

To Whom the Cracks Tell

A CLOSER LOOK AT CRAQUELURE IN GLASS AND GLAZE

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In contrast to paint and varnish, craquelure in glass and glaze has been neglected as an information source for conservation. A closer look shows differences that can give surprising clues (e.g. evidence for the Roman quenching of cremation ashes or against Roman thermally toughening) or provide a better interpretation of cracks in authentic glazes. A descriptive framework has to look at differences in the form of individual cracks and peculiarities of their network pattern. This may lead to a better theoretical understanding of their fractal geometry and new discoveries of information hidden in them.

INTRODUCTION

The more we know about objects from the past, the more we can appreciate them. Therefore, besides preserving objects, the conservator is also obliged to decipher as far as possible the material traces they show. Unlike varnishes and paint, craquelure in glass and glaze has been almost totally neglected by the profession in this context. Some crack patterns may be the consequence of intentional processes (e.g. for increasing fracture strength by thermally toughening, or for decoration in ice glass or Raku ceramics). Others occur because of physical deterioration (e.g. because of thermal shock caused by fire extinguishing) or chemical weathering (a time-dependent phenomenon potentially relevant for authenticity studies). In every case, there is a story hidden behind the distinctive features of the pattern, but a descriptive terminology for the various patterns and a systematic comparison has not been developed so far.

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CASE STUDIES IN CRACK PATTERNS

As a start to the systematic study of glass craquelure, three examples of different observed patterns and what they can tell us about the history of the objects are presented.

Proving a burial rite

Some Roman glass fragments from the archaeological context of a cremation (*bustum*) from the Roman vicus of Bonn (RLMB E77/89, Fundnr. 71/10) were found to have a network of superficial cracks, appearing only on the exterior of vessels (Figure 1). Only a few of these fragments had been deformed by heat. Cracks of the narrow honeycomb-like pattern do not extend through the entire thickness of the glass. Weathering, which produces different crack patterns in glass, cannot be the cause, as it would have acted similarly on both surfaces of the totally sedimented glass [1].

Experiments showed that such a superficial network with no total fractures appears when glass heated above the transformation temperature is quenched with cold

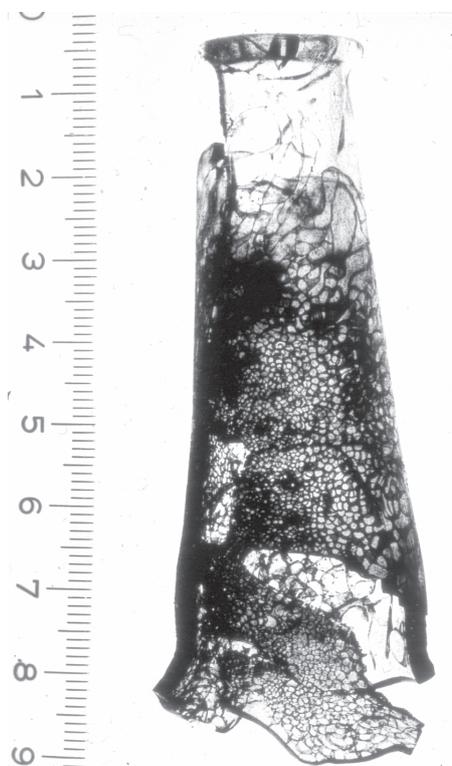


Figure 1 Roman bottle neck (Rheinisches Landesmuseum Bonn E 77/89) with superficial honeycomb craquelure (scale in cm).

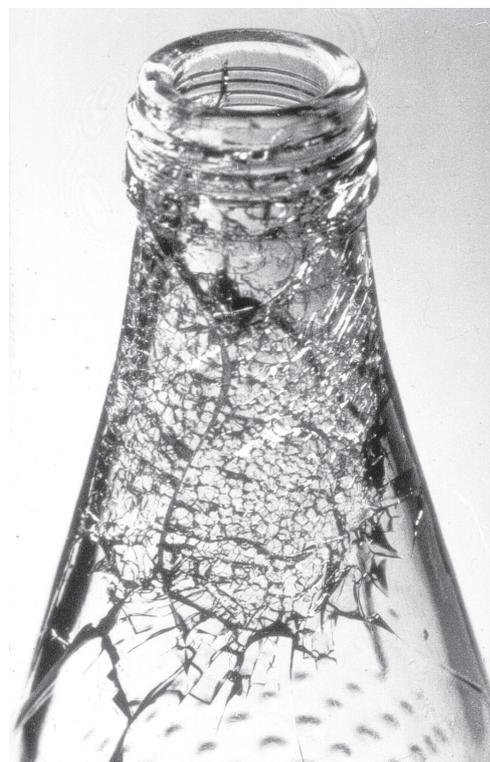


Figure 2 Reconstruction experiment: Modern bottle locally heated with a gas torch, then quenched in cold water (outer diameter of mouth 2.5 cm).

water. In the interior the glass still flows like a liquid, so no large stresses can build up and, therefore, the cracks occur only in the surface region. Only at places with a lower temperature (e.g. around the spot directly heated with a flame, Figure 2) where the glass was not plastic enough, did the normal thermally induced fractures, which run through the whole thickness, occur. The unusual craquelure pattern is known today from fire-extinguishing damage on glass windows [2: Figure 12.20]. It also occurs as an initial step in one method of producing ice glass, when the partially blown gather of white-hot glass is plunged momentarily into cold water.

The pattern is caused by the directional solidification that occurs when the contraction produces a tensile stress that can no longer relax through viscous flow (as the glass is now too cold on the outside) and exceeds the strength of the material. During the slow cooling of magmas under comparatively small temperature gradients, a homogeneous stress distribution causes a highly symmetrical crack network system consisting of

near-identical polygons. In principle, there are only three different regular polygons (all sides and angles equal) that can cover a surface fully: triangles, squares, and hexagons [3]. And for a given area the hexagon is the polygon with the smallest circumference (i.e. it needs the lowest fracture energy to form new surfaces). Many basalt columns are indeed hexagonal. But in the catastrophic event of accelerating and then branching cracks, as in a quenched glass surface, kinetic instead of thermodynamic arguments are needed. For a fast-running crack, the direction of the maximum tensile stresses (where the branches go after bifurcation) is 60° to either side of its path [4]. A series of bifurcations at 120° then forms the hexagonal, honeycomb-like pattern [5: 52].

Clearly, glass added to the pyre had become hot, but not necessarily so hot that the glass lost its shape. Then a torrent of liquid must have come into sudden contact with the glass to form such a network. This means intentional quenching; single raindrops do not suffice as

an explanation because they only form cracks where they are directly in contact with the hot glass and not in the surrounding area.

Liquids played an important role in Roman burial rites. Besides the distribution of fragrances and the washing of bone fragments after cremation, liquids also extinguished the still-glowing relics of the pyre. At least one passage by Statius [6: 2, 6, 90–91], ‘The Setian wine quenched (*restinxit*) the hoary ashes’, clearly speaks of quenching/extinguishing, and not only of sprinkling (Cicero [7: 2, 23, 60]: *respersio*; Pliny [8: 14, 88]: *respargito*). But the performance of rites can only be proved when they leave unique material traces in the archaeological record. Primary additions to the pyre like bone, ceramic, wood or metal do not show unquestionable marks. For example, there is no way to distinguish metallographically the structural effects of quenching during burial from that during production by a blacksmith. Glass seems to be the only material where this rite leaves unequivocal traces in the form of the craquelure pattern described. Once recognized, few other examples could be identified. A closer look at craquelure on cremation finds will certainly bring more examples to light. On the other hand, its absence does not prove that no quenching was practised: the torrent of liquid might have missed the glass, or the glass temperature might have been too low and the glass then fractured totally.

Roman glass – thermally toughened?

Modern thermal toughening (‘tempering’) of glass to increase fracture strength was invented by Alfred Royer de la Bastie in 1874 [9]; he quenched very hot glasses in hot oil. At the moment when the glass ‘solidifies’ (i.e. when stresses can no longer relax by viscous flow) the outer zones are colder than the interior. Therefore, their tendency to contract is lower than in the interior, which sets them under compression balanced by tensile stress in the interior. The outer compressive stress acts against the opening of cracks on the surface and, therefore, increases the fracture strength. At the time this invention was made the story was remembered [10] of an unbreakable *vitrum flexile*, told by Pliny [8: 36, 195] and Petronius [11: 51] and repeated by many authors until recent times [12]. Could a similar Roman technique of thermal toughening be the truth at the heart of the legends? This hypothesis became testable when Rottländer connected the stories with a definite group of Rhenish glass finds [13]. They appear to have been broken during burial into very small fragments that lay close together. One

find was even described by an archaeologist as fractured like ‘Sekuritglas’, a registered trademark for thermally toughened glass [14].

Nevertheless, thorough inspection of the fracture pattern of these finds revealed significant differences to the typical ‘dicing’ of thermally toughened glass (Figures 3 and 4): the areas of the fragments vary too much and can be different on either side (Figure 5). Some of the fragments are rather pointed, which would be unacceptable in modern safety glass. Even on fracture surfaces that look uncorroded, no typical marks for thermally toughened glass could be identified (i.e. a rough zone in the middle or Wallner lines; for details see, for example, Shinkai [15] and for definitions ASTM C1256-93 [16]). Many fractures through the glass are not perpendicular to the surfaces as in tempered glass [17].

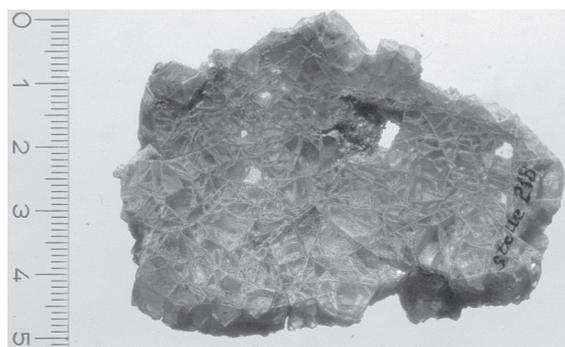


Figure 3 ‘Cracked like Sekuritglas’? Inner surface of a fragment of a Roman vessel with high, narrow neck (Rheinisches Landesmuseum Bonn E 252/84, scale in cm).

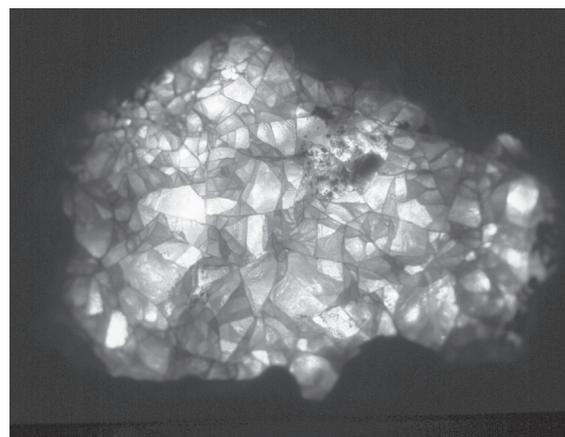


Figure 4 Same as Figure 3, but in transmitted light.

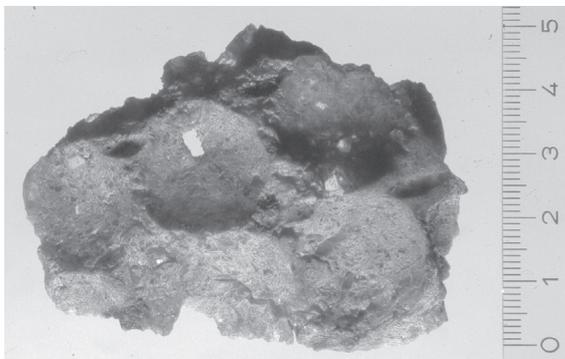


Figure 5 Outer surface of the fragment in Figures 3 and 4 with spherical cuts, 'sugar cube' appearance because of very fine craquelure.

The system of compressive and tensile stress makes glass anisotropic and causes a corresponding birefringence in the glass, which partially remains in fragments after fracture. Polarization microscopy could not detect the expected compression/tension system found with modern fragments. Last but not least, even modern technology can thermally toughen thicker glass (> 4 mm) only in open forms such as sheets, plates, and cups, but not vessels like the Roman ones with high, narrow necks and thin walls; they would simply fracture during production. Rottländer's other arguments (reconstruction experiments, manganese content, use of sulphur on glass) have been discussed in detail elsewhere [18].

Corrosion, perhaps combined with a selective weathering of pre-existing scratches (most Roman glasses with this crack pattern were cut), is a much more likely explanation of the pattern: the network pattern is formed when the leached outer gel layer dries out. This confirms Pliny's own critical comment about the legend of *vitrum flexile*: 'The story has hardly been well-enough authenticated to warrant the publicity which it has long received.' [8: 36, 195].

Craquelure in Chinese glaze and authenticity

To avoid the glaze peeling off when the ceramic body contracts more than the glaze on cooling, potters can use glaze compositions with larger thermal expansion coefficients. Then the glaze has the tendency to shrink more on cooling than the body allows, which can lead to the development of cracks if the tensile strength of the glaze is exceeded. Swelling by rehydration of the body can contribute to this crazing. If not enough stress

is relieved by primary cracks, secondary ones start over time at flaws and are directed by the residual stress to intersect at right angles and are arrested. A perpendicular crack network is created where one can easily see which crack was first. In some wares the craquelure formation is intended as decoration.

Lead-glazed burial figurines of the T'ang Dynasty (618–906 AD) have often been imitated. Fleming investigated the idea that craquelure as an ageing effect occurring over time might help in authenticity studies of them [19]. He argues that during time a finely meshed network of crackles (which can also be seen in older figurines, but not in recent imitations) is superimposed on the coarser structure that developed directly at the time of firing. He illustrates for the first time the variability of patterns on authentic pieces dated by thermoluminescence (TL) and measures the average spacing of fissures. In one case, he fails to recognize the special pattern of formation which is clearly depicted by him in a photograph [19: Plate 17b] and drawing [19: Figure 2ii]. Parallel initial cracks are crossed by slightly curved secondary cracks stopping at the initial cracks. This 'coarse network' looks very similar to the pattern in Guan and Jun ware which was termed 'columnar crazing' by Hodges [20] in apparently the first and only paper on glaze craquelure patterns in the conservation literature. But in the T'ang glaze example crack formation proceeds: the rectangles formed by primary and secondary cracks are bisected by tertiary cracks into smaller ones, which are themselves bisected by quaternary cracks and so on (Figure 6). Even cracks of the ninth order can be seen and there might be more on the object if it was seen under magnification. Once recognized, similar spots, but not total fields, could now be detected in perpendicular craquelure on glaze of many wares which looked totally random at first sight.

Fleming's distinction between a coarse and fine network becomes rather meaningless if both follow the same law of formation. The generation principle of dividing a nearly rectangular shaped area by bisecting the longer sides into halves creating similar smaller ones exhibits fractal geometry of repeated, self-similar structures at varying scales. The spacing of fissures is, therefore, not of much use in characterizing the patterns that occur. Fractal forms, which can be seen in many natural deterioration processes of artifacts – as was realized by Scott [21] – are today open to mathematical description which might help in better distinguishing and learning more about them.

As an aside, the special crack pattern also has a parallel in Euclidian geometry: the generation of A paper

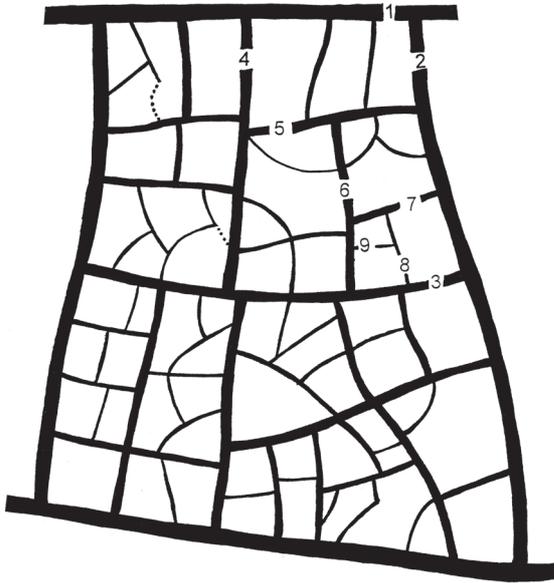


Figure 6 Schematic drawing of the craquelure in a chestnut glaze splash on a Tang horse figurine after Fleming [19: Plate 17b, and for lower right quarter also Figure 2ii]. Size of field c. 0.86 x 1.12 cm. Numbers indicate sequence of formation of individual cracks.

formats with constant ratio of the sides of $\sqrt{2}:1$ according to ISO 218 by starting with a rectangle of 1 m² (A0) and halving the longer side to create A1, and so on.

DISCUSSION AND CONCLUSIONS

These examples illustrate that not only the individual fracture surface (as analysed by fractography) but also the overall pattern, the craquelure, contains information about what happened to objects or how they can be distinguished. Despite their visibility and their occurrence in many fields (permafrost ice, magmatic rocks, drying concrete or mud, aged amber, varnish, plastics, etc.), these contraction crack patterns seem to lack an overall scientific theory. Pattern distinctions created in one field could prove fruitful in others. Lachenbruch [5], who interpreted the random or oriented orthogonal polygon networks in permafrost as evolved by successive subdivision and the non-orthogonal (hexagonal) ones by successive branching of fast cracks, already drew a parallel to columnar basalt joints and mud cracks. As has been shown here, he could also have listed glass and glaze as examples.

The only field in conservation where progress has been made in the description of craquelure in the last

decade is paintings on hygroscopic supports (wood, textile), due to the work of Bucklow [22, 23]. The craquelure pattern here is related to the materials and methods employed by the artist. To test the claim of connoisseurs that craquelure provides clues to art-historical attribution, Bucklow [22] developed and tested a descriptive framework of seven dichotomies that expressed the extreme poles of a range of possibilities:

- 1 predominant orientation of cracks;
- 2 changes in direction (smooth or jagged, straight or curved);
- 3 orthogonal or non-orthogonal network;
- 4 distance between cracks;
- 5 uniformity of thickness of cracks;
- 6 junctions or terminations of cracks;
- 7 organization of cracks (ordered or random).

The pattern can either be classified by subjects assisted by rules or by computer analysis of digitized images [23]. These dichotomies can also be taken as a starting point for a closer look at craquelure in glass and glaze and a more systematic approach to their distinction. In contrast to opaque materials or thin transparent layers (varnish, glaze), transparent glass poses the additional problem that the image of the superficial lines is superimposed by the crack surface itself (see Figures 3 and 5). Images in transmitted light (Figure 4) might be one way partially to overcome this practical problem.

Once an empirical database is collected, physical modelling of individual types, perhaps with the help of fractal geometry, could lead to a better recognition. This would test the author's hypothesis: there is certainly much more to be seen and new insights can be expected!

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Résumé — À la différence des craquelures observées dans les peintures ou les vernis, les craquelures dans le verre et les glaçures ont été négligées en tant que source d'information en conservation. En regardant de plus près il est possible d'observer des différences qui sont autant d'indices surprenants (indiquant par exemple le refroidissement des cendres de crémation romaines ou au contraire invalidant la thèse du renforcement thermique chez les Romains) ou qui fournissent une façon de mieux interpréter les craquelures dans les vernisures authentiques. Un cadre descriptif doit prendre en compte les différences de forme des craquelures prises isolément et les particularités de leur réseau. Cela peut conduire à une meilleure compréhension théorique de leur géométrie fractale et à de nouvelles découvertes d'informations jusque là cachées.

Zusammenfassung — Im Gegensatz zu Krakelee in Malschichten und Firmis wurden Rissmuster in Gläsern und Glasuren bisher als Informationsquelle für die Restaurierung vernachlässigt. Ein genauerer Blick zeigt Unterschiede auf, die überraschende Hinweise geben können, z.B. auf das Abschrecken von Beigaben der Leichenverbrennung, gegen thermisches Vorspannen von Gläsern bei den Römern oder für ein besseres Verständnis von Rissen in authentischen Glasuren. Eine Terminologie zur

Beschreibung muss einerseits Unterschiede in der Form der einzelnen Risse, andererseits Besonderheiten des Rissmusters erfassen. Dies könnte ein besseres Verständnis ihrer fraktalen Geometrie und der in ihnen verborgenen Informationen ermöglichen.

Resumen — *Al contrario de lo que ocurre con la pintura y el barniz, los craquelados en el cristal y en el vidriado no han sido considerados como fuente de información en el campo de la conservación. Una observación atenta de éstos nos puede mostrar diferencias que pueden aportar sorprendentes pistas (por ejemplo, en lo que se refiere a las evidencias de la tradición romana del apagado de las cenizas de la cremación, o en contra del endurecimiento termal romano), además aporta una mejor interpretación de los craquelados en vidriados auténticos. Todo modelo descriptivo tiene que fijarse, tanto en las diferencias en las formas individuales de los craquelados, como en las peculiaridades de las redes o tramas que producen. Todo esto puede llevar a una mejor comprensión teórica de su geometría fractal y a nuevos descubrimientos de información oculta en ellos.*