JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, B10203, doi:10.1029/2005JB003854, 2006

Click Here for Full Article

Acoustic emission and velocities associated with the formation of compaction bands in sandstone

Jérôme Fortin,[1] Sergei Stanchits,[2] Georg Dresen,[2] and Yves Guéguen[1]

Received 31 May 2005; revised 2 May 2006; accepted 22 June 2006; published 7 October 2006.

[1] A series of laboratory experiments has been conducted in which three-dimensional (3-D) locations of acoustic emissions (AE) were recorded and used to analyze the development of compaction bands in Bleurswiller sandstone, which has a porosity of 25%. Results were obtained for saturated samples deformed under triaxial compression at three different confining pressures (60, 80, and 100 MPa), a pore pressure of 10 MPa, and room temperature. We recorded acoustic emissions, compressional and shear wave velocities, and porosity reduction under hydrostatic condition and under triaxial loading conditions at a constant axial strain rate. Our results show that seismic velocities and their amplitude increased during hydrostatic pressure build up and during initial axial loading. During shear-enhanced compaction, axial and radial velocities decreased progressively, indicating an increase of stress-induced damage in the rock. In experiments performed at confining pressures of 80 and 100 MPa during triaxial loading, acoustic emissions were localized in clusters. During progressive loading, AE clusters grow horizontally, perpendicular to the maximum principal stress direction, indicating formation of compaction bands throughout the specimens. Microstructural analysis of deformed specimens confirmed a spatial correspondence of AE clusters and compaction bands. For the experiment performed at a confining pressure of 60 MPa, AE locations and microstructural observations show symmetric compaction bands inclined to the cylinder axis of the specimen, in agreement with predictions from recent theoretical models.

Citation: Fortin, J., S. Stanchits, G. Dresen, and Y. Guéguen (2006), Acoustic emission and velocities associated with the formation of compaction bands in sandstone, *J. Geophys. Res.*, *111*, B10203, doi:10.1029/2005JB003854.

1. Introduction

[2] Brittle deformation of rocks frequently involves formation of narrow, localized bands on the grain scale that may evolve into macroscopic fracture zones. The micromechanics of fracture nucleation and growth in rocks have been investigated in a wealth of studies since the 1960s. The location of acoustic emission (AE) sources during deformation of rock has proven to be a useful nondestructive analytic technique to study the formation and growth of faults [*Lockner*, 1993; *Lei et al.*, 1992, 2000].

[3] Although dilatancy is generally observed as a precursor to brittle faulting and to the development of shear localization, recent field [*Mollema and Antonellini*, 1996] and laboratory [*DiGiovanni et al.*, 2000; *Olsson*, 1999; *Haimson*, 2001; *Klein et al.*, 2001; *Fortin et al.*, 2005] observations have also focused attention on the formation of localized compaction bands in porous sandstones. Laboratory experiments have shown that compaction bands occurred in dry and saturated sandstones with porosities ranging from 20 to 28%, deformed at room temperature. Formation of compaction bands was found to occur in homogeneous sandstones like Bentheim sandstone [*Klein et al.*, 2001], but also in sandstones containing clay or feldspars, such as Diemelstadt [*Fortin et al.*, 2003; *Baud et al.*, 2004], Castlegate [*Olsson*, 1999], and Bleurswiller sandstones [*Fortin et al.*, 2005].

[4] Compaction bands are narrow planar zones of material that formed without apparent shear. They extend in planes perpendicular to the main compressive stress. Compaction bands display significantly reduced porosity and act as barriers for fluid flow [*Holcomb and Olsson*, 2003; *Vajdova et al.*, 2004]. This suggests that the presence of compaction bands may affect fluid circulation in the crust, extraction of oil and gas from reservoir rocks, groundwater circulation in aquifers, as well as the sequestration of carbon dioxide.

[5] Reassessment of bifurcation theory produced theoretical models predicting the conditions required to localize deformation [*Rudnicki and Rice*, 1975; *Bésuelle and Rudnicki*, 2004; *Issen and Rudnicki*, 2000; *Rudnicki*, 2004]. These authors used a constitutive model with two-yield surfaces in the stress space; the shear yield surface provides a condition for the onset of dilatant, frictional failure while the onset of plastic compaction is represented by a yield cap. *Rudnicki* [2004] has analyzed conditions for both compaction band and shear band formation for stress states on an elliptic yield cap as applied to standard axisymmetric compression tests. His analysis also provides a

---

[1] Laboratoire de Géologie, Ecole Normale Supérieure, Paris, France.
[2] GeoForschungsZentrum, Potsdam, Germany.

Copyright 2006 by the American Geophysical Union.
0148-0227/06/2005JB003854$09.00

theoretical explanation for the occurrence of compacting shear bands at a very high angle to the compressive stress direction σ_1.

[6] In porous rock, micromechanisms involved in localized compaction are significantly different from those producing localized shear bands in dense rocks. In particular, grain crushing and pore collapse are associated with radiation of acoustic emissions [*Paterson*, 1978; *Zhang et al.*, 1990; *Olsson and Holcomb*, 2000]. More recently *DiGiovanni et al.* [2000] performed triaxial compression experiments on Castelgate sandstone and used electron and optical microscope investigations to elucidate the micromechanics of compaction. The authors found that acoustic emissions are associated with grain crushing and pore collapse.

[7] Effective elastic moduli of rocks and the velocity of elastic waves are significantly reduced in the presence of cracks [*Walsh*, 1965]. In deformation experiments at elevated pressures, elastic wave velocities are affected by two competing mechanisms [*Scott et al.*, 1993; *Fortin et al.*, 2005; *Schubnel et al.*, 2005]. With increasing mean pressure, velocities first increase due to elastic compaction and crack closure. When differential stress is increased further, localized grain crushing and the opening of new cracks will decrease the velocity of elastic waves. In this study, we investigate the nucleation and the growth of compaction bands in sandstone using advanced acoustic emission techniques. In particular, we investigate AE hypocenter locations and the evolution and anisotropy of compression and shear wave velocities.

[8] To address these issues, we performed triaxial compression experiments on Bleurswiller sandstone. *Fortin et al.* [2005] have shown that discrete compaction bands appeared in Bleurswiller sandstone in triaxial compression tests at effective confining pressures higher than 30 MPa (Figure 1). Here we report results from three triaxial compression experiments performed on saturated samples at a constant pore pressure of 10 MPa and confining pressures of 60, 80, and 100 MPa. In addition, a comparison between the acoustic emission locations and microstructural observations of a sample is made in order to relate the acoustic emission signature to the deformation microstructures.

2. Experimental Details

2.1. Rock Samples

[9] Specimens were prepared from Bleurswiller sandstone exposed in the Vosges mountains in eastern France (Frain Quarry). Bleurswiller is a gray sandstone containing 50% quartz, 30% feldspars, and 20% oxide micas. Porosity is about 25%. Grains are mostly subangular to subrounded. Grain size was determined from thin sections in the optical microscope using the linear intercept method and a correction factor of $\frac{3}{2}$, which accounts for the statistical unlikelihood of intercepting a grain across its full diameter [*Underwood*, 1970]. Grain sizes range from 80 to 150 μm with a mean value of approximately 110 μm. Cylindrical cores were cut from the same blocks of rock used in the *Fortin et al.* [2005] study and precision ground to yield specimens 50 mm in diameter and 100 mm in length.

2.2. Mechanical Data

[10] The experiments were performed at the GeoForschungsZentrum (Potsdam, Germany). We used a servocontrolled 4.6 MN loading frame from Material Test Systems (MTS) with a stiffness in compression of 11×10^9 N m^{-1}. All experiments were carried out at a constant axial strain rate of 10^{-5} s^{-1} at room temperature. The confining pressure was measured with an accuracy of 0.1 MPa, and during triaxial loading was held constant to within 0.5 MPa. Axial load was measured with an external load cell with an accuracy of 1 kN. Oil was used as the confining medium.

[11] Samples were saturated with distilled water and deformed under drained conditions at a constant pore pressure of 10 MPa. The variation of pore volume throughout a test was determined using a volumometer, allowing the evolution of connected sample porosity to be monitored.

[12] Axial strain, ε_z, was measured by a linear variable displacement transducer (LVDT) mounted at the end of the piston and corrected for the effective stiffness of the loading frame. Local axial strain, ε_z^*, and local radial strain, ε_r^*, measurements were acquired using strain gauges (TML FLA-20, Tokyosokki), each of which was glued directly to sample and mounted in a Wheatstone bridge. Uncertainty in strain was estimated to be 5×10^{-4} when calculated from the LVDT signal, and 10^{-5} when measured directly by the strain gauges. The local axial strain determined from the strain gauge measurements was different from the overall axial strain determined from the LVDT measurements, notably during the formation of compaction bands.

2.3. Acoustic Emissions

[13] Twelve piezoelectric transducers (PZT) each with a resonant frequency of 1 MHz were used in each triaxial test to determine the AE locations (Figure 2). The piezoceramic crystals were encapsulated in brass housings that conformed to the cylindrical surface of the sample. The housings were glued to the sample. Two additional *P* wave sensors were installed in the axial direction on the two end pieces (P_{11} and P_{12} in Figure 2). To monitor AE activity we used lead-zirconate-titanate piezoceramic discs 5 mm in diameter and 2 mm in thickness. After an amplification of 40 dB, fully digitized waveforms were recorded by a 10 MHz/16 bit data acquisition system (DaxBox, Prökel GmbH, Germany). Advanced software was used to automatically pick the onset time of AE signals and used for automated AE hypocenter determination. The hypocenter location algorithm is based on the downhill simplex algorithm [*Nelder and Mead*, 1965] modified for anisotropic and inhomogeneous velocity fields. AE hypocenter location error is estimated to be approximately 2.5 mm.

2.4. Elastic Wave Velocities

[14] The PZT transducers were also used for measuring *P* wave velocities during the experiments. The pulse transmission method was used to measure the elastic wave velocities. Receiver and source functions of the transducers were switched automatically. Monitoring deformation-induced changes in elastic wave velocities was necessary to accurately locate the AE hypocenters. In addition, elastic wave velocities are very sensitive to the presence of cracks, allowing one to detect whether compaction bands appeared with or without the formation of new cracks.

[15] In this experimental setup, *P* wave velocities were measured in directions perpendicular to the compressional axis, along five horizontal traces each passing through the