ABSTRACT: Energy production, deformation, and fluid transport in reservoirs are linked closely. Recent field, laboratory, and theoretical studies suggest that, under certain stress conditions, compaction of porous rocks may be accommodated by narrow zones of localized compressive deformation oriented perpendicular to the maximum compressive stress. Triaxial compression experiments were performed on Castlegate, an analogue reservoir sandstone, that included acoustic emission detection and location. Initially, acoustic emissions were focused in horizontal bands that initiated at the sample ends (perpendicular to the maximum compressive stress), but with continued loading progressed axially towards the center. This paper describes microscopy studies that were performed to elucidate the micromechanics of compaction during the experiments. The microscopy revealed that compaction of this weakly-cemented sandstone proceeded in two phases: an initial stage of porosity decrease accomplished by breakage of grain contacts and grain rotation, and a second stage of further reduction accommodated by intense grain breakage and rotation.

1 INTRODUCTION

Energy production, deformation, and fluid transport in reservoirs are linked strongly. Hydrocarbon extraction reduces pore pressure and causes an increase in the effective stress (e.g. Teufel et al. 1991). For very porous or weakly consolidated formations, the increase in effective stress may be sufficient to cause inelastic deformation of the reservoir rock (e.g. Jones & Leddra 1989, Goldsmith 1989, Rhett 1988, Schutjens et al. 1988, Fossum & Fredrich 1998). The consequences of reservoir compaction can be severe and can include surface subsidence, casing damage, and other production problems (e.g. Smits et al. 1988, de Waal & Smits 1988, Ruddy et al. 1989, Elf Aquitaine 1991, Myer et al. 1996, Fredrich et al. 1996, 1998, Patillo et al. 1998). The inelastic deformation of the producing formation can also, in turn, affect fluid flow patterns within the reservoir.

Recent field (Mollema & Antonelli 1996), laboratory and theoretical (Olsson 1999, Issen & Rudnicki 1999) studies suggest that, under certain stress conditions, compaction may be accommodated by narrow zones of localized compressive deformation oriented perpendicular to the maximum compressive stress. In this paper, we describe recent laboratory tests that resulted in formation of compaction bands and microscopy studies that were conducted on a sample deformed triaxially under conditions conducive to compaction band formation.

2 LABORATORY EXPERIMENTS

The rock used in our study was from the Castlegate Formation, and is a weak high porosity sandstone that is used commonly as an analogue reservoir rock. The Castlegate is a fine to medium-grained (~0.2 mm grain size) sublitharenite with quartz being the dominant phase (70–80%) and a clay content that ranges from 5–10% (TerraTek, Inc.). Other minor phases include feldspar, siderite, and lithics including chert. The bulk porosity is 28% and intrinsic permeability measured under a few thousand psi (i.e. tens of MPa) effective confining pressure is 0.2–0.4 × 10⁻¹² m² (Fredrich, unpublished data). The microstructure of the pristine material, and its relation to the mechanical behavior, is described subsequently in more detail.

2.1 Experimental procedures

Conventional triaxial compression experiments were conducted on cylindrical test specimens prepared parallel to bedding with a diameter to length dimension of 50.8 × 127 mm. Specimens were first wrapped in a thin foil of copper and twelve piezo-
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2.2 Stress-strain behavior

The material behavior during the hydrostatic loading was essentially elastic, with no significant anisotropy indicated by the radial and axial strains (Fig. 1a). There was no pronounced inflection in the pressure-volume behavior during the hydrostat to 80 MPa, and the initial yield surface associated with the onset of inelastic compaction (e.g., see Fossum & Fredrich this volume) was intersected during the triaxial segment (Fig. 1b). After reaching a peak stress of ~150 MPa, the sample experienced a small stress drop, and then deformed at an approximately constant differential stress of 155 MPa before being unloaded at a (total) axial strain close to 5%. Note that the deformation measured during the triaxial segment by the radial strain transducer that was located at the sample mid-point tracks almost identically for loading versus unloading. That is, the deformation in the radial direction at that location up to the point of unloading was dominantly elastic.

2.3 Acoustic emission data

The AE data were analyzed in time and space (Fig. 2). Forty thousand of 10 million total events were locatable. The criteria for location included that the event was recorded by at least four of the twelve transducers. The location error was ±2 mm.

A small number of AE were recorded during the hydrostatic loading (Fig. 2, left). The events were distributed throughout the sample volume, with a slight concentration at the sample ends. The initial part of the triaxial segment was relatively quiet; but when the total axial stress increased to ~50 MPa, an escalation in AE rate was associated with the development of two distinct bands of AE that were located initially at the sample ends (Fig. 2, second from left). Olsson & Holcomb (2000) discuss the stress conditions at the sample ends and this aspect is not discussed here. As the stress approached the peak value, the AE bands moved away from the sample ends, and propagated towards the sample center throughout the portion of the triaxial segment during which the stress maintained a roughly constant value (Fig. 2, center, right and far right). Note that the presence and subsequent movement of the bands of intense AE are superimposed on a background of diffuse AE events that were distributed throughout the sample during the course of the triaxial loading.

2.4 Macroscopic observations

Visual observations of the sample made after removal of the jacketing material suggested the existence of three macroscopically distinct zones of de-
Figure 2. Three-dimensional volume renderings of AE events in the sample during the (left) hydrostatic segment, and during the triaxial loading segment to (second from left) just prior to peak stress, (center) through peak stress and over the duration of the small stress drop, and (second from right and far right) during the extended period of approximately constant stress difference. For clarity, the extent of the five time segments are indicated in Figure 3. The diameter to length dimension of the sample is 50.8 x 127 mm, and the linear voxel dimension is 1 mm.

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Figure 3. Total axial stress versus axial strain during the hydrostat and triaxial loading. The intervals marked correspond to the time increments for the AE volume renderings shown in Figure 2. Note that load-unload loops were performed at several stages for measurement of incremental elastic moduli.

3 MICROSCOPY

To substantiate the occurrence of compaction bands and to elucidate the micromechanics of compaction we conducted microscopy studies on the deformed samples using light optical and scanning electron microscopy. The deformed sample was vacuum impregnated with a low-viscosity epoxy that was doped with rhodamine-B. Following curing of the epoxy, several 25.4 mm diameter cylindrical subcores were diamond-cored from different locations within the large sample and used subsequently to prepare polished (to 0.05 μm) thin sections for optical and thick sections for scanning electron microscopy. The cores were taken horizontally from locations in the upper, central, and lower thirds of the sample, and orientation was maintained throughout the preparation of the polished microscopy sections. Observations made on sections prepared from the upper and lower portions of the sample were similar so that we do not discriminate between them here and these samples are denoted simply as CG6-SD. Samples sub-cored from the central region of the sample are referred to as CG6-UD. A pristine sample was similarly impregnated, sub-cored, and sectioned for direct comparison with the deformed sample. This sample is referred to as CG0.

3.1 Observations

As noted above, both optical and scanning electron microscopy was performed. Optical microscopy reveals the gross features of the deformation but the resolution is insufficient to resolve the details of the grain scale cracking and fragmentation. Scanning electron microscopy was performed on carbon coated polished thick sections using a Hitachi S-4500 SEM operated at 25 kV using the backscat-
Figure 4. Backscattered scanning electron micrograph of pristine Castlegate sandstone CGO (the image is 0.80 mm across). Quartz is the dominant phase, and the light colored grain on the upper edge is potassium feldspar. The dark phase partially coating some quartz grains, and occasionally partially filling pores, is clay (dominantly illite and kaolinite).

terred imaging mode and only those results are shown here.

A micrograph of the undeformed Castlegate (sample CG0) is shown in Figure 4. The dominant mineral is quartz, and lithic fragments and potassium feldspar are minor framework phases. Clay phases include kaolinite, illite, and possibly montmorillonite. Clays are present occasionally as pore-lining, sometimes as pore-filling, and frequently cementing minimally the framework grains. Also of note is the high number of point and tangential contacts between grains; that is, the original texture of the sand has not been affected significantly by subsequent diagenesis and a pre-compaction texture has been largely maintained. The small amount of pore-filling clays in combination with the occasional local enhancement of porosity by dissolution results in a pore network that is extremely well connected with pore sizes that occasionally exceed the size of the largest grains by a factor of 2 or more.

The microstructural evolution during the triaxial compression experiment is revealed in Figure 5 of the deformed sample CG6. As discussed previously, the central region of the sample was associated with only diffuse AE activity during the hydrostatic and triaxial loading (Fig. 2) and showed no pronounced outward signs of deformation. The microscopy,

Figure 5. Backscattered images (0.80 mm across) from (Top) the central region of sample CG6 (CG6-UD) which appeared largely undeformed to the naked eye, and (Bottom) the lower region of CG6 (CG6-SD) which exhibited obvious signs of deformation and through which the band of high AE activity propagated. In CG6-UD, grains are intact but closer together than in the CG0 (see Fig. 4), and edge (tangential) grain contacts have increased (decreased). In CG6-SD, porosity is further reduced and grains are intensely comminuted. The maximum compressive stress was vertical.
Figure 6. High magnification backscattered images (0.20 mm across) showing intense grain scale microcracking in CG6-SD (see Fig. 5, bottom, for detail area). (Top) The grain on the left is quartz and is only lightly damaged. The lighter grain on the right is feldspar and is intensely comminuted. Fine microcracking parallel to the strong cleavage in the feldspar is apparent, as is subsequent rotation of the cleaved grain fragments. (Bottom) Intense microcracking developed in two quartz grains that may have originally had a point contact. The maximum compressive stress was vertical.

The microstructure is dramatically different in the upper and lower regions of the sample (Fig. 5, bottom). As described previously, these parts of the sample showed obvious deformation to the naked eye, and they were the regions of the sample through which bands of intense AE activity had migrated during the triaxial loading portion of the experiment. The original fabric of the sandstone has been completely destroyed. The porosity is reduced markedly both in terms of its bulk amount and the size of the remaining pores. Grain fragmentation is profound; few grains show no sign of damage, and many grains are fractured heavily and crushed (Fig. 6). The less rigid clay phases sometimes filling the original pore space have in some instances deformed markedly. The large reduction in bulk volume has been accommodated through both fragmentation and subsequent rotation of the crushed grains.

3.2 Quantitative stereology

Stereological techniques (Underwood 1970) were applied to quantify the microstructural evolution during the initial phase of compaction that is accomplished with rare or no grain fragmentation. The mean phase intercept length, $L_3$, and the number of interceptions of objects per unit line length, $N_L$, were measured for the CGO and CG6-UD samples. Measurements were not made on sample CG6-SD because of the inherent complexity of the microstructure (see Fig. 5, bottom) associated with the second stage of compaction (i.e. accommodated by pronounced grain fragmentation and crushing and associated with the intense AE activity that propagated as a band).

The method was implemented as follows. Original grayscale digital images at (1024 $\times$ 816) were divided into four (513 $\times$ 409) images and overlain with a regular array of 13 evenly spaced test lines that were the length of the image and with a second array of 34 randomly distributed line segments of length $l$. The quarter image fields were 398.4 $\mu$m in height and 499.7 $\mu$m in width. The short line segments were 75 $\mu$m in length. Three (1024 $\times$ 816) images (yielding $3 \times 4 = 12$ quarter images) were
used for each sample, such that an area equal to 2.4 mm² was covered for both CGO and CG6-UD.

The array of regularly spaced lines was used to measure the number of intercepts of the object of interest per unit test line length, \( P_L \), here defined as boundaries separating individual grains (\( P_{L(a)} \)) and boundaries separating the pore and grain phases (\( P_{L(b)} \)). Tangential intercepts were counted as \( \frac{1}{2} \). The clay solid phase contains a significant amount of microporosity, and this was not measured in our analysis. That is, the measurements reported here were intended to characterize exclusively changes in the macroporosity with deformation. From the number of intercept points per line, the number of particles per unit length, \( N_L(a) \), for the grain phase is given by

\[
N_L(a) = \frac{1}{2} (2P_{L(a)} + P_{L(b)}). \tag{1}
\]

Because a boundary cannot exist between pore phases, \( N_L(a) \) for the pore phase is equal to

\[
N_L(a) = \frac{1}{2} P_{L(b)}. \tag{2}
\]

The array of random line segments was used to determine the mean phase intercept length \( L_3 \). Each line segment has two end points, and the number of end points falling in the phase of interest, \( P \), and the number of intersections of line segments with the phase boundary, \( P \), were counted. The mean phase intercept length is given by

\[
L_3 = l P / P \tag{3}
\]

and can be related to a mean grain diameter for a particular assumed grain shape as detailed in Underwood (1970).

Finally, the calculations of \( N_L \) and \( L_3 \) were used to calculate the volume fraction for the phase of interest, \( V_L \), by the relation

\[
V_L(a) = N_L(a) L_3 \tag{4}
\]

and the mean free path, \( \lambda \), between grains using

\[
\lambda = (1 - V_L(a)) / N_L(a). \tag{5}
\]

The results for the grain and pore phase are shown in Tables 1 and 2. The data support clearly the qualitative microscopy observations discussed previously. Specifically, (1) the particle size in the central region of the test specimen (sample CG6-UD) has not been reduced in comparison to the pristine material CGO (identical \( L_3 \)), and (2) there was a 40% reduction in the inter-grain spacing for sample CG6-UD versus the pristine sample CGO. This corresponds to a 27% reduction in the macroporosity, or, equivalently, a net reduction in the volume fraction of macroporosity from 22 to 16%. Note also that the data for CGO imply that the clay microporosity accounts for \( \sim 6 \% \) of the total bulk porosity of 28%.

<table>
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<th>Sample</th>
<th>( P_{L(a)} ) /mm</th>
<th>( P_{L(b)} ) /mm</th>
<th>( N_L(a) ) /mm</th>
<th>( L_3 ) µm</th>
<th>( \lambda ) µm</th>
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<td>1.8±0.7</td>
<td>7.1±1.2</td>
<td>76.4±14.7</td>
<td>68.0±22.7</td>
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<td>76.5±22.6</td>
<td>41.4±14.5</td>
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<tr>
<th>Sample</th>
<th>( P_{L(a)} ) /mm</th>
<th>( P_{L(b)} ) /mm</th>
<th>( N_L(a) ) /mm</th>
<th>( L_3 ) /µm</th>
<th>( V_L ) %</th>
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<td>32.1±10.7</td>
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4 DISCUSSION

The microstructural observations confirm the existence of fundamentally distinct zones of deformation within the test specimen. In conjunction with the macroscopic stress–strain (Fig. 1) and acoustic emission (Fig. 2) data, the microscopy analyses suggest that compaction of this weakly cemented sandstone under the triaxial load path followed during the test was accommodated in two distinct stages. The first stage of compaction was associated with breakage of the minimal cement bonding the framework grains and subsequent rotation of the intact framework grains to yield a more compact grain packing. This stage reduced the macroporosity by an estimated 27%. The second stage of compaction was associated with intense grain comminution and subsequent rotation of the grain fragments and resulted in substantial additional reduction in porosity and bulk volume.

The acoustic emission data reveal that the second stage of compaction propagated as a localized band of deformation through the test specimen. The mechanical data indicate that the sample deformed at an approximately constant deviatoric stress during this stage as the localized compaction band propagated through the sample. Olsson (1999) and Issen and Rudnicki (1999) proposed that the occurrence of localized compaction bands can be understood within the framework of the bifurcation theory of localization proposed originally by Rudnicki and Rice (1975). In particular, Issen and Rudnicki (1999) present a modification to the theory that incorporates the possibility of cap plasticity. Olsson & Holcomb (2000) discuss this aspect of our experiments in further detail.

Our microscopy observations have significant implications for the micromechanical sources of acoustic emission during the inelastic deformation
and failure of porous rock. In particular, the observations suggest that the processes involved in the first stage of compaction are reasonably inefficient generators of acoustic emissions. As discussed above, the first stage of compaction was associated with breakage of grain bonds and subsequent rotation, but was marked by only limited diffuse AE activity. In contrast, the second stage of compaction that was accommodated by intense grain-scale microcracking was associated with intense AE activity. Lockner (1993) has discussed previously the complexities related to the interpretation of micromechanical sources of AE during the failure of low porosity rock. Our work suggests a similarly complicated scenario for the deformation of porous rock, and we hope to resolve further this issue by detailed analysis of the waveform data in conjunction with microstructural analysis.

The micromechanical compaction behavior that we observed for the Castlegate sandstone is in marked contrast to previous observations for Berea sandstone (Menéndez et al. 1996). Those workers performed a suite of compaction tests under different load paths including hydrostatic compression and triaxial compression. They observed, however, that the initiation of inelastic yield (compaction) under both hydrostatic and triaxial loading conditions was associated with the onset of brittle microcracking at grain contacts (see Figure 5 of Menéndez et al.). In contrast, our study of Castlegate shows clearly an initial stage of compaction accommodated by breakage of grain contacts and subsequent rotation of intact grains with no grain fragmentation. The primary differences between the two sandstones are their fabric and cementation. The Berea has undergone a diagenesis that has resulted in a more indurated fabric with well-developed grain boundaries and significantly more cementation. In contrast, as discussed previously, the Castlegate has maintained a pre-compactied fabric throughout its diagenesis, the grain contacts are often point or tangential, and the cementation is minimal. Thus, the Castlegate fabric is sufficiently weak such that a large amount of volume reduction can be accomplished through grain re-arrangement alone in the absence of significant grain breakage and fragmentation.

The different micromechanical behaviors observed for the Castlegate versus that observed for the Berea (Menéndez et al. 1996) have significant implications for the evolution of fluid transport properties during deformation. Specifically, the pronounced grain crushing that is associated with the onset of inelastic compaction in the Berea reduces permeability dramatically by both reducing the local hydraulic conductance of the pores and by increasing the tortuosity of the flow paths (Zhu and Wong 1997). Our microstructural analyses suggest that the permeability evolution during the initial stage of compaction in the Castlegate may differ, in that the dominant microstructural change relates to grain re-arrangement as opposed to grain fragmentation. Therefore we expect the tortuosity of the flow paths to be approximately maintained during the initial stage of compaction. Furthermore, the second stage of compaction that occurred as a localized band of deformation that propagated through the samples is expected to result in significant spatial anisotropy of the fluid transport properties.

5 CONCLUSION

This paper describes microscopy studies that were performed to elucidate the micromechanics of compaction during triaxial compression experiments performed on Castlegate sandstone. The microscopy revealed that compaction of this weakly-cemented sandstone proceeded in two phases: an initial stage of porosity decrease that is accomplished by breakage of grain contacts and subsequent grain rotation, and a second stage of further volume reduction that is accommodated by intense grain breakage and rotation. Furthermore, the second stage of compaction was revealed through acoustic emission location to have occurred as a localized compaction band that propagated through the sample in a direction perpendicular to the maximum compressive stress. Recent work by Olsson (1999) and Issen and Rudnicki (1999) suggests a theoretical framework for predicting this behavior.

To complement the optical and scanning electron microscopy that is presented here, we have also performed recently three dimensional imaging on both the pristine and deformed samples using synchrotron computed microtomography in collaboration with M. L. Rivers and others at the Advanced Photon Source at Argonne National Laboratory. That work, which includes quantitative analysis of the three-dimensional microgeometry and numerical simulation of fluid flow (e.g. Fredrich 1999, O'Connor and Fredrich 1999), will be reported elsewhere.

Depending upon the generality of the deformation behavior observed here (i.e. in terms of the microstructural characteristics, stress states, and load paths that favor such behavior) researchers may need to consider whether this deformation mode of localized compaction needs to be considered in numerical simulations of complex geosystems. Applications involving compacting materials such as basin evolution or coupled reservoir-geomechanics may need to include a more complex constitutive model that allows for bifurcating compaction behavior (i.e. Issen & Rudnicki 1999) rather than the uniform deformation that is predicted by traditional cap plasticity models (e.g. see Possum & Fredrich, this volume). Barnichon & Charlier (1999) described recently the
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REFERENCES


