Comments on the Yule Marble Haines Block—Potential Replacement, Tomb of the Unknown Soldier, Arlington National Cemetery

By Victor G. Mossotti

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Cover: Photograph of Tomb of the Unknown Soldier, Arlington National Cemetery, SE and NW corners. Close-up: Northwest corner; Ruler width=11mm. Photographed by Victor G. Mossotti, U.S. Geological Survey.

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Comments on the Yule Marble Haines Block—Potential Replacement, Tomb of the Unknown Soldier, Arlington National Cemetery

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Abstract

Marble for the Tomb of the Unknown Soldier at Arlington National Cemetery was cut from the Colorado Yule Marble Quarry in 1931. Although anecdotal reports suggest that cracks were noticed in the main section of the monument shortly after its installation at the Arlington National Cemetery in Arlington, Virginia, detailed documentation of the extent of cracking did not appear until 1963. Although debate continues as to whether the main section of the Tomb of the Unknowns monument should be repaired or replaced, Mr. John S. Haines of Glenwood Springs, Colorado, in anticipation of the permanent closing of the Yule Quarry, donated a 58-ton block of Yule Marble, the so-called Haines block, as a potential backup. The brief study reported here was conducted during mid-summer 2009 at the behest of the superintendent of Arlington National Cemetery. The field team entered the subterranean Yule Marble Quarry with the Chief Extraction Engineer in order to contrast the method used for extraction of the Haines block with the method that was probably used to extract the marble block that is now cracked. Based on surficial inspection and shallow coring of the Haines block, and on the nature of crack propagation in Yule Marble as judged by close inspection of a large collection of surrogate Yule Marble blocks, the team found the block to be structurally sound and cosmetically equivalent to the marble used for the current monument. If the Haines block were needed, it would be an appropriate replacement for the existing cracked section of the Tomb of the Unknown Soldier Monument.

Introduction

The Tomb of the Unknown Soldier was unveiled on April 9, 1931, although the remains of an unknown U.S. soldier from World War I were laid to rest at the location a decade earlier. A report in 1963 first documented the occurrence of cracks in the tomb monument, though the cracks probably existed well before that date. As the cracks have continually grown, now reaching around the entire Tomb, debate also continues as to the cause of the cracks and strategies for dealing with the cracked monument. As this polemic has evolved, Mr. John S. Haines from Glenwood Springs, Colorado, donated a block of Yule Marble to replace the main rectangular block of the existing monument that separates the cap of the monument from the base; this architectural element is referred to as a die. When the 57-ton Haines block was cut from the Yule Marble Quarry in Colorado in 2004, exceptional practices were followed in the removal and transport of the block to minimize physical impacts that might trigger structural defects. The chronology of the exhaustive effort at the quarry has been formally documented by Bailey (2009). Figure 1 shows the Haines block at its present location near the Yule Marble Quarry. The dimensions of the rough block and of the finished monument are given in table 1.

Table 1. Dimensions of the rough Haines block and of finished die (Raphael, 2004).

	Rough (m)	Finished (m)
Height	1.8	1.577
Width	1.7	1.991
Length	4.5	3.733

The brief study reported here was supported by the Office of the Superintendent of Arlington National Cemetery/Department of Defense (OS/ANC/DOD). The report was first delivered as an administrative field report to the OS/ANC in 2009, and was only recently released for publication. The field party entered the subterranean Yule Quarry with the Chief Extraction Engineer in order to understand the potential physical shock delivered to a large marble block during extraction and transport. The field team also closely examined the Haines block in the storage area to provide a qualitative assessment of structural stability of the block when transported, carved, and exposed to the weathering conditions at ANC. An attendant purpose is an inquiry into the possible cause of the cracks in the existing monument, within the context of evaluating the suitability of the Haines block as a replacement for the existing Tomb of the Unknown Soldier die.

Yule Marble

Yule marble is quarried outside the town of Marble in central Colorado (39°4′20″N, 107°11′22″W; cf: Ref. Colorado Stone Quarries). The marble is named for George Yule, a mining engineer who discovered and realized the value of the marble deposit in 1873. The marble deposit occurs as a massive white bed, about 200 feet thick; the quarry is located on the east side of Treasure Mountain, and west of Yule Creek, several miles upstream (south) of where Yule Creek joins the Crystal River. The entrance to the quarry is about 1,400 feet above Yule Creek (figure 2). The mine was closed by its previous owner, Polycor, in 2009, and it was reopened in 2011 by a partnership of the RED Graniti Company and Locati Luciani Enrico & C.S.A.S. of Carrara, Italy (Colson, 2012). The Haines block was extracted from a location in the quarry close to where the stone for the original monument was taken. The block was cut from the quarry wall at an angle such that, after removal, the light-colored inclusion trains ran parallel to the length of the block, in keeping with the patterns on the existing tomb. At that time, the block was examined closely for obvious structural fractures and surficial blemishes. The Haines block was found to be remarkably similar in quality to the existing monument in Arlington National Cemetery (ANC), apart from the latter’s cracks, of course.

Observations at Yule Marble Quarry

The observations reported here are based on close examination of the Haines block and of about 1000 ft^2 of large interior fracture surfaces of 24 formally intact Yule Marble blocks; quantitative statistical analysis was not carried out on the observations. The Haines block’s cut surface revealed the block to be of the highest cosmetic quality. The light-gray mineral inclusion trains apparent in the Haines block, were identified as mica or feldspar (McGee, 1999). Perhaps the most troublesome observation was the discovery of a set of small set of hairline cracks on the top of the Haines block. In an attempt to discover how deep the specific hairline cracks run from the top of the Haines block into the stone, three 4-cm diameter cores were taken from the top of the block with each drill hole centered on a crack; the holes were drilled to a depth of about 4.5 cm (figure 4). Close inspection of the inner walls and bottom of the bore holes revealed that the small cracks penetrated the Haines block at least to the full depth of the holes. Because the hairline cracks extended beyond the depth of the drill holes, it was not possible to determine the full trajectory of the fractures by coring the surface.

It would seem at first that sophisticated techniques (for example, ultrasound reflection, x-ray or gamma-ray tomography) could be used to ascertain the presence of fractures and voids inside a marble block. For example, Mossotti and Castanier (1988) used computer-aided tomography scanning to track the percolation of a water flow-front through limestone. However, such density imaging techniques applied to the massive texture of the Yule Marble would produce a low signal-to-noise image. Instead, the analysis provided in this report is based on the use of surrogate Yule Marble surfaces exposed by breaking, rather than by sawing, to provide a view of the internal texture of the stone. Conveniently, there are many broken marble blocks strewn about the quarry yard with exposed natural surfaces. The availability of such blocks is a consequence of the way large blocks were historically removed from the quarry wall. It is common practice that blocks are defined for removal from the quarry wall by vertical and horizontal cuts into the wall. The bottom cut is made sufficiently wide to permit the insertion of rollers below the block, and the side cut opposite the open bench is made of sufficient size to accommodate a hydraulic pump or air bag that can apply lateral stress to the hanging block. The back of the block is typically cut using a wire saw, but the block is generally not cut all of the way through from the wall, leaving the block “hanging” on the wall on the side distal to the exposed face. This allows the operator sufficient control over the heavy mass and an opportunity to remove the wire saw. When the hydraulic pump is actuated, torque is applied at the point of attachment. At a particular stress threshold, the block simply breaks off the wall onto the rollers and becomes available for off-loading from the quarry bench.

Figure 5 is a photograph of the back side of a block of stone that was first cut by wire saw and subsequently broken from the quarry wall; the final circular track of the wire saw is apparent at the separation of the smoothly cut surface from the rough broken surface. On the sawed faces, the natural internal texture of the block is shaved off and otherwise obscured by the action of the saw, whereas the broken corner shows internal texture of the block to the depth of the breakage. Although the wire saw freed most of the block from the rock formation, the entire corner of the block was sacrificed by the hydraulic technique that broke the remaining corner attachment wall, resulting in some mechanical shock to the block. At the scale of observation in figure 5, there appears to be no directional correlation of the inclusion trains with structural features associated with the host rock. Figure 6, a blow-up of the visible inclusion trains in figure 5, shows that inclusions penetrate the stone below the cut surface and that the growth history for the trains probably involved fluid flow along original bedding planes.

The photograph in figure 7 also shows the backside of a block that was cut by the wire saw and broken from the quarry wall. In this case, the violent release of the block from the wall may have initiated or extended an existing horizontal fracture that has propagated from the broken surface across the block and around the corner of the block. The width of the mildly curved fracture appears to decrease with distance from the point of shock. The fracture trajectory seems to be associated with cracks initiated by mechanical shock to the stone. In this case, the crack runs almost perpendicular to the direction of the inclusion trains in the block, indicating the crack trajectory was not guided by the original bedding layers in the marble protolith.

Figure 8 shows a series of images at increasing resolution of the broken skyward-facing surface of a block of marble resting next to the Haines block at the quarry. These photos show a complex network of natural grain aggregations that permeate the stone at all scales. One can discern lenticular grain aggregations in the exposed surface, possibly resulting from a preferred stacking of calcite crystals, in these images. Thousands of micro aggregations appear to be closely packed in a given volume of stone and the stone contains a smaller number of larger aggregations. Because the basic pattern of packed aggregations includes sizes covering a wide range of scale, the pattern appears to be scale invariant. Such textures are described as fractal, which in this case implies that there are no characteristic boundary lengths or characteristic distances between boundary intersections. While such fractal structure may be consistent with the classification of Yule Marble as massive over a range of scales for which textural properties are isotropic, the power-law distribution of lenticular grain aggregations allows for a finite probability of local schistosity over complementary scales. The finite probability of alignment of grain aggregations is significant, because water may anisotropically penetrate the stone over a spectrum of scales by preferentially flowing along the flat faces of the grain aggregations. Also, the grain aggregation boundaries are analogous to expansion joints in concrete sidewalks. As such, they represent a mechanism that inhibits crack propagation due to weathering or mechanical shock, also over a spectrum of scales. Just as a crack in a concrete sidewalk is stopped by an expansion joint, the probability of a fracture propagating across the stone by weathering along connected grain boundaries is expected to be quite low, as long as the shear strength threshold of the grain aggregations is not exceeded by mechanical shock. One would expect that natural weathering along such boundaries would follow a jagged course. Figure 9, a close-up photograph of interlocking grain aggregations, highlights a possible mechanism by which the growth of micro-cracks by natural weathering might be inhibited; the stone in figure 9 is located in the marble storage yard near the Yule Marble Quarry.

The following is a summary of observations on the Haines block and on other large marble blocks in the stone yard:

- Inclusion trains penetrate the stone to considerable depth.
- Fractures generally do not have any spatial relation to the inclusion trains.
- Fracturing mechanisms within the Haines block can be understood using conventional photography of surfaces on proxy blocks that were produced by the stone being broken rather than sawed.
- Relatively few and only small voids have been visually observed on examination of broken marble-block surfaces.
- Grain aggregations exhibit lenticular shape; such aggregations, and the collection of grain boundaries inside the stone, appear to be fractally distributed in size over a broad range of scale (micro to macro).
- Water may move into and out of the marble in preferential directions along the flat faces of lenticular grain aggregations.

Observation of Cracks on the Tomb Die

Figures 10–15 show close-up photographs of two relatively large cracks that define nearly parallel fracture planes that dip between 11° and 13° from the northwest to the southeast corners of the die. The maximal widths of the cracks at the northwest to the southeast corners are approximately 4 mm. The crack on the northwest corner, perhaps the better documented of two horizontal cracks on the die, has been referred to as the primary crack. The lower crack cutting the southeast corner is referred here as the secondary crack.

In 1963, the combined horizontal extent of the two cracks was estimated to be about 34 feet around the die. A decade later, the cracks were noted as having extended by about 21 percent. By 1989, the horizontal extent of the cracks had increased to 44.6 feet, an increase exceeding 10 feet since first reported (Department of the Army, 2008). On the basis of measurements made by a field party to ANC in October 2009, the primary crack now extends to about 92 percent across the south elevation and about 66 percent of the east elevation.

Figure 10 shows close-up photographs of relatively large cracks on the southeast and northwest corners of the tomb die where the maximal widths of the fractures are approximately 4 mm.

Similar to the fracture on the block shown in figure 7, the width of the primary crack on the north elevation (figure 11) decreases with distance from north to east, terminating on the east elevation the around the northeast corner. Note also that the primary crack traverses the west elevation starting from the northwest corner, wraps around the southwest corner (figure 12), traverses the south elevation (figure 13), and terminates at a point about two-thirds the distance across the east elevation (figure 14).

Interpretations and Conclusions

There are three significant properties related to the genesis of Yule Marble that are the basis for the interpretation of the observations reported in the following section. These are: texture, bedding, and internal stress.

Stone texture. Yule Marble is a product of contact metamorphism about 12 million years ago of the Leadville Limestone, which was deposited 350 million years ago (Vanderwilt and Fuller, 1935; Gaskill and Godwin, 1966). Contact metamorphism occurs around intrusive igneous rocks as a result of temperature increase caused by the intrusion of magma into cooler surrounding rock. Because they do not experience differential metamorphic stress that deforms the rock in one plane, contact metamorphic rocks generally do not exhibit large-scale foliation features. Also, if in the metamorphic process there is a rapid temperature drop away from the intrusive body, the crystalline structure of the metamorphosed rock is fine grained. A large-scale nonfoliated fine-grained rock is generally described as having a massive texture; it is this large-scale massive texture that gives Yule Marble its special strength and the aesthetic appeal that favors Yule as a material for sculpture and architecture. However, as we will see, the strictly "massive" classification for Yule Marble may be deceptive, because some materials classified as massive can display varying degrees of schistosity when examined at particular scales (McKee and Weir, 1953). In the case of Yule Marble, the protolith (limestone) is predominately calcium carbonate, a mineral well known to be mechanically anisotropic, having preferred glide-planes depending on the direction of imposed stress (Griggs and Miller, 1951). In the limestone metamorphic process, where rock generally is not fluidized, there may have occurred marginal directional stress perpendicular to the bedding plane of the protolith, resulting in local schistosity over a spectrum of scales in the large-scale massive texture.

Bedding layers. The next structural matter of relevance, also related to the metamorphic genesis of Yule Marble, is the notion of bedding. The Yule Marble protolith was originally deposited in horizontal beds, subsequently uplifted and tilted. However, because metamorphism was uniform over large volumes of rock in the deposit, the process obscured most traces of bedding in the texture of the marble. The visible linear trains of mineral inclusions, such as quartz, feldspar, and mica, were most likely deposited by fluid flow along the original bedding layers, so reflecting their complex genesis.

Internal stress. This issue may inform our understanding of the spawning of fractures in the original Tomb die at ANC. In the final stages of the metamorphic process, the rapid drop in temperature as the igneous intrusion and adjacent rocks cool can lock in stress in deep internal structures of the stone. Eventually, as locked structures relax with the release of confining external pressure, the energy associated with the internal stress can manifest itself as deformational strain at the stone surface, whereupon the stone may crack.

Implied assumptions associated with the interpretations in this section include the following:

- Cracks initiated by mechanical impact will appear relatively straight near their origin if the shock wave exceeds the shear-strength threshold of grain aggregations.
- Cracks driven by natural weathering will follow a jagged course if the weathering energetics do not exceed the shear strength-threshold of grain aggregations; such cracks will follow aggregation surfaces, tracing out fractal grain boundaries.
- A significant control on the width of a crack is the stress field at the point of advance of the crack through the stone matrix.
- Interlocking grain aggregations inhibit the growth of micro cracks.
- Water may anisotropically penetrate Yule Marble over a spectrum of spatial scales by preferentially flowing along the flat faces of lenticular grain aggregations.

The geometry of the twin fractures on the die, as evident in figures 10–14, suggests an interpretation of compression along the central vertical axis of the die with possible down-drop tensional stress focused on the northwest and southeast corners of the die. Such a stress field could be the consequence of an upward warp of the 16-ton base supporting the die, resulting in a northeast-to-southwest trending ridge under the die. Such bowing could have been introduced in the original production of the base element, or it may have evolved with the natural anisotropic release of internal stress in the base element (Siegesmund and others, 2008).

Alternatively, the damage could have been caused by mechanical shock, possibly when the die was originally put in place. The fractures on the bottom of the northwest corner of the die (north elevation view) as seen in figure 15 are evidence in favor of such an alternative hypotheses. The widths of the primary and secondary cracks on the die diminish as they propagate in opposite directions from the northwest corner and the southeast corners, respectively. This indicates that the primary crack originally opened at the northwest corner of the die and the secondary crack at the southeast corner (Mossotti, 2009). The quantitative similarity of the widths of the primary and secondary fractures at their origin indicates that the twin fractures were initiated around the same time.

Note that cracks on the west and east elevations run nearly parallel, dipping between 11° and 13° (figures 12 and 14), respectively, while cracks on the north and south elevations run parallel in the horizontal direction. On the east elevation, it is clear that the fractures cut across the direction of the various inclusion trains, invalidating any notion that the cracks follow the original bedding planes in the Yule Marble protolith. Close inspection of the photos in figures 10, 13, and 14 shows no discernible lateral displacement of the fractured sections of the die, indicating that the fractures do not penetrate all the way through the block. Thus, the geometry of the fractures shown in figures 10–14, and the parallel projected fracture planes on the ANC die (about 12°), suggests a strong relation between the primary and secondary fractures on the die as depicted in figure 16. On the basis of these observations, the separation between the projected fracture planes is about 30 cm. Given the apparent vulnerability of Yule Marble to shear stress as illustrated in figures 5 and 7, the disquieting prospect exists–probably with a low probability–that at a particular shear stress threshold, the upper part of the block may radically break from the lower section without having been fractured on either the primary or secondary fracture planes through the center of the block.

On the basis of the observable attributes of the Haines block, the cosmetic quality of the block is of the highest quality, and the block appears to be free of structural defects. Although it may be possible to cut other blocks of similar quality, few would exceed the apparent quality of the Haines block. The Haines block is an outstanding piece of Yule Marble; if it were needed, it would be an acceptable replacement to the existing die.

Acknowledgments

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Appendix

Glossary (All definitions taken from Jackson, 1997)

Anisotropic: Having different properties in different directions.
Die: An architectural cube-like element positioned between architectural units above and below.
Dimension: Preparation of quarried stone according to specifications.
Foliation: Planer parallelism of flaky minerals and compositional layering.
Inclusion train: A trail of small crystals or minerals.
Isotropic: Having the same properties in all directions.
Schistosity: Foliation due to parallel alignment of platy mineral grains such as mica or crystals of other minerals.

Figures

Figure 1. Photograph of the Haines block at its present location near the Yule Marble Quarry.

Figure 2. View of Yule subterranean marble quarry below portal two.

Figure 3. Photograph of light gray mineral inclusions trains, not unlike those on the Arlington National Cemetery die and on the Lincoln Memorial.

Figure 4. Photograph of core hole ~3.5 cm diameter and ~4.5 cm deep, centered on hairline crack (graphically outlined for visibility) on the top of the Haines block; observed microcracks penetrated the Haines block at least to the full depth of the hole.

Figure 5. Photograph of the back side (last face attached to quarry wall) of a block first cut by wire saw and subsequently broken away from wall at the Yule Marble Quarry. The circular track of the wire saw is apparent at the boundary of the smoothly cut surface and the rough fractured surface.

Figure 6. Close-up photograph of inclusion trains on the block shown in figure 5.

Figure 7. Photograph of the back side of a block, about 1.7 m across, cut by wire saw, and broken from the Yule Quarry wall.

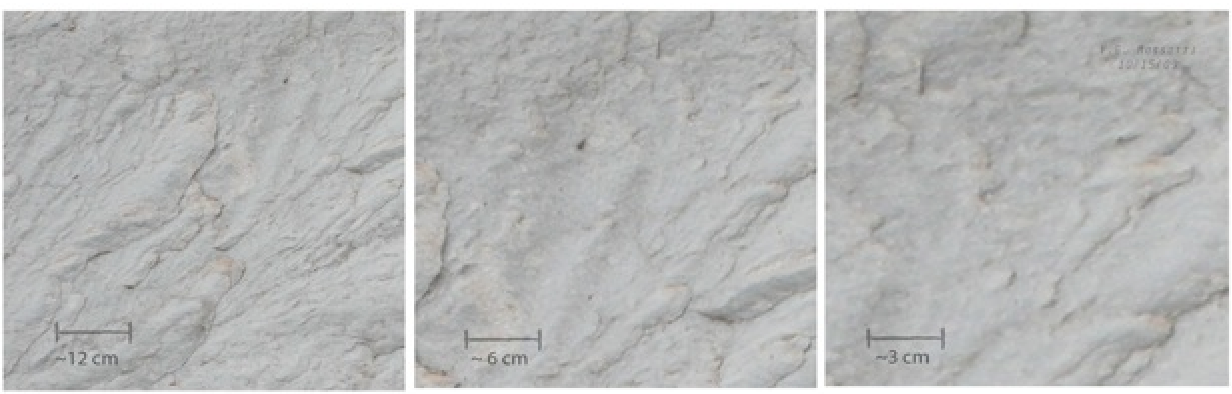

Figure 8. A series of images, at systematically increasing resolution (zoomed-in), of Yule Marble internal texture as revealed on the broken surface of a block. Note that the network of natural boundaries between grain aggregations appears unchanged across the range of scale.

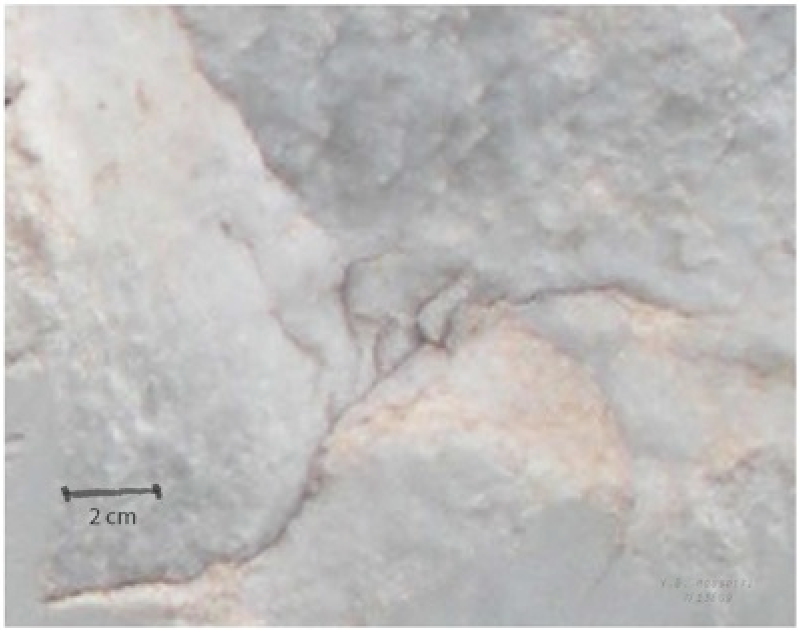

Figure 9. Close-up photograph of interlocking grain aggregations—a possible mechanism by which the growth of micro-cracks by natural weathering might be inhibited. Photograph of the back side of a block, about 1.7 m across, cut by wire saw, and broken from the Yule Quarry wall.

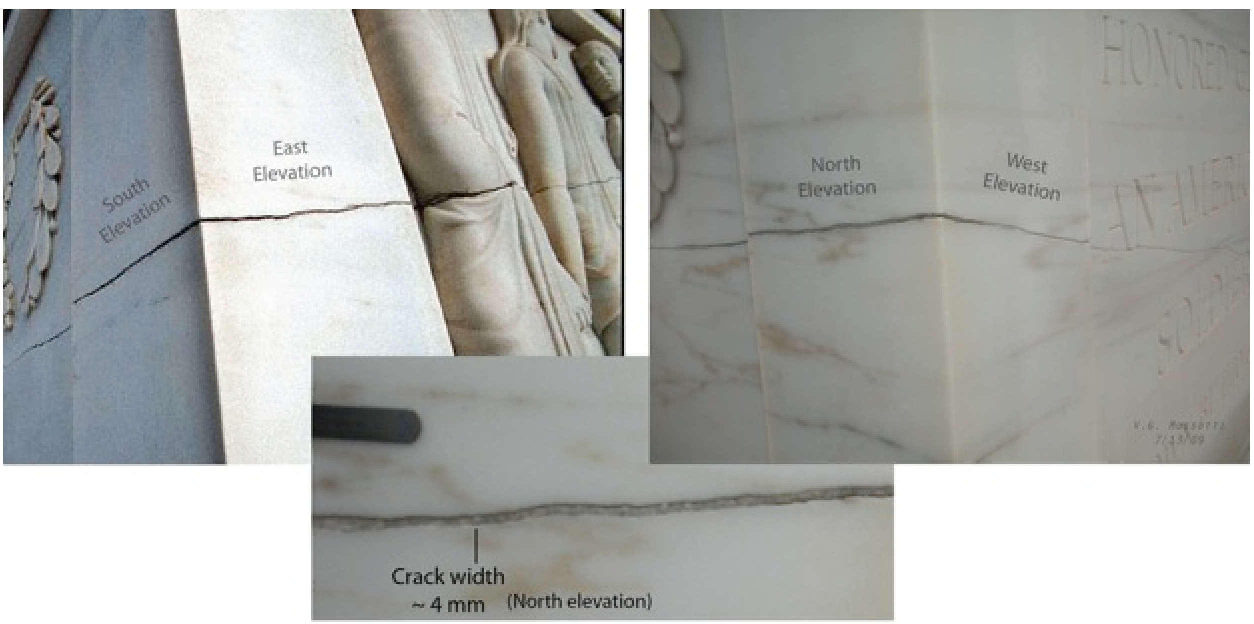

Figure 10. Photographs showing cracks on the southeast and northwest corners of the tomb die; maximal widths of the fractures are approximately 4 mm. (Ruler width, 11 mm).

Figure 11. Crack across the north elevation of the die at the Tomb of the Unknown Soldier, Arlington National Cemetery.

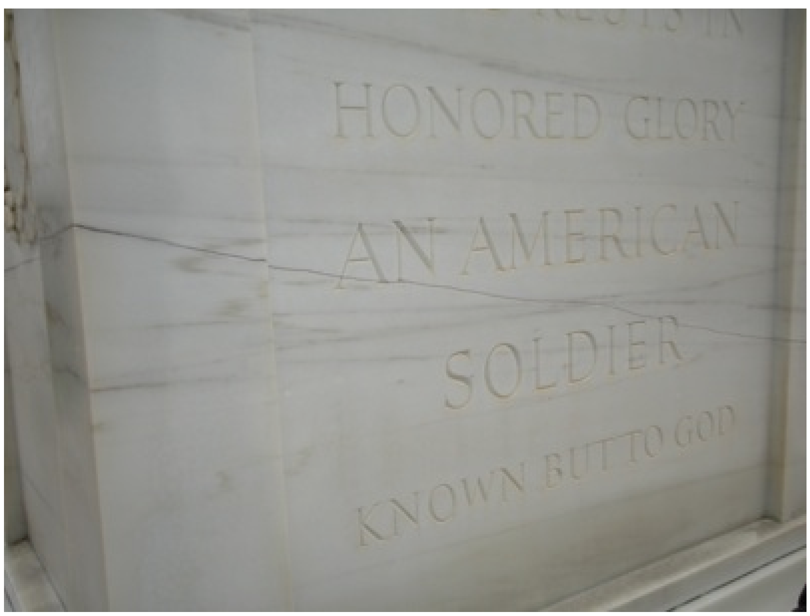

Figure 12. Crack across west elevation of the die at the Tomb of the Unknown Soldier, Arlington National Cemetery.

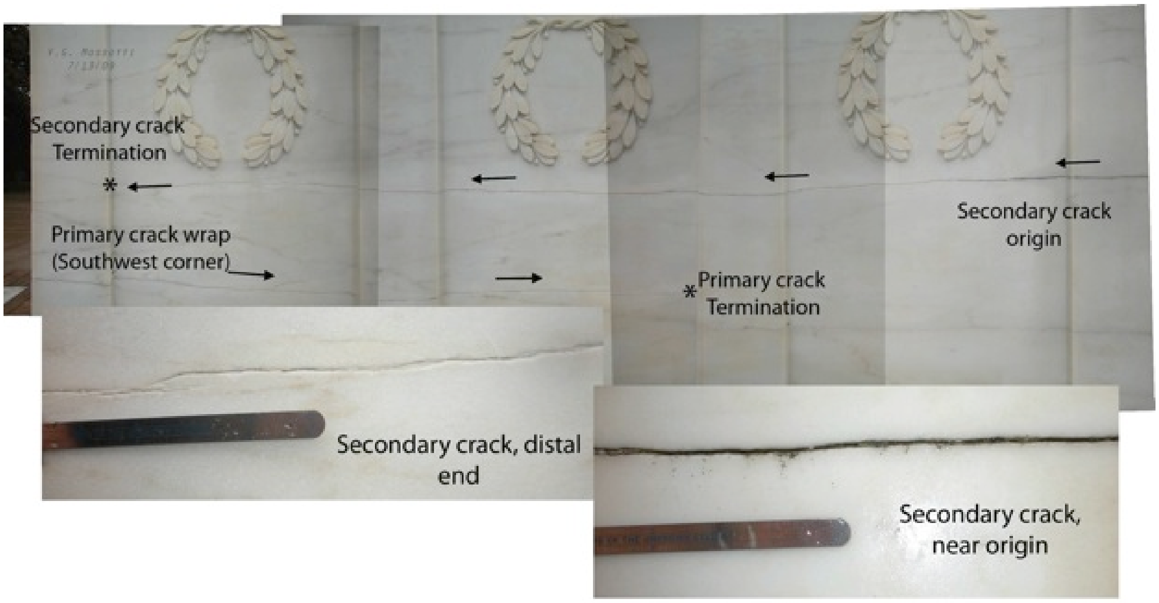

Figure 13. Cracks on south elevation of the die at the Tomb of the Unknown Soldier, Arlington National Cemetery. Close-up inserts: Secondary crack near east and west ends. (Ruler width, 11 mm).

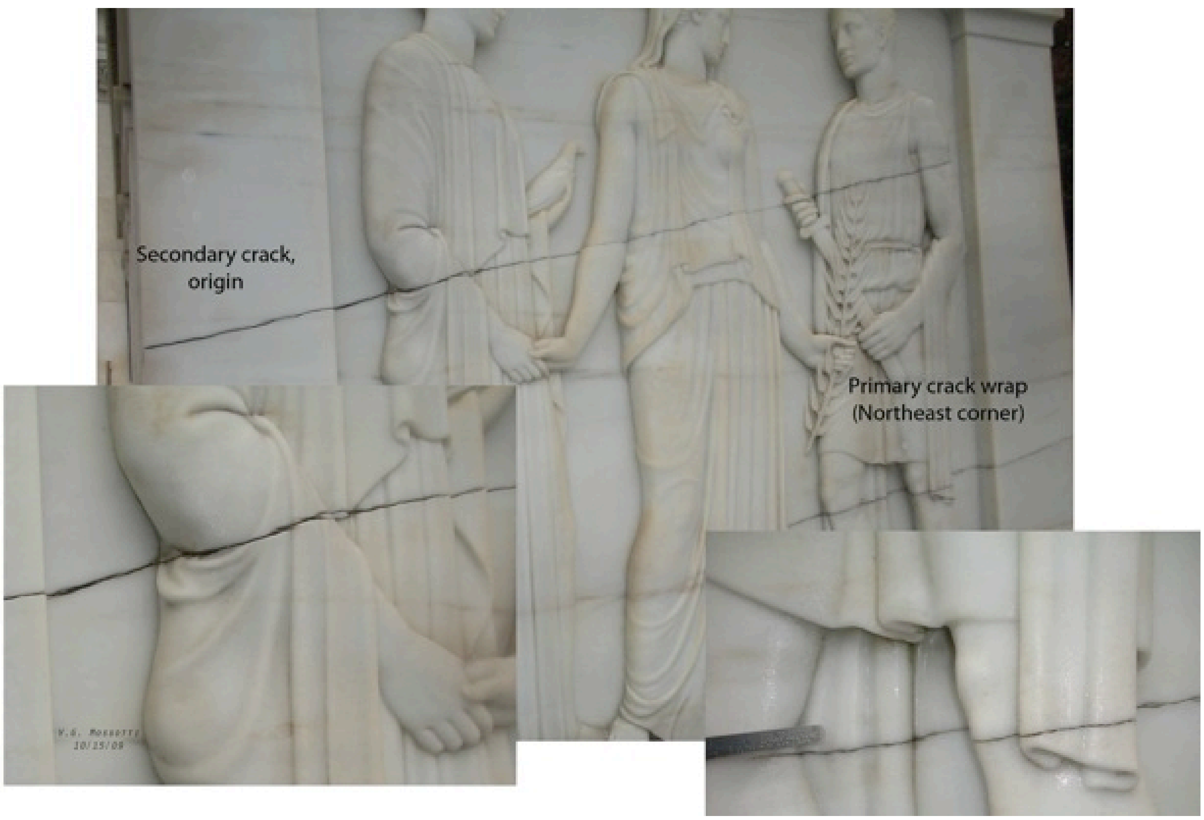

Figure 14. Cracks on the east elevation of the die at the Tomb of the Unknown Soldier, Arlington National Cemetery. Close-up insert: Crack on the right arm on the left figure above the insert near the origin of the secondary crack.

Figure 15. Fractures on the bottom of the northwest corner of the die at the Tomb of the Unknown Soldier, Arlington National Cemetery (north elevation view).

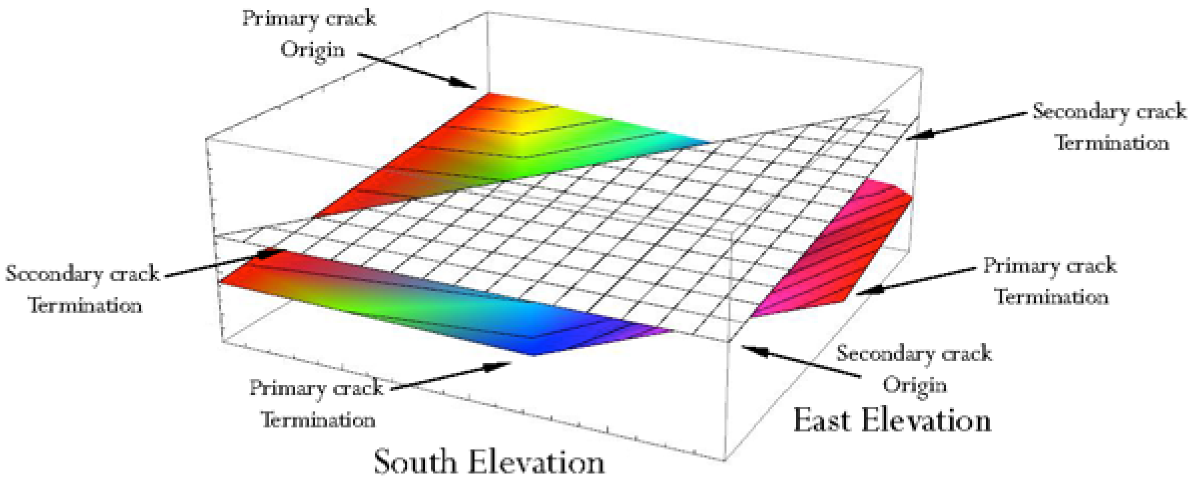

Figure 16. Schematic projection of fracture planes in the die at the Tomb of the Unknown Soldier, Arlington National Cemetery (South elevation perspective, not to scale).

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