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ISAMU NOGUCHI'S "BLACK SUN": INVESTIGATION OF A CRACKING PHENOMENON

Patricia Leavengood, John Twilley and Thomas Van Halm

Abstract

The monumental sculpture by Isamu Noguchi entitled "Black Sun" was carved in Mure, Japan from a single 30-ton block of stone quarried from the Tijuca formation in Brazil. The finished piece, a polished torus shape nine feet in diameter and weighing 12 tons, was installed on an outdoor viewing plaza in front of the Seattle Art Museum in 1969. Small hairline cracks in a radial pattern were noticed on the west face of the sculpture during the 1980's. In 1992 the cracks were mapped and measured; by 1994 a definite increase in the width and length of some of the cracks was verified. A core sample and acetate peel samples were taken and analysed. The stone was characterized mineralogically as a black gabbro. The core sample was examined petrographically for evidence of weathering or mineral transformations that might be associated with the crack development. The results disclosed nothing of this sort and suggested that the cracking is a purely physical phenomenon related to stresses in the stone. A program of thermal monitoring was established and measurements were taken over a one year period. A computer model of the sculpture was constructed and the collected data was used to plot expected thermal tension stresses in the sculpture due to temperature differentials. The computer modelling indicated thermal stress patterns consistent with the cracking pattern on the sculpture.

To prevent water penetration into the cracks and the development of secondary deterioration phenomena a fill material of Acryloid B72 bulked with microballoons was applied in January 1995 and has been monitored for loss and shrinkage since. To date the cracks appear to have stabilized, which might indicate a state of thermodynamic stasis has been reached. Sheltering of outdoor stone sculptures during severe winter weather when the exhibit is closed has been undertaken at the Noguchi Foundation in New York. However, permanent shading of "Black Sun" to minimize cyclical solar heating has been deemed to be aesthetically unacceptable. Considering the size and weight of the sculpture, as well as its site specificity, movement of the piece to another location is not feasible. Constant monitoring and maintenance of the fill material is the recommended treatment for the present.

1. Introduction

When Isamu Noguchi created the monumental "Black Sun" in 1969 he was at the height of his career and enjoying an intensely productive and creative period. A major retrospective of his work had been held at the Whitney Museum in New York in 1968. His sculptures were internationally known, and he had recently completed and installed major pieces for Chase

Manhattan in New York, the Israel Museum in Tel Aviv, Beinecke Library at Yale University, and the city of Spoleto, Italy. In 1968 the Japanese-American artist was commissioned jointly by the Municipal Arts Commission of Seattle and the National Foundation for Arts and Humanities to create a large-scale sculpture for installation in a public space in Seattle (Figure 1a). The sculpture was one of three major works by various artists commissioned for public spaces in the United States by the fledgling National Foundation for Arts and Humanities, under a new program designed to provide the nation's cities with publicly-accessible high quality artworks.

To create "Black Sun" Noguchi purchased a 30-ton block of black gabbro (often mis-identified in catalogues of Noguchi's work as "granite"), directly from a quarry in Brazil and had it shipped to his studio compound in the city of Mure, on the island of Shikoku, Japan. Noguchi had recently begun to work with a young Japanese stone carver, Masatoshi Izumi. "Black Sun" was the first monumental sculpture Izumi had ever carved, but it was followed by many significant works during a long and fruitful collaboration with Noguchi (Ashton 1992). When completed in the summer of 1969 the sculpture, a highly polished, torus-shaped piece approximately 9 feet in diameter and weighing 12 tons, was shipped from Japan to Seattle, Washington where it was installed in Volunteer Park in front of the Seattle Art Museum. Noguchi saw "Black Sun" as a companion piece to the 1964 white marble "Sun", a major element in the Beinecke Library sunken garden installation. It fulfilled Noguchi's desire that a "Sun" sculpture be on each coast of the United States.

A condition survey of the city's public art in 1991 documented on "Black Sun" a hairline crack which seemed to section the sculpture radially in the top north quadrant and which was intersected by an almost complete circular crack extending around the center of the west face (Figure 1b). These cracks had not been visible as late as 1986, when Mr. Izumi visited Seattle and closely examined "Black Sun", which he deemed at the time to be in excellent condition. Over the course of two years, between 1991 -1993, the cracks in the sculpture were monitored. In 1994 it was clear that the cracks were growing, both in length and in width. At this time most of the cracking could no longer be described as "hairline".

Through the Isamu Noguchi Foundation in New York contact was made with Masatoshi Izumi, who provided valuable information about the carving of "Black Sun". Samples were obtained of the residual stone, which had remained outdoors at the Noguchi compound in Mure. Izumi recalled that the stone had been extremely fine-grained and non-stratified, with no internal flaws or irregularities, and very "pleasing" to carve. The stone removed from the central hole of "Black Sun" was used to carve an interior column capital for one of the buildings in the Mure studio complex. According to Izumi, no other Noguchi sculptures were ever carved from Brazilian gabbro (Izumi 1993).

2. Examination

The rock mass from which Black Sun was cut is of highly uniform composition. There are a couple of very faint lines passing through the sculpture which represent a slight increase in one mineral phase along a thin plane. These are in no way related to the developing system of cracks. The grainsize of the stone is remarkably uniform and free of phenocrysts throughout.

In September 1993 the fracture features of Black Sun were examined and samples taken of the stone at surface points where fracturing was evident. A core sample was extracted to a depth of roughly 2 cm at a point on the upper surface where a crack extended over the top from one side to the other. Additional samples were collected from those few locations where weathering products were noted on the surface by the use of cellulose acetate peels. The cracking occurs in both radial and circumferential directions at very widely spaced intervals. It does not seem related to any drainage pattern. Over most of their lengths the cracks never divide. Detached chips are rare and very small. Typically, a subtle darkening within the stone follows the cracks over their entire lengths. Apart from the very small amount of white mineral matter which appears to have leached from the crack, the only observed evidence of chemical breakdown of any minerals is very occasional rust-like spots where individual iron-rich grains have decomposed. An alternative explanation for the whitish matter along the cracks is that moisture held in the crack causes dust to adhere in that region.

The sculpture has maintained a significant degree of its polished finish. Where the surface has most roughened (the lower inside of the hole) this seems to be the effect of mechanical wear on the soft minerals (biotite) caused by visitors climbing or sitting in the opening.

3. Origin of the stone

Neither the Noguchi Foundation nor the City of Seattle possesses any documentation on the source of the stone beyond its Brazilian origin. No bill of sale that would relate it to a specific quarry or geological formation has been found to date. A proximal location has been determined based upon what is known of the Brazilian stone industry in the 1960s. This question is of more than academic interest. Other outdoor installations of the same stone in buildings or sculptures would be the best potential sources for comparative information that could serve to separate the effects of insolation, freezing, rainfall and biodeterioration. Therefore, considerable effort was invested in determining whether Noguchi used the same stone in any other sculpture. Review of a number of Noguchi's catalogues and books on his work reveals very few "black granite" sculptures which are not ascribed to some other source and no others described as Brazilian. One indoor example of a Noguchi water basin/table which appears to be the same, or very similar, stone was examined in a private collection and found not to be affected by any deterioration.

The excess material removed from Black Sun is apparently all still in Mure, Japan. A fragment provided by Noguchi's stonecutter, Mr. Izumi, exhibits all the traits of a stone rich in iron minerals and biotite. Its exposure over the past 25 years to the coastal weathering conditions of Japan has led to a considerable degree of surface roughening, deterioration of iron minerals, and patina formation. The major difference leading to the premature development of these effects, which are not yet seen on Black Sun, is the lack of surface finishing on the fragment. Polishing removed unstable surface material from Black Sun and reduced the surface area to a minimum. This can greatly slow the weathering process and is an argument in favor of maintaining a polished surface on Black Sun once the cracking problem is dealt with.

A literature search was conducted for the purpose of identifying sites where the stone was in use and any relevant geological literature on typology and weathering (Pires et. al. 1982, Purves 1973). Lamego depicts the geological features of the Tijuca peak region to the southwest of Rio and reproduces a sectional geological diagram passing through this locality from which it is clear that a variety of intrusive igneous rocks are available (Lamego 1938). Ramos and Barbosa have published petrographic views of a few plutonic rocks from the area including a granite from the Tijuca Forest (Ramos and Barbosa 1965). In the 1960s there was only one igneous rock being exploited in the area of Rio de Janeiro which came from the Tijuca, a pre-Cambrian formation which includes the extreme escarpments which typify the landscape around the city. The areas being quarried were reportedly above the city and are closed today due to increased urbanization. Sources indicate that the quarrying at this time consisted of collecting exposed rock from the escarpments (Dromens 1993). The name Tijuca also refers to a forest area and national park, so only an approximate location is clear at this time.

A thesis by Odin, contemporaneous with the execution of the sculpture, referred to the use of this stone at the Occidental Center in Los Angeles (Odin 1971). Ultimately the same, or visually nearly identical stone was noted to be in use on two public buildings in California. These installations are comprised of thin panels of cladding. They are roughly the same age as Black Sun and are free of cracking and distortions with the exception of minor impacts near ground level.

4. Characterization of the stone and its weathering state

4.1 Sampling

A core sample was drilled in such a way as to intercept one of the cracks for the dual purpose of providing a petrographic thin section to characterize the stone and a look at the microstructure associated with the cracking. Features which could occur at this crack which could be expected to be diagnostic of the problem include chemical transformation of unstable minerals, expansion of foliose minerals such as micas, deposition of slightly soluble minerals leached from the deeper rock and so on. Secondary phenomena which could be indicative of the onset of more rapid

deterioration that were to be searched for include: colonization by microorganisms; disaggregation of individual mineral grains near the surface; and crack widening due to freeze-thaw cycling. Despite the immense size of the sculpture, its highly finished surface required that sampling be kept to a minimum in order to be unobtrusive.

4.2 Instrumental analysis

Characterization of the mineralogy of the stone started with the segregation of visually distinct minerals for X-ray diffraction analysis. It had been noted during the core drilling that one of the unique features of this stone is a high content of magnetic minerals. The black magnetic fraction was analyzed by X-ray diffraction and confirmed to be magnetite. A non-magnetic black foliose mineral phase was separated for analysis. This was determined by X-ray diffraction to be an iron-rich biotite, siderophyllite, represented in the ICDD standards by pattern 25-1355. A third phase analyzed consisted of grey translucent crystals. These were found to be high-calcian albite corresponding closely to ICDD standard 20-548. Deviations from this standard include additional peaks due to incomplete separation of the albite and peak shifts due to the existence of a complete solid-solution series in the plagioclase feldspars running from purely sodium varieties to purely calcium ones. A much smaller fraction of clear colorless grains were analyzed and determined to be quartz.

Each of the segregated samples analyzed by X-ray diffraction was also analyzed by X-ray fluorescence to determine its complement of major elements. Elements detected in this analysis, conducted in air rather than vacuum, is limited to elements above atomic number 16 (sulfur). In addition to the elements whose presence may be inferred from the X-ray diffraction results, titanium was found to be abundant in the dark material, suggesting the presence of ilmenite.

The detachment of the core also produced three fragments from approximately 1.5cm beneath the surface. The faces of these fragments which met at the crack being investigated were covered with a very uniform grey powder of fine mineral matter. All of the above XRD determinations were made using a Siemens D500, theta/2-theta goniometer diffractometer with a cobalt X-ray tube calibrated against NIST silicon. The grey powder lining the face of the crack was available in much smaller quantities and was analyzed by the Gandolfi camera powder method. The results suggest that most of what is present is merely small particles of the main minerals in the stone. An unmatched line at 7-angstroms is significant as it indicates the presence of a clay. This clay, if it is not infiltrating the crack from outside (which seems unlikely), is probably the result of feldspar weathering. Testing of the grey powder by Fourier Transform Infrared Spectroscopy yielded little more information. The spectrum was dominated by silicate and hydroxyl absorptions. The lack of sharp characteristic hydroxyl absorptions for clay or mica is probably due to their states of disorganization, being in an intermediate stage of weathering. The infrared spectrum also discloses the presence of a little carbonate in the fissure, indicating that by this depth (about 1.5cm beneath the surface) any acidic precipitation has already been neutralized. It

is significant that no gypsum was to be found within the crack. At least at the point sampled near the top of the sculpture, there are no soluble minerals undergoing recrystallization in the crack and thereby causing it to widen. It is further significant that no brown or red coloration is occurring within the crack. Considering the enormous amount of iron in this stone, it is notable that this element does not, as yet, appear to be involved in any significant weathering phenomenon such as the oxidation of pyrrhotite or pyrite.

Taken together, the results of the analysis of white surface residues and of these constituents of the crack suggest that the slight amount of chemical weathering takes the form of feldspar decomposition with the excess calcium being released in the form of gypsum, most of which is being carried away by moisture.

Surface peel replicas were taken from areas where deterioration residues were apparent on the sculpture surface. White powdery residues collecting along either side of a crack margin were determined to be gypsum by X-ray diffraction. Previous studies carried out on the 15th century Chinese marble sculptures of the Seattle Art Museum at this same location have shown that gypsum is a prevalent weathering product when calcium is available in the stone (Twilley 1986). This occurrence is indicative of a small degree of leaching of calcium from the plagioclase feldspars in the rock by the action of sulfuric acid in precipitation.

4.3 Petrographic analysis

A petrographic thin-section prepared from a plane perpendicular to that of the crack was examined in order to find any incipient mineral transformations and to examine the physical form of the fracturing. This section was embedded under vacuum and prepared scrupulously avoiding any water so as to retain all soluble minerals which might be present. The thin section is also necessary to characterize the texture and mineral interrelationships that are the diagnostic basis for the classification of igneous rocks.

Figures 2 and 3 show the majority of the thin section in plane polarized light rotated 90 degrees with respect to each other. In these views the highly twinned birefringent mineral grains are the high calcium albite. Siderophyllite varies dramatically from pale to dark between the two views, becoming indistinguishable from the opaque minerals at extinction. A number of additional grains are clear but nearly full of fine opaque particles.

The most important observation made from this petrographic section is that the crack is a transgranular tensile fracture. That is to say that the crack passes, indiscriminantly, through the minerals of all types rather than following the boundaries between them. The stresses on the stone are greater than the tensile strength of the intact minerals of which it is made. Furthermore, no indications of any significant weathering proceeding into the minerals exist along the edges of the crack. At this location virtually no loss of mineral grains from the sculpture's surface along

the crack has yet occurred. No mineral transformations are apparent at the outer surface either. Biotite (siderophyllite) has not yet begun to expand or exfoliate.

The most notable compositional feature of this rock is its high content of ore minerals. These are largely responsible, along with the iron-saturated biotite, for the black color of the stone and take many forms. Figure 4, in reflected light at 400x, shows one common form of iron-titanium oxide assemblage surrounding a sphere of magnetite which itself surrounds a bit of brassy colored pyrrhotite (magnetic, i.e. mixed valence, iron sulfide). This striped grain type, often in the form of chevron-like twins, is a common feature of the stone. It consists of ilmenite and another more iron-rich iron-titanium oxide. Another region rich in opaques contains euhedral crystals of magnetite and ilmenite along with a trace of pyrrhotite, intermingled with quartz and pyroxenes. The entire assemblage is surrounded by siderophyllite (Figure 5, 100x in reflected light). Pyrrhotite was also found surrounded by calcium silicate (pyroxene), itself surrounded by high-calcium albite in an apparent exsolution series. The generally low pyroxene content of the stone is a determining factor in its classification.

Transmitted light views such as Figure 6 (50x) disclose the reason for the grey "clouding" of the plagioclase. The interiors of these grains are filled with needles of opaque ore minerals. Zoning of the plagioclase is apparent in the absence of these inclusions near the grain boundaries. Figure 6 also discloses the disposition of quartz in this rock. The quartz, mostly a dark grey in this view, exists primarily in the form of doubly terminated hexagonal prisms. A cluster of these may be seen in the center of the frame, standing upright and reduced to stubby hexagonal posts by the grinding of the thin section. These occur inside both biotite and albite grains. Quartz also occurs in areas full of small crystals of magnetite such as the spotty (as opposed to "streaked") areas of Figure 7 at 50x. Densely oriented needles of ore minerals fill another unidentified silicate mineral, probably olivine, in this view. Hornblende completes the list of commonly encountered minerals in this rock. Locally, areas of myrmekitic texture were observed.

5. Petrological classification

Based upon what has been learned from this one petrographic section one cannot apply a strictly quantitative criterion to its classification. The grain size (averaging about 2 mm) is large enough that the total number of grains in the sample is too few. However, it clearly is an intrusive igneous rock close to a gabbro in composition. Its very high level of ore minerals puts it slightly outside the usual classification schemes which, in any case, vary slightly from country to country and school to school. It has been suggested that the surface quarrying above Rio de Janeiro involving this formation resulted in the exploitation of a pyroxene tonalite (Dromens 1993). However, the level of pyroxene found seems too low for this category, as does the content of quartz. The actual content of dark minerals is lower than might be expected from the appearance of the sculpture and places this stone in an intermediate or "mesocratic" category as regards its content of mafic materials.

6. Implications for weathering and deterioration

The unfinished fragments of the sculpture returned from Mure, Japan, are quite instructive in that they exhibit the onset of deterioration typical for the minerals of this stone which remain unaffected up until now in "Black Sun". The high concentration of iron minerals, particularly those which incorporate ferrous iron and the small proportion incorporating sulfur, may be expected to begin to release iron which will gradually alter the color of the surface to a warmer, brown shade (Schiavon 1993). Biotite typically weathers to chlorite. The plagioclase feldspars, the biotite and the hornblende may all, in time, begin a transformation into clays (Rogers and Holland 1979). The byproducts, alkali cations for the most part, may be expected to leach out, being carried away as salts or semi-soluble minerals such as gypsum.

Perhaps the most serious potential effect of weathering is the tendency for biotites (in this case siderophyllite) to exfoliate (Bustin and Matthews 1979). This will be observed as an increase in surface roughening and it will greatly increase the vulnerability of the sculpture to all other forms of weathering. At present very little of this has occurred with the exception of the lower inside surface where handling and climbing have dislodged grains of stone. The high degree of surface finishing given by the artist, and the corresponding removal of damaged stone left from the shaping operations, has been the single most beneficial factor in preserving the sculpture. By thus minimizing the surface area, chemical and physical erosion have been kept to a minimum. Two conclusions of Bustin and Matthews' study are relevant: that the degree of alteration increased with the amount of biotite in the rock, and that coarser grained rock tends to disintegrate more readily due to easier crack propagation.

Furthermore, in a study conducted in Baja California on the causes of the disintegration of boulders (a scale to which Black Sun may certainly be compared), Conca and Rossmann determined that the less weather-resistant biotites were the iron-rich type as are present in "Black Sun". They found that "these high-Fe layers appear highly etched and indicate that they are dissolving at a much faster rate than the low-Fe layers" (Conca and Rossmann 1985). They also note that other authors have observed iron-rich hornblende to be completely dissolved leaving the rest of the hornblende unchanged. Conca and Rossmann have explained the phenomenon underlying the development of caverns inside boulder-sized tonalite monoliths. A situation slightly different than the more common "case-hardening" of the exterior occurs, which they term "core softening".

It is remarkable that there is no evidence for the colonization of the crack studied here by microorganisms (Frankel 1977). Microorganisms are prolific at this site and have been found to be aggressively colonizing both the exterior of the Seattle Asian Art Museum building and the marble sculptures formerly displayed there. There are three possible reasons for this disparity. The dark stone may be too warm or too dry, on average, for the species found on the lighter colored stones to flourish. There may also be inhibitory metallic elements which are toxic to these

organisms in "Black Sun", as chromium, cobalt, copper and arsenic (among others) often accompany the iron oxides and sulfides minerals found here. The only study of igneous rock weathering in Rio de Janeiro which was found involved a stone of a different type (Smith and Magee 1990).

7. Thermal fracturing

In light of the information provided by the petrographic analysis and literature search, the following potential causes of fracturing on this scale considered were: 1) the release of unconfined tectonic stresses; 2) volume expansion of mineral phases undergoing alteration; 3) fabrication damage; and 4) thermal stress. Tectonic stresses seem unlikely to manifest themselves in patterns conforming to the sculpted shape of the object, as has occurred with "Black Sun" and its circular crack pattern. Volume expansion of mineral phases is not occurring according to the analytical data. Fabrication damage was ruled out on the basis of observation and Masatoshi Izumi's testimony as to the ease of carving "Black Sun" and lack of untoward incident during the process, as well as eye-witness accounts of the faultless installation process. Therefore, the focus was placed on thermal stress.

Attention has been drawn to the obvious temperature rise which this stone experiences in the sun and the potential for crack propagation which thermal cycling would pose. As yet no evidence of thermal expansion problems in building panels of the same, or similar, stone has been observed. However, the much greater thickness of "Black Sun", and its toroidal shape, may be crucial to the manner in which cracking occurs. Insolation has been periodically raised and, in varying degrees, dismissed as a prime cause of rock weathering (Rice 1976). It was very clear in the present case that, given the absence of significant mineralogical weathering in the sculpture, an investigation of a physical cause for the cracking should be initiated. In the interim, overall treatment with a water-repellent or consolidant was excluded until the role of thermal expansion and contraction could be better understood, as such surface treatment could have a serious impact upon this property. However, the prevention of chip losses from along the cracks and the exclusion of water and ice from the cracks was essential. For this purpose a reversible fill of the cracks was carried out.

8. Thermal monitoring

In order to test the hypothesis that thermal stresses could be the cause of cracking on "Black Sun", a program of twice-weekly temperature measurements was undertaken during the months of January through December, 1995. An infrared thermometer was chosen for these measurements to assure that they were not influenced by faulty contact with a temperature probe or by the temperature of the probe itself. The emissivity value for the Raytek infrared thermometer was set to 0.83 after verification in the laboratory on the stone sample. The

measurements were taken at approximately 9:00 a.m. and 4:30 p.m., on 8 pre-selected sites on the sculpture. Four sites on the east face and four on the west, at approximately the cardinal points on an interior circle halfway between the inner and outer circumferences, were monitored. The collected data revealed expected temperature gradients between the east and west faces of the sculpture. A clear warm morning following a cool night would typically show a rapid thermal gain on the east face, occasionally with as much as a 50 degree F difference between the east and west face. The thermal gain on the west face towards the end of a warm day was more dramatic, where temperature differentials between the two faces were measured as high as 87 degrees. Due to the height of the sculpture it was not possible to measure the temperature on the top plane, where it is surmised the greatest thermal gain would occur. The temperature measurements at the four sites on each face typically varied only by a degree or two.

9. Stress modeling

To analyze the thermal stresses on the sculpture it was necessary to create a computer model of "Black Sun" using what is known as a finite element modeling program. The theoretical basis for this program was developed during the late 1960's, but it was not until the 1980's that personal computers were powerful enough to utilize finite element programs. The software programs currently available are used primarily by specialized structural engineers who study the complex stresses in solid bodies such as engine parts. The software program used to create the model of "Black Sun" is "Stardyne", a multi-purpose finite element program supported by Research Engineers of Yorba Linda, California.

The model of the sculpture is created as in a computer-aided drafting, or CAD system. The model is composed of thousands of brick-like blocks called finite elements. The eight corners of each block are known as "nodes" (Figure 8). Each node has six degrees of freedom, meaning it has six directions (three linear and three rotational) in which it may move given a thermal stimulus. Thus for each block, or finite element, 48 equations are formulated by the computer in order to evaluate the six degrees of freedom possible for each of the eight nodes given a particular stress load (in this case a particular temperature). The equations for each finite element are compiled into a matrix of equations for the entire model. The variable in each equation is the temperature experienced by each node. For the purposes of the computer model, a gradient of 100 degrees F was programmed under four different conditions: from top to bottom of the model, east to west, south to north, and outside ring to inside ring. The other factors in the equations, which remain constant, are Young's Modulus, Poisson's Ratio, and the coefficient of thermal expansion. These statistics were derived from Touloukian, Judd and Roy (1981) and are as follows:

Young's Modulus	$E = 6,300,000 \text{ psi}$
Coefficient of Thermal Expansion	$\alpha = .000006 \text{ in/in/deg F}$
Poisson's Ratio	$\nu = .2$

Stress levels are calculated for each of the finite elements based on these equations. Stresses typically occur in a material where temperature-induced expansion is blocked by external or internal restraint. Tension stress occurs in a cooler material that is being pulled by adjacent hotter material; compression stress occurs in the hotter material which is being constrained by the adjacent cooler material. In curved bodies, such as a torus, radial tension stresses will occur when the (for example) hotter outer portion of the torus pulls away from the cooler inner portion. These radial stresses occur in a direction normal to the temperature-induced tension/compression stresses.

9.1 Results

Stresses are measured in pounds per square inch. The computer program calculates the maximum principal stress for each finite element. Maximum principal stress is the highest stress level experienced by the element, regardless of the direction of the stress (up, down, in, out or any angle in between). The maximum principal stresses are plotted on the model using coded colors to correspond to specific psi stress levels. It was found that in the simulated situations of a temperature gradient from south to north, and from top to bottom of the model, (the sun to the south and high in the sky) (Figures 9, 10) the maximum principal stress varied between 709.3 psi to 957.9 psi. Note that the tension stresses in the psi range of 543 to 709 under these conditions follow the actual cracking pattern on the sculpture. The ultimate tensile strength of the stone has been estimated at 1000 psi. However, this number does not take into account the fatigue of the stone induced by cyclical thermal stress, which effectively lowers the ultimate tensile strength.

The other loading conditions (east to west and outer ring to inner ring) applied to the model indicated clearly that the stresses due to a radial gradient are much more significant than those occurring due to a gradient through the thickness of the stone. This would indicate that while large temperature differentials between the east and west faces of the sculpture were recorded during the monitoring program, the temperature differential (and hence stress tension) between the outside, especially the top of the sculpture, and the interior and lower part of the sculpture is considerably greater.

9.2 Model limitations

The following limitations of the computer model should be noted:

The temperature gradients used were only a very rough approximation of the actual temperature distributions that may occur. However, the 100° F total difference in temperature is very reasonable based on actual measurements. The model is a linear static model while the fracturing of stone under cyclic dynamic thermal stresses is a non-linear dynamic process. Cyclical loading experiments have demonstrated that fatigue phenomena are an important factor in lowering the

ultimate strength of stone. These have not been considered in the present model and can be expected to have played a significant role with “Black Sun”. It is also important to note that after a crack is initiated it tends to propagate. This is due to the high stress concentration that occurs at the tip of the crack.

The tensile breaking strength for the stone is estimated to be 1000 psi. Unfortunately no material existed upon which to directly measure this parameter. The estimate is based upon experimental values measured on stones in current commercial use which are loosely referred to as “black granites”. While some contain comparable levels of feldspar and magnetite, they often contain considerably more pyroxene or fall into the category of a monzonite. None of them contains the levels of biotite observed in “Black Sun”. The extremely easy basal cleavage of this mineral makes it likely that the bulk tensile strength of a stone will decrease in proportion to an increase in this mineral. Therefore, the estimate of 1000 psi has been made which is approximately 30% below values typically encountered in other types.

10. Conclusion

The magnitude of the thermal stresses revealed by the computer model indicate that thermal factors probably have contributed significantly to the cracks found in “Black Sun”. Because of its massive size and its site specificity, removal of the sculpture to another environment was not considered. In order to prevent water penetration into the cracks and the development of secondary deterioration phenomena, a fill material of Acryloid B72 bulked with microballoons was applied and is monitored for loss and shrinkage. To date the cracks appear to have stabilized, which might indicate that a state of thermodynamic stasis has been reached. However, monitoring of the cracks continues on a regular basis.

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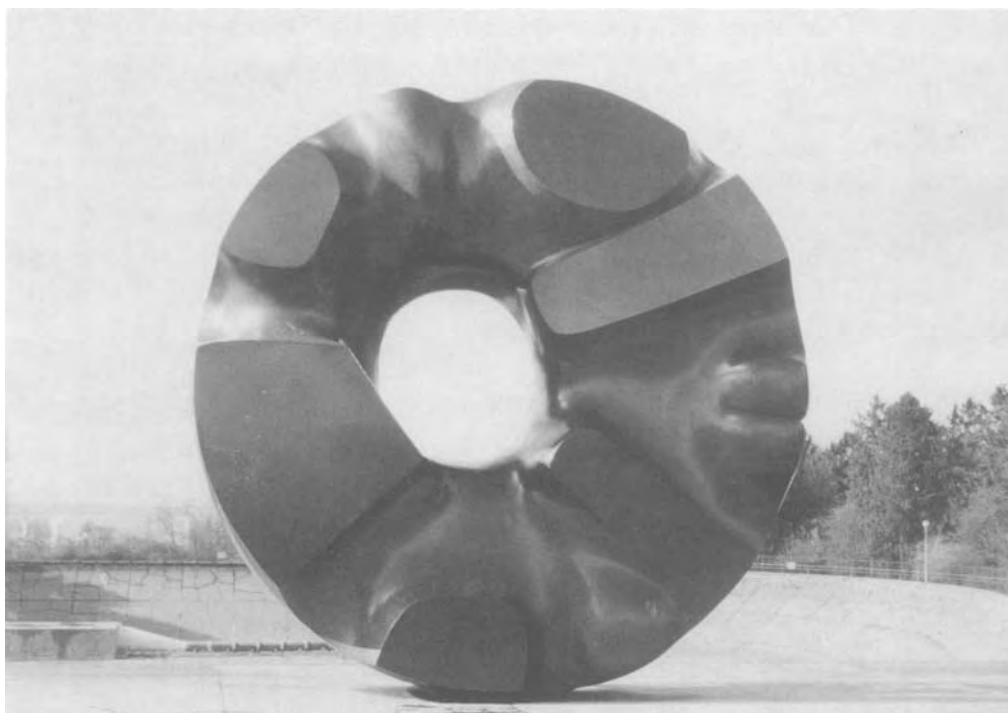


Figure 1a. *Black Sun* on exhibit in Seattle.

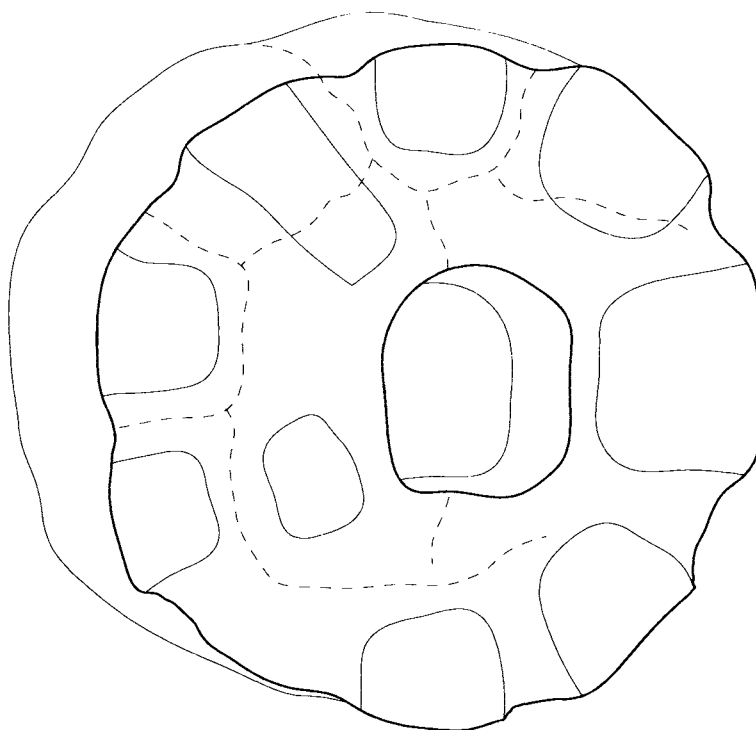


Figure 1b. Drawing showing the cracks in the stone.

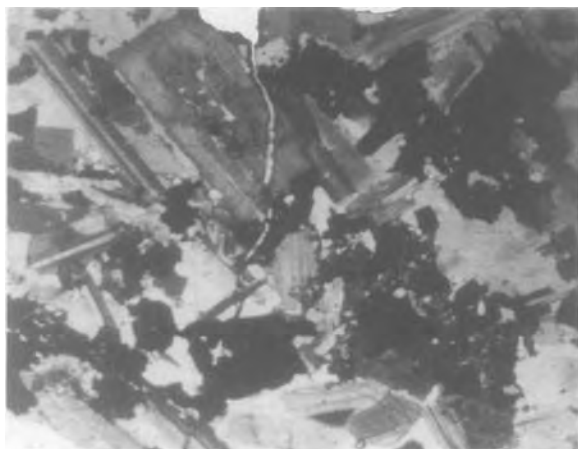


Figure 2, 10x, transmitted, polarized light

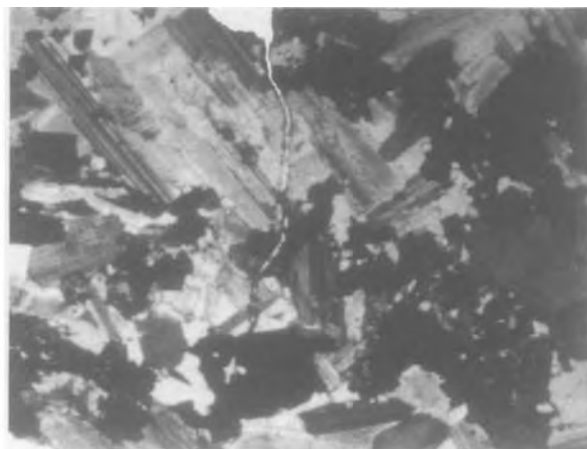


Figure 3, 10x, transmitted, polarized light

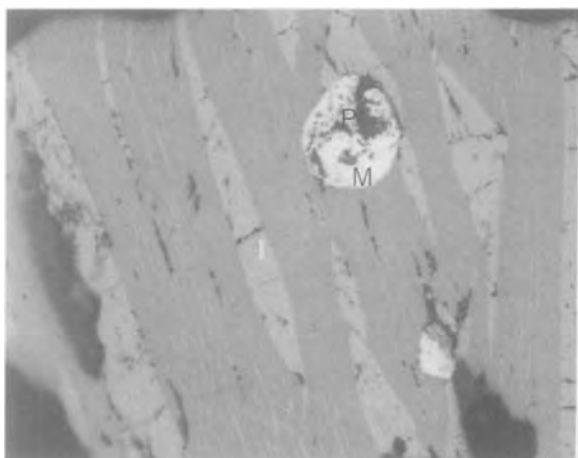


Figure 4, 400x, reflected light, ore minerals
M=magnetite, P=pyrrhotite, I=Fe-TiO matrix

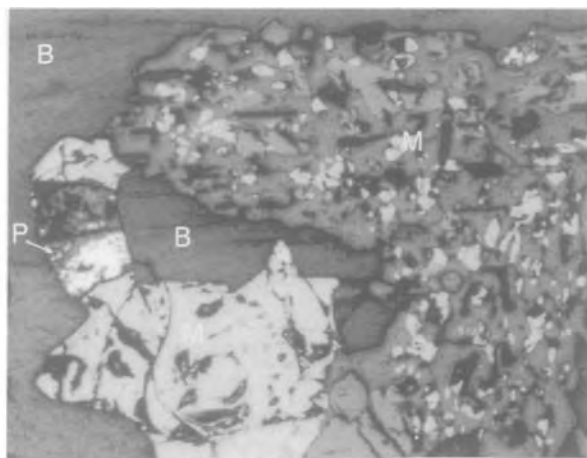


Figure 5, 100x, reflected light, B=biotite,
M=magnetite, P=pyrrhotite

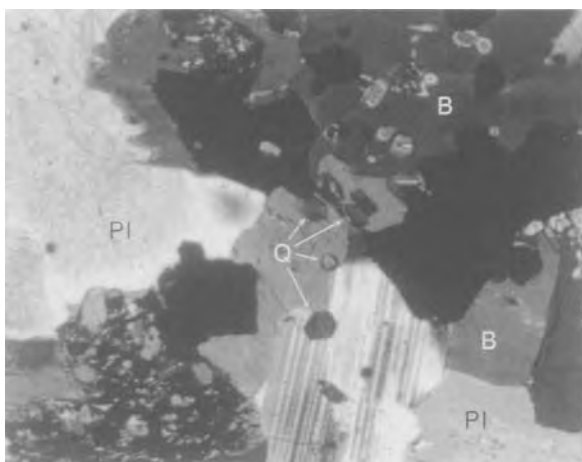


Figure 6, 50x, transmitted light w/crossed polars
B=biotite, Q-quartz, Pl=zoned plagioclase with
fine inclusions



Figure 7, 50x, transmitted light w/crossed
polars, silicates filled with magnetite and
ilmenite euhedra

FINITE ELEMENT

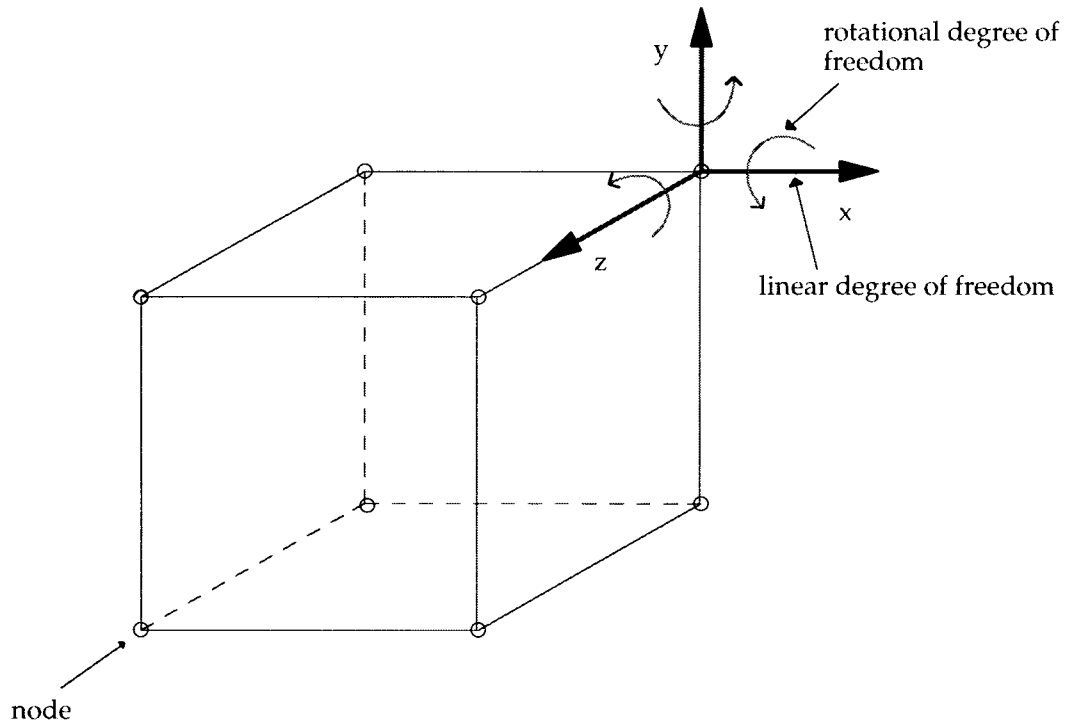


Figure 8. Unit of the finite element modeling program.