

Final Report

**DEFORMATION AND FRACTURE OF POORLY CONSOLIDATED MEDIA –
Borehole Failure Mechanisms in High-Porosity Sandstone
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Borehole Failure Mechanisms in High-Porosity Sandstone

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Scope

We investigated failure mechanisms around boreholes and the formation of borehole breakouts in high-porosity sandstone, with particular interest in the grain-scale micromechanics of failure leading to the hitherto unrecognized fracture-like borehole breakouts and apparent compaction band formation in poorly consolidated granular materials. We also looked at a variety of drilling-related factors that contribute to the type, size and shape of borehole breakouts. The objective was to assess whether these phenomena could be put to use to enhance in situ stress estimation, borehole stability prediction, and hydrocarbon/water extraction in general.

Work Accomplished

Our experimental program consisted of simulating in situ deep drilling in sandstones by boring central vertical holes in typically 150 x 150 x 230 mm blocks, which were already subjected to three true-triaxial principal far-field stresses $\sigma_H \neq \sigma_v \neq \sigma_h$ (where σ_v is the vertical stress and the other two are the principal horizontal stresses). All three orthogonal and unequal far-field stresses remained constant throughout drilling. Tested specimens were dissected into 10-12 mm thick slices, and borehole cross-section shape and dimensions recorded. Thin sections were prepared of selected slices and subsequently analyzed for grain size, type of cementation, and microstructural damage, using optical microscopes equipped with digital cameras. Also, thin and thick sections were analyzed under a scanning electron microscope (SEM).

The focus of our research during this 3-year period has been an investigation of the mechanical behavior of three distinct sandstones subjected to borehole drilling under far-field stresses simulating in situ (field) conditions. These sandstones vary in mineral composition, porosity, strength, grain-bonding/cementation, and sphericity (Tables 1 and 2).

Table 1. Mineral composition and textural characteristics.

Rock → ↓ Property	St. Peter sandstone	Tablerock sandstone	Mansfield sandstone
Mineral composition	99% quartz, 1% iron oxide	55% quartz, 37% feldspar, 5% mica, 3% clay	90% quartz, 7% mica and altered mica, 2% feldspar, 1% iron oxide
Primary cementation	Quartz overgrowth suturing	Microcrystalline quartz	Quartz sutured grain contacts
Mean grain size	Bimodal: 0.1mm; 0.4mm	0.20 (±0.07) mm	0.20 (±0.06) mm
Grain geometry (sphericity)	Well rounded	Angular	Subangular to subrounded
Color	Variable from white to yellow to red	Tan to white	Light yellow to dark brown

Table 2. Physical and mechanical properties.

Rock → ↓ Property	St. Peter sandstone	Tablerock sandstone	Mansfield sandstone
Porosity (helium gas porosimeter)	10-22%	28±3%	26±1%
Elastic modulus	27.8±3.5 GPa (for n=16%)	14.7±0.3 GPa	9.6±0.1 GPa
Poisson's ratio	0.25±0.02 (for n=16%)	0.20±0.00	0.27±0.04
Uniaxial compressive strength	33-92 MPa (varies inversely with porosity)	39.5±4.8 MPa [†]	22.4±0.5MPa
Brazilian tensile strength	2.5±0.52 MPa (for n=16%)	4.4±0.2 MPa [†]	1.8±0.3MPa

(a) *St. Peter Sandstone*

The first year of the project was spent primarily on drilling experiments on St. Peter sandstone. It is Ordovician aeolian sandstone, which in its outcrops near Verona, Wisconsin is composed exclusively of quartz grains, with minor iron oxide at grain boundaries. Its porosity varies considerably from layer to layer (Table 2). We discovered major differences in grain-scale features that distinguish the high-porosity ($n = 16-22\%$) from the low porosity ($n = 10-12\%$) St. Peter sandstone. The high porosity variety is bonded by narrow, nearly point-wise grain sutures, whereas low porosity samples contain much wider sutures, which in some cases nearly envelope the grain boundaries.

Our tests revealed that irrespective of porosity St. Peter sandstone develops long, fracture-like borehole breakouts that propagate in the direction of the minimum horizontal principal stress. Breakout length is highly dependent on the far-field horizontal principal stress magnitudes. The higher the maximum horizontal stress σ_H for given σ_h and σ_v magnitudes, the longer the breakout. However, the span at the borehole wall and the average width of the fracture-like breakout are approximately constant, and equal to several grain diameters, irrespective of the far-field stress conditions. This reinforces a previous suggestion that breakout width is a material property.

The porosity of St. Peter sandstone becomes an important factor in the micromechanism of breakout failure. Fracture-like borehole breakouts in high-porosity samples are often preceded by failure of the weak nearly point-wise grain sutures within a narrow zone aligned with the σ_h springline, resulting in the apparent debonding and repacking of intact grains and creating localized compaction. Subsequent removal of loosened, mainly intact, grains by circulating drilling fluid creates long fracture-like breakouts (Figure 1).

A considerably different type of localized failure was found to occur in low-porosity St. Peter sandstone. Here the critical σ_H necessary to produce fracture-like borehole breakouts of a certain length is much higher than in the high-porosity variety for the same σ_h and σ_v magnitudes. Moreover, breakouts are preceded by the creation of a narrow zone of crushed grains (Figure 2). We interpret these two phenomena to imply that the broad quartz overgrowth grain sutures in the low-porosity sandstone renders grain bonding practically as strong as the grains themselves, and hence the high stresses required to induce localized compaction are also sufficient to crush the grains inside.

The constant and narrow breakout width in all samples tested, its orientation perpendicular to the direction of the maximum far-field stress, and the inferred compaction ahead of breakout tips

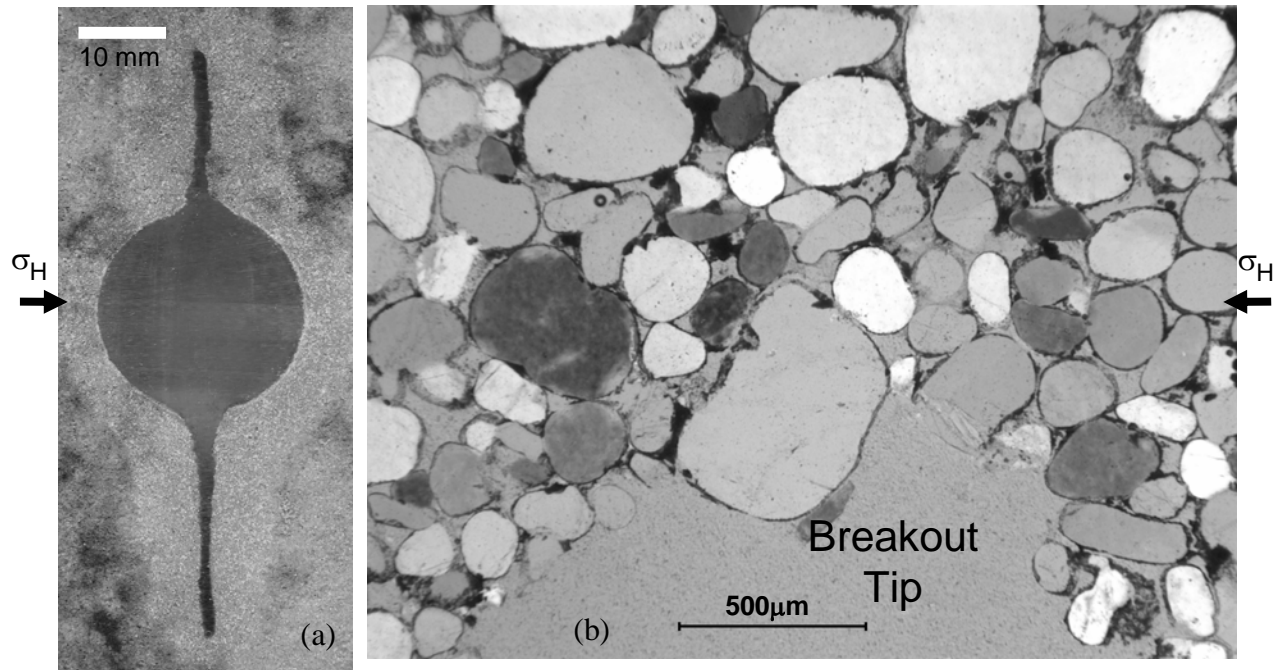


Figure 1. (a) Typical fracture-like breakout in 19%-porosity St. Peter sandstone. (b) Cross-polarized view of a thin section of the breakout tip in this rock shows that the grains ahead of the breakout tip remain practically intact, but appear to be largely debonded.

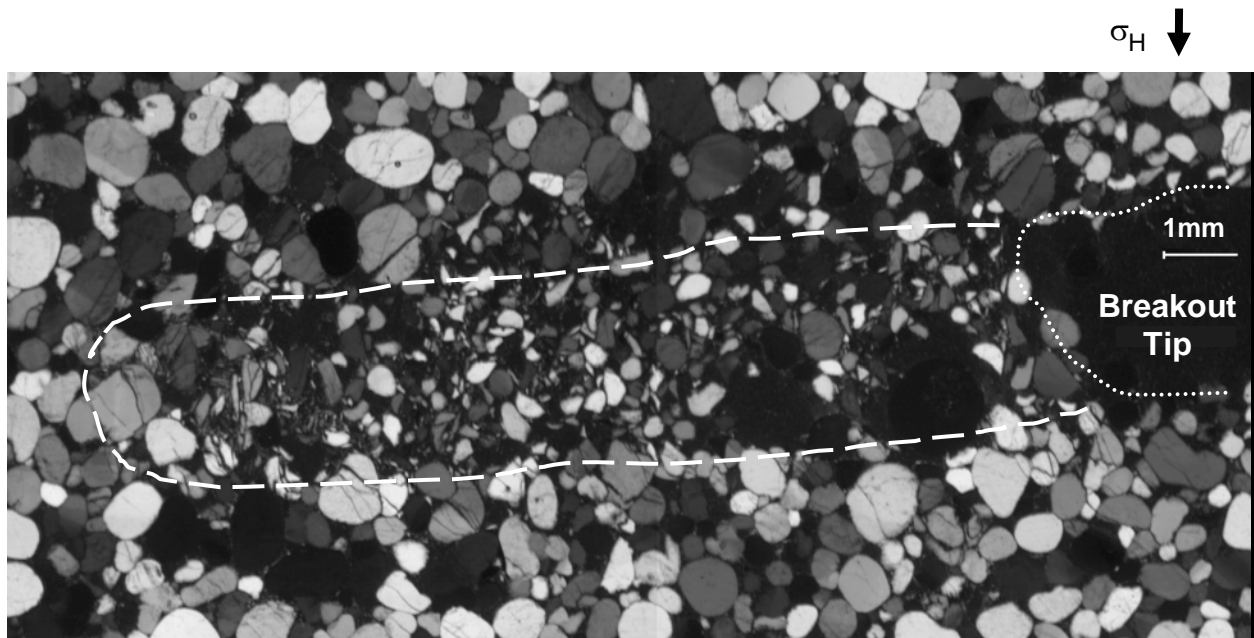


Figure 2. Cross-polarized view of a thin section of the breakout tip in a 11%-porosity St. Peter sandstone, showing a long and narrow zone of cracked, crushed, and re-packed grains ahead of the breakout tip, resembling a compaction band..

suggest that fracture-like borehole breakouts in St. Peter sandstone are preceded by the development of compaction bands that are then emptied by the circulating drilling fluid.

A series of tests in which water was replaced by drilling mud (mixture of water and bentonite) as the circulating fluid, revealed that drilling mud has a stabilizing effect on St. Peter sandstone fracture-like breakouts, shortening breakout length, and widening their angular span at the borehole wall.

(b) Tablerock sandstone

Tablerock sandstone belongs to a sequence of sandstone layers within the upper Miocene lower Idaho Group. It is highly porous ($n=28\%$), but is quite different from the other two sandstones listed in Tables 1 and 2 in that it contains large amounts of feldspar, and possesses angular grains that are well cemented by microcrystalline quartz.

Drilling into Tablerock sandstone subjected to far-field stress conditions beyond a critical threshold, induced diametrically opposed failed zones along the σ_h springline that consistently exhibited 'V'-shaped (also called 'dog eared') breakouts, wide at the borehole wall and relatively short (or shallow). This breakout shape is common in crystalline rocks (Lee and Haimson, 1993), limestones (Herrick and Haimson, 1994), and lower porosity sandstones (Haimson, 2003). Previously, our experience with high porosity rocks was that they failed in a fracture-like manner. The dog-eared breakouts in Tablerock sandstone were therefore quite unexpected.

Precision measurements of breakout depth and their angular span at the borehole wall revealed substantial increases in both with the magnitude of σ_H , for constant magnitudes of σ_h and σ_v . This clear correlation between far-field stress and breakout dimensions supports previous results in granitic and calcitic rocks (Lee and Haimson, 1993; Herrick and Haimson, 1994). It suggests that measurement of breakout orientation and depth or/and angular span in field boreholes drilled into Tablerock sandstone are correlatable to one of the in situ stress magnitudes and directions if the other two components can be assessed independently. (Note: The vertical in situ stress σ_v can be estimated from the weight of the overburden, and the least horizontal stress σ_h is often obtained from leak-off tests.) This result is of particular importance because borehole geophysical logging tools, such as the sonic televiewer and the electrical Formation Micro Imager, provide an accurate measurement of breakout orientation and dimensions. A method of computing one of the in situ principal stresses when the other two components are known, based on knowledge of the breakout orientation, span and rock strength criterion, has been successfully used in the amphibolite of the KTB ultra deep scientific hole in Germany (Haimson and Chang, 2002).

SEM micrographs of polished sections of tested Tablerock sandstone show extensive grain damage in the form of primarily intra- and trans-granular dilatant microcracking immediately ahead of the breakout tip where stress concentration is the highest (Figure 3). Feldspar grains (light gray in Figure 3), which form 37% of the Tablerock sandstone, and are the weaker of the two most abundant minerals, appear to have cracked first and more extensively than the quartz. Most of the microcracking is extensile, originates along the σ_h springline, and is simultaneously subparallel to the maximum principal stress σ_H and to the borehole wall. Microcracks extend away of the σ_h springline, where they gradually reorient toward the borehole wall, following trajectories of maximum compression (Figure 3). Detached grain fragments at the breakout tip resulting from the intense microcracking there, fall into the drilled hole or are easily removed by the circulating drilling fluid. As the breakout advances, the stress concentration shifts forward and additional cracking occurs, releasing more grain fragments, and lengthening the failed zone. The breakout narrows as it progresses, and we speculate that this is because some fragments at the breakout edges remain locked in place and prevent dislodging of additional cracked grains behind them. The zone of intense cracking ahead of the breakout tip is no longer than a few millimeters, and its intensity

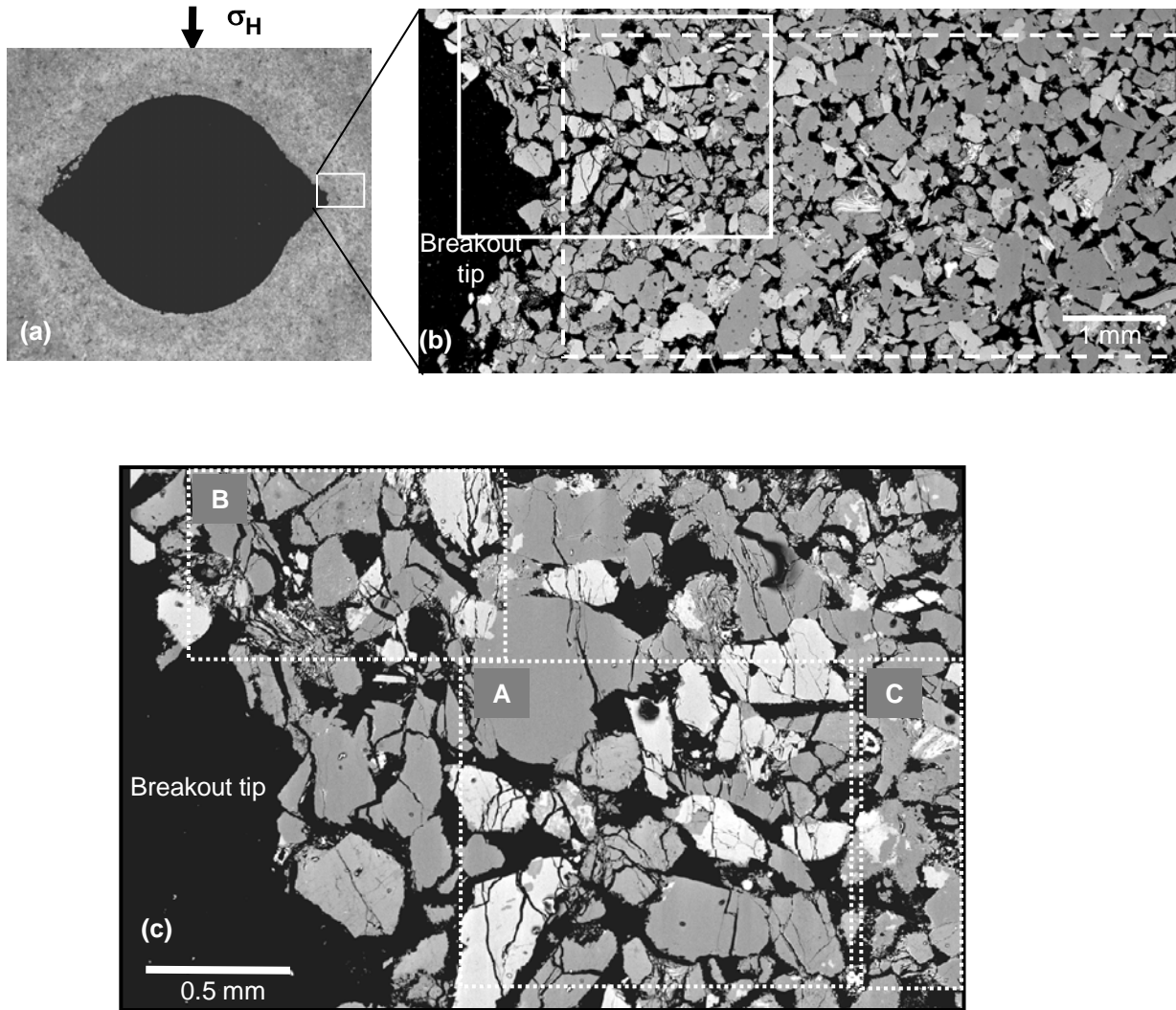


Figure 3. (a) Cross section of borehole and breakout in Tablerock sandstone. (b) Back-scattered SEM image of breakout tip. 2-D porosity within dashed-line box was 19.5% (compared to 20% for untested rock). (c) Detail of the area within solid line rectangle in (b), showing intra- and trans-granular extensile microcracks subparallel to far-field σ_H (area A). Away from the σ_h springline (area B) cracks appear to rotate toward the borehole wall, following the trajectory of the local maximum stress. Just 2-3 mm away from the breakout tip (area C) no microcracks are visible.

fades with the distance from the tip. As of now, however, we still lack a convincing explanation as to the mechanism behind the dog-eared shape of the breakout. We would also like to understand the micromechanics controlling the final breakout length, since the breakout tip should theoretically be under increasingly higher compressive stress concentration as the borehole plus breakout grow.

The entire failure mechanism is dilatant, since the extensile microcracks (Figure 3) create an increase in total rock volume, and is similar to that observed in previous experiments in igneous and sedimentary rocks of low to medium porosity. The development of V-shaped breakouts in the high porosity Tablerock sandstone indicates that porosity may not necessarily be the governing factor, and that there may be other microstructural properties that control the mechanism of breakout formation and final breakout shape.

(c) Mansfield sandstone

The Mansfield sandstone comes from Brazil, Clay County, Indiana. It is stratigraphically part of the Mansfield formation, Racoon Creek Group, Lower Pennsylvanian period. It is different from Tablerock sandstone in that it contains 90% quartz and very little feldspar, and its grains are primarily bonded by sutured contacts, with few grains held together by interstitial clay cements. It is also different from St. Peter sandstone in that it is not aeolian, and is not exclusively quartz grains (Table 1).

Drilling experiments in Mansfield sandstone induced entirely different breakouts than those in Tablerock sandstone despite their nearly identical porosities. They were thin, long, and tabular, (fracture-like) and initiated and extended along the springline of the far-field minimum principal horizontal stress (Figure 4). Breakout lengths in some experiments were several times larger than the borehole radius, suggesting that occurrence of such fracture-like breakouts in field situations could be a source of ‘sand production’, an undesirable phenomenon in petroleum extraction. The fracture-like breakouts were similar in appearance to those in the St. Peter sandstone.

Another similarity to St. Peter sandstone was the clear correlation between the fracture-like breakout length and the far-field stress (Figure 4), suggesting that logged breakout length could potentially be utilized as a stress magnitude indicator. The main obstacle here is the technical difficulty of determining breakout depth in deep boreholes. The average width of the narrow breakouts in Mansfield sandstone can be considered to have remained practically unchanged regardless of the applied state of stress. A similar observation was made in St. Peter sandstone, as well as earlier in high-porosity Berea sandstone (Haimson and Kovacich, 2003). This reinforces the suggestion that breakout width is a material property, perhaps related to grain size and/or the sandstone microstructure (the average width varies from rock to rock).

SEM studies in high porosity Mansfield sandstone suggest that fracture-like breakouts form as a result of an apparent localized compaction along a narrow band the axis of which coincides with the σ_h springline, where the highest stress concentration occurs. Figure 5 shows a typical fracture-like breakout obtained under a moderate state of far-field stress. The narrow band along the σ_h springline (dashed-line box in Figure 5) shows a reduced two-dimensional porosity as compared with that in unaffected areas away from the borehole (porosities determined from an image analysis using Optimas, commercial software). For the compaction band to form, weak grain contacts (primarily from suturing in Mansfield sandstone) have to breakdown, enabling grains to repack in a denser pattern. Although this phenomenon was not directly observed, we hypothesize that breakouts are generated by removal of these loosely bonded grains. Thus, the suggested failure mechanism is not dilatant as in Tablerock sandstone, since it is not the result of extensile cracking, and could even be named anti-dilatant since it involves loosening of grains and their compaction, i.e. a shrinking of the volume.

In the immediate vicinity of the breakout tip grains within the compaction band are typically

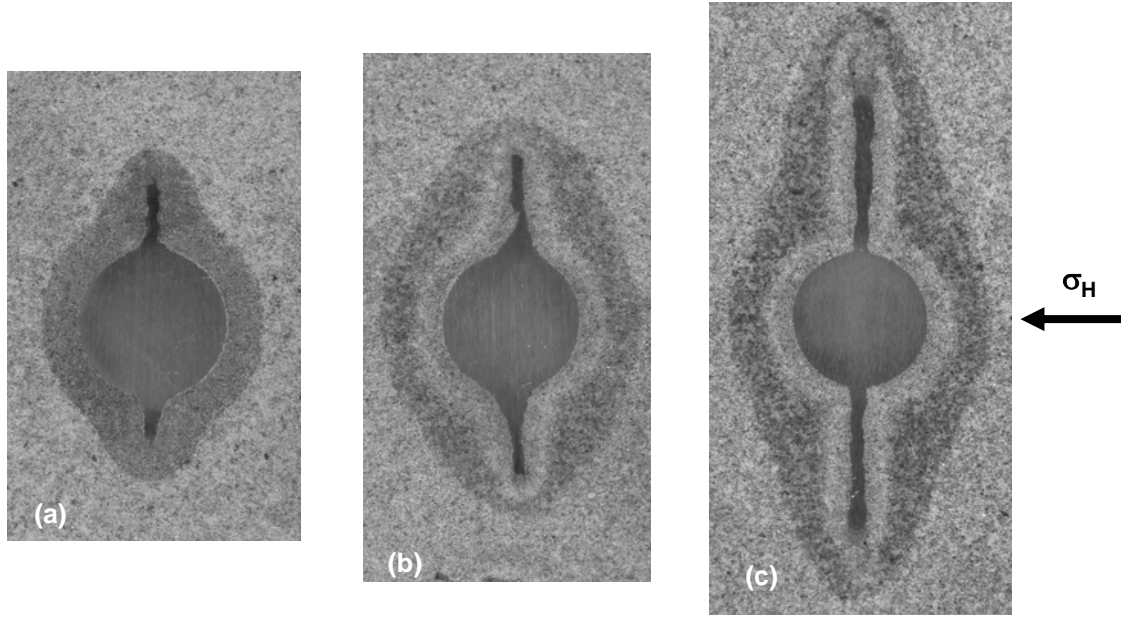


Figure 4. Borehole cross-sections of Mansfield sandstone showing narrow and long fracture-like breakouts extending in a direction orthogonal to σ_H . The applied minimum horizontal and vertical stresses were identical, $\sigma_h = 30$ MPa, $\sigma_v = 50$ MPa, but the maximum horizontal stresses varied from sample to sample: (a) $\sigma_H = 50$ MPa, (b) $\sigma_H = 60$ MPa, and (c) $\sigma_H = 70$ MPa.

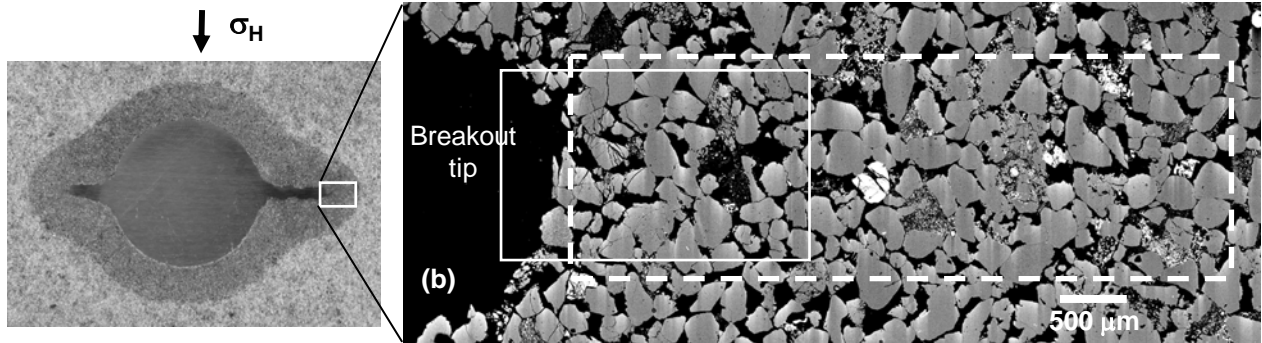
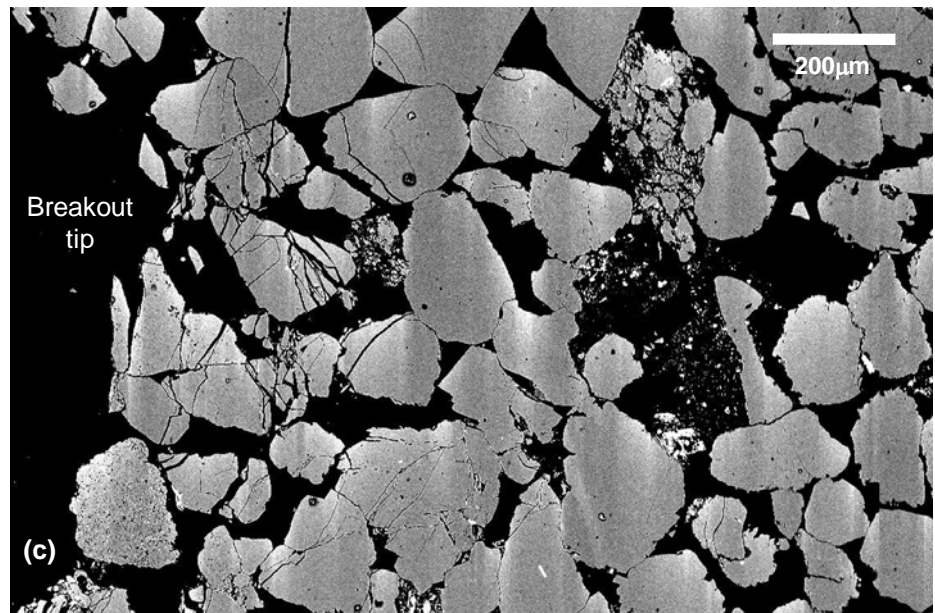


Figure 5. (a) Cross section of borehole and breakout in Mansfield sandstone. (b) Back-scattered SEM image of breakout tip. 2-D porosity within dashed-line box was 18% (compared to 22% for untested rock). (c) Detail of the area within solid line rectangle in (b), showing that most grains, except for those immediately ahead of the breakout tip, are uncracked, but apparently debonded and repacked (lower porosity).



cracked and sometimes even crushed due to the extreme stress concentration (Figure 5). However, this is viewed as occurring only after the initial non-dilatant failure, as evidenced from the observed cracks and the final breakout being limited by the compaction band boundaries (Figure 5). Just a few millimeters away from breakout tip but within the compaction band, grains remain mainly intact. Cracked and crushed grains just ahead of the breakout tip resemble those in compaction bands reproduced in the laboratory triaxial tests (Olsson, 1999; Klein et al, 2001).

We infer that fracture-like breakouts grow as a result of loosened grains and grain fragments removal from within the apparent compaction band by the circulating drilling fluid. As the breakout advances, the stress concentration at its tip moves along as well, extending the compaction band, and allowing more grain removal. Ideally, this process should continue indefinitely. However, this is not the case. We speculate that the circulating fluid loses its grain-removing effectiveness as the breakout depth increases, and equilibrium is reached at some critical depth, where a stable arch across the breakout tip develops that enables the compacted zone to transmit the high normal stresses. The mechanism leading to the final breakout depth appears to be at least in part related also to the far-field state of stress, but in general is still a mystery that we are trying to solve. The shape of the fracture-like breakout is attributed to its being an emptied compaction band.

A parallel project consisted of several series of laboratory experiments in Mansfield sandstone in which we tested the relationship of shape and size of fracture-like breakouts to varying drill-bit types, borehole sizes, drilling-fluid flow rates, drill-bit penetration rates, and drilling-fluid weights. We also looked at the influence of these variables on the zone of localized compaction that appears to form just in front of the breakout tip. Results indicate that several factors can significantly influence breakout length. Larger boreholes and increased drilling-fluid flow rates were both found to produce longer fracture-like breakouts, suggesting that breakouts in field-scale wellbores could reach considerable lengths. On the other hand, increased drilling-fluid weight and increased drill-bit penetration rate resulted in a decrease in breakout length. The implication is that breakout growth can be controlled to some degree by manipulating drilling variables. The use of the bi-cone drill-bit or the diamond coring drill-bit did not produce significant differences in breakout size or shape. Regardless of the parameter tested, breakout width remained constant furthering the assertion that breakouts are emptied compaction bands. Some results obtained in this research differ than those obtained in previous studies of other sandstones. This suggests that the effect of drilling variables is dependent on the microstructural properties of the rock. Realizing how these drilling variables impact borehole breakout formation is important in understanding the process by which breakouts form and their potential use as indicators of the far-field in situ stress magnitudes and as sources of sand production. As our research indicates, the final breakout size and mechanism of formation can be a function of several variables and conditions, meaning there is still much to be understood about this phenomenon. The results suggest that all these variables have to be taken in account when fracture-like breakouts are employed as indicators of in situ horizontal stress magnitudes. In addition, these variables and may have important applications to drilling, oil-field design, and production in the petroleum industry.

(d) Conclusions

Summarizing our major research achievements under this DOE grant, we have identified two types of localized narrow compacted zones that develop in front of fracture-like breakout tips, one in which grains within the band are largely left intact, and one in which grains are not only compacted but also cracked and crushed. The first type occurs when suturing between grains is limited in surface area, while the other develops when suturing covers most of the grain outside surface. Both types were observed in St. Peter sandstone. We also determined that porosity is not the dominant factor affecting the type of breakout failure. Rather, the type of grain bonding or

cementation, the mineral composition, and the roundness of the grains appear to be important contributors to micromechanics of borehole failure and the development of apparent compaction bands. However, we still need to understand what are the actual micromechanics of failure and how each of these properties contributes to it. Regardless of the mechanism of formation and the final breakout shape and size, we found that one of its dimensions (length) is correlatable to the in situ stress, and can provide important information on one principal stress magnitude, if the other two stresses are known. However, what makes the fracture-like breakout length extend a finite amount that is dependent on the far field stress is still unresolved.

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