A Lagerstätte of Rift-Related Tectonic Structures from the Solite Quarry, Dan River–Danville Rift Basin

Rolf V. Ackerman, Roy W. Schlische, Lina C. Patiño, and Lois A. Johnson

The Solite Quarry within the Dan River–Danville basin contains an extensive suite of rift-related structures. The cyclical upper member of the Cow Branch Formation has been deformed both in continuous fashion and via three brittle failure modes, exhibiting fracture partitioning such that failure mode is lithologically dependent. All structures are tectonic; extension estimates are roughly comparable for all failure modes; and there is an absence of bedding-parallel detachment horizons with normal separation. All extensional structures formed in response to Triassic rifting. These observations imply that different beds failed coevally or semicoevally in extension. All contractional structures are consistent with earliest Jurassic inversion.

The small normal faults are in most ways like larger faults and occur both as isolated features and as segments of relay systems. The faults exhibit slickensided, mineralized fault surfaces, footwall uplift, hanging-wall subsidence, relay ramps, and elliptical fault surfaces, with maximum displacement occurring at fault centers and tapering to zero at the tips. Detailed analysis of these structures and integration with other data sets suggest that faults exhibit linear length-displacement scaling over nine orders of magnitude of fault length. These small faults can be divided into two subsets based on length and on their spatial distribution within the rock volume, with the set of smaller structures exhibiting anticlustering with respect to the larger structures (called master faults), forming fault shields due to the presence of stress-reduction shadows around the master faults.

A field locality in the Dan River–Danville basin known as a major lagerstätte—or a location that contains an exceptional suite of fossils, minerals, and the like—for Triassic terrestrial arthropods and flora (e.g., Fraser et al. 1996) also contains an exceptionally well exposed suite of rift-related discontinuous (brittle) and continuous (ductile) deformation features. Detailed study of the exquisite array of structures found in the Solite Quarry permits verification or nullification of a range of empirical relationships related to fault-population studies, a topic of considerable interest in recent years (e.g., Cowie, Knipe, and Main 1996). The goal of these studies is to unravel the scaling laws of fractures—including their size and spatial distribution—the relationship between displacement or aperture and fracture length, and the strain accommodated by fractures. In addition to advancing our understanding of the me-
chanics of fracturing and the evolution of fracture systems (e.g., Cowie and Scholz 1992b; Cowie 1998), these scaling relations also have more practical applications. For example, studies of small-scale systems potentially can provide information relevant to an understanding of large-scale systems such as rift basins (studies of which commonly are hampered by poor exposure and complex basin architecture)—if the scaling laws and the scale range over which these systems operate are known. In addition, models of fractured bedrock systems, such as the eastern North American rift system, require detailed information on the size and spatial distribution of fractures in order to be effective for groundwater prospecting, petroleum exploration and exploitation, and the remediation of contaminated aquifer systems. To address these issues, we require high-quality data sets from well-exposed regions with relatively simple strain histories in which the fractures span at least two orders of magnitude of size. The fractures in the Solite Quarry meet or exceed these requirements.

In this chapter, we systematically discuss the rift-related structures present within the Solite Quarry. We describe the features first by category (brittle/discontinuous versus continuous; tension versus shear) and then by type of strain accommodated (extensional versus contractional). We then examine the size and spatial distribution of some of the fractures within the quarry and discuss the implications of these observations for fault scaling relationships, lithologically dependent failure modes (mechanical stratigraphy), and the existence of stress-reduction shadows (regions of lower shear stress compared with the remote stress) around normal faults.

**Geologic Setting**

Outcrops discussed in this chapter are located in the main and new quarries of the Virginia Solite Corporation located in the Dan River–Danville basin, directly on the border between Virginia and North Carolina (figure 8.1). The Dan River–Danville basin is part of the Mesozoic rift system on the eastern coast of North America, which formed in response to the Triassic initiation of breakup of the supercontinent Pangea. At the time of rifting, $\sigma_1$ and $\sigma_3$ are inferred to have been vertical and NW–SE directed, respectively (Schlische, chapter 4 in this volume). The basin itself is a highly elongate half-graben with a SE-dipping border fault system (Chatham fault zone) (figure 8.1). The basin experienced inversion during earliest Jurassic time, most likely due to reorientation of the principal stresses at the onset of seafloor spreading in the central Atlantic Ocean (Withjack, Schlichte, and Olsen 1998).

The 4,000 m of basin fill (Dan River Group) rest in depositional unconformity over basement and dip antithetically to the border fault system at angles from 20 to 50° (Kent and Olsen 1997). The Solite Quarry lies within the upper member of the Cow Branch Formation, as defined by Olsen (1997). Kent and Olsen (1997) have described this member as an approximately 1,950 m thick sequence of cyclic gray to black mudstones of deep-water lacustrine facies. Within the quarry, bedding dip angles range from 30 to 40°. In subsequent sections of this chapter, we have corrected all structural orientations for bedding dips.

**Structures Within the Quarry**

**Brittle/Discontinuous Deformation–Extension**

**Mode I Fractures.** Mode I fractures are common within the Solite Quarry and exhibit in both cross section and plan view the classic “penny-shaped crack” described by Pollard and Aydin (1988) (figure 8.2a). Layers containing Mode I fractures are typically medium to fine-grained feldspathic sandstones. The vast majority of Mode I fractures in the quarry are calcite veins with cockscomb texture (e.g., Davis 1984). They are restricted to discrete lithologies, are oriented subnormal to bedding, terminate at sharp lithologic boundaries, and have a median fracture spacing (at this scale range) that is roughly proportional to mechanical layer thickness (e.g., Gross et al. 1995) (figure 8.2a). The fractures can be divided into two sets based on dominant orientations. The dominant set is subvertical, striking approximately 045° (figure 8.3), suggesting that $\sigma_1$ and $\sigma_3$ were vertical and NW–SE directed, respectively, at the time of formation, which is consistent with stress directions inferred from basin geometry and intrabasinal faults. The subordinate set is also subvertical, striking approximately 005°, subparallel to a regional (subordinate) dike set (~358°) (Schlichte, chapter 4 in this volume) (figure 8.4) that postdates the initiation of basin inversion in earliest
Jurassic time (~200 Ma). The dominant regional dike set (~320°) (Schlische, chapter 4 in this volume) (figure 8.4) is believed to be coeval with the initiation of basin inversion (Withjack, Schlische, and Olsen 1998).

Extensional strain accommodated by Mode I fractures was calculated using the sum of bed segments between veins along a scan line and the length of the scan line. The average strain estimate is 5.4%. As yet, no quantitative thin section work has been done on the Solite rocks. Hence our average strain estimate for Mode I fractures should be regarded as a minimum at this time. A histogram of vein spacings (figure 8.4) for a bed in the main Solite Quarry resembles a skewed, log-normal distribution of spacings that is commonly observed where extension fractures are restricted to lithologically controlled mechanical layers.
Brittle extensional features of the Solite Quarry. (a) Medium-fine-grained sandstones that contain calcite veins, interbedded with black shales that failed continuously. Lens cap for scale. (b) Hybrid fractures that formed in medium-coarse-grained feldspathic sandstones. The feature trending from top-left to bottom-right of the photo is a shear zone. Coin is 2.3 cm in diameter. (c) Single small normal fault that formed in fine-grained massive siltstones. The fault surface contains fibrous slickenlines that indicate predominantly dip-slip motion. Lens cap for scale. (d) Small normal faults separated by a relay structure. The fault surfaces contain tool-and-groove slickenlines. Coin is approximately 1 cm in diameter. (e) Sawed section of a slab that contains small faults. The arrow points to a prime example of footwall uplift and hanging-wall subsidence (reverse drag) along a bedding-plane parting cut by a normal fault. (f and g) Close-ups of a boxed fault; image g is interpreted. Notice that displacement along the fault is at a maximum toward the center of the fault, tapering to zero at the tips, where the structure terminates in zero-displacement cracks.
Synoptic diagram and stress-orientation analysis for brittle features present at the Solite Quarry. Extensional structures are consistent with Triassic rifting; contractional structures are consistent with earliest Jurassic rifting. Great circles are means based on multiple structures: 100 normal faults, 50 veins, one reverse fault, one imbricate thrust stack, and five quarry buckles.

Hybrid Fractures. Hybrid fractures are shear fractures with a substantial tensile component (e.g., Dunne and Hancock 1994). Within the Solite Quarry, hybrid fractures formed within medium- to coarse-grained feldspathic sandstones (figure 8.2b) and are restricted to discrete lithologic intervals in the same manner as Mode I fractures. Hybrid fractures are the least-common fracture type in the Solite Quarry.

Shear Fractures (Small Normal Faults). Shear fractures, or Mode II/III—the third brittle failure mode of fractures—are represented by very small, newly formed normal faults (figure 8.2c). They are restricted to fine-grained massive siltstones that occasionally separate cleanly along bedding-plane partings. These structures formed prior to basin-scale reverse drag associated with hanging-wall subsidence, as well as normal drag associated with reverse faulting and inversion, and are thus best called early tectonic shear fractures. Such fractures are the smallest normal faults studied in detail to date and are of particular interest because they are exceptionally well exposed and better constrain the scale range over which faulting takes place. They exhibit normal stratigraphic separation in both plan (figure 8.2c) and cross-section views (figure 8.2e–g), as well as footwall uplift and hanging-wall subsidence (figure 8.2e). Isostasy is not a consideration at this scale range; hence the footwall uplift must have been caused by coseismic elastic deformation of the volume surrounding the fault (e.g., Gupta and Scholz 1996). The bedding surfaces shown in figure 8.2c can be traced continuously around the tips of the faults and thus can be used as an offset marker. These very small faults (~0.5 cm < L < ~300 cm) are planar and (originally) blind, dip at 70° to bedding (figure 8.2d), and are synthetic to the border fault system of the basin. They are in many ways like their larger cousins, although they are unaffected by factors such as isostasy, erosion, and sedimentation. Some (~50%) of the structures exhibit a slight tensile component. The orientations of the small faults are consistent with Triassic rifting (figure 8.3). Bedding thickness remains constant across the faults, indicating that they are not syn-
Rift-Related Tectonic Structures from the Solite Quarry

Log-log plot of displacement versus length for 201 small faults in the Solite Quarry. The relationship between displacement and length is approximately linear ($D = cL^n$) with $R^2 = 0.724$.

Depositional. Their elliptical fault surfaces (Gupta and Scholz 1996) contain either tool-and-groove (figure 8.2d) or fibrous (calcite) slickensides (figure 8.2c), ensuring their brittle origin. Slickenlines rake at high angles, indicating predominantly dip-slip motion. The faults occur both as isolated features and as segments of relay systems, with relay ramps between overlapping fault segments in map view (Schlische et al. 1996; Gupta and Scholz 2000) (figure 8.2c and d). Relay structures are common to faults at a variety of scales (e.g., Larsen 1988; Peacock and Sanderson 1991; Dawers, Anders, and Scholz 1993). The faults also overlap in vertical section.

Extensional strain in beds containing small faults was calculated using the sum of heaves collected along scanlines oriented normal to the fault traces. The average extensional strain is approximately 4%. Along the length of the faults, displacement is at a maximum at the center of the fault and tapers to zero at the tips (figure 8.2c), consistent with displacement profiles observed on larger structures (e.g., Dawers, Anders, and Scholz 1993). This is the geometry predicted by models of fault growth that incorporate a process zone, according to which inelastic and nonbrittle processes such as plastic deformation, frictional wear, and mechanical breakdown occur at the fault tip (Cowie and Scholz 1992b). Displacement also varies along the height of the faults, such that larger displacements occur toward the center of the structures, tapering to zero toward the upper and lower tips (figure 8.2e–g), where the faults terminate into zero-displacement cracks.

Far-field deformation affecting the volume surrounding the fault (required to maintain geometric coherence [e.g., Barnett et al. 1987]) is expressed as bedding deflection (reverse drag) that decreases away from the faults, generally consistent with elastic models of fault growth (Gupta and Scholz 1996) and with observations of faults at a variety of scales (e.g., Bariientos, Stein, and Ward 1987; Barnett et al. 1987; King, Stein, and Rundle 1988; Schlische, chapter 4 in this volume).

The relation between maximum observed displacement, $D$, and trace length, $L$, for 201 isolated or completely linked faults is linear over approximately 2.5 orders of magnitude of fault length (Schlische et al. 1996) (figure 8.5). Thus in the $D$–$L$ scaling relation $D = cL^n$, the value of the scaling exponent $n = 1$ ($c$ is a constant related to rock properties and tectonic environment). The Solite faults extend the global $D$–$L$ data set by two orders of magnitude to a total of eight orders of magnitude of fault length and indicate that there is no significant change in the linear $D$–$L$ scaling relation between small and large faults. Although the value of $n$ has been controversial in the past (cf. Cowie and Scholz 1992a, 1992b; Gillespie, Walsh, and Watterson 1992), the Solite data set and others that have appeared in recent years (e.g., Dawers, Anders, and Scholz 1993; Villemin, Angelier, and Sunwoo 1995) indicate that $n = 1$ and that fault growth is largely self-similar. The determination of $n = 1$ supports Cowie and Scholz’s (1992b) elastic-plastic model of fault growth.

Continuous Deformation-Extension

The fourth style of extensional deformation present within the section is continuous (nonbrittle). Black shales are interbedded with the three aforementioned lithologies but do not exhibit brittle failure (figure 8.2a). There are no bedding-parallel extensional detachments within the section: all beds are welded together. Thus in order to maintain strain compatibility, the black shale layers deformed continuously. Deformation of this type is manifested as deformed mudcracks and stretching lineations or microfolds that are
perpendicular to the strike of small faults in adjacent lithologies.

**Brittle/Continuous Deformation—Compression/Inversion**

Contractional structures present in the Solite Quarry (figure 8.3) are likely related to inversion of the basin during earliest Jurassic time (Withjack, Schlische, and Olsen 1998; Schlische, chapter 4 in this volume). Inversion is indicated by the high length:width ratio of the basin (11:1) and the steep bedding dips (Schlische, chapter 4 in this volume). Some of the contractional structures in the quarry are thought to be newly formed, whereas others are reactivated extensional features. One such structure is a relatively large ($L = 15$ m) normal fault that has been reactivated as a reverse fault and exhibits reverse separation (figure 8.6a); the structure is parallel to all other small, intermediate, and large normal faults within the quarry. Small faults ($\sim 2$ cm < $L < \sim 10$ cm) located in the hanging wall of the inverted fault continued to slip as normal faults during inversion but have anomalously high displacements for their lengths (figure 8.6b). This anomaly suggests that these faults did not lengthen according to the same scaling relation they followed during their initial formation. We attribute this difference to changes in the rock properties and, thus, $c$, between the time of formation of the extensional features and the time of initiation of inversion, which corresponds to the burial and thermal maximums for these rocks (Withjack, Schlische, and Olsen 1998).

Several individual shale layers were shortened during inversion of the Dan River–Danville basin. Black shales occasionally serve as compressional décollement surfaces with multiple imbricate thrust sheets (figure 8.6c). Microlaminated organic-rich shale layers known for their terrestrial fossils have also been shortened, forming very small folds in advance of propagating reverse faults (figure 8.6d). The fossils themselves have been deformed (Olsen, Schlische, and Gore 1989; Fraser et al. 1996).

**Neotectonic Structures**

Quarry buckles present within the Solite Quarry (figure 8.6e) suggest a NE–SW-directed maximum principal horizontal stress (figure 8.3). The buckles formed due to unloading as material was removed during the quarrying process. The resultant folds (buckles) formed such that their fold axes are perpendicular to the maximum horizontal principal stress direction (Stewart and Hancock 1994). Extension fractures associated with the buckles parallel the axes of the buckles.

**VERTICAL DISTRIBUTION OF STRUCTURES**

Within the Solite Quarry, deformation style and failure mode correlate closely with lithology, such that Mode I fractures, hybrid fractures, and small normal faults are restricted to discrete lithologic layers; there is no vertical connection among most of the fractures. In order to quantify this relation, we analyzed three samples of rock exhibiting each extensional deformational style (tension, hybrid, shear, continuous) to constrain their composition using a combination of geochemical x-ray diffraction techniques (Ackermann 1997). Because quantitative x-ray diffraction was not possible within the financial and time constraints of the study, we combined the oxide and phase data to generate the bulk mineral compositions of the samples. We did this using a modified least-squares–based magma-mixing model; such models combine the same types of data to determine the bulk compositions of igneous rocks.

X-ray diffraction indicates that all samples have a strong peak at 28° 20 (albite); all samples are at least 50% albite. Albite is likely the cement for these rocks, consistent with their saline lacustrine origin (P. E. Olsen, personal communication 1996). Other minerals present in the samples are phyllosilicates (biotite), tectosilicates (Na- and K-feldspars, quartz, analcime), carbonates (dolomite, calcite), and inosilicates (riebekite).

Figure 8.7a presents the results of the oxide analysis in terms of general carbonate versus sandstone compositions, following Brownlow (1979). The data are sorted by failure mode and show a correlation between increasing shear failure component and decreasing carbonate component (carbonates are generally considered to be “strong” [Suppe 1985]). There does not appear to be a correlation between failure mode and sandstone component within the samples. In figure 8.7b, the oxide data are shown in terms of CaO:Al$_2$O$_3$ ratios, with decreasing CaO and increasing Al$_2$O$_3$ trends following phyllosilicate (“weak” platy minerals) composition trends. The Solite data show a correlation between increasing shear component to the deforma-
Figure 8.6 Contractional structures present at the Solite Quarry. Parts a through d are related to inversion in earliest Jurassic time. (a) Large normal fault reactivated as a reverse fault. The person’s hand is on the hanging wall, and the feet are on the footwall. (b) Small faults present in the hanging wall of the fault in a, where they were reactivated as normal faults. (c) Black shale layer that serves as a décollement surface, forming a series of imbricate thrust slices. Lens cap for scale. (d) Thin section of one of the arthropod beds, showing small reverse faults with less than 1 mm of separation (photograph courtesy of Nick Fraser). 

e) Neotectonic quarry buckles. Arrows indicate the buckle axes, which are perpendicular to neotectonic σ1.

Figure 8.7c summarizes the results of the least-squares regression analysis, where the major oxide and relative mineral abundance data were combined. The data are presented in terms of percentages of “weak” and “strong” minerals. “Weak” minerals are defined as phyllosilicates; all other minerals present in the sam-

tion and increasing phyllosilicate composition trends. Notice that the outlying point in figure 8.7a and b is sample S2395BT. Some vein material (calcite) may have been incorporated erroneously into the sample during crushing of this Mode I sample, leading to an anomalous high CaO content.
Sedimentary geochemistry of the rocks of the Solite Quarry. (a) Increasing carbonate components correlate with decreasing shear failure components. Note that the sandstone component does not appear to correlate with the failure mode (characterization adopted from Brownlow 1979).  

(b) CaO:Al₂O₃ ratios are another way of presenting sedimentary geochemical data, with decreasing CaO and increasing Al₂O₃ trends following phyllosilicate (platy minerals) composition trends. For the Solite data, increasing shear failure components correlate with increasing phyllosilicates. (c) Summary of bulk mineralogy versus failure mode, in terms of weak minerals (phyllosilicates) versus strong minerals (tectosilicates, carbonates, inosilicates). Increasing shear failure components correlate with increasing proportions of weak minerals.

There is a very good correlation between increasing proportions of “weak” minerals and increasing shear failure components (figure 8.7c). An interesting fact is that the hybrid samples contain hydrous inosilicates (riebekite), which may have made them more prone to shear failure.

The correlation between failure mode and bulk mineralogy, the comparable strain estimates for Mode I fractures and faults, and the distinct absence of extensional bedding-parallel detachments within the section suggest that all the brittle structures failed approximately coevally in response to the same remote applied stress. This phenomenon is known as fracture partitioning and has been described by Gross (1995) for the Monterey Formation in California. Based on the approach outlined by Gross (1995), Ackermann (1997) constructed a two-component (Mode I and shear) macroscopic failure model based on the boundary conditions outlined earlier and on average mechanical properties derived from the rock mechanics literature. This failure model indicates that brittle failure occurred at a burial depth of approximately 4 km in the presence of a pore fluid pressure of approximately 15 MPa.

The macroscopic failure models of Gross (1995) and Ackermann (1997) invoke a specific set of boundary conditions and potentially may be used to construct a predictive mechanical stratigraphy based on the mechanical properties of the rocks. Such a predictive tool will be useful for studies of groundwater and hydrocarbon accumulation and migration. However, these models have limitations. A fundamental weak-
ness is that the mechanical properties used in the models are based on values published in the literature and not the actual samples themselves. Published data listing mechanical properties, bulk mineralogy, sedimentary geochemistry, and good lithologic descriptions are lacking, thus making these failure models more conceptual than case specific. This lack, in turn, points to another weakness: it is not clear if the samples we have now are mineralogically, geochemically, and mechanically similar to how they were when they failed at depth, making load tests questionable even if they are feasible. In the Solite example, the rocks have been metamorphosed to zeolite facies and are thermally mature. The thermal maximum for the basin occurred after the initial formation of the fractures and just before inversion of the basin in earliest Jurassic time (Malinconico 1996, chapter 6 in this volume; Withjack, Schlische, and Olsen 1998). In addition, the stress orientation analysis for the Solite rocks suggests that failure occurred prior to significant tilting of the basin fill, some of which is due to hanging-wall subsidence and reverse drag associated with rifting, but most of which is due to inversion (Schlische, chapter 4 in this volume). Whether or not the details of the failure model are correct, it is clear that the different types of fractures are controlled by lithology and that they are formed semicoevally.

**Lateral Distribution of Structures**

**Mode I Fractures**

A bedding-plane exposure of Mode I fractures (extension gashes) from the Solite Quarry is shown in figure 8.8. There is a uniform distribution of features across the surface. The average extension accommodated across the slab (measured using apertures along a series of scanlines) is approximately 3%, with a standard deviation of 0.5%; this estimate is lower than those determined using bed lengths along a cross-section scanline. The reason for this lower estimate is that the bed shown in figure 8.8 has broken at a mechanical layer boundary—the view is thus of the “top” of the mechanical layer, where Mode I fractures terminate. Thus the apertures measured were not maximum apertures, which would have required sampling at the level in the bed where the fractures nucleated, if there is a single level. Nonetheless, the strain appears to be evenly distributed across the sampled surface.

Figure 8.9 is a cumulative frequency plot (number of features greater than a given size plotted versus size) in log-log space for the lengths of the Mode I fractures shown in figure 8.8. The entire distribution is best fit using an exponential function rather than a power-law function (which applies to only a very limited scale range [figure 8.9, dark circles]). The definition of a mean value or characteristic size is a diagnostic feature of exponential distributions (Cowie et al. 1994). The exponential distribution is probably a result of a lack of spatial correlation in the system due to the effect of mechanical layer thickness on lateral positioning of fractures, which in turn suppresses the short- and long-range interactions of structures that ordinarily result in power-law (fractal) distributions (e.g., Cowie et al. 1994).

The population of Mode I fracture lengths shown in figure 8.8 exhibits a characteristic length of approximately 2.60 cm, based on the slope of the best-fit exponential curve in figure 8.9. The slope (0.384) is the reciprocal of \( L \), the mean value of \( L \) (e.g., Cowie et al. 1994). This estimate of 2.60 cm contrasts with an average length of approximately 4.25 cm, based on field observations. The difference likely stems from the structural level where fractures were sampled: lengths were sampled at the mechanical layer boundary (a limiting level for fracture height), not at the nucleation level or levels. As a result, small fractures were under-sampled, either because they do not intersect the sampled level or because they fall below the resolution of the sampling level (naked eye). The estimate of 4.25 cm is derived from a sample in which small fractures were underrepresented, thus overestimating the average or characteristic length. The estimate of characteristic length of 2.60 cm is likely to be more accurate because it relies on the distribution of fracture sizes. The distribution of sizes (the slope of the line in figure 8.9) will not vary appreciably with structural level, provided most fractures have achieved a height equal to mechanical layer thickness. Some lengths sampled at the layer boundary will be less than the maximum lengths. In other words, depending on the structural level sampled, the intercepts of the cumulative frequency plot will change, but the slope will not, and it is the slope that provides the characteristic length.
Spatial distribution of Mode I fractures across a bedding surface. View is of the top of the bed, which is a mechanical layer boundary. Lines are scan lines along which one-dimensional strain data were collected.

Cumulative frequency diagram of Mode I fracture lengths for the bedding surface shown in figure 8.8. It is not clear if there is a "flat" central segment suggestive of a power-law distribution of sizes. The data as a whole are better fit using an exponential function. If the data do indeed follow a power-law distribution, then truncation and censoring effects are severe for this sample.

Small Normal Faults

Over large areas of the Solite Quarry, the small normal faults appear to be distributed fairly uniformly within the units that fail in shear. These structures range in size \(0.1 \text{ cm} < L < 200 \text{ cm}\), although the vast majority of them are less than 10 cm long. A division based on fault size (length) can be made (Ackermann and Schlische 1997) (figure 8.10): there are small faults \(L < 20 \text{ cm}\) and larger faults \(L \geq 20 \text{ cm}\,\text{, usually } L \geq 100 \text{ cm}\). The larger faults are fairly uncommon and appear to be uniformly distributed within the rock volume. Around these larger faults (master faults), there appear to be ellipsoidal zones devoid of smaller brittle structures (figure 8.10), which are otherwise ubiquitous in the surrounding volume. The smaller faults are thus anticlustered around the master faults. These regions lacking smaller faults are called fault shields. Master faults are defined by the presence of a fault shield around them, regardless of their size. The width of the fault shield in plan view scales linearly with the displacement on the master fault (Ackermann and Schlische 1997) and is geometrically similar to the deformation field surrounding a normal fault (e.g., Gibson, Walsh, and Watterson 1989) (figure 8.11a).
Figure 8.10  (a) Small faults anticlustered around a larger normal fault (the footwall surface is shown in foreground). Notice the absence of faults within an elliptical region around the larger structure, except for where there is a breached ramp structure in the lower right (arrow). Ruler at the top of image is 15 cm wide. (b) Distribution of faults exposed on the bedding surface of a quarried boulder. Faults are highlighted with chalk. Scale bars normal to fault traces are 10 cm long. (c) Fault shields in cross section, with faults highlighted. Arrows point to tips of master faults. Master faults and small faults offset bedding. Coin for scale.
The shields are apparent in plan view (figure 8.10a and b) and in cross section (figure 8.10c). The smaller faults appear to follow a semiregular arrangement around the master faults, such that they change step near the center of the fault along its length and around the tips (figure 8.10). The amount of strain accommodated within a rectilinear two-dimensional area around a master normal fault, including smaller faults outside the fault shield, varies along the length of the larger fault, mirroring a length-displacement profile (figure 8.12a). When the master faults present are not included in the strain calculation, strain on the smaller structures does not vary appreciably across the study area, and the amount of strain accommodated is substantially less. The master faults are dominating the strain. If one considers an area without a master fault present (figure 8.12b), the small faults do not exhibit stepping patterns, and the amount of strain accommodated is fairly uniform and substantially less than in areas with master faults. As documented fully in Ackermann and Schlische (1997), anticlustering also affects the distribution of fault sizes, such that the population as a whole is best described by two power-law curves: one covering the smaller faults, which tend to be unbounded structures, and the other covering the master faults, which have completely spanned the mechanical layer containing the faults.

The fault shields are interpreted to correspond to a critical stress-reduction shadow, which prevented the nucleation and growth of smaller faults around the earlier formed master faults (Ackermann and Schlische 1997). This interpretation is based on the nearly complete absence of brittle structures in the fault shields; the geometric similarity between fault shields and the deformation fields around normal faults (which represent regions where the rocks have been strained and the stresses relaxed [Gibson et al. 1989]); and the similarity between the shield geometry and regions of stress reduction derived from numerical models (e.g., Willemse 1997) (figure 8.11).

The Solite Quarry represents the first definitive field documentation of an anticlustered spatial distribution of faults and the existence of stress-reduction shadows around faults (Ackermann and Schlische 1997). In contrast, several workers (e.g., Gillespie et al. 1993; Little 1996) have noted that smaller faults most often are clustered positively around larger faults. The two observations need not be mutually exclusive: numer-
rical modeling conducted by Willemse (1997) shows higher shear stresses in the regions surrounding the fault tips (figure 8.11b). It is thus possible that both positive clustering (figure 8.10a, arrow) and anticlustering (in the form of fault shields) can occur along the same fault, with anticlustering dominating near the center of the fault and positive clustering dominating near the tips. A better understanding of the spatial distribution of fractures, made possible by exceptional field localities such as the Solite Quarry, ultimately will lead to the refinement of fractured-rock models, which are so important for groundwater and hydrocarbon prospecting.

CONCLUSIONS

The Solite Quarry contains an exquisite suite of rift-related deformation structures that provide a unique opportunity to study fracture geometries, kinematics, size and spatial distributions, and population systematics in great detail.

Mode I fractures, hybrid fractures, and shear fractures (small normal faults) are the dominant brittle structures related to Triassic rifting. The faults and Mode I fractures are geometrically and kinematically distinct, and it is therefore unlikely that the faults originated as macroscopic Mode I fractures. Also present are reactivated normal faults, imbricate thrust faults, and microfolds—all of which are late-stage features related to inversion of the Dan River–Danville basin in earliest Jurassic time.

All these features are restricted to certain interbedded lithologies, such that beds with greater percentages of weak minerals failed with increasing shear components. There is a distinct absence of extensional detachment horizons between mechanical layers. The Mode I fractures and the small normal faults have undergone comparable one-dimensional strains. All observations suggest coeval brittle failure of interbedded lithologies under the same remote applied stress.

The Solite faults extend the global D-L data set by two orders of magnitude to a total of nine orders of magnitude of fault length and indicate that there is no significant change in the linear D-L scaling relation. The faults can be subdivided into two subsets based on their spatial distribution. Larger (master) normal faults accommodate the majority of the strain but, compared with the smaller faults, are relatively uncommon. The other subset of smaller faults is ubiquitous within the rock volume but exhibits anticlustering with respect to the larger structures, forming ellipsoidal fault shields around the larger faults. The shields are
geometrically similar to the deformation fields of the master faults, corresponding to a stress-reduction shadow that prevented the nucleation of smaller faults around the master faults.

Acknowledgments

We thank C. H. Gover and the Virginia Solite Corporation for their support of this and other research conducted at the Solite Quarry. Our research was supported generously by Mobil Technology Company, the Virginia Museum of Natural History, Sigma Xi, and the Department of Geological Sciences at Rutgers University. Alison Lighthart kindly and expertly made numerous thin sections. Anu Gupta and MaryAnn Malinconico generously shared unpublished data. Mike Carr, Jeff Niemitz, and Gene Yogodzinski provided advice regarding the analytical geochemistry and x-ray diffraction. We thank Karen Bemis, Jim Carpenter, Amy Clifton, Patience Cowie, Nancey Dawers, Gloria Eisenstadt, Nick Fraser, Mike Gross, Anu Gupta, Peter Hennings, Paul Olsen, Chris Scholz, ShayMaria Silvestri, Martha Withjack, and Scott Young for many engaging and enlightening discussions regarding the features at Solite, fault-population systematics, and the Mesozoic rift system. Finally, we appreciate Mike Gross’s and Chris Scholz’s helpful reviews of the manuscript for this chapter.

Literature Cited


Gross, M. R. 1993. The origin and spacing of cross joints: Examples from the Monterey Formation, Santa Bar-


