Interesting crazing pattern. Photo credit: Howard Sawhill

PHOTO GALLERY

Puzzling and Beautiful Crazing Patterns

HOWARD SAWHILL (HTTPS://STUDIOPOTTER.ORG/HOWARD-SAWHILL)

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There's something mystical about a piece of ancient pottery covered in a light glaze with contrasting cracks. I find that a widely spaced crazing pattern with meandering lines conveys a sense of calm and strength – a balance between the shattered look of too many cracks and the broken look of too few. Although every piece has its own unique pattern, the crack networks from piece to piece appear to have regular features, a phenomenon that is evident in a range of materials including: mud cracks in dry lake beds, cracks across the surfaces of planets, oil paintings, and craquelure in ceramic glazes.[1, 2]

Figure 1. Vase exhibiting spiral crazing in the neck area. Guan Ware, Southern Song Dynasty, 13th Century. Photo by William M. Carty during a visit to the Percival David Foundation of Chinese Art. This collection is now part of The British Museum.

Permission granted by William M. Carty.

In 2016, I attended a ceramic glaze workshop[3] where the explanation behind crazing formation was presented. Always intrigued by exceptions to the rule, I found my interest piqued when the instructor showed a photo of a thirteenth-century Chinese Guan ware vase with an unusual series of spiral cracks in the neck region (**figure 1**), a pattern he described as "puzzling." The cracks seemed to defy general rules governing crazing networks. For most knowledgeable potters, the explanation might seem simple: the cracks follow a spiral pattern of the throwing lines. It's a concise, believable explanation that I would eventually discover was incorrect.

This essay is about my journey to uncover factors that influence crazing patterns and attempts to provide a plausible explanation for the "puzzling" pattern in the Chinese Guan ware vase. Along the way, I ran across an interesting method to create new, unusual crazing patterns. My hope is that fellow potters and ceramic artists can use these findings to guide their future explorations with crazing glazes.

As background or reminder for those who are not regularly immersed in minutiae of glaze chemistry, several physical changes occur to a piece of pottery during firing. As the kiln heats up, the clay body and glaze(s) undergo shrinkage. Water and porosity are removed and chemical reactions, such as whiting converting to calcium oxide and carbon dioxide gas, occur. At peak temperature the clay body is dense and stiff while the glaze is in a molten state. Upon cooling, the glaze transforms from molten liquid into a solid in contact with the clay body. As the cooling process continues, stresses[1] begin to build due to the solid clay body and solid glaze layer contracting at different rates. When these two rates of contraction are close in value, the glaze is described as having a "good fit" to the clay body. When the fit is poor, crazing (**figure 2a**) or shivering (**figure 2b**) can occur.

Figure 2a. Example of crazing.

Figure 2b. Extreme shivering.

The expansion or contraction of a material upon heating or cooling is characterized by its coefficient of thermal expansion (CTE).[2] A higher CTE value denotes a larger amount of expansion and contraction during heating and cooling. It is the difference between the CTE of the clay body and the CTE of the glaze that determines whether the glaze is a good or poor fit. When the glaze CTE is larger than the CTE of the clay body, tensile[3] stress builds up in the glaze layer during cooling and compressive[4] stress builds up in the clay layer. Crazing results when the tensile stress in the glaze exceeds the tensile strength of the glaze[4] and cracks begin to form and grow to alleviate the stress. Conversely, when the glaze CTE is smaller than the clay body CTE, compressive stress builds up in the glaze layer. Shivering results when the compressive stress in the glaze exceeds the mechanical strength of the glaze and clay body interface. A guide to fitting glazes to clay bodies can be found on the digitalfire website.[5] Estimating the CTE value of a glaze is described in Appendix A (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Use%20This%20App%20A) and factors affecting crack formation are discussed in Appendix B (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Use%20this%20App%20B).

I began the experimental work for this project by developing a series of glazes that ranged in CTE values from extremely low to very high. I wanted to have physical examples of how the glaze appeared across the spectrum of good and poor fit. (The glaze compositions and clay body used in this study are listed in Appendix C (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Use%20this%20App%20C), and the results are shown in **figure 3**). The range of good glaze fit spans from a glaze CTE value of 4.4 to 6.4, centered around the clay body CTE value of 5.4. More precise measurement of crazing density versus CTE mismatch can be found in a number of studies.[6-8] One interesting finding is that shivering begins with failure at the clay body/glaze interface with small areas of glaze being forced away from the clay body. The initial appearance is similar to crazing, but with increased stress, these areas detach completely, leaving behind only the clay body.

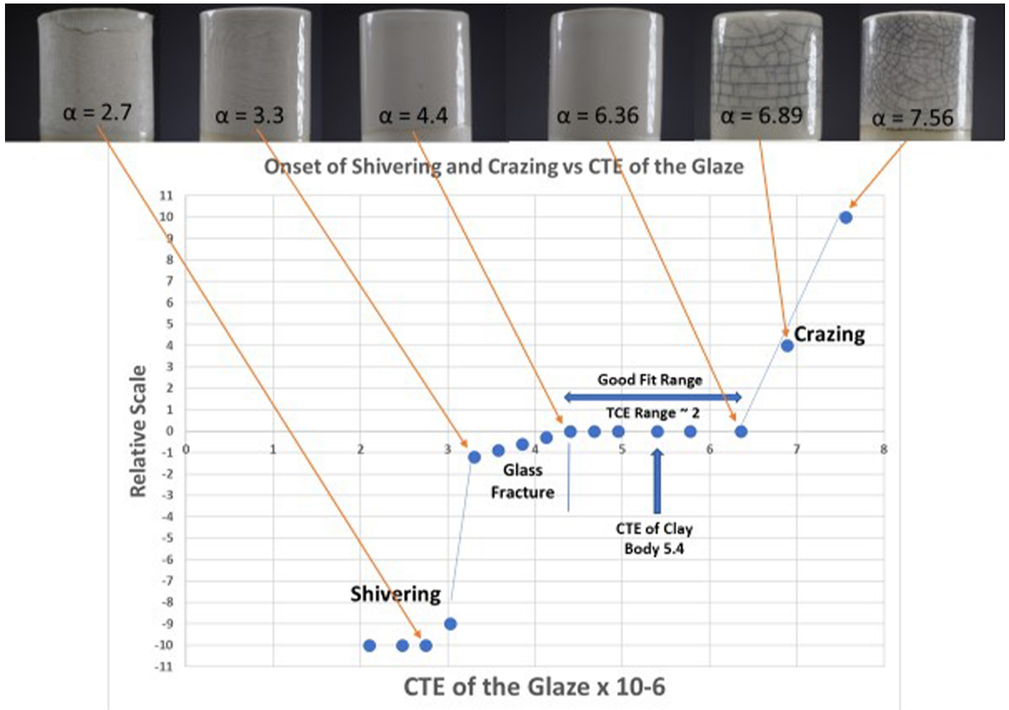

Figure 3. Mismatch of thermal expansion (CTE) between the glaze and the clay body can lead to crazing or shivering depending on the degree of mismatch and whether the glaze is contracting more or less than the clay body. Glaze compositions shown in Appendix C, Table 1, and Table 2. Clay body is Little Loafers from Highwater Clay in North Carolina.

In the crazing region of **figure 3**, higher glaze CTE values lead to increased crazing density. This effect is further evident in the series of glazes shown in **figure 4**. The good glaze fit in **figure 3** extends up to a glaze CTE value of 6.4, yet almost all the glazes in **figure 4** have CTE values below 6.4. This is where the caveats around calculated CTE values presented in Appendix A (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Appendix%20A) (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Use%20This%20App%20A)come in. The glaze chemistries in **figure 3** and **figure 4** are quite different. The takeaway from **figure 4** is that the higher the CTE value the higher the density of crazing. One can see in **figure 5** that, although there are some slight crazing density changes with the addition of different colorants, the basic crazing pattern remains unchanged.

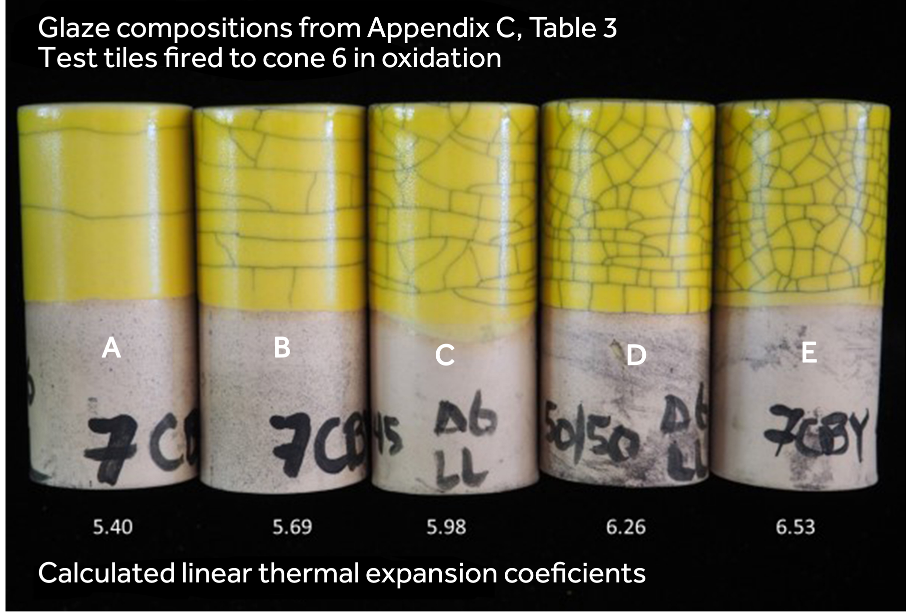

Figure 4. Crazing density increases with increasing mismatch between the clay body CTE and the glaze CTE. Values shown are the glaze CTE values.

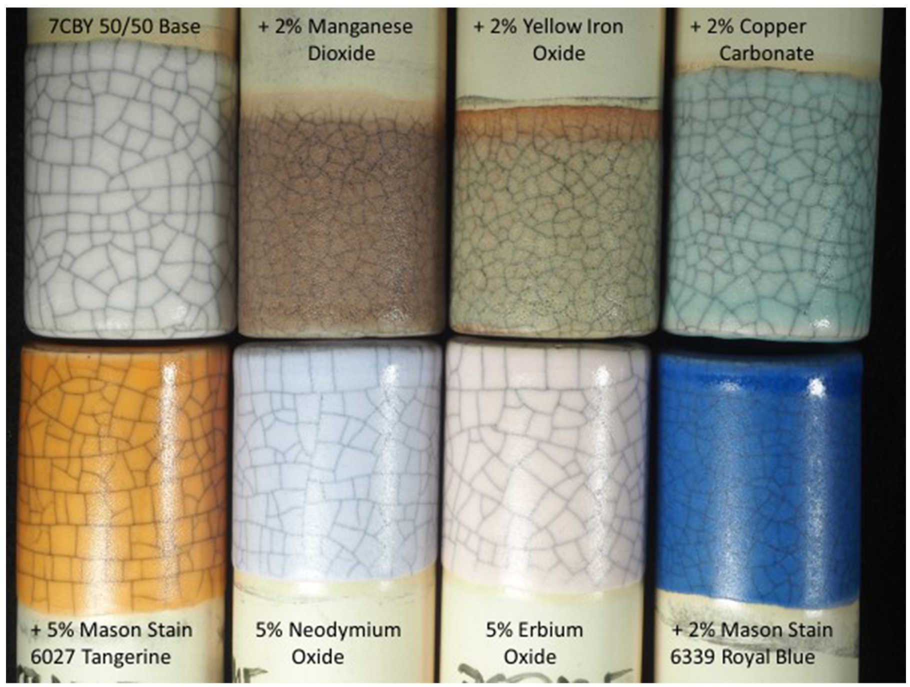

Figure 5. Test tiles with different colorant additions to the same base glaze.

After showing some of the colored test tiles to my son, he said they reminded him of streets on a map. For fun, I transferred the outline of the arrondissements of Paris onto a plate and colored them in with different colored glazes of several CTE values. I learned the transfer process through an online class on drawing Afghan geometric designs, which involved flipping the design over and tracing it for a clean transfer. I lost track of which side was which during the transfer and ended up with the mirror image on the plate, but solved this problem by taking the picture of the fired plate in the mirror (**figure 6**).

Figure 6. A plate decorated using a variety of glazes with different CTE values and colorants arranged to represent a map of the Paris arrondissements.

At any given time I work with a number of different clay bodies in my studio. Since the clay body in conjunction with the glaze determines the glaze fit, I chose to test a crazing glaze over different clay bodies (**figure 7**). The crazing density changes were expected since the clay bodies all have different CTE values. Because some clay bodies were under fired in this group, I'll defer the discussions of pattern changes to the sections that follow. Delayed crazing can be seen on tiles inked two days after firing versus these same tiles inked one day after firing. As long as the residual stress continues to exceed the fracture strength of the glaze, cracks can continue to form until the distance between cracks reaches a limit of about three times the glaze thickness.[1] We may all be familiar with the sound of occasional pinging in the studio from glazes fired some time ago. In the testing I did, finding which tile caused the sound was like looking for a needle in a haystack! Moisture absorption by the clay body,[9] as well as glaze surface reactions, can contribute to new crazing appearing many years after the initial firing.

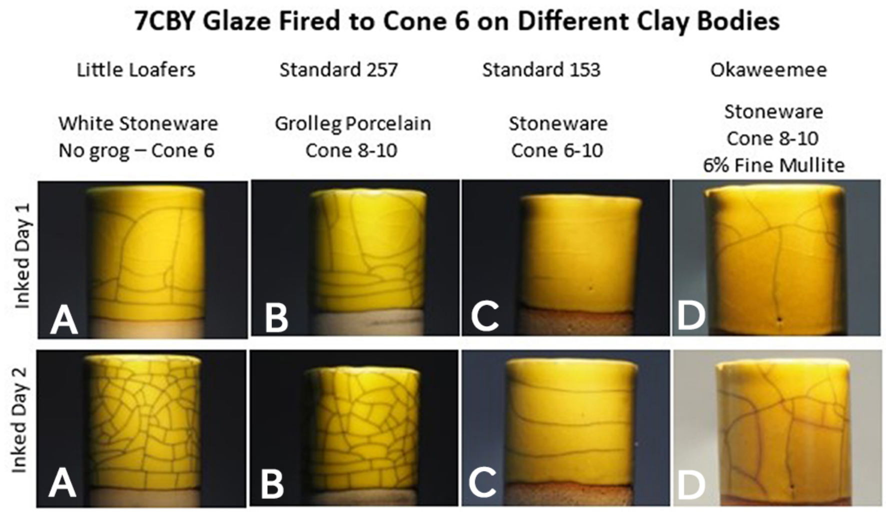

Figure 7. Examples of a glaze crazing on different clay bodies.

I tested the effect of glaze thickness by dipping the test tiles into glaze several times (**figure 8**). Models for stress estimates of flat[10] and cylindrical shaped[11] test tiles predict a uniform stress level across the glaze that is dependent upon the clay and glaze CTE values and on the relative thicknesses of the glaze and clay. The roughly 30% reduction in average craze spacing seen between single and triple dipped glaze thicknesses in **figure 8** is on par with model prediction. However, I saw no change to the crazing pattern itself as a result of changing the glaze thickness. I spoke with one potter who applies additional glaze using a wide brush in a free-flowing pattern in an attempt to produce more organic looking crazing patterns. She liked the results, but mentioned the crazing patterns were neither reproducible nor did they follow the pattern she applied.

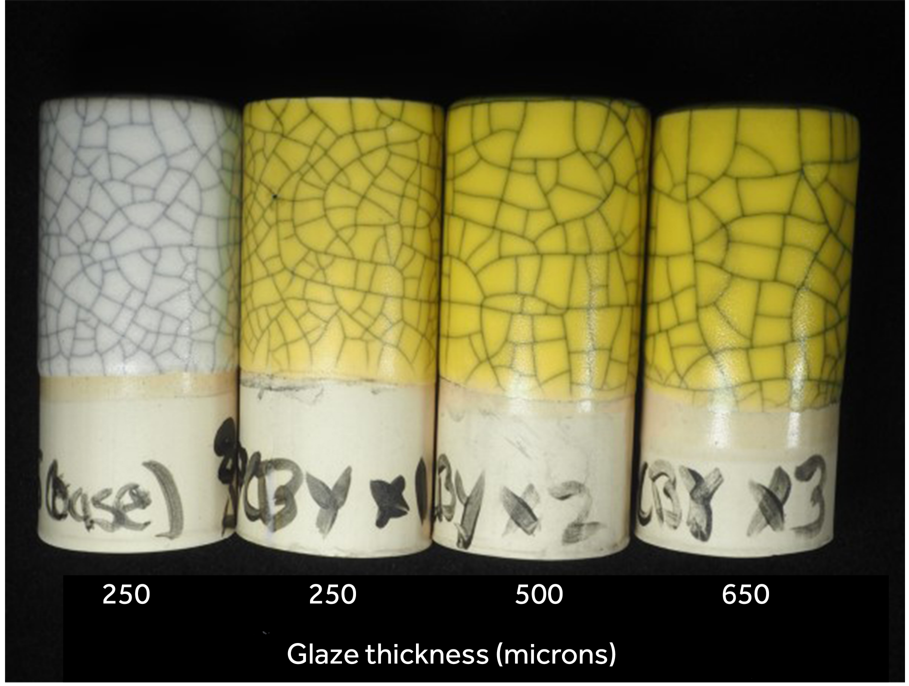

Figure 8. Base glaze and glaze 7CBY 50/50 dipped once, twice, and three times.

The conventional description of how a crazing pattern is formed goes something like this: Tensile stress in the glaze layer is relieved by the formation and growth of the first or primary crack(s) forming in a direction perpendicular to the maximum stress. As these cracks relieve stress, the direction of maximum stress changes to an orthogonal direction (approximately ninety degrees), causing secondary cracks to form perpendicular to the primary. A third set of cracks forms in a direction perpendicular to the second and so on.[12]

I came across the idea of adding a buffer glaze[5] between the test tile clay body and the principal glaze while reading about genuine craquelle glazes.[6] The authors showed several crazing patterns resulting from spraying a buffer glaze underneath a principal glaze. The reference to a "beautiful pattern" in a densely technical article inspired me to glaze the bowl shown in **figure 10**[6] using this approach. The resulting crazing pattern was truly unexpected! For anyone interested in working with crackle glazes, this buffer glaze approach is ripe for further exploration.

I used India ink on all the crazing glazes in this study in order to increase the contrast between the glaze and the crazing. As for the safety of crackle glazes and inks, the consensus is they are not food safe. This is a common concern and detailed discussions can be found at numerous podcasts,[13] websites,[5] and glaze workshops.[14] So far, I had demonstrated how glaze thickness and glaze

CTE differences from the clay body CTE impact crazing density and how a two-glaze approach can lead to interesting crazing patterns. Yet, I was still no closer to finding an explanation for the puzzling crazing pattern of the Chinese Guan ware vase. That's when I tried a lot of different things, including slip-trailing of both clay and glaze into different patterns to change the relative thickness between the glaze and clay body. I cut deep grooves on the back of flat test tiles, rolled out wedge-shaped tiles, and formed cone shaped tiles. There was only one experiment I ran that resulted in a fundamental change to the crazing pattern. I scratched a series of horizontal or vertical lines through the unfired glaze layer.[7] The resulting crazing patterns on the scratched and flip sides of the test tiles are shown in **figure 9**. Both crazing patterns looked fundamentally different from each other. I learned at an early age that the scientific method involves posing a hypothesis, then running experiments to prove or disprove it. I was now in the unfortunate position of having data to explain the horizontal cracks of **figures 4** and **7**, the helical cracks in **figure 1**, and the different patterns in **figure 9b** with no accompanying hypothesis!

Figure 10. Bowl with interesting crazing pattern. Glaze 7CBY50/50 (table 3) was applied over glaze 7CTE-M (table 2). Both were sprayed onto a bisque fired bowl made using Little Loafers from Highwater Clay, in North Carolina.

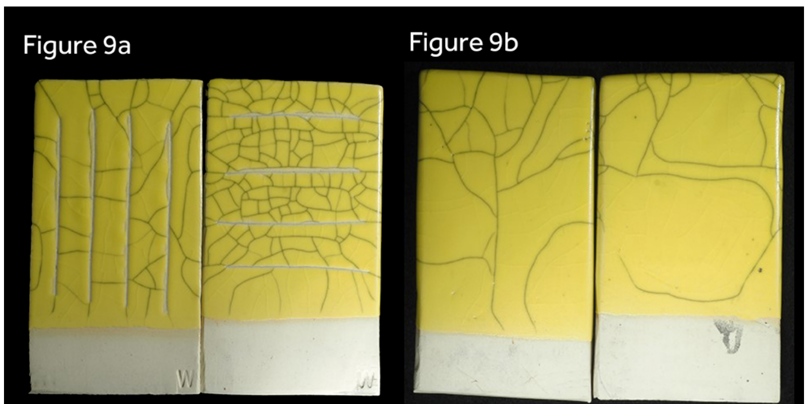

Figure 9. Scratches in the vertical and horizontal directions in the unfired glaze layer produced significantly different crazing patterns on both the scratched side (a) and the flip side(b).

After much digging, I found a paper on the interactions between cracking, delamination, and buckling.[15] Their models assumed the glaze stopped, formed an edge, and did not completely cover the underlying body. This is known in engineering models as a "boundary condition." Think of the point where the sea meets the shore as a boundary condition. In much the same way as weather at the shoreline can be quite different from thirty miles out to sea, the stress state in the glaze can vary considerably moving away from the boundaries. This matched the conditions in my test tiles in a way that the earlier stress models mentioned in paragraph seven (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Paragraph%207) did not. As opposed to a uniform stress, their model predicts a parabolic-like stress relationship with maximum stress in the middle going to zero at the edge of the glaze. This suggests the horizontal and vertical scratches through the glaze resulted in creating a series of glaze edges on one side of the substrate that impacted the stress generated, not only between and around these scratches, but also on the flip side of the test tile. This helped explain the more circular-shaped patterns seen in **figure 9b**.

What about the circular throwing lines? They form spiral features after all.

For the final experiment, I asked a potter friend[16] to throw two small cups, one with the wheel rotating counterclockwise and one with the wheel rotating clockwise. I chose porcelain clay because she had made a couple of these no-trim cups previously, plus I liked the fact that delayed crazing would be slower and would occur over a longer period of time. The fired cups are shown in **figure 11a**. What I surmise from these results is that some texture in the clay has been created that impacts the stress state in the fired piece. Delayed crazing of these two pieces by one month shows the conventional pattern of craze network formation. I think the stress is similar to the well-known effect of wheel-thrown teapot spouts rotating between the dry and fired state. The throwing process aligns clay platelets in a preferential direction and determines how the clay sinters during firing. The same effect appears to have a similar consequence on the residual stress state formed during glaze firing, such that the resulting primary crazing lines form with a slight twist around the cup. I found no evidence that the patterns in **figure 11a** and **11b** are related to throwing lines.

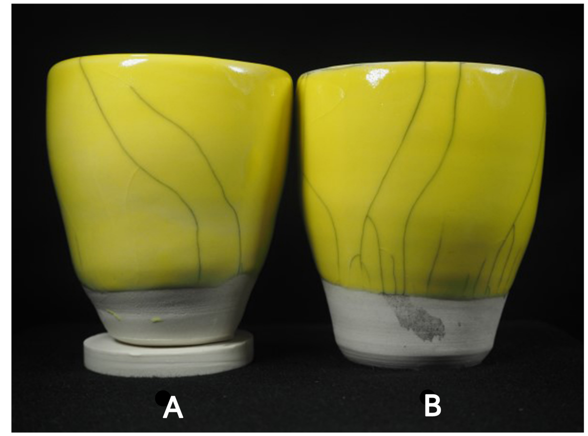

Figure 11a. Crazing direction of porcelain cups thrown on a pottery wheel rotating in a clockwise fashion (A) and in a counterclockwise fashion (B). Glaze 7CBY50/50 (Table 3) applied by dipping over bisque fired cups made using English porcelain clay (Standard Ceramic Supply Company). The cups were fired to cone 8 in oxidation.

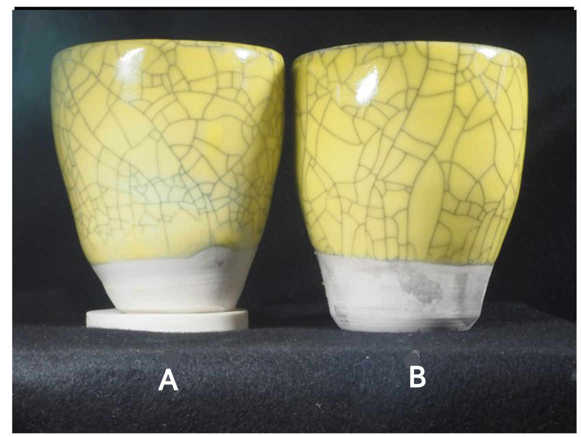

Figure 11b. Delayed crazing of the two cups in figure 11a by one month.

Based on my work, here's what I think is going on with the "puzzling" craze on the neck portion of the thirteenth-century Chinese Guan ware vase. Primary spiral cracks with little to no orthogonal cracking result from the glaze CTE value being close to, but higher than, the clay CTE value – a sufficient difference that generates stresses resulting in primary crazing, yet not different enough to result in orthogonal cracking and form a network pattern of cracks. This is the case as well in **figure 4a** and **figure 7c** (day two). I believe that boundary conditions associated with the glaze termination at the top lip of the vase and the form change below the neck reduce the vertical stress below the value of the horizontal stress (as the model in reference 15 predicts), causing the primary cracks to form in a predominantly vertical direction. Finally, I would posit that the vase in **figure 1** was made on a potter's wheel by a right-handed potter.

It feels good to have developed a plausible explanation for the origin of the puzzling crazing pattern. An added bonus was uncovering a technique that produces other unusual and beautiful crazing patterns. I enjoy working on glaze projects that begin with an interesting question. Moreover, it's rewarding to share my work with fellow potters and ceramic artists. Ultimately, my hope is to foster an interest in exploring novel and unique ceramic glazes.

Appendix A – Calculating the Thermal Coefficient of Expansion for a Ceramic Glaze:

An estimate of the CTE value of a glaze can be obtained by entering its recipe into one of many on-line spreadsheets designed to perform the calculation, including Tony Hansen's DigitalFire.com and Derek Au's Glazy.org. YouTube tutorials[17, 18] help speed up the learning curve. However, these are rough estimates only and are best used in comparing one glaze to another. There are many reasons for this: Firstly, the CTE calculation is based on using the sum of oxide component weight percentages in the fired composition multiplied by oxide expansion factors. The expansion factors can be found in several references.[4, 11, 19-21] However, each was sourced from different studies using different glass chemistries to empirically derive the expansion factors for individual oxides as explained in reference.[21] Since the online models rely on these expansion factors, the different models predict different CTE values, as illustrated in the last three rows of **table 2** (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#use%20this%20T2) in Appendix C (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Use%20this%20App%20C). Secondly, this calculation assumes the glazes in the molten state are uniform. This is not the case for crystalline or phase-separated glazes, underfired glazes, or ancient glazes containing large, undissolved quartz and other minerals. Still, this is a reasonable assumption for many glazes. Even the physical measurements made using a dilatometer, which we think of as the "true" CTE values, are estimates since they are determined by fitting a "best fit" line to the data which is inherently non-linear. So beware, these values are rough estimates, best used for comparing different glazes and clay bodies.

I developed my own spreadsheet to facilitate glaze development to specific CTE and Unity Molecular Formula (UMF) values and to allow impurities and colorant oxides (where CTE values were available) to be included in the calculation. I used the expansion factors found in reference[11] in combination with a spreadsheet of measured oxide compositions of commercial ingredients provided in a ceramic glaze workshop.[3] For those wishing to explore this further, it's important to remember to use the fired composition weight percentages of ingredients. For example, the weight percentage of whiting must be converted to calcium oxide since that's what will be in the fired glaze. Similarly, oxides fired in reduction must be converted to their reduced state.

Clay body CTE values are extremely difficult to calculate due to the complexity of resulting multi-phase, largely crystalline microstructures, and would require ceramography analysis[22] of the fired clay bodies. Translated, this means either you have an x-ray diffractometer and scanning electron microscope with electron probe analyzer at your disposal or you will be making 30-micron thin petrographic sections and using a series of oils with different diffraction indices in a microscope with crossed polars to determine the different crystalline phases. Add to that the need to estimate the percentage of each phase, all the while hoping the CTE values of the mineral phases you identified are included in one of the published tables.[23] I will politely pass on this. Instead, I used the measured values of the clay body CTE provided by the clay manufacturers for this study. European suppliers responded within a couple of days with a table of CTE values for all their clays. US suppliers were less responsive, but I'm not exactly sure why.

Appendix B – How Cracks Form

I learned about defects in materials in graduate school materials science classes. It's the atomic defects in metals that allow metals to bend and glass to crack. The science of modeling crack formation in brittle materials is still evolving. What we do know is stress can be concentrated in any area where there is a non-uniformity and glazed pottery is full of non-uniformities. The clay surface is anything but mirror smooth; the glaze can pick up bits of debris floating around in the kiln atmosphere, ingredients can be incompletely dissolved in the molten glaze, and the list goes on. This might explain why colorants added to a non-crazing base glaze sometimes result in a crazing glaze. These colorants may change the CTE value of the glaze as described in Appendix A (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Appendix%20A), which could lead to crazing. It's hard to know which mechanism is more important without a lot more testing. Scientists talk about sources and sinks as places where cracks can start or stop, with pores and pinholes commonly given as examples. I tried to artificially match the form of the spiral crack in a test tile by creating a series of pinholes in the form of a spiral using a needle tool in the dry glaze. The cracks did intersect all the pinholes, but they were not persuaded to follow my design, and instead formed the common crazing network pattern. Models designed around crack formation principles predict different behavior than models based on stress build-up from differences between the CTE values of the clay body and the glaze. This is an interesting area for graduate students to pursue, and a nod to Professor Carty who has trained so many.[3]

Appendix C – Glaze Compositions Used in This Paper

All samples in this paper were fired in oxidation to cone 6 on Little Loafers clay from Highwater Clays in North Carolina, with the following exceptions: **figure 7** glaze 7CBY-50/50 was fired on the different clays bodies indicated. Glaze 7CBY-50/50 over English Porcelain was fired to cone 8 in oxidation (**figures 11a and 11b**) and wood-fired in reduction to cone 8 in **figure 2a**. All glazes used additions of Darvan 7 in amounts equal to 1% of the EPK China Clay content.

I formulated a series of unique glazes at the low range of CTE value to explore the onset of shivering. The compositions and calculated CTE estimates are shown in **table 1** (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Table%201).

Glaze Code	Barium Carbonate	Lithium Carbonate	Flint (SiO_2)	EPK China Clay	Subtotal	CTE Calculated
758A	0.00	17.88	54.6	27.52	100	2.2
758B	3.53	16.09	53.60	26.78	100	2.5
758C	7.06	14.30	52.60	26.04	100	2.8
758D	10.59	12.52	51.60	25.29	100	3.0
758E	14.12	10.73	50.60	24.55	100	3.3
758F	17.65	8.94	49.60	23.81	100	3.6
758G	21.18	7.15	48.6	23.07	100	3.9
758H	24.71	5.36	47.60	22.33	100	4.1
758I	28.24	3.58	46.60	21.58	100	4.4
758J	31.77	1.79	45.60	20.84	100	4.7
758K	35.30	0.00	44.60	20.10	100	5.0

Table 1. Composition and calculated CTE values of glazes that were used to test the onset of shivering at the low end of glaze CTE values. The glaze series are a blend between lithium and barium fluxed compositions that have equivalent UMF.

Glaze Components	7CTE-L	7CTE-ML	7CTE-M	7CTE-MH	7CTE-H

Glaze Components	7CTE-L	7CTE-ML	7CTE-M	7CTE-MH	7CTE-H
Frit 3134	29	26	20	29	8
G-200 Feldspar	9	22	37	47	30
Talc	10	8	9	2	0
Wollastonite	4	6	5	0	0
EPK	22	20	18	10	18
Silica	26	20	12	10	7
Whiting	0	0	0	12	14
Frit 3110	0	0	0	0	19
Strontium Carbonate	0	0	0	0	5
Subtotal	**100**	**100**	**100**	**100**	**100**
Calculated CTE	4.5	5.1	5.7	7.0	7.7
Measured CTE	5.4	5.8	6.4	6.9	7.6
Digifire CTE	6.2	6.7	7.0	8.1	8.7

Table 2. Composition and calculated CTE values of glazes that were used to test the onset of crazing at the high end of glaze CTE values. This series of well-characterized glazes is described in the book *Mastering Cone 6 Glazes*, chapter 5, ”Fitting Glazes to Your Clay Body”.[24]

Glaze Code	Whiting	Lithium Carbonate	Flint (SiO_2)	EPK	Nepheline Syenite	Subtotal	Calculated CTE
7CBY-65/35	14.07	3.68	25.63	21.62	35	100	5.4

Glaze Code	Whiting	Lithium Carbonate	Flint (SiO_2)	EPK	Nepheline Syenite	Subtotal	Calculated CTE
7CBY-60/40	12.99	3.40	23.66	19.96	40	100	5.7
7CBY-55/45	11.90	3.11	21.69	18.29	45	100	6.0
7CBY-50/50	10.82	2.83	19.72	16.63	50	100	6.3
7CBY-45/55	9.74	2.55	17.75	14.97	55	100	6.5

Table 3. Composition of glazes with increasing CTE values starting at a CTE value equivalent to the CTE value of the clay body. Mason stain 6450 Praseodymium was added at the level of five percent to the compositions in table 3.

Endnotes

1. The temperature at which stress begins to develop in the glaze is referred to as the set point or softening point (Ts). There is no generally accepted way to measure Ts, so it is taken as the midpoint between the glass transition temperature and the dilatometric softening point.

2. CTE values are very small numbers. For convenience, the linear CTE value of 5.4 x 10-7/ °C is reported simply as 5.4. Some tables report the volumetric CTE values which are three times the linear CTE value.

3. Tensile stress is created when an object (such as a wire) is pulled at both ends.

4. Compressive stress is created when an object (such as a lemon) is squeezed or compressed.

5. I am using the term "buffer glaze" to describe a glaze with CTE value between the CTE value of the principal glaze and the CTE value of the clay body. The principal glaze is applied over the top of the buffer glaze.

6. 7CTE-M, table 2 Appendix C (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Appendix%20C). (https://studiopotter.org/puzzling-and-beautiful-crazing-patterns-0#Use%20this%20App%20C)

7. I know from experience (with these glazes and clay body) that applying glaze to one side only results in significant bowing. Therefore, all my samples were dipped into a jar of glaze in order to coat all sides.

Reference List

[1] Goehring, Lucas "Evolving Fracture Patterns: Columnar Joints, Mud Cracks, and Polygonal Terrain." *Philosophical Transactions of The Royal Society A - Mathematical, Physical and Engineering Sciences*, 2013. p. 1-18.

[2] Nandakishore, Pawan and Lucas Goehring, "Crack Patterns Over Uneven Substrates." *Soft Matter*, 2016. 12: p. 2253-2263.

[3] Carty, William M., *Ceramic Science & Glaze Calculations for the Artist.* 2016; Presented at Peters Valley School of Craft. Being offered in 2022 at the Sugar Maple Center for Creative Arts, NY. https://www.catskillmtn.org/ (https://www.catskillmtn.org/) (https://www.catskillmtn.org/our-programs/arts-education/sugar-maples/course-for.html?id=449)under the title *Melt It Perfect but Just for You: Glaze and Materials Technology for the Ceramicist.*

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