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The Kinematics and History of Brittle Deformation in the Petersburg Granite

Richmond, Virginia

James McCulla
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Abstract

The Petersburg granite forms a large Carboniferous pluton in the eastern Piedmont of Virginia and is well exposed in the James River along the Fall Zone in Richmond. These expansive outcrops were studied to characterize the fracture geometry and understand the kinematic history of brittle deformation in the Petersburg granite. Previous workers have suggested some fractures in the Richmond area are radial fractures associated with the 35 Ma Chesapeake Bay impact crater in eastern Virginia. We mapped fractures at five locations along an 8 km transect of the James River.

The Petersburg granite in Richmond is cut by two dominant fracture sets. The older set strikes NE to ENE, dips steeply to the north, and commonly displays gently plunging mineralized slickensides that record dextral slip. P- and T-axes for these shear fractures are clustered and consistent with a subhorizontal $\sigma_1$ oriented WNW-ESE. Quartz, muscovite, and biotite indicate mineralization and slip occurred under greenschist facies conditions. The younger set strikes NNW to NNE, is subvertical, and rarely mineralized. Cross cutting relations and surface ornamentation indicate the younger set are extension fractures, although rare fractures were reactivated as reverse faults.

We interpret the older set to have formed during WNW-directed contraction in the Alleghanian orogeny. The orientation of the younger set records E-W extension and is parallel to extensional faults in the Richmond Triassic basin, exposed 15 km to the west. Reactivation of these extension fractures may have occurred under the late Cenozoic compressional stress field. Regardless, there is no tenable evidence linking fractures in the Petersburg granite to deformation associated with the Chesapeake Bay impact crater.

1. Introduction
To a structural geologist, sets of fractures in rocks offer a great opportunity to learn about those rocks’ stress history. Fractures, the product of brittle deformation, form when stress on a rock exceeds the rock strength and the rock breaks along a creating joints and faults. Fractures and joints are related; joints record small amounts of movement at right angles to the fracture plane. These planar features on the rock surface. Fractures can record the orientation of stresses active upon the rock during its deformation; this applies especially if fractures have any lateral movement during the fracturing event. These shear fractures commonly form lineations on the fracture surfaces, recording the general orientation of stresses during deformation. Workers can then compare this information with knowledge of the rock’s age to determine what actually might have caused the fractures to form; if geochronology is not available, fractures and fractures sets can often serve as relative dating tools. If one rock formation is fractured while an adjacent is not, the adjacent rocks are younger than those fractured.

The Peterburg Granite is a large batholith in east-central Virginia (Fig. 1) consisting of K-feldspar, quartz, and plagioclase with minor amounts of biotite and muscovite and is characterized by several readily examinable fracture sets, suggestive of extensive deformation. The granite is 330 Ma in age (Wright et al., 1975) and intruded during the Alleghanian orogeny (Gates & Glover, 1989). Possible causes of fractures in the Peterburg Granite include fracturing during the actual orogenic event, Mesozoic rifting that led to the opening of the Atlantic Ocean, and radiating and concentric fractures created by from the Eocene Chesapeake Bay Impact Structure.
Structural data were collected from the Peterburg Granite exposed in Richmond, Virginia; these data included orientations of fractures, slickenlines, and dikes throughout the granite. Fracture and slickenline data, as well as crosscutting relations, were analyzed in an attempt to characterize extension fractures from shear fractures, and the shear fractures were in turn analyzed to determine the sense of shear and the implied orientation of principal stress during deformation. All of this information was used to determine an overall deformation history of the Peterburg Granite, which was unique to the Richmond, VA area and the first of its kind. This deformation timeline can be compared to other deformation histories of rocks in the area to help create an overall timeline of deformation and learn about the geologic history of eastern North America.

2. Fracture Geometry

There are two types of fractures: shear and extension. It is relatively simple to determine the difference between shear and extension fractures if obvious indicators like slickenlines are present; these give a “sense of shear” and point towards shearing as the deformation mechanism. Extension fractures can be indicated by small, parallel cracks at an angle to the orientation of the fracture and are often filled in with post-fracturing mineralization like quartz. If such indicators are not present, other methods can be used to determine what types of forces are responsible for the deformation. For example, Reidel shear structures are formed in the early stages of development of a shear zone and can be easily identified in field samples (Katz et al., 2002). Fractures like these are only found in shear environments and form in sets at certain angles to the principal stress; they can be used to differentiate between extension and shear fractures.
It is also possible to examine a fracture set in order to determine the direction from which stresses were applied during the actual deformation of the rock. Computer programs like Stereonet and FaultKin have computerized this process, but other manual methods exist wherein a worker plots great circles and lines on a 3-D stereographic projection in order to determine $\sigma_1$ and $\sigma_3$ for a given fault population. $\sigma_1$ is usually oriented between 30º and 45º from the fault; visualizing fracture orientations in a fracture set using stereographic projections enables one to estimate $\sigma_1$ using this fact (Marshak & Mitra, 1988). Marshak and Mitra (1988) also outline another method for determining $\sigma_1$ using stereographic projections for larger fault populations (i.e. >100 faults or fractures). This method is useful only for fractures with numerous lineations indicating slip direction. Fracture planes are plotted on an equal area stereographic projection and compared to another plot of the lineations for the fractures. Most slips for a fracture population should point away from the $\sigma_1$ direction, allowing one to determine the principal stress orientation by transposing the lineations projection over that of the fractures (Fig. 2).

3. Geologic Setting

The Piedmont geologic province is situated in the center of Virginia and is bounded by the Fall Zone on the east (and the Coastal Plain beyond that) and the Blue Ridge on the west. Petersburg Granite is the main member of the Fall Zone in the Richmond area and has been studied by geologists as far back as the late 1800s, and Watson (1906) documented two dominant sets of joints, one striking to the NE and dipping subvertically and one striking to the NW and dipping subvertically. Watson (1906) observed two secondary sets, also dipping subvertically: one striking to the east
and one striking to the north. He noted that any joints not dipping subvertically dipped between 20° and 82° in all compass directions. Watson (1906) concluded these secondary joints were products of weathering and exfoliation.

Bloomer (1939) presents more data regarding the Peterburg Granite. According to Bloomer, rocks of the Peterburg Granite extend from Hanover County in Virginia into northern North Carolina. He observed evidence for a Carboniferous (now Mississippian) age based on knowledge of orogenies in the east coast of the United States and on the presence of Peterburg Granite boulders in Triassic basins in the Richmond area. Bloomer (1939) notes some high-angle faulting in the western edge of the exposed Peterburg Granite about 25 km to the west of Richmond but does not supply more structural data or hypotheses about deformation.

Wright et al. (1975) attempted to date the Peterburg Granite in addition to commenting on the emplacement of the pluton and the age of the pluton in relation to other igneous bodies in the eastern United States. Zircons from the Peterburg Granite in the Richmond area were dated to 330 ± 8 Ma, but their results were not completely concordant; they attribute the discordant ages of about 25 Ma to weathering-related lead leaching. An age of roughly 330 Ma would agree with the Carboniferous age assigned by Jonas (1932) based solely on correlating rock units. Wright et al. (1975) suggest that the rocks were exposed within the last 25-20 Ma and that less lead in the zircons than expected is due to percolation of groundwater through the granite.

Bobyarchick and Glover (1979) describe a series of brittle deformation events in the Hylas zone, a high-strain zone immediately west of some outcrops of the Peterburg Granite. They observed shear fractures and a set of NE-striking high-angle faults and
half-grabens indicative of Triassic extension; the Hylas Zone is a dextral shear zone that deformed rocks of the Peterburg Granite into mylonitic rocks. Gates and Glover (1989) report Ar/Ar ages of 310-285 Ma for movement and cooling of the zone.

Dalide and Diecchio (2005) hypothesized that fractures in the Peterburg Granite where it is exposed at Belle Isle in order to determine the origin of the fractures; their hypotheses included deformation caused by an igneous intrusion, seismic activity in Virginia, or the Chesapeake Bay impact structure. They posit that lineaments found in the Peterburg Granite are radiating fractures from the Chesapeake Bay impact crater, and suggested the igneous intrusion model to be the least likely of their choices.

Carter et al. (2008) analyzed fractures and joints in the Petersburg Granite and overlying sediments as part of an overall geologic characterization of the Bon Air, Virginia quadrangle. They described 992 joints in the Petersburg Granite in addition to brittle faults in the Petersburg Granite and bordering Triassic basin. Carter et al. (2008) observed high-angle, brittle faults forming the western boundary of the Richmond basin and extending eastward to the Fall Line; they characterized them as Mesozoic-Cenozoic extension faults.

4. Methods

We used Google Earth imagery and prior knowledge of the geology of the Richmond area to choose four sites of good rock exposure along a 10 km transect of the James River (Fig. 3). Three sites occur in the actual river channel and could only be accessed at low river levels. The two remaining sites were granite quarries located along the James River and were particularly useful as they yielded numerous lineament measurements in the form of slickenlines.
We collected structural data at each site and used topographic maps and satellite imagery to ensure an even distribution of sampling across the outcrops. Structural data collected at a given data point included fracture, joint, dike, and/or schlieren/foliation orientation. Fracture plane data were projected onto equal area stereographic projections using the Stereonet (version 6.3) computer program and analyzed to determine local concentrations of data. Shear fractures with lineations were also projected and analyzed using the FaultKin computer program to determine the principal stresses during deformation, or the P and T axes. The P axis, or pressure, represents the maximum stress for deformation and is oriented at an angle of 45° from the fracture plane. The T axis, or tension, represents the minimum stress for deformation and is located at 90° to the P axis. The P axes were in turn used to infer the approximate orientation of the maximum compressive principal stress, or $\sigma_1$.

5. Results

5.1. Lineament analysis

As a preliminary method for determining the density and strike of fractures at the South of Belle Isle field site, we performed a lineament analysis of Google Earth satellite imagery of the site. The images were captured at a period of low water in the James River that allowed for exceptional exposure of the bedrock in the river channel. About 60,000 m$^2$ of rock is exposed in the photograph, and both McCulla and Bailey performed analyses in order to compare results to achieve maximum test reliability. Figure 4 shows McCulla’s lineament analysis; note the abundant exposure of bedrock.

In my analysis, I recorded 149 individual lineaments with 1,430 m in total length; the lineament density for my analysis was 0.036 m/m$^2$. Bailey’s lineament trace resulted
in slightly different results; he observed 127 individual lineaments that totaled to 2,320 m with a lineament density of 0.058 m/m². Rose diagrams of the data show that both Bailey and I observed a dominant NE-trending set of lineaments (~055°), but they also show some differences. I observed a secondary set of NW-trending lineaments, while Bailey did not; he observed a secondary NNE-trending lineament set that I did not (Fig. 5). Despite these differences, comparing our separate rose diagrams shows that our results were actually quite similar. The maximum mismatch between the two analyses was 7.4%, and average mismatch between the two analyses was only 1.8% (Fig. 6).

Upon visiting the field site, we observed that the NNE-trending set observed in Bailey’s analysis is actually the strike of foliation in the granite. The James River preferentially eroded the rock along this plane of weakness and along fractures and created the linear feature easily seen in the satellite imagery. The dominant NE-trending set observed by both McCulla and Bailey is the strike of a NE/SW-striking set of dextral strike-slip faults present at the South of Belle Isle field site, and the NW-trending lineaments observed by McCulla parallels a set of NW/SE-striking extension fractures.

5.2. Fracture analysis

Collecting quality data at the field sites relied heavily on the stage of the river; low stages exposed of the bedrock channel while high stages made it impossible to collect data. The westernmost site was the Bridges site, located between the I-76S Powhite Parkway bridge and a train trestle bridge. At this location, heterogeneous banded granite and massive granite are exposed. The dominant fracture set strikes at 355° and is subvertical 357 (Fig. 7). These are extension fractures that appear to offset a secondary set of dextral shear fractures striking at 060° and also dipping subvertically. The north-
striking extension fractures at this site are compatible with a subhorizontal E/W striking \( \sigma_3 \) during deformation and occurred after the shear fracturing.

The next study site is Belle Isle, an island situated in the middle of the James River in immediately southwest of downtown area. The Peterburg Granite, a homogeneous massive equigranular granite at this location, was quarried on the island, leaving good exposure at old quarry sites in addition to the usual bedrock outcrops. We collected 122 individual fracture measurements on Belle Isle, and the data from this site were similar to data from the Bridges site. On Belle Isle, the dominant fractures were dextral shear fractures striking at 060 and dipping at 80º to the NW. This was a shear fracture set and was crosscut and offset by a secondary set of extension fractures striking at 015 and dipping 80º to the SE (Fig. 8a).

A large (15 m x 40 m) quarry face on Belle Isle yielded slickenline lineations on a dextral shear fracture face whose orientations were used to estimate the primary P and T axes for shearing. 33 slickenlines gave a pressure axis (inferred \( \sigma_1 \)) gently plunging ESE/WSW (Fig. 8b), and quartz and muscovite mineralization of fractures suggest the granite was fractured under the greenschist facies. This set of dextral shear fractures is thought to have formed concurrently with the dextral shear set at the Bridges site. The extension fractures at the Belle Isle site also strike and dip similarly to those at the Bridges site, implying they also may have formed at the same time.

The third of my field sites was the South of Belle Isle site (Fig. 9); the fracture data collected here was compared to the lineament analysis of Google Earth data to test the accuracy of the remote sensing lineament analysis. The rock in this location was classified as a massive equigranular and banded/foliated granite. This site had incredibly
good exposure of the granite, and 401 individual fracture measurements were collected. Data were again similar to the previous two sites, suggesting the two sets observed here also formed concurrently with the fractures elsewhere in the Richmond exposures of the Peterburg Granite. At this location, the dominant fractures were extension fractures striking between 325 and 340 and dipping subvertically. This fracture set crosscut a set of dextral shear fractures striking at 055 and dipping an 80º to the NW (Fig. 10a).

Fourteen shear fractures at the South of Belle Isle field site had mineralized slickenlines indicating a dextral sense of shear. When plotted on a first motion diagram, these slickenlines give similar P and T axes to those observed on Belle Isle, with $\sigma_1$ inferred to be subhorizontal and oriented E/W (Fig. 10b). Mineralization indicates that these fractures were also formed under the greenschist facies and were later cut by extension fractures.

The fourth and final field site was the Tidewater Quarry operated by Vulcan Materials; it is located about 4.8 km to the southeast of Belle Isle and the quarry rim is only 150 m to the west of the James River. The quarry walls feature great exposure of the Peterburg Granite in addition to other rocks. The fracture geometry in this area was complex, but the geometry observed could be divided into two dominant fracture sets (Fig. 11a): one striking at 350 and dipping subvertically and the other striking at 060 and dipping at 70º to the SE. The thirteen slickenlines measurements taken reveal no real trends on first analysis besides the fact that all plunge to the east (Fig. 11b).

6. Discussion

Fracture data from all four field sites show some shared trends. A NE/SW-striking dextral shear fracture set dipping steeply to subvertically to the SE is present at all four
sites, often with quartz and muscovite mineralization. There is also a younger N/S-striking extension fracture set dipping steeply to subvertically to the east at all four sites. A time versus depth diagram shows the temporal history of brittle deformation in the granite (Fig. 12), and it shows two regional episodes of deformation: the Alleghanian Orogeny and the rifting of the Atlantic basin. The timing of fracturing in the Peterburg Granite is generally constrained by the exhumation curves and important boundaries associated with the brittle/ductile transition, the minimum temperature of quartz ductility, and the limiting depth at which tensile fractures occur.

NE-striking dextral faults (abbreviated D_1 for deformation event #1) must have formed after the Peterburg Granite cooled below the brittle/ductile transition, but before the granite cooled below ~275º C. These dextral faults were produced with \( \sigma_1 \) oriented WNW/ESE, consistent with dextral contraction, likely during the Alleghanian Orogeny in the Permian. ~N-striking extension fractures (D2) formed at relatively shallow crustal depths and record E/W extension (roughly parallel to \( \sigma_3 \)) consistent with crustal extension, likely during Atlantic rifting in the Triassic to Early Jurassic. Some NW to NNE-striking fractures were reactivated under a NW/SE maximum compressive stress (\( \sigma_1 \)) associated with the stress field that developed in the Cretaceous.

7. Conclusions

The Peterburg Granite, along the James River in Richmond, is cut by two dominant fracture sets. The older set strikes NE to ENE and dips steeply to the north with gently plunging mineralized slickensides that record dextral slip. These faults may have formed during WNW-directed contraction in the Alleghanian Orogeny. The younger set of extension fractures strikes NW to NNE, is subvertical, and is rarely mineralized. This
joint set records E-W extension and may have formed during early Mesozoic rifting. Some fractures were reactivated in a NW-SE compressional stress field from the Cretaceous to late Cenozoic. There is no tenable evidence linking fractures in the Peterburg Granite to deformation associated with the Eocene Chesapeake Bay Impact Structure; fractures resulting from the Chesapeake Bay Impact Structure would have a completely different $\sigma_1$ to show pressure coming from the E-SE, and this is not the case.

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Figure 1

Simplified geologic map of east-central Virginia. The Peterburg Granite is bordered to the east by Tertiary and Quaternary sediments and to the west by Triassic and Paleozoic units.
Figure 2a. Collect fracture and slickenline orientation from a fracture set. In this example, there is a fracture striking at 065 and dipping 85° to the south. Lineations on the fracture face rake 10° to the east.

Figure 2b. Data is plotted on a 3-D stereographic projection; fault planes are represented as great circles on the sphere, and poles to the planes as well as lineations on fracture faces are represented as dots.
Determine P and T axes of deformation using FaultKin program and plot in a first motion diagram. P and T axes are used to infer the orientations of $\sigma_1$ and $\sigma_3$. 

- $T$-axis = 020 11 $\sim \sigma_3$
- $P$-axis = 111 04 $\sim \sigma_3$
Figure 3.

Simplified geologic map showing four field sites in the Richmond, Virginia area.
Figure 4.

Tracing # 1
McCulla

149 individual lineaments

*total lineament length = 1,430 m*
*lineament density = 0.036 m/ m²*

A sample lineament analysis showing both McCulla’s lineament trace and the abundant bedrock exposure in the river channel south of Belle Isle.
Figure 5a.

Rose diagrams showing lineation orientation distribution for McCulla’s lineament analysis. Note the dominant NE-striking set and the secondary NW-striking set.

Figure 5b.

Rose diagrams showing lineation orientation distribution for Bailey’s lineament analysis. Note the dominant NE-striking set and the secondary NNE-striking set.
A comparison of McCulla’s and Bailey’s lineament analyses. The average mismatch between the two analyses was 1.8%.
Figure 7.

(a) Equal area stereographic projection showing distribution of poles to fracture planes at the Between the Bridges site. Data has been contoured using the Kamb contour method with a contour interval of 2 sigma. The average fracture orientation in this set (green) is oriented 357.89 E. The blue dot represents the average pole in a secondary fracture set with great circle of orientation 063.89 S. (b) Rose diagram showing distribution of fracture lineaments at the Between the Bridges site. The largest two petals represent the dominant N/S striking fracture set with average strike of 357. Note the secondary NE/SW striking fracture set with an orientation of 063.
Figure 8a.

(a) Equal area stereographic projection showing distribution of poles to fracture planes for all data collected in the Belle Isle area. Data has been contoured using the Kamb contour method with a contour interval of 2 sigma. The blue dot represents the average pole of the dominant fracture set, and the blue great circle (240 83 N) is a fracture representing this set. (b) Rose diagram showing distribution of fracture lineaments for all Belle Isle data. The largest two petals represent the dominant N/S striking fracture set with the average strike of 240.
Figure 8b.

(a) Equal area stereographic projection showing distribution of slickenlines and fracture planes for all data collected in the Belle Isle quarries. Slickenlines were generally subhorizontal with a dextral sense of shear. (b) Equal area stereographic projection showing P (red) and T (blue) axes of deformation. $\sigma_1$ is inferred to be 100.06, and $\sigma_3$ has been inferred to be 188.00. The data has been interpreted to be dextral shear fractures formed in a low-grade system with subhorizontal pressure oriented ESE/WNW.
Geologic map of the South of Belle Isle field site.
Figure 10a.

(a) Equal area stereographic projection showing distribution of poles to fracture planes for all data collected at the South of Belle Isle field site. We observed two dominant fracture sets. (b) Rose diagram showing distribution of fracture lineaments for all Belle Isle data. The largest two petals represent the dominant N/S striking fracture set with the average strike of 240.
Figure 10b.

(a) Equal area stereographic projection showing distribution of slickenlines and fracture planes for all data collected at South of Belle Isle field site. Slickenlines were generally subhorizontal with a dextral sense of shear. (b) Equal area stereographic projection showing P and T axes of deformation. $\sigma_1$ is inferred to be from the ESE, and $\sigma_3$ has been inferred to be from the SSW. The data has been interpreted to be dextral shear fractures formed in a low-grade system.
Figure 11a.

(a) Equal area stereographic projection showing distribution of poles to fracture planes for all data collected at the Tidewater Quarry. We observed two dominant fracture sets; one striking to the NE and one striking to the NNW. (b) Rose diagram showing distribution of fracture lineaments for all Tidewater Quarry data. The largest two petals represent the dominant N/S striking fracture set with the average strike of 240.
Figure 11b.

Equal area stereographic projection showing distribution of slickenlines and fracture planes for all data collected at the Tidewater Quarry. The gray lines represent the orientation of the fractures, and the diamonds represent the trend and plunge of lineaments found along the fractures.
Figure 12.

Time vs. depth diagram showing the temporal history of the Peterburg Granite since its crystallization ~320 Ma.
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