Of particular interest is the presence of areas of calcite, gypsum or phosphate deposited in fine voids within ceramics during their burial in the ground. These can form patches and horizons (e.g. Quinn 2013, figure 6.71, p. 210) that might be confused with plastic or aplastic features of another clay type that occur in both naturally variegated clay and intentionally mixed pastes. The presence of colour differences within the clay matrix of sherds caused by uneven oxidation during firing should also be ruled out when examining heterogeneity in ceramics in thin section.

7. Conclusion

The experiments presented in this paper demonstrate the similarity between natural heterogeneity occurring in incompletely homogenised variegated clay and that resulting from the intentional mixing of two sources of compositionally distinct clay. Both can exhibit plastic features such as streaks and laminations, as well as non-plastic and semi-plastic argillaceous clay lumps and lenses. The proportions of these microstructural features are related to the degree of moisture present in the clay source(s) during mixing, the grain size of dry powdered clay, as well as the degree (method and length of time) of mixing. The experiments in this study suggest that clay lumps with internal heterogeneity are likely to be suggestive of the incomplete homogenisation of variegated clay source in a dry state. In addition, plastic features exhibited by homogenised variegated clay are more likely to be more gradational, while those in intentionally mixed pastes tend to be more ordered.

The present study has only considered the mixture of two clay sources. In cases where ancient potters combine three, four or more clay-rich ingredients (e.g. Hampe and Winter 1962; Jones 1986, p. 873; Bettina 2019), the compositional and microstructural phenomena are likely to be even more difficult to interpret in thin section. The addition of separate particulate temper material to mixed clay pastes (e.g. Tobert 1984; Tschopik 1950) will surely further complicate the reconstruction of the original ingredients. The methods used to form clay into a ceramic object are another variable that was intentionally left out of the experiments in this study. Forming is likely to deform features produced by incomplete homogenisation and intentional mixing to differing degrees, depending on the forces applied and their directions. Finally, the mixture of one or more clay source as a wet slurry has not been tested, though it can be assumed to result in more thorough homogenisation.

Clearly the topic of clay mixing is a complex and problematic one, given the many ways in which it can be carried out, the different microstructures that it can result in, the overlap between these and naturally-occurring phenomena in clay deposits and its close relationship with the practice of tempering. While the present study has not entirely clarified these long-standing issues, it has hopefully shed more light on the problem by presenting a detailed review of the topic of clay mixing and conducting much needed controlled experiments. The latter have helped defined more clearly the various features that can be encountered in both intentionally mixed and homogenised naturally heterogeneous clay sources, and the ways in which they are dependent on the moisture content of the raw material(s). It is hoped that the

detailed treatment of clay mixing can be used inform future archaeological, ethnographic or experimental studies on this important but poorly understood technological practice.

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Figure and Table Captions

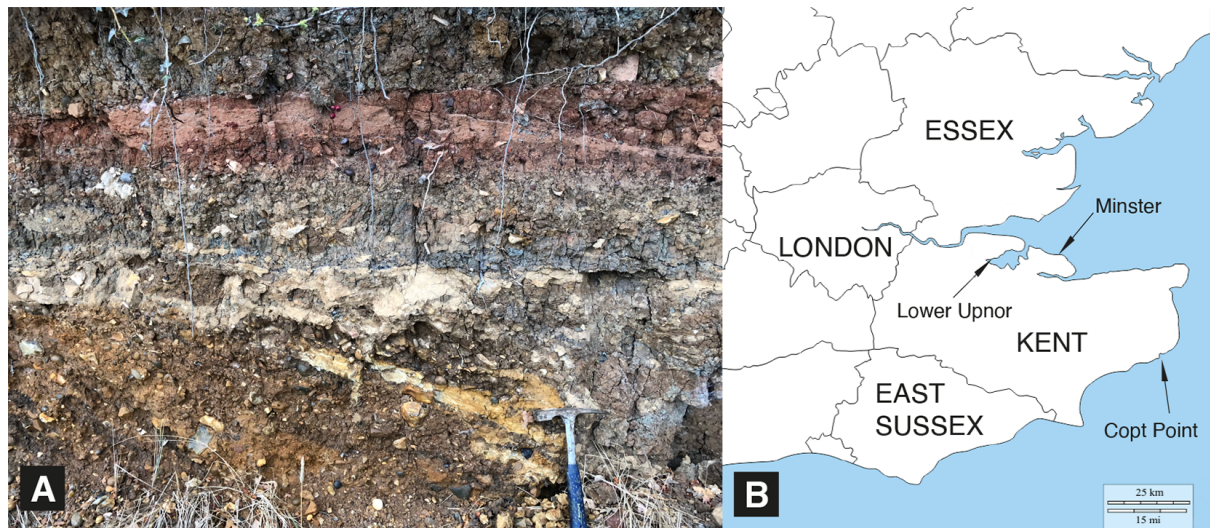


Figure 1. Map of southeastern England with clay sampling locations (A). Outcrop of the Eocene Lambeth Group at Lower Upnor, Kent.

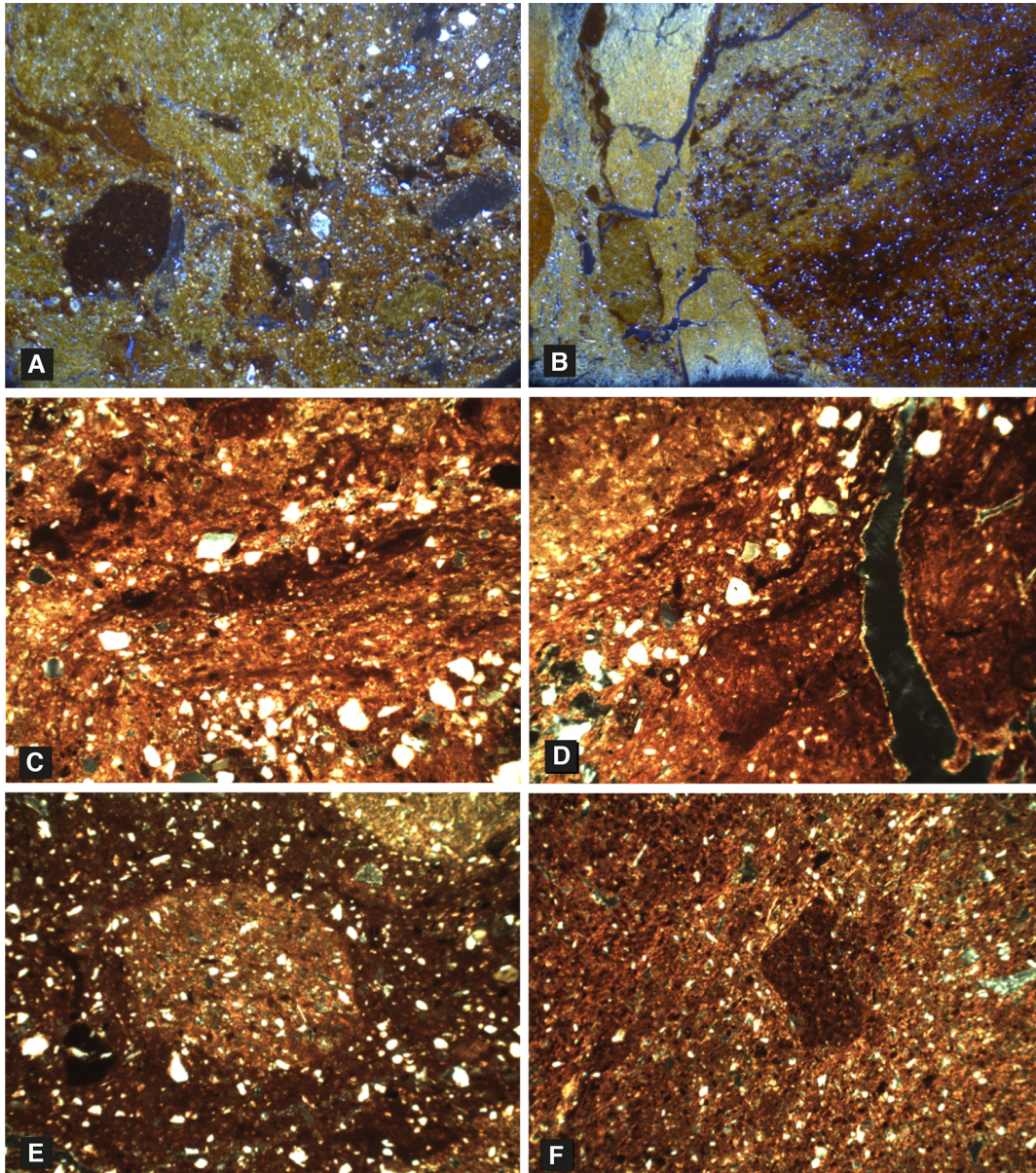


Figure 2. Photomicrographs of unprocessed variegated clay (A and B) and specimens of the same material homogenised in a moist (C and D) and dry powdered state (E and F). All images taken in crossed polars. Image width = 10.7 mm (A and B); 3.0 mm (C–F).

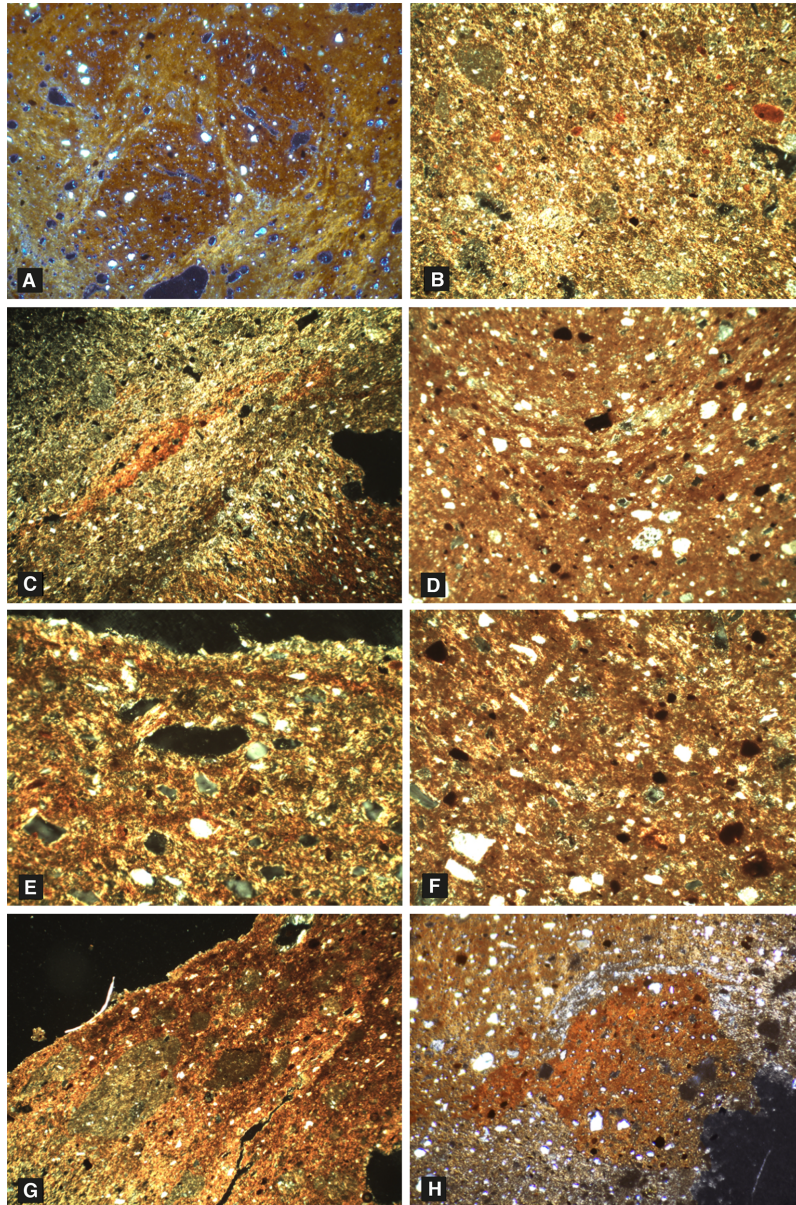


Figure 3. Photomicrographs of mixed experimental pastes. Dry-dry mixing of powdered terracotta and ball clay (A). Dry-dry mixing of powdered London Clay and Gault Clay (B and C). Moist-moist mixing of terracotta and ball clay (D and E), for extended length of time (F). Dry powdered Gault clay mixed with moist London Clay (G). Dry powdered terracotta mixed with moist ball clay (H). All images taken in crossed polars. Image width = 10.7 mm (A); 3.0 mm (B–H).

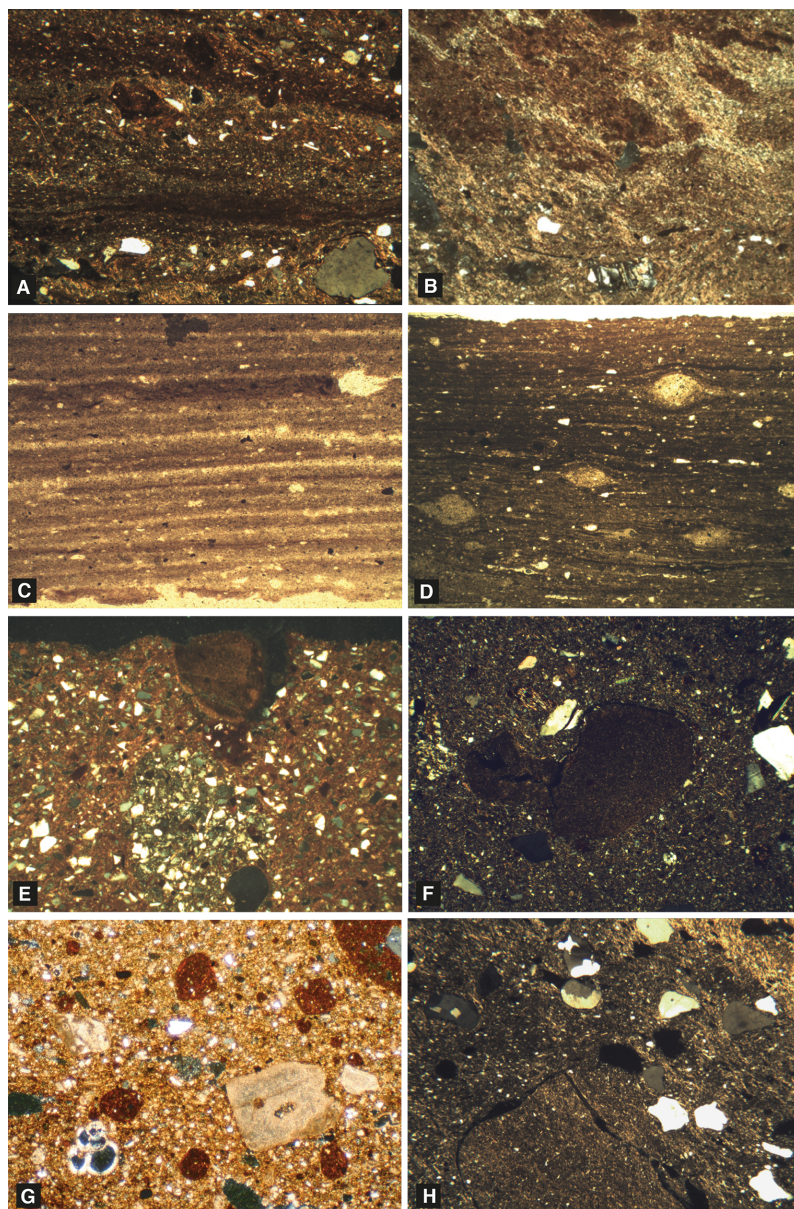


Figure 4. Photomicrographs of possible clay mixing and the use of naturally variegated clay in archaeological ceramics. Post-Medieval brick, England made from incomplete homogenisation of naturally variegated clay (Quinn 2013, fig. 3.5, p. 43) (A). Bronze Age pot, England made from incomplete homogenisation of naturally variegated clay in moist state (Cootes and Quinn (2017, fig. 5, p. 10) (B). Experimentally moist-moist mixed clay sample (Quinn 2013, fig. 6.21, p. 170) (C). Eighteenth century pot, England made by moist-dry clay (Hurley 2009, illustrated in Quinn 2013, fig. 6.22, p. 170) (D). Medieval tile, England made by dry-dry clay mixing (Quinn 2013, fig. 7.2, p. 214) (E). Qin Dynasty brick, China made by dry-dry clay mixing Quinn et al. (2017, fig. 3f, p. 970) (F). Bronze Age pot, Crete, Greece, made by moist-dry clay mixing (Day et al. 2011, fig. 4e, g and h, p. 525) (G). Argillaceous lump resulting from the incomplete hydration of powdered clay in a tempered paste made from a single clay source (Quinn 2013, fig. 6.26, p. 173) (H).

Table 1. Details of clay mixing experiments and homogenisation of naturally variegated clay in the present study. Hydrated powdered clay sources were brought to a moist state before mixing.

Table 2. Definition and illustration of terminology used in this study for clay-rich inclusions and other argillaceous features. Compare to Figures 2–4.

Table 3. Microstructural and textural observations of experimentally mixed clay pastes and homogenised naturally variegated clay under the microscope in this study. Frequent (30-50%), Common (15-30%), Few (5-15%), Very Few (2-5%), Rare (0.5-2%), Very Rare (<0.5%), Absent (0%). For definition of features see Table 3.