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Elastic wave velocities and permeability evolution during compaction of Bleurswiller sandstone

J. Fortin[a,*], A. Schubnel[b], Y. Guéguen[a]

[a]*Ecole Normale Supérieure, Laboratoire de géologie, 24 rue Lhomond 75005 Paris, France*
[b]*Lassonde Institute, 170 College Street, Toronto, ON, Canada M5S3E3*

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Abstract

Field observations and laboratory experiments have recently documented the formation of compaction bands in porous sandstones [Mollema and Antonellini, Tectonophysics 1996;267:209–28; Olsson and Holcomb, Geophys Res Lett 2000;27:3537–40; Bésuelle, J Geophys Res 2001;106:13435–42; Klein et al., Phys Chem Earth 2001;26:21–5]. It has been observed experimentally [Wong et al., J Geophys Res 2001;28:2521–4; Baud et al., J Geophys Res 2003, submitted; Fortin et al., 2003, Abstract EGS-AGU Nice] that under axisymmetric compression, compaction bands develop sub-perpendicular to the main compressive stress which is predicted theoretically in the framework of strain localization theory [Bésuelle, J Geophys Res 2001;106:13435–42; Issen and Rudnicki, J Geophys Res 2000;105:21529–36]. Volumetric strain, fluid transport and elastic properties are intimately coupled to one another, for they all depend on a few intrinsic parameters such as the porosity, the crack density, and the matrix and fluid elastic properties. On the one hand, Scott et al. [Rock Mech Min Sci Geomech 1993;30:763–9] showed that elastic wave velocities were clearly affected during the deformation of porous sandstones. On the other hand, Zhu and Wong [J Geophys Res 1997;102:3027–41] showed that the relation between the evolution of permeability and volumetric strain during compaction of sandstones was not straightforward. In this study, we present for the first time the simultaneous evolution of volumetric strain, elastic wave velocities and permeability for a set of deformation experiments of Bleurswiller sandstone. We show that, although very coherent to one another, those three sets are not systematically correlated. Indeed, inelastic compaction, whether it is distributed or localized, is accompanied by a drastic decrease of elastic wave velocities due to grain crushing, a decrease of permeability and porosity due to pore collapse. Using simple statistical physics concepts based on the study of Kachanov [Adv Appl Mech 1993;30:259–445] and Guéguen and Dienes [Math Geol 1989;21:1–13], we try to understand and address the issue of coupling/decoupling between volumetric strain (mainly sensitive to equant porosity variations), elastic properties (mainly sensitive to crack density) and permeability (theoretically sensitive to both) during the formation of compaction bands. Finally, we show that the mineral composition of a sandstone is a key parameter controlling the effective pressure at which the onset of pore collapse P^* takes place.

Keywords: Compaction; Compaction bands; Elastic wave velocities; Permeability; Sandstone

1. Introduction

Strain localization occurs on all scales in the earth's crust. From the microscale level of grains to fault zones, the deformation of rock mass frequently occurs in narrow, localized bands that can evolve into fracture zones consisting of several bands. Although brittle faulting has generally been associated with dilatancy, recent field observations [1,2] have also focused attention on the formation of compaction bands in porous sandstones. Mollema and Antonellini [2] described those bands in a very porous aeolian sandstone which consisted of thin planar zones of pure compressional deformation, without apparent shear.

*Corresponding author. Tel.: +33 (0) 1 44 32 22 09; fax: +33 (0) 1 44 32 20 00.
E-mail address: fortin@geologie.ens.fr (J. Fortin).

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Since then, different laboratory studies [3–6] have documented the occurrence of strain localization in high-porosity sandstones. In particular, the formation of discrete compaction bands was observed in Bentheim sandstone [3] and in Diemelstadt sandstone [7]. Compaction within thin layers was also observed in recent descriptions of borehole breakout [8], which suggests that the phenomenon is pervasive in sandstone formations.

Previous authors [9–11] extended the results of Rudnicki and Rice [12] for high-porosity rocks. These models use a yield surface 'cap' and predict compaction bands under different conditions.

While investigations were conducted on the mechanical behavior of compacted rocks and microstructural observations of deformed samples, there is a paucity of data on the consequences of the development of compaction bands on the physical properties of the rock, i.e. the evolution of the transport and elastic properties.

On the one hand, Vajdova et al. [13] and Holcomb and Olsson [14] showed that permeability across compaction bands was generally reduced by one to two orders of magnitude. Consequently, localized compaction bands may therefore act as barriers to fluid flow in otherwise porous rock and, for example, trap hydrocarbons. However, Zhu and Wong [15] showed that there was no straightforward relation between the evolution of permeability and volumetric strain during the compaction of sandstones.

On the other hand, Scott et al. [16] investigated the evolution of elastic wave velocities during shear-enhanced compaction of Berea sandstone. These authors highlighted the fact that the velocities were clearly being affected at the brittle–ductile transition. However, and once again, the relationship between porosity and elastic properties seemed not to be straightforward and in their data, during triaxial compression test, elastic wave velocities were affected by two distinct and competitive mechanisms. First, elastic wave velocities were correlated to the damage in the rock [17]. Second, as was noted by Schubnel et al. [18], the mean pressure was increasing the velocities due to crack closure and compaction.

In this study, we present for the first time the simultaneous evolution of volumetric strain, elastic wave velocities and permeability for a given set of sandstone samples deformed in a triaxial cell. This sandstone is a 25% porosity Vosgian sandstone, named 'Bleurswiller sandstone'. The experimental program included a set of triaxial compression experiments at confining pressures of 12, 30, 50, 70, 90, 110 MPa. Experiments were performed under wet conditions at a pore pressure of 10 MPa. We present here the complete set of mechanical, elastic wave and permeability data together with microstructural observations of the samples, allowing identifications of the failure modes. The possible existence of a coupling/decoupling between volumetric strain, elastic properties and permeability is investigated in the discussion using this broad set of results.

2. Experimental set-up

The triaxial cell installed in the Laboratoire de Géologie of Ecole Normale Supérieure is made of a pressure vessel, which is a prototype that was designed and constructed by the company Geodesign, based in Roubaix, France. The solid and pore pressure are driven by two hydraulic pumps and two water pumps. The main advantage of this apparatus is the existence of 34 electric feedthroughs which allows the simultaneous measurement of seismic velocities in several directions as well as other properties, such as volume variation and permeability. The first results obtained with this new cell were reported in Schubnel et al. [18].

2.1. Description of the vessel

The Geodesign triaxial cell can reach 300 MPa confining pressure (Fig. 1). The confining medium is oil. The confining pressure is servo-controlled with an accuracy of 0.1 MPa thanks to two different pressure sensors: one sensor for the 0–60 MPa pressure range and another one for 60–300 MPa. The pressurization ramp may be as slow as $\sim 0.05\,\mathrm{MPa\,s^{-1}}$.

Axial load is performed through an auto-compensated hydraulic piston (i.e. one that does not move as confining pressure varies). Loading can be both strain rate or stress rate servo-controlled. Taking the piston deformation into account, the minimum strain rate is $10^{-6}\,\mathrm{s^{-1}}$, while the maximum can be up to $10^{-2}\,\mathrm{s^{-1}}$. It is monitored by two DCDTs placed on the top of the piston, outside the vessel. Axial load is servo-controlled with two pressure sensors located outside the vessel. An internal load cell, manufactured by AMC automation, measures the load applied directly on the top of the sample. The axial stress is calculated by dividing the load measured with the internal load cell by the initial cross-sectional area of the sample. We assume that the sample cross-sectional area remains constant throughout the experiment, which is a reasonable approximation within an error of a few percent in stress. The maximum applied stress for 40 mm diameter samples is 717 MPa. The minimum axial stress rate for 40 mm diameter samples is $0.01\,\mathrm{MPa\,s^{-1}}$. Confining and axial pressure systems are given by hydraulic pumps (0–35 MPa) and two intensifiers: (35–300 MPa) for the confining pressure and (35–100 MPa) for the axial stress. The vessel contains a thermocouple for the monitoring of temperature inside the vessel as well as 34 electric wire