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ARTICLE

The Right Red: Comparing Red Pigment Hues with CIELAB

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Abstract

During the seventeenth and eighteenth centuries, women from Northern Rio Grande pueblos joined Ndee communities in western Kansas, where they made a local version of unpainted Tewa red ware. We investigate potential slip materials in the eastern High Plains and adjacent Central Plains, using CIELAB color data to graph red hue variation in collected pigments and slipped archaeological ceramics from 14SC1 and 14SC304. Although use of the CIELAB color system by archaeologists is well established, our approach is unique in its use of a* and b* graphs to describe and compare hue. Our graphs illustrate hue variation between red and yellow on the color wheel, facilitating comparisons and communicating color patterns more effectively than is possible using the Munsell system. We demonstrate that potters could have reproduced the red hues of Northern Rio Grande red ware in the different geological landscape of the Great Plains. Our collected pigments systematically vary in hue by geological formation or system. Two sampled geological formations in the eastern High Plains and adjacent Central Plains include pigments that fire to the "right" red, or the red hues of Northern Rio Grande red slips, and potters may have used one or both.

Resumen

Durante los siglos XVII y XVIII, las mujeres de los pueblos del norte de Río Grande se unieron a las comunidades Ndee en el oeste de Kansas, donde fabricaron una versión local de la cerámica roja Tewa sin pintar. Investigamos los posibles materiales de engobe en las Altas Llanuras orientales y las Llanuras Centrales adyacentes, utilizando datos de color CIELAB para graficar la variación del tono rojo en pigmentos recogidos y cerámicas arqueológicas engobadas de 14SC1 y 14SC304. Aunque el uso del sistema de color CIELAB por los arqueólogos está bien establecido, nuestro enfoque es único en su uso de gráficos a* y b* para describir y comparar el tono. Nuestros gráficos ilustran la variación de tonalidad entre el rojo y el amarillo en la rueda cromática, facilitando las comparaciones y comunicando los patrones de color de forma más eficaz que con el sistema Munsell. Demostramos que los alfareros podrían haber reproducido los tonos rojos de la cerámica roja del norte de Río Grande en el diferente paisaje geológico de las Grandes Llanuras. Nuestros pigmentos recogidos varían sistemáticamente en tonalidad según la formación geológica o el sistema. Dos formaciones geológicas muestreadas en las Altas Llanuras orientales y en las Llanuras Centrales adyacentes incluyen pigmentos que despiden el rojo «correcto», o los matices rojos de los engobes rojos del Norte de Río Grande, y los alfareros pueden haber utilizado uno o ambos.

Keywords: CIEL*a*b* color space; color measurement; Pueblo-Plains interactions; pigment; slip

Palabras clave: espacio de color CIEL*a*b*; medición del color; interacciones Pueblo-Planos; pigmento; engobe

Red is a color of immense power in Native North America, and "red paint is considered one of the most powerful animating substances in the universe" (Zedeño 2009:412). Throughout the Puebloan Southwest, Great Plains, and Midwest, red is a color that denotes the sun, life, blood, and war (Diaz-Granados 2015; Diaz-Granados and Duncan 2000; Fletcher and La Flesche 1911; Munson 2020; Murie 1981). It is the color of sacred Minnesota pipestone quarried in and around Pipestone National Monument, widely exchanged across the continent (Buffalohead 2004; Hughes 1995; Scott et al. 2006).

Approximately 1,000 years ago, craftspeople at Cahokia worked with red flint clay from Missouri's Ozark Highlands, carving human figures that circulated throughout the Mississippian world (Emerson and Hughes 2000; Emerson et al. 2002, 2003). Seventeenth-century migrants from the Northern Rio Grande region valued red-slipped ceramics enough to reproduce them in the eastern High Plains (Beck et al. 2016; McGrath et al. 2017).

"Red" is rarely just red, however—it varies in hue, which relates a color to the principal colors of red, yellow, green, and blue (Cleland 1921). Certain reddish hues may be favored over others, as with the "strong reds" of Middle Pleistocene ochre in southern Africa (Watts 1999:127) or the vivid reds of textiles dyed with cochineal (Greenfield 2005). Hue may vary by source and its underlying mineralogy (Wisseman et al. 2012), rendering the source visible and contributing to the meaning the pigment carries (e.g., Beck et al. [2022] and Lozier [2017] on ochre and vermilion). We focus on red hue variation in this article and present a new approach to graphing color data from the CIELAB (Commission internationale de l'éclairage [International Commission on Illumination] L*a*b*) three-dimensional color space system (CIE 2004). We argue that graphs of a* and b* effectively convey hue variation between red and yellow on the color wheel, facilitating comparisons between archaeological objects, potential source materials, and Munsell colors.

Red hue variation can be challenging to describe and evaluate. Munsell color observations (Munsell 1915; Munsell Color 2000), which require a human observer to visually compare colors with Munsell color chips, are the standard approach to recording slip, paint, and clay colors, as well as soil colors (e.g., Beck 2006; Cordell et al. 2017; Eiselt et al. 2011; Shepard 1985; Turk and Young 2020; see also Bloch et al. 2021). Some shades of red are particularly difficult for the human eye to distinguish (Martínez et al. 2001), however, and color perception varies due to lighting, moisture, luster, and physiological differences between human observers (Frankel 1980; Post et al. 1993; see discussions in Bloch et al. 2021; McGrath et al. 2017). Munsell color groups used in oxidation analyses (e.g., Beck 2006) express color similarity and difference but present data in nominal categories and require a human analyst to decide group membership. Munsell colors must also be converted into Cartesian coordinates before they can be graphed or used in statistical analyses (D'Andrade and Romney 2003; Ruck and Brown 2015).

Here we use CIELAB color data to graph red hue variation in collected pigments and ceramic slips in the Great Plains, building on our previous use of CIELAB to characterize slip color (McGrath et al. 2017). The CIELAB color system (CIE 2004; Fairchild 2005; Hunt and Pointer 2011) defines colors in three dimensions: a* (red-green coordinate), b* (blue-yellow coordinate), and L* (lightness). Like Munsell colors, CIELAB data represent hue, chroma, and lightness or value (McGrath et al. 2017; Munsell Color 2000). The a*, b*, and L* coordinates may be collected from digital photographs (e.g., Bernatchez 2012; McGrath et al. 2017; Oestmo 2013) or with an instrument such as a spectrophotometer or color meter (e.g., Wisseman et al. 2012). Either approach avoids human observer variation in recording color and enables color measurement from small areas, facilitating analysis when slip preservation or visibility is limited.

Throughout this article, we consider pigments not just as colorants (Rapp 2009) but specifically as mineral colorants also labeled as "ochre" (Beck et al. 2022). We sampled red or red-firing pigments from geological contexts in our study area, targeting material with sufficiently high clay content to be mixed with water to make slip (Rye 1981). The collected pigments could also have been used as paint, which covers less of the vessel surface. Paints do not always use pigments with high clay content, although less clay necessitates the addition of a binder (Eiselt et al. 2011; Rye 1981; Shepard 1985; see discussion in Beck et al. 2024).

We start below by introducing our study area in Scott County, western Kansas, focusing on two seventeenth- or eighteenth-century archaeological sites (14SC1 and 14SC304) along Ladder Creek (Figure 1). We then describe our pigment collection strategy and the small archaeological ceramic sample, which includes both Ledbetter Red (a version of unpainted Tewa red ware produced by Puebloan potters after their move to the eastern High Plains) and red-slipped ceramics made in the Northern Rio Grande region (Beck et al. 2016; McGrath et al. 2017). After presenting our methods for recording CIELAB data, we compare the collected pigments with each other and with the red-slipped ceramics to

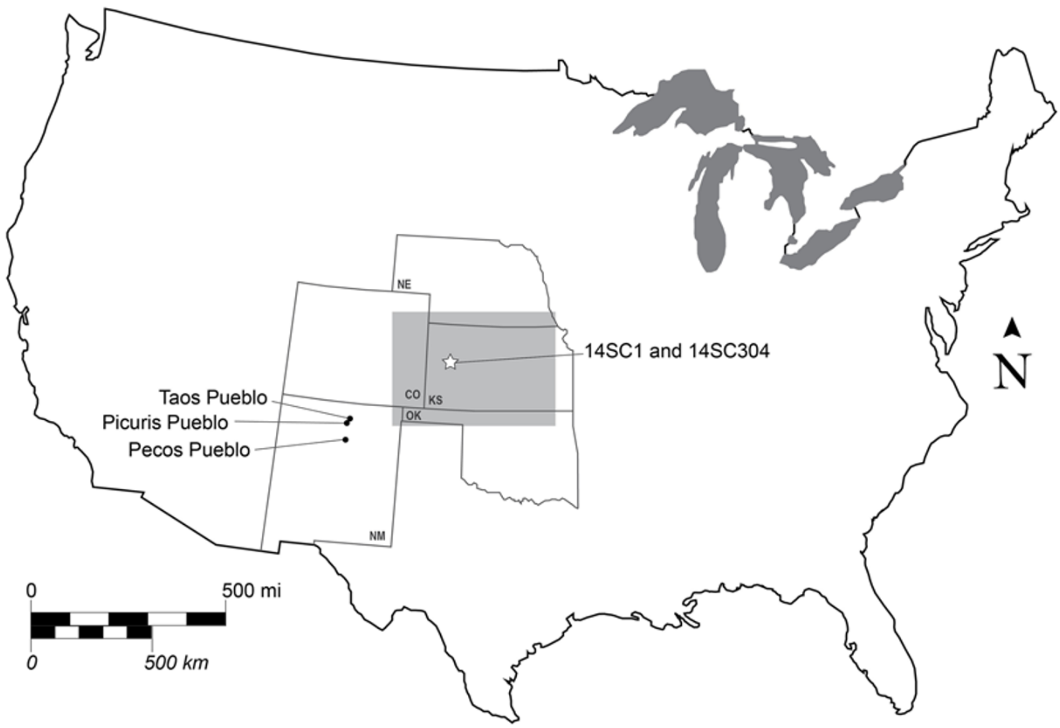

Figure 1. Location of the study area. The shaded area represents the geological map in Figure 2.

determine which, if any, of the Great Plains pigments are similar in hue to the slips and could have been used to make Ledbetter Red.

Although use of the CIELAB color system by archaeologists is well established for multiple material classes (e.g., Chenoweth and Farahani 2015; Devlin and Herrmann 2015; Mödlinger et al. 2017), our approach is unique in its use of a* and b* graphs to describe and compare hue. These graphs represent where a measured hue falls around the color wheel between red and yellow. Some materials are more red or more yellow, and graphs convey this relative assessment to an audience who cannot see the colors in person. Here we find that our collected "red"-firing pigments systematically vary in hue, plotting along a line with a characteristic slope and intercept for each geological formation or system. Two sampled geological formations include pigments that fire to the "right" red, which we consider to be the graph area around Northern Rio Grande red ware. Western Kansas potters at least occasionally reproduced the red slip colors of Northern Rio Grande red ware on Ledbetter Red and could have done so using materials from the Great Plains. They also may have experimented with slip materials from multiple geological formations, suggesting part of the landscape learning process (Rockman 2003) for Puebloan potters in a new region.

The Study Area and Sample

During the seventeenth and eighteenth centuries, women and perhaps entire families from Northern Rio Grande pueblos joined Ndee (non-Navajo Apache) communities in western Kansas, including the community at 14SC1 (Beck 2022; Beck and Trabert 2014; Beck et al. 2016, 2023; Hill and Trabert 2018; Hill et al. 2018, 2022; Trabert 2015, 2017, 2018; Trabert et al. 2016, 2022, 2023; Wilfong and Hill 2022). The Ndee occupation of 14SC1, which appears archaeologically as the Dismal River complex, began sometime in the early fifteenth century or later. In the early seventeenth century, people from one or more North Rio Grande pueblos joined the local Ndee residents at 14SC1 and built a seven-room masonry pueblo. After the pueblo was closed in the period AD 1645–1680, some Puebloan people or their descendants apparently moved to nearby Ndee sites such as 14SC304.

Potters in the seventeenth- and eighteenth-century Puebloan world, including those who had moved to the eastern High Plains, made unpainted red-slipped ceramics (Beck et al. 2016). In the Española Basin after AD 1600, Tewa-speaking potters made unpainted Tewa Red ceramics with a "bright red to maroon" slip (Wilson 2011:225) and used a similar red slip for painted Tewa Polychrome (Wilson 2010). Potters at other Northern Rio Grande communities also made unpainted red-slipped ceramics, known simply as Plain Red at Pecos Pueblo (Kidder 1936; Schaafsma 2002; Shepard 1936; Warren 1976, 1977; Wilson 2010). Petrographic analysis confirms that a few Tewa Red and Tewa Polychrome ceramics from the Española Basin made their way to 14SC1, as did Plain Red ceramics probably from the area of Pecos Pueblo (Beck et al. 2016).

Ledbetter Red ceramics made in the eastern High Plains contain arkosic sand with occasional grains of tuff, pumice, basalt, and caliche, a range of inclusions found in sand deposits originating from the Tertiary Ogallala formation. The slip of Ledbetter Red ceramics is often brownish in color rather than red, particularly at 14SC1, although slips redden when refired (Beck et al. 2016:Tables 1, 2, 5). Even at 14SC304, however, where potters oxidized red slips more consistently, a previous CIELAB analysis found a "subtle difference in hue" between red slips on Ledbetter Red and those on Tewa Red, Tewa Polychrome, and Plain Red ceramics recovered in our study area (McGrath et al. 2017).

Nineteenth- and twentieth-century Puebloan potters had *chaînes opératoires* that included slip materials from specific geological contexts, such as red-firing shales (Blair and Blair 1999; Dillingham 1999; Guthe 1925; LeFree 1975). We assume that at least the earliest Puebloan potters in western Kansas wanted to reproduce the red hues of Northern Rio Grande slips as closely as possible. They would have found that their prior locational knowledge (Rockman 2003) about slip materials did not transfer well to this new landscape dominated by Quaternary alluvium, Tertiary cemented calcium carbonate, Ogallala formation gravel eroded from the Rocky Mountains, and Cretaceous chalk (Bradley and Johnson 1957). As archaeologists, we were certainly confused about possible slip materials here, given our expectations for Puebloan slip choice from the ethnographic record. Because no red or yellow (red-firing) shales outcrop within a 100 km radius of 14SC1 and 14SC304, we expanded our pigment search up to 200 km or greater from the sites (Figure 2).

Pigment Collection and Preparation

Our pigment collection began by identifying geological formations with surface exposures in the eastern High Plains and adjacent Central Plains (see Figure 2), including those shown on interactive Surficial Geology of Kansas map (https://maps.kgs.ku.edu/state_geology/). We then searched those formation descriptions (Hattin 1982; Merriam 1963; Zeller 1968) for possible sources of iron oxides or iron-rich clays, looking specifically for references to red or purple shale or mudstone, iron oxides, hematite, limonite, or ironstone. These search terms were chosen based on previous ethnographic and archaeological descriptions of red-firing slip and paint raw materials (Beck et al. 2022, 2024; Blair and Blair 1999; Dillingham 1999; Eiselt et al. 2011; Wilson and Severts 1999).

Our search of formation descriptions identified possible sources of iron oxides or iron-rich clays in both the Cretaceous and Permian systems. In the Cretaceous system, these include multiple members of the Pierre Shale in the Montana Group (limonite and clay-ironstone concretions), the Smoky Hill Member of the Niobrara Chalk in the Colorado Group (limonite), the Blue Hill Shale Member of the Carlile Shale in the Colorado Group (clay-ironstone concretions), the Graneros Shale in the Colorado Group (clay-ironstone concretions), and the Dakota formation in the Dakota Group (red claystone, mudstone, and shale and iron oxide concretions [Hattin 1962, 1982; Merriam 1963; Zeller 1968]). In the Permian system, possible slip materials include red beds such as the shales in the Nippewalla Group (Zeller 1968). Within a 200 km radius around 14SC1 and 14SC304, the only sources of red-firing claystone, mudstone, or shale—materials most similar to slip materials in the Northern Rio Grande region—are in the Dakota formation and Permian system. All other possible slip raw materials are limonite or clay-ironstone concentrations within shale or chalk.

As shown in Figure 2, the closest potential deposits of iron oxides or iron-rich clays are in the Cretaceous Colorado Group, including the Niobrara Chalk, Carlile Shale, and Graneros Shale (a minimum of 7 km from 14SC1) and the Cretaceous Montana Group including the Pierre Shale

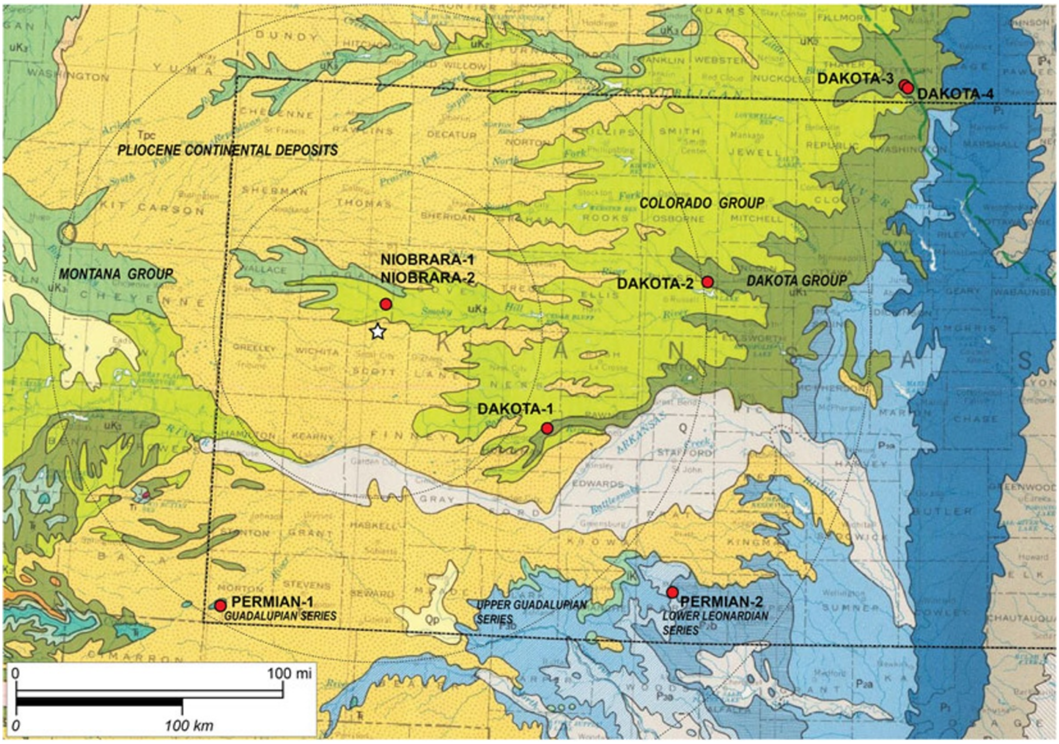

Figure 2. Location of collected geological samples. The mapped bedrock geology (King et al. 1974) appears courtesy of the US Geological Survey. The dashed circles represent the 100 km, 200 km, and 300 km radii around sites 14SC1 and 14SC304.

(a minimum of 24 km from 14SC1). The Dakota Group is more distant (a minimum of 111 km from 14SC1). Permian formations are located at a minimum of 166 km from 14SC1.

After identifying formations with possible sources of iron oxides or iron-rich clays, we reviewed geological literature for relevant field trips to target specific exposures for sampling (Table 1). We collected samples in a series of trips between May 2021 and May 2023. Not all identified exposures of our target formations contained iron oxides or iron-rich clays. For example, although we located surface exposures of Pierre Shale (Montana Group) in Logan County (see Figure 2), we did not find any limonite or clay-ironstone concretions in these exposures and therefore did not collect any Pierre Shale samples. Of the remaining Cretaceous identified possible sources, we prioritized the Niobrara Chalk and the Dakota Formation because they are highlighted as "Ocher Deposits in Nebraska" (Burchett 1991) for their commercially viable amounts of iron oxides. The Dakota Formation is also mined commercially for brickmaking (Brenner et al. 2000; Gould 1899–1900; Joeckel et al. 2008; Kinney 1942; Plummer 1959), which significantly increased the available geological data for this formation.

This study includes eight geological pigments collected from the Smoky Hill Member of the Cretaceous Niobrara Chalk (Colorado Group), the Cretaceous Dakota Formation (Dakota Group), and Permian red beds (Guadalupian and Leonardian series). All samples are soft enough to be easily ground by hand in a porcelain mortar and pestle. Each Niobrara, Dakota, and Permian sample in this study was ground and mixed with water and then applied as a slip to two test tiles (Figure 3; Table 2). One test tile was burnished with a rock to create a polished surface, and the other was left with a matte finish. All tiles were fired in a Fisher Scientific Isotemp Muffle Furnace to 800°C, a temperature chosen for consistency with other pigment studies (e.g., Eiselt et al. 2011).

Archaeological Ceramics

Slipped and/or painted ceramics overall are rare at 14SC1 (n = 98; 0.3% of ceramics) and 14SC304 (n = 50; 6% of ceramics; Trabert et al. 2022:Table 9.3). We collected CIELAB data on nine sherds

Table 1. Geological Pigment Samples.

Sample ID	Period	Formation or Group	County	References
Niobrara−1	Cretaceous	Niobrara, Smoky Hill member	Logan Co., KS	Johnson 1958; Hattin and Siemers 1987
Niobrara−2	Cretaceous	Niobrara, Smoky Hill member	Logan Co., KS	Johnson 1958; Hattin and Siemers 1987
Dakota−1	Cretaceous	Dakota	Hodgeman Co., KS	Johnson and Woodburn 2012
Dakota−2	Cretaceous	Dakota	Russell Co., KS	Berry 1952; Buchanan et al. 1990
Dakota−3	Cretaceous	Dakota	Jefferson Co., NE	Beck et al. 2022; Joeckel et al. 2008; Pabian 1977 [Exp 3]
Dakota−4	Cretaceous	Dakota	Jefferson Co., NE	Beck et al. 2022; Joeckel et al. 2008; Pabian 1977 [Exp 5]
Permian−1	Permian	Big Basin, Guadalupian series	Morton Co., KS	Johnson et al. 2009; Sawin 2016; Smith et al. 2015
Permian−2	Permian	Flower-pot Shale (?), Nippewalla Group, upper Leonardian series	Barber Co., KS	Buchanan and McCauley 1987:46–51; McCauley 2007; West et al. 2010

from 14SC1, including Ledbetter Red, Tewa Red, Tewa Polychrome, and Plain Red ceramics (Figure 4; Table 3). We intentionally selected Ledbetter Red sherds with slips that appeared most similar in color to the Tewa Red slips. Two sherds in the 14SC1 sample (one Ledbetter Red and one Plain Red) were refired in a previous oxidation analysis (Beck et al. 2016). We also included one Ledbetter Red fragment from 14SC304 remaining after petrographic analysis (Beck et al. 2016:Table 2). All analyzed sherds were polished except for the Ledbetter Red fragment from 14SC304, on which the slip was wearing away.

All ceramics in this study are curated by the Kansas Historical Society (KSHS). Following KSHS guidance, no examples of Tewa Red or Tewa Polychrome were refired, and we conducted no additional oxidation analyses for this study. In February 2024, KSHS paused all access to and research on the archaeological collections in its care, including the nonmortuary collections from 14SC1 and 14SC304, as part of the institution's response to the revised Native American Graves Protection and Repatriation Act (NAGPRA) Regulations, which went into effect January 12, 2024 (see https://documents.saa.org/container/docs/default-source/catf/final_nagpra_rule_fact_sheet_revised-(1).pdf?sfvrsn=8293d816_3). No further data collection is possible during this pause.

Munsell Color Data

For comparison, we include previously recorded Munsell colors on the red slips of Tewa Red and Tewa Polychrome ceramics and on Ledbetter Red from a previous oxidation study (Beck et al. 2016). In the ceramic type collections in the H. P. Mera Room (Laboratory of Anthropology, Museum of Indian Arts and Culture, Santa Fe, New Mexico), Tewa Polychrome red slips are usually 10R 4/6 or 10R 5/6. Tewa Red slip colors include 10R 5/6 and 10R 6/6, with less oxidized areas of the surface represented by 10R 5/3 and 10R 5/4 (Beck et al. 2016:155). When fully oxidized after refiring, Ledbetter Red slip colors are 10R 4/4, 10R 5/4, 10R 4/6, 10R 5/6, and 2.5YR 4/6 and 5/6 (Beck et al. 2016:Table 5).

Methods for CIELAB Data Collection

We recorded CIELAB coordinates on slipped test tiles, archaeological ceramics, and Munsell color chips from digital photographs, using techniques like those of previous researchers (Bernatchez 2012;

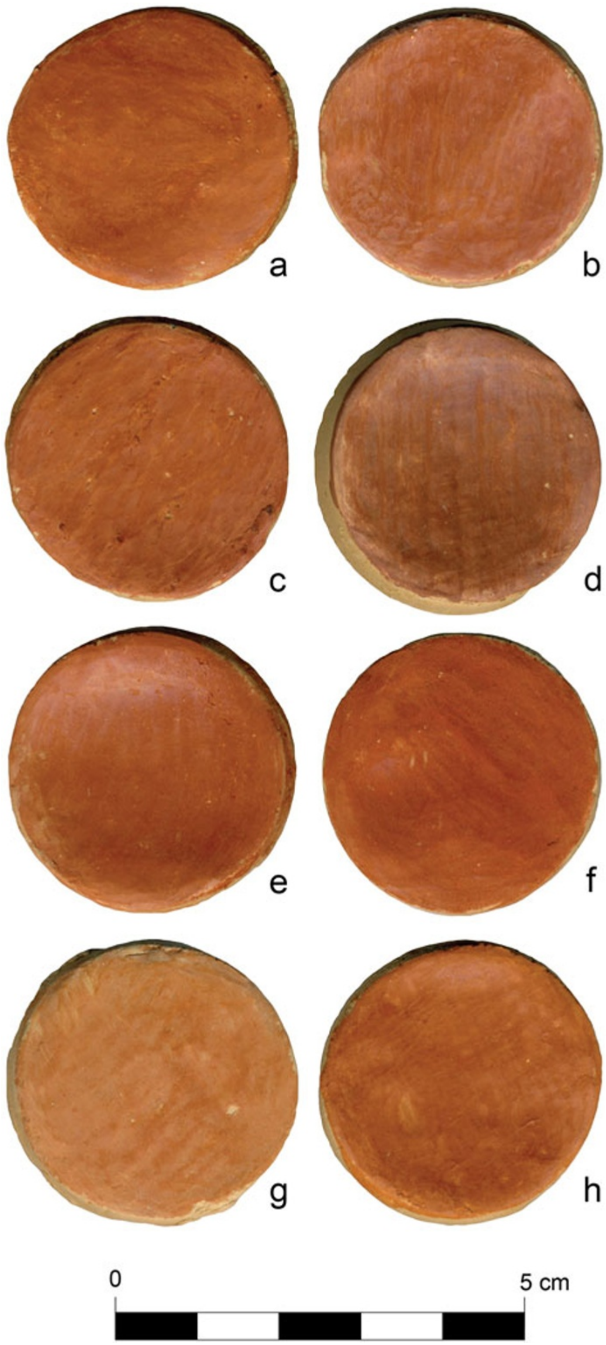

Figure 3. Slipped and polished test tiles: (a) Dakota-1; (b) Dakota-2; (c) Dakota-3; (d) Dakota-4; (e) Niobrara-1; (f) Niobrara-2; (g) Permian-1; (h) Permian-2.

McGrath et al. 2017; Oestmo 2013). Our steps for taking and color-correcting photos and collecting CIELAB coordinates, as outlined below, are modified from methods presented by McGrath and colleagues (2017).

1. Photograph all samples for direct comparison *in one sitting* in natural light, using the .RAW file format (.CR2 files). Include a black-and-white standard (e.g., X-Rite ColorChecker Classic) in each photo.

Table 2. Test Tiles Slipped with Pigment Samples.

Formation	Samples and Surface Treatment	Tile Count
Niobrara	Niobrara–1: polished, unpolished	4
	Niobrara–2: polished, unpolished	
Dakota	Dakota–1: polished, unpolished	8
	Dakota–2: polished, unpolished	
	Dakota–3: polished, unpolished	
	Dakota–4: polished, unpolished	
Permian	Permian–1: polished, unpolished	4
	Permian–2: polished, unpolished	
Total		16

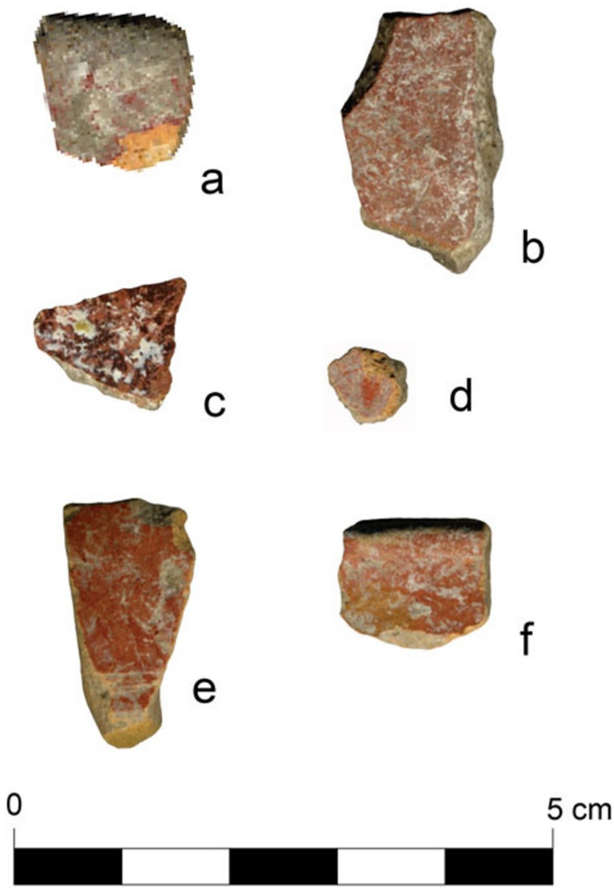

Figure 4. Examples of archaeological ceramics in this study: (a) Ledbetter Red, 14SC1 cat 1130; (b) Ledbetter Red, 14SC1 cat 6742; (c) Ledbetter Red, 14SC1 cat 22773; (d) Ledbetter Red, 14SC304 cat 376; (e) Tewa Red, 14SC1 cat 6765; (f) Tewa Red, 14SC1 cat 22774.

2. In the same sitting, photograph the 10R and 2.5YR pages of the Munsell color chart, including a black-and-white standard.
3. Color-correct all photos in Adobe Photoshop using the black-and-white eyedroppers. Merge down image layers and save as a .TIFF file.

Table 3. Archaeological Ceramic Samples.

Type	Site and Catalog Number	Sample Count
Ledbetter Red	14SC1 cat 1130, 6742, 22773; 14SC304 cat 376 [SC−27]	4
Ledbetter Red (refired)*	14SC1 cat 6742	1
Tewa Red	14SC1 cat 6765, 22774	2
Tewa Polychrome	14SC1 cat 4591, 5404	2
Plain Red (refired)	14SC1 25401	1
Total		10

*Sherd described in previous oxidation analysis (Beck et al. 2016:Table 5).

4. Open each .TIFF file in Adobe Photoshop to collect CIELAB data.
5. In the Color Panel, set the color channels to Lab.
6. Using the eyedropper tool, sample the color and record the L*a*b* color coordinates in the Color Panel. Take three measurements in different areas.
   a. For slips, take measurements where the slip is best preserved.
   b. For slipped test tiles and Munsell colors, take measurements in the upper left, lower right, and middle.
   c. Take measurements on relevant color chips on the photographed Munsell pages. In this study, we added Beck and colleagues' (2016) recorded colors for Tewa Red, Tewa Polychrome, and oxidized Ledbetter Red.
7. Average the three sets of L*a*b* values for each sample.
8. Plot the average values for each sample and the Munsell colors ($x = b^*$, $y = a^*$).

Three topics above warrant further discussion: Step 1 ("Photograph all samples to be directly compared *in one sitting* in natural light)"; Steps 2 and 6 (photographing and collecting color data from Munsell color chips); and Step 9 (plotting CIELAB values a* and b*).

Step 1 (Photos in One Sitting in Natural Light). Prior researchers using this technique emphasize the need to keep lighting conditions constant—by completely controlling the light source or taking all analysis photos at the same time, or both—so that variation in lighting conditions do not contribute to color variation between samples (Bernatchez 2012:309; McGrath et al. 2017; Oestmo 2013:4432). We took our analysis photos in natural light outdoors, which is standard for Munsell color observations (e.g., Turk and Young 2020). Our photos were taken within a one-hour sitting in February 2024 (afternoon direct light in sunny conditions) using a Canon EOS Rebel T3i digital single-lens reflex camera.

Steps 2 and 6 (Photos of Munsell Colors). As noted above, the photographs include the 10R and 2.5YR pages of the Munsell color chart. This enabled us to compare colors in our ceramic and pigment samples to standard reference colors, such as previously recorded Munsell colors for the archaeological ceramic types in our study.

Step 9 (Plotting CIELAB Values). Although the CIELAB color system (CIE 2004; Fairchild 2005; Hunt and Pointer 2011) includes a*, b*, and L* (lightness), we graph only a* (the red-green coordinate) and b* (the blue-yellow coordinate) to evaluate hue. The a* and b* CIELAB coordinates of a given color determine the hue angle, placing the color around the color wheel. The hues in this study of red slips only fall within one-quarter of the color wheel between red and yellow (Figure 5). Colors that are more red than yellow have $a^* > b^*$ so that the a* and b* coordinates plot closer to the *y* or red axis. Chroma also appears in our graphs and is captured in the absolute values of a* and b*. Chroma is a color's saturation, relating it to a neutral standard (Cleland 1921) or a color with a* and b* values of zero. Values farther away from zero indicate more vibrant colors with higher chroma. We exclude L* from our discussion, which would be graphed perpendicular to a* and b* on the color wheel.

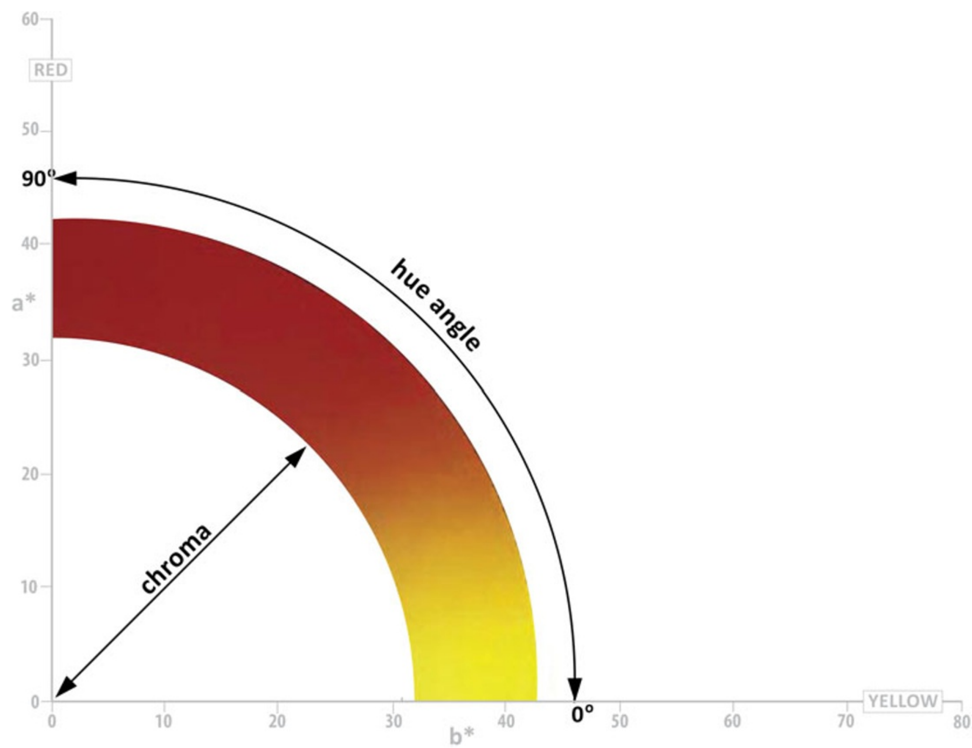

Figure 5. Quadrant of the CIELAB color wheel used in this study (following McGrath et al. 2017).

Results and Discussion

We define the color range of each geological formation or system (Niobrara, Dakota, and Permian) as the shaded area occupied by its slipped test tiles on the graph, representing the hue and chroma range (Figure 6). Each geological formation or system has a characteristic hue regardless of sample location or surface finishing technique, illustrated by trendlines with different slopes and intercepts (all with $R^2 = 0.90$ or higher). Niobrara and Dakota samples have similar trendlines and are consistently closer to the red axis than Permian samples, which are more yellow in hue.

In Figure 7, the archaeological ceramics and Munsell colors are plotted against the color range of the three geological formations or systems sampled in the eastern High Plains and the Central Plains. Pigments from two of them (Niobrara and Dakota) have hue and chroma ranges overlapping Northern Rio Grande red slips and the 10R 4/6 and 10R 5/6 Munsell color chips. As noted earlier, well-oxidized Tewa Red and Tewa Polychrome slips are 10R 4/6, 10R 5/6, and 10R 6/6 (Beck et al. 2016). Dakota pigment samples that are dark red and purple before firing (e.g., Dakota-3 and Dakota-4 samples) plot especially close to the Tewa Red and Tewa Polychrome sherds in this study. Potters at 14SC1 and 14SC304 may have used pigments from either the Niobrara or Dakota formation, or both, as suggested by two Ledbetter Red sherds in Figure 7 (14SC1 cat 6742 after oxidation analysis and 14SC304 cat 376).

The Dakota formation includes red-firing claystone, mudstone, and shale—the types of sedimentary rock used as slip materials by Puebloan potters in the US Southwest (Blair and Blair 1999; Dillingham 1999; Guthe 1925; LeFree 1975)—but the closest Dakota exposures are over 100 km away from 14SC1 and 14SC304 (see Figure 2). The Niobrara Chalk is a different kind of sedimentary rock, but it contains inclusions with limonite and other iron minerals that can be used for red slips. It is also available nearby; the samples in this study were collected on the north bank of the Smoky Hill River, approximately 16 km away from 14SC1 and 14SC304. Future research should explore limonite and clay-ironstone concretions in the Cretaceous Pierre Shale, Carlile Shale, and Graneros Shale formations, which may also produce colors in the range of Dakota and Niobrara pigment colors.

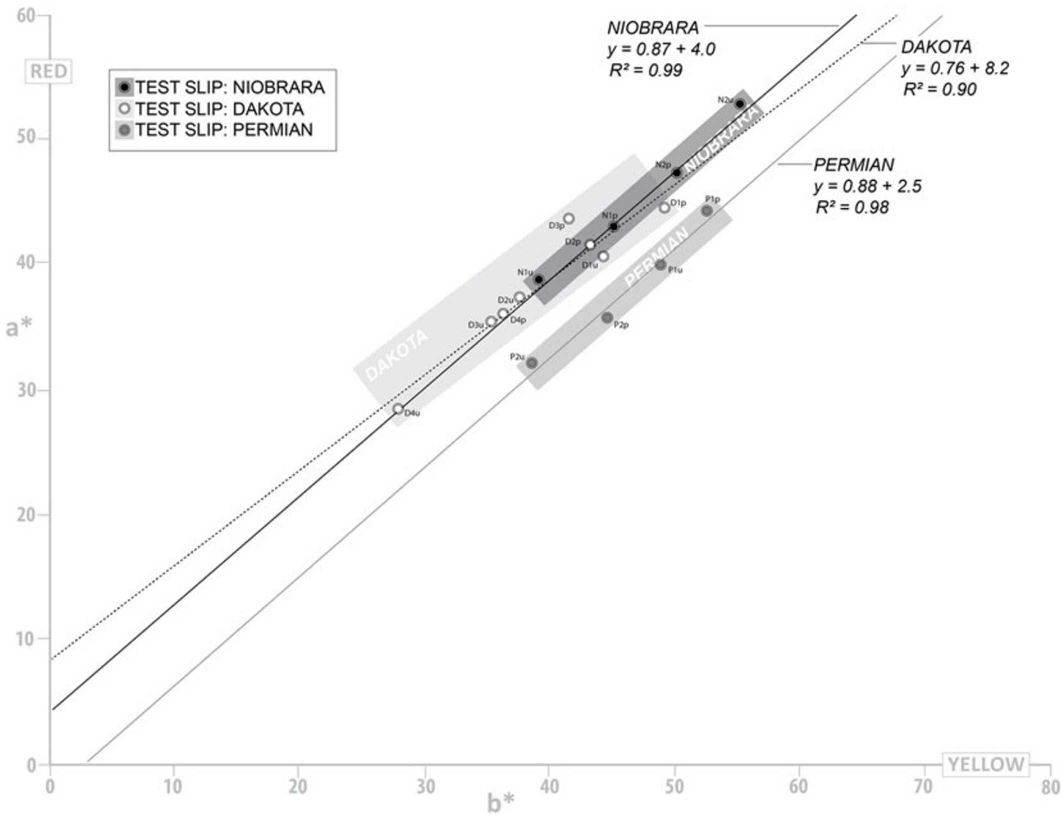

Figure 6. Plotted coordinates for slipped test tiles from three geological formations or contexts (Niobrara, Dakota, and Permian). Each collected sample (e.g., D4 for Dakota-4) appears as two tiles (polished [p] and unpolished [u]). Each geological formation or context has a color range, depicted by the shaded graph area around its tiles, and a trendline.

Permian-system red beds are not red enough to match the archaeological ceramics in this study but instead are more yellow in hue (see Figure 7). They could produce slips in the range of 2.5YR 4/6 and 5/6, however, which are among the recorded colors for Ledbetter Red slips after oxidation analysis (Beck et al. 2016:Table 5). Permian red beds are nearly 200 km away from 14SC1 and 14SC304 (see Figure 2), and we suspect that pigments of the "wrong" red were not a priority for long-distance travel or exchange. Closer pigments with similar yellowish-red hues may be available, such as alluvial clays excluded from our sampling strategy because they usually fire to 2.5YR and 5YR hues rather than 10R (e.g., Roper et al. 2010:Tables 4 and 6).

Three Ledbetter Red sherds (14SC1 cat 22773, 14SC1 cat 1130, and 14SC1 cat 6742 before oxidation analysis) plot near the trendlines for Niobrara and Dakota pigments but are too low in chroma to overlap with test tile color ranges. They appear near the 10R 5/3 and 10R 5/4 Munsell color chips, which represent poorly oxidized areas of Tewa Red slips (Beck et al. 2016). Ledbetter Red from 14SC1, the earlier of the two sites in this study, was routinely fired without sufficient air flow to fully oxidize the red slip (Beck et al. 2016). Ndee potters in the eastern High Plains made vessels with reduced surfaces and "probably left vessels to cool where they were fired, rather than removing hot vessels, which would have oxidized carbon from the hot vessel surface in the open air" (Beck et al. 2016:157). For whatever reason, early Puebloan potters here struggled to completely oxidize vessel surfaces. Beck and colleagues (2016:157) ask, "Did these Ledbetter Red pots cool a little too much before being removed from the fire? If firing materials or conditions at the site differed from those to which Puebloan potters were accustomed, they may have misjudged the rate of cooling and pulled vessels out too late."

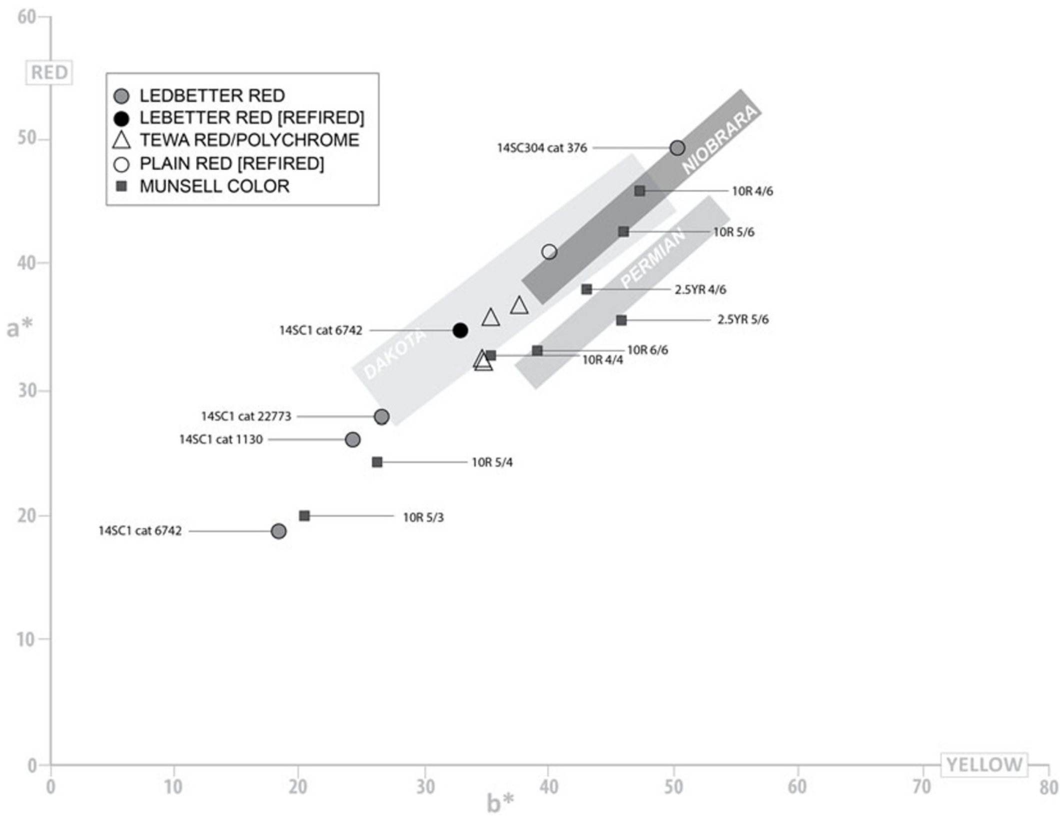

Figure 7. Plotted coordinates for archaeological ceramics in this study and selected Munsell color chips. The color range for each geological formation or context is depicted by the shaded graph area around its tiles.

Conclusions

We collect CIELAB color data with established methods but analyze the data in a new way, using a* and b* graphs to describe and compare hue. In our case study, we graphically illustrate the red hues of collected pigments and ceramic slips, plotting them around the color wheel between red and yellow. Our collected pigments systematically vary in hue, plotting along a line with a characteristic slope and intercept for each geological formation or system. Two sampled geological formations in the eastern High Plains and adjacent Central Plains (the Niobrara and Dakota formations) include pigments that fire to the "right" red, or the red hues of Northern Rio Grande red slips, and potters at 14SC1 and 14SC304 may have used one or both. Given the hue and chroma variation on fully oxidized Ledbetter Red ceramics, as shown in Figure 7 and by Beck and colleagues (2016), they also may have experimented with slip materials from multiple geological formations or contexts. Such experiments would have yielded visibly different results in slip color.

Color can be used to identify plausible pigment materials, but color alone cannot establish their use in the archaeological record. Stronger arguments are made by incorporating mineralogical and chemical analyses, such as Raman spectroscopy, laser ablation inductively coupled plasma mass spectroscopy, and instrumental neutron activation analysis (e.g., Beck et al. 2022, 2024; Eiselt et al. 2011; Zarzycka et al. 2019). We suggest that our CIELAB approach is particularly useful within the context of raw-material surveys when deciding where to expand efforts and which samples to send for compositional analyses. There is little point in pursuing a geological formation or context that does not contain pigments of an appropriate hue. Color is an important guide when searching for possible materials, particularly in regions lacking ethnographic data on raw-material choice.

Our approach here is useful for a focused comparison and much less useful for building a large dataset from multiple collections over time. The advantage of collecting CIELAB data from digital photos is that the necessary equipment is widely accessible. The disadvantage is that, as noted earlier, the lighting conditions for photography must be kept constant by completely controlling the light source or taking all analysis photos at the same time, or both (Bernatchez 2012; McGrath et al. 2017; Oestmo 2013). Visual color determination is consistent in natural light except for early-morning light (Turk and Young 2020). We are therefore confident in the relative position of samples around the color wheel in our afternoon photographs but restrict our comparisons to samples photographed in the same sitting. Within our focused comparison, our a* and b* graphs present hue data more effectively than is possible using the Munsell system.

The challenges of reproducing a slip color ultimately speak to the challenges of relocation. Ceramic manufacturing traditions are rooted in earthen raw materials—the physical stuff of a home landscape—as explored within the framework of ceramic ecology (Arnold 1975, 1985; Kolb 1982; Matson 1965). Preferred raw materials are a part of the *chaîne opératoire* that may be hard to replace after a move. In their nineteenth-century migration, Laguna potters brought not only the practice of slipping but also the actual slip material to Isleta Pueblo (Dillingham 1999; Parsons 1928). We have not disproved the movement of slip material from the Northern Rio Grande to the eastern High Plains, but we demonstrate that potters could have reproduced the red hues of Northern Rio Grande red ware in the different geological landscape of the Great Plains. Although Ndee potters in western Kansas had no tradition of slipping or painting ceramics, their communities may have shared information about pigments with which the Puebloan potters could experiment. Our work on color becomes a lens through which we see potters adapting traditions to new materials and ultimately making a new home.

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