

Petrographic and Image Analysis of Thin Sections of Classic Wares of Song Dynasty

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Abstract Thin-section petrography, augmented by image analysis, is used to compare variation between Ru, Jun, Ding, and Laohudong Guan wares and to discern variation within each ware. Examining the sequence of sherds from low to high quality, and from underfired to correctly fired to overfired, can shed light on glaze raw materials and on differences between lesser and higher quality products. Incompletely melted batch materials in underfired Ru glazes indicate that crushed igneous rocks and clay were glaze ingredients; and low quality products lacked the biscuit firing of high quality ones. Clay was also added to Jun glazes, which are filled with phases typical of long firing and slow cooling; but firing too long or cooling too slowly produces long, thick, feathering anorthite that adversely affects the glaze appearance. The mineralogy of Ding wares indicates a high-temperature oxidized firing. Clay is often pulled up from the body through the entire width of the very thin glaze, where it nucleates anorthite. Laohudong Guan bodies are very thin, but glazes are very thick; evidence of multiple layers is sometimes, but not always, present. Underfired glazes are saturated with crystals, and differences in anorthite form differentiate underfired, high quality, and overfired glazes.

Key words thin section petrography image analysis classic wares Song dynasty

Thin-section petrography is a traditional technique for examining archaeological ceramic sherds to identify phases and characterize production processes (Reedy, 2008). Especially when modernized by newer image analysis software (Reedy et al., 2014, 2015), it remains an important tool for understanding ceramic technologies. Here this approach is applied to the study of ceramic sherds from four kiln traditions appreciated during Song Dynasty (Ru, Jun, Ding, and Laohudong Guan) (Kerr, 2004). Goals were to first understand variation between each of the four wares, to better compare them; and secondly, to discern variation within each ware to understand the intent and results of potters and kiln managers as they aimed to produce the highest quality products but often fell short due to difficulties in controlling raw material preparation, fabrication methods, and firing conditions.

For this second goal, a crucial technique is to examine the sequence of thin sections within a ware starting from underfired sherds, to correctly fired ones of higher quality, and then to overfired sherds. Since achieving the highest quality products requires careful actions with materials and technologies that may be difficult to

control precisely, variation is difficult to avoid. Variation is assessed by examining differences in porosity, mineralogy, and the size, amount, and distribution of phases.

1 Materials and methods

The Palace Museum Ancient Ceramics Laboratory provided 51 archaeological sherds, supplemented by an additional 6 from Dr. Pamela Vandiver of the University of Arizona. The sherds included 22 Ru, 15 Jun, 12 Ding, and 8 Laohudong Guan. All 57 were cut and prepared as standard (30 μm -thick) thin sections, with blue-dyed epoxy to highlight pores. In some cases ultrathin sections (15 μm) were also made to enhance study of the smallest minerals in the ceramic bodies.

Minerals and textures of the bodies and glazes were identified via transmitted polarized light microscopy. Thin sections were also scanned in a high-resolution film scanner (5 μm /pixel resolution) for image analysis using entire thin sections. Image analysis of ceramic bodies measured Total Optical Porosity (area % occupied by pores) and the percentage of silt and sand particles, along with a variety of size and shape parameters. Body and glaze thickness, percentage of glaze area occupied by bubbles, and the maximum bubble size were also measured.

All quantitative data from image analysis and presence-absence data from qualitative microscopy were statistically analyzed by analysis of variance and cross-tabulation to identify any significant differences.

2 Results and discussions

2.1 Ru

The analysis highlights some technological aspects of Ru sherds that distinguish them from the other three wares, as well as differences between lower and higher quality Ru examples. While the percentage of Total Optical Porosity does not differ significantly among the four wares, the Ru group does show larger pore size overall. The lower quality Ru sherds vary more in pore shape, implying the higher quality ones were more consistently prepared, wedged, and fired. The higher quality sherds also have more silt and sand and the bodies are thinner.

Few Ru bodies have cracked quartz grains; this may indicate gradual temperature rise during firing. There are indications of a relatively lower firing temperature for Ru in the glaze mineralogy: abundant quartz but few examples with cristobalite; 40% have incompletely melted batch materials visible in the glaze (including still-angular quartz, some incompletely dissolved feldspars, and chunks of clay) (Fig. 1). It has been proposed that crushed igneous rock might have been an ingredient of Ru glazes, with clay added for extra alumina (Wood, 1999). The incompletely melted batch materials found here support that hypothesis.

In some glazes, anorthite needles appear as segregated swirled lines, surrounded by clear (anorthite-free) glass (Fig. 2); these appear in 40% of the higher quality sherds and are not present in the lower quality ones. This

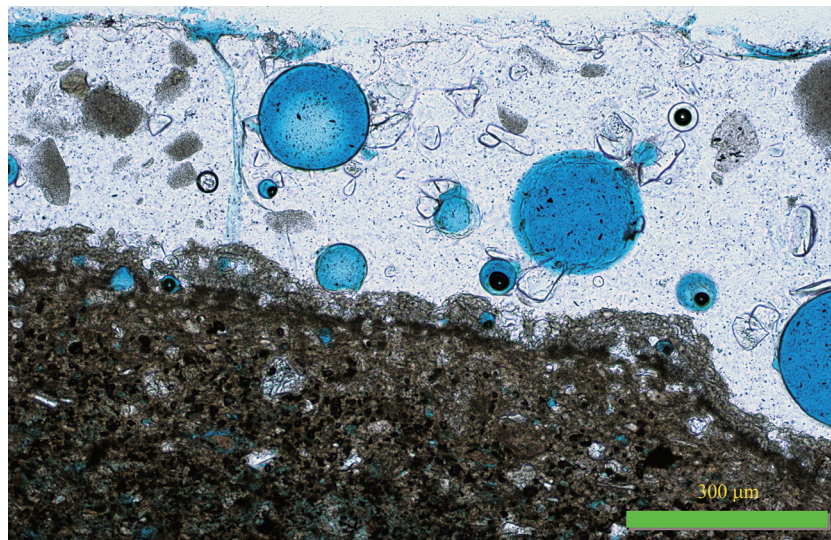


Fig. 1 Incompletely-melted batch materials in a lower-quality Ru glaze

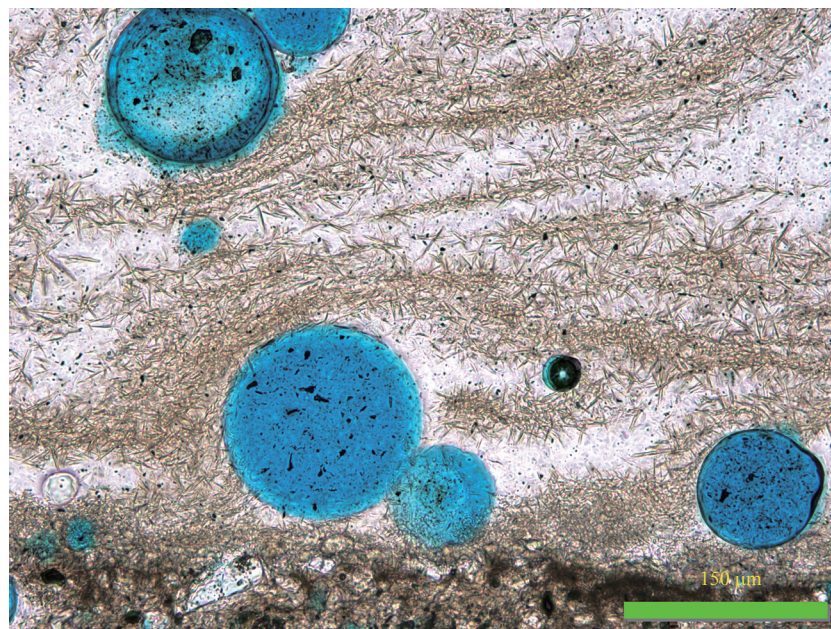


Fig. 2 Swirled lines of anorthite surrounded by clear glass in a high-quality Ru glaze

pattern indicates heterogeneous nucleation; perhaps the feldspars or clay that appear to have been part of glaze ingredients were relatively coarse and melted in place and formed anorthite-rich areas. In contrast, in unpatterned ones, anorthite grains randomly dot or fill large areas of the glaze, indicating more homogeneous nucleation resulting from raw materials that were pre-melted, ground, and then applied, or were more finely ground.

Many low quality glazes (Fig. 3) have no anorthite, or only rare grains, so unsuccessful nucleation. Most of the low quality sherds also have clay pulling up into the glaze from the body (Fig. 3). This is an indication that no biscuit firing was done; the clay was still wet when the glaze was applied. In contrast, this is very rare for the high quality examples.

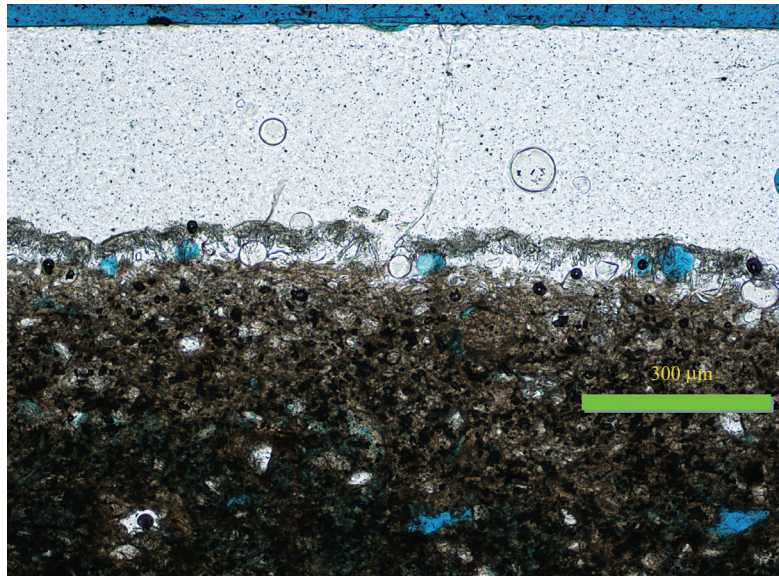


Fig. 3 Lower-quality Ru sherd with clay pulling up into the mostly crystal-free glaze

2.2 Jun

The Jun ceramic bodies are distinct from the others in having a significantly lower silt and sand content overall, yet the sand grains of this group show the largest maximum size. Mullite is frequently present, often in patches of long needles or thick rods, sometimes surrounding pools of silica glass. The bodies are thicker than in the other wares, covered by a glaze that is thicker than Ru or Ding glazes, but not as thick as Laohudong Guan ones.

Cristobalite is often abundant in the Jun glazes. While there is still some incompletely melted quartz in low-quality glazes, often all but the center of the grain has been converted to cristobalite (Fig. 4). This cristobalite is evidence of the long firing time and slow cooling that produces the optical effects of Jun ware

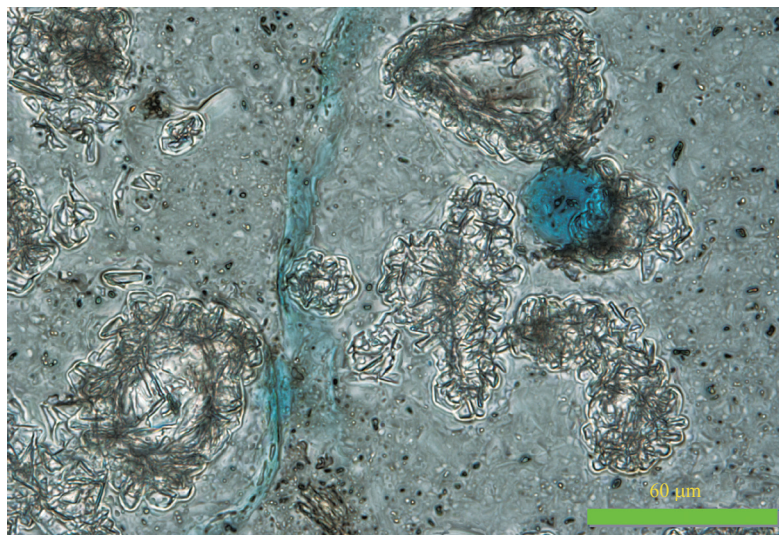


Fig. 4 Quartz cores with cristobalite edges, in a lower-quality Jun glaze

(Kingery and Vandiver, 1986). Wollastonite also tends to be prominent, and the Jun glazes have the largest maximum bubble size of the four wares.

Two other glaze characteristics distinguish Jun wares. Visible color swirls or large spots (Fe and Cu) are found in 60% of the Jun glazes and 40% have a dendritic feathery formation of anorthite intergrown with hematite (Fig. 5).

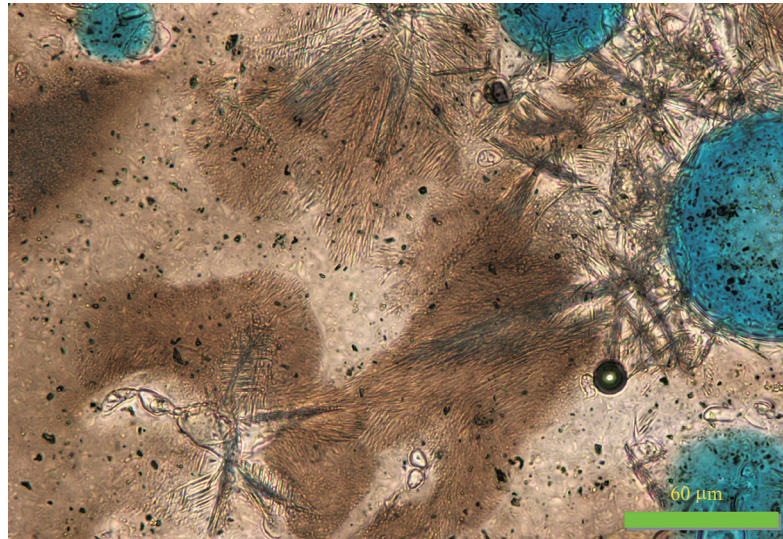


Fig. 5 Feathery, dendritic anorthite intergrown with hematite, in an overfired Jun glaze

Extensive and large anorthite crystals, feathering on the ends, filling the glaze randomly without any pattern, marks a significant difference between lower and higher quality Jun glazes (Fig. 6). They occur in two-thirds of the lower-quality and none of the higher-quality examples; firing for too long and/or cooling too slowly creates anorthite needles that are very long and thick, affecting the glaze appearance.

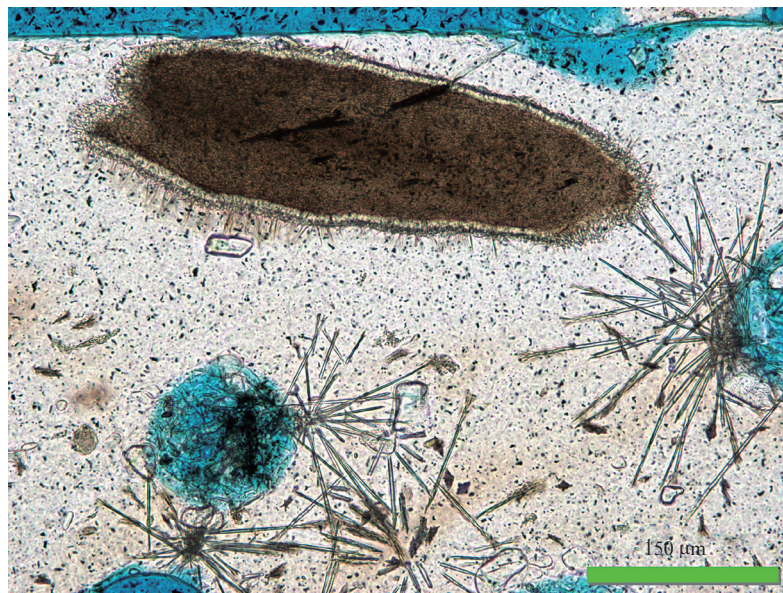


Fig. 6 Large lump of clay in low-quality Jun glaze; tabular anorthite along its edge forms small needles as it interacts with the glaze. Clumps of long anorthite needles, feathering on the ends, randomly fill the glaze

Some of the sherds still have many, and sometimes quite large, lumps of clay in the glaze (Fig. 6). The edges of these clumps are always lined with anorthite, in a thick, wormy, tabular form that becomes needle-like as it interacts with the glaze. Clay may provide nucleation sites for anorthite, and perhaps also for wollastonite, and bring iron into the glaze.

As with many of the Ru examples, we sometimes see the upper edge of Jun bodies being pulled up into the glaze. This would indicate that sometimes the glaze was applied without a biscuit firing, with the outer edge wet enough to pull up.

2.3 Ding

Interestingly for a white ceramic, one-half of the Ding sherds have abundant hematite in the body, highlighting the presence of an oxidizing firing atmosphere (Kerr and Wood, 2004). Also connected with firing regimes is the presence of glass solution rims around the edges of many quartz grains in the body (Fig. 7), not seen in the other three groups where cristobalite more commonly lines the edges of quartz. As with the Jun group, extensive mullite growth throughout the body is common (Fig. 7).

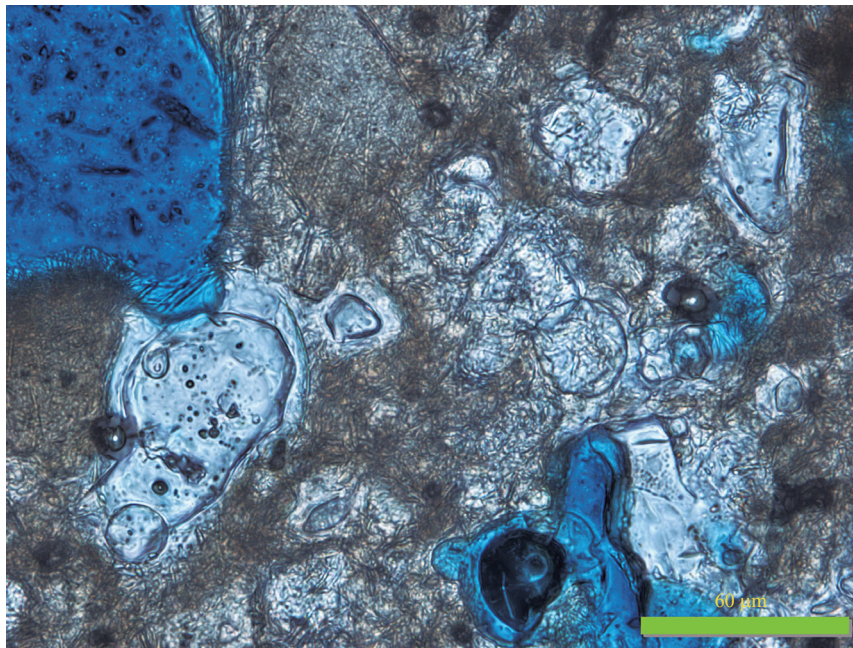


Fig. 7 Quartz grains (some partially converted to cristobalite in the centers) surrounded by glass solution rims in a high-quality Ding body; tiny rods of mullite cover feldspar relics and the clay matrix

Ding sherds have a much thinner glaze application than do the other wares. The ceramic body, however, is not correspondingly thin. In fact, overall, the Ding bodies are thicker than all but those of the Jun group.

Some underfired examples have incompletely dissolved raw materials still visible in the glaze, including incompletely melted quartz and feldspars. Chunks of clay are also seen, which might at first glance imply that clay was another glaze raw material. However, the thinness of the glaze implies a different story. In many cases it appears that the clay entered the glaze by being pulled up from the body where it then nucleates anorthite

needles (Fig. 8). This often happens only in patches here and there and not extensively over the entire glaze area. Clearly this would have an effect on the optical qualities of the glaze.

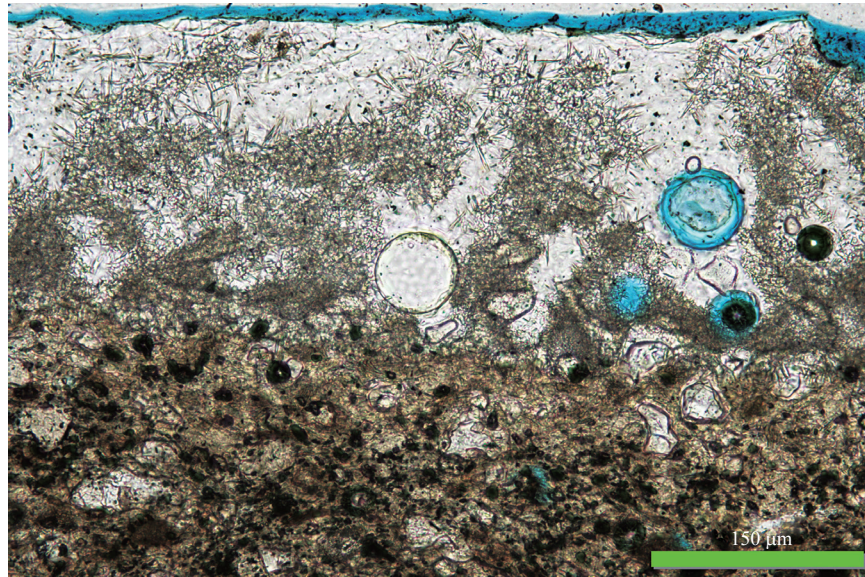


Fig. 8 High-quality Ding sherd with clay pulled up from the body into the thin glaze

In other cases, the clay itself did not move up into the glaze, but anorthite originating at the interaction layer grew so long in some patches that it actually reaches the surface of the very thin glaze (Fig. 9). Perhaps these anorthite patches growing the full length of the thin glaze created somewhat the same optical effects as the patches of anorthite-nucleating clay pulled into the glaze provided.

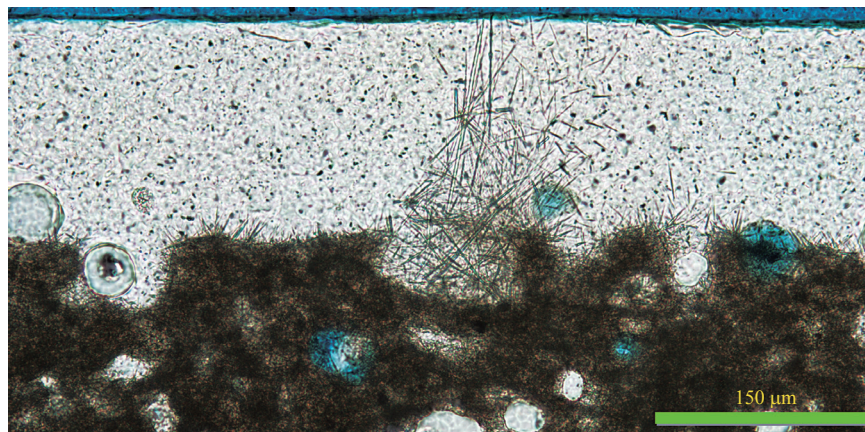


Fig. 9 An isolated patch of anorthite extending from the body to the surface through the full length of the thin glaze in this high-quality Ding example

Many of the glazes, including the highest quality ones, have many quartz remnants, some quite large. Their size is actually rather startling given the thinness of the glaze. Some of the quartz appears to have been dragged upward from the body along with clay in the many cases in which clay was pulled up into the glaze. Most often, that quartz is in the process of converting to cristobalite along the edges, with the core still remaining partially or wholly alpha quartz.

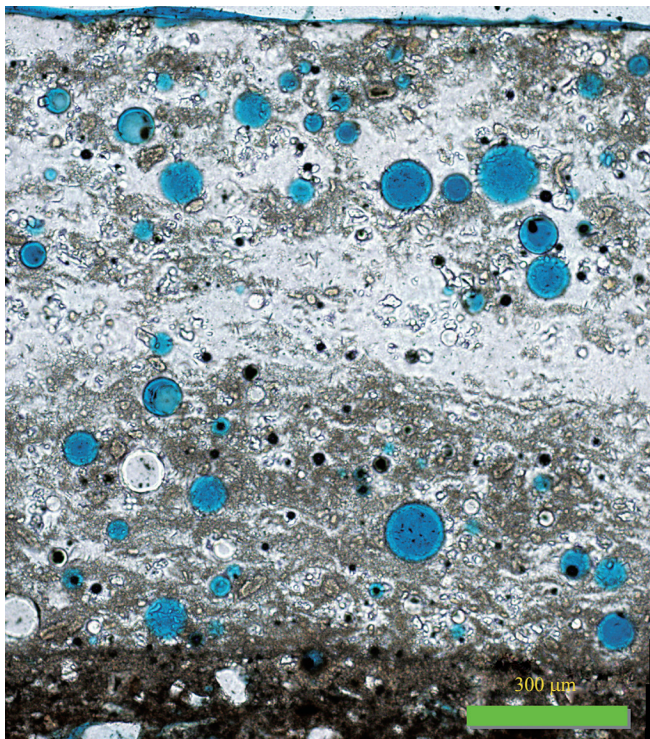


Fig. 10 Underfired Laohudong Guan glaze showing evidence of multiple-layer application

2.4 Guan

Guan bodies are the thinnest of all four groups, in spite of the fact that the glazes are by far the thickest. It is often said that Guan glazes were applied in multiple layers (Kerr and Wood, 2004; Wood and Li, 2015). If there were a biscuit firing, then dipping in glaze and firing, followed by dipping in glaze again and a final firing, we would expect to see glass between the layers. We would also expect more crystals to nucleate and grow in the first layer, rather than the second layer to be applied. Both features are visible in some cases (Fig. 10). But evidence for the application of multiple layers is lacking in other sherds, including the highest quality one in the group, which has a more homogeneous distribution of crystals and glass in the glaze (Fig. 11).

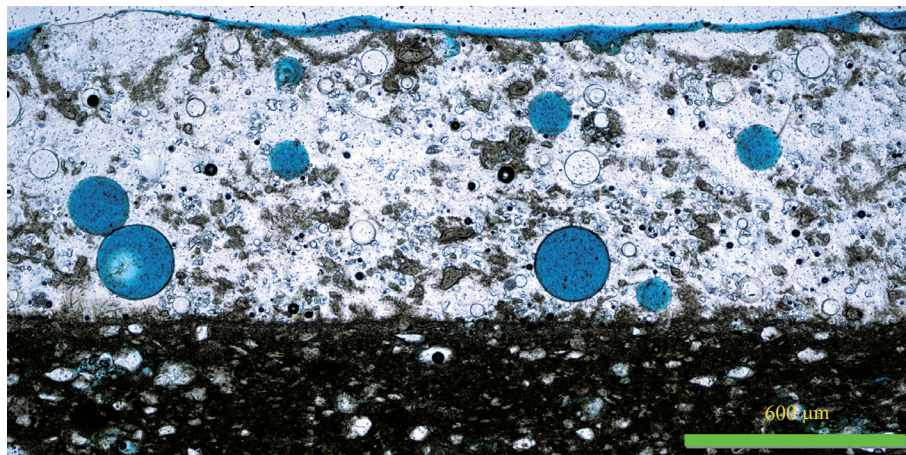


Fig. 11 High-quality Laohudong Guan glaze with no visible evidence for multiple layers

Many of the sherds available for analysis in this group were underfired. This provides an opportunity to study raw materials, and supports past hypotheses that Guan glazes were made by underfiring coarsely-ground raw materials (Vandiver and Kingery, 1985). Here underfired glazes are filled with a heavy saturation of crystalline material (Fig. 10) including quartz, granular anorthite, small anorthite rods, and needle-like anorthite, sometimes rather long. The highest quality glaze in this group (Fig. 11) has a medium saturation of crystalline material that is a mix of quartz, cristobalite, granular anorthite, tiny anorthite rods, and many patches of small needles; the firing and cooling regime prevented long

anorthite needles from developing, even at the interaction zone. The one overfired piece in the group (Fig. 12) has a very glassy glaze with much less crystalline material. Much, but not all, of the quartz and cristobalite melted and formed glass, and the anorthite that is present is only in the form of needles; granular anorthite is no longer present.

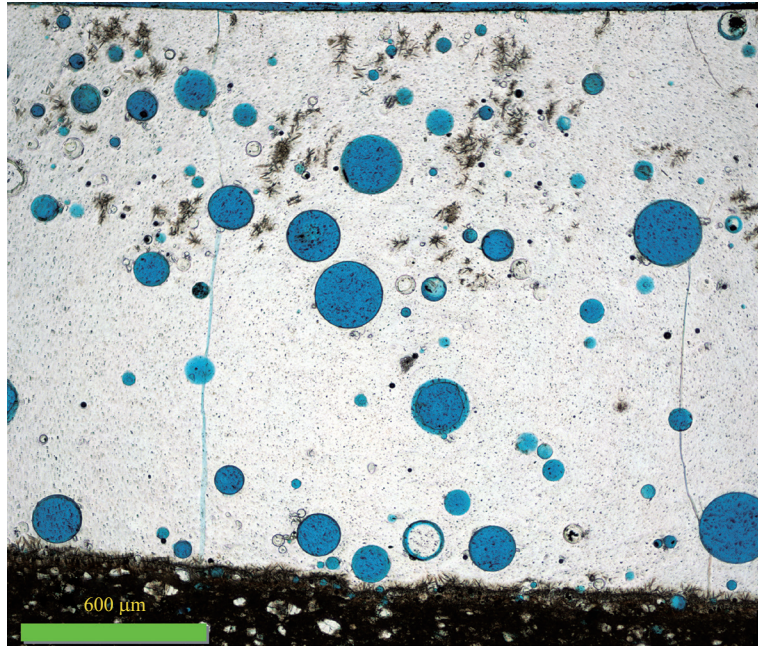


Fig. 12 An overfired Laohudong Guan glaze is glassy; most quartz and cristobalite grains have melted, and the small patches of anorthite are needle-like rather than granular in form

Conclusions

Thin-section petrography provides a range of useful information about raw materials and technological processes of glazed ceramics. New insights and additional evidence for existing theories come from using both traditional microscopy and emerging methods of image analysis; combining qualitative and quantitative data with statistical tests that help identify significant variations; and examining differences in low and high quality products that are underfired, correctly fired, and overfired.

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