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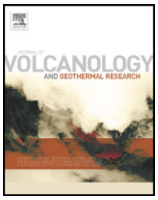

Deformation modes in an Icelandic basalt: From brittle failure to localized deformation bands

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ABSTRACT

According to the stress state, deformation mode observed in rocks may be very different. Even in the brittle part of the crust a differential stress can induce shear failure but also localized compacting deformation, such as compaction bands in porous sedimentary rocks. The mode of deformation controls many hydrodynamic factors, such as permeability and porosity. We investigate in this paper two different modes of deformation in an Icelandic basalt by using laboratory seismological tools (elastic waves and acoustic emissions) and microstructural observations. First of all, we show that at low effective confining pressure ($P_{eff}=5$ MPa) an axial loading induces a shear failure in the basalt with an angle of about 30° with respect to the main stress direction. On the contrary, at high effective confining pressure ($P_{eff}\geq 75$ MPa and more) an increase of the axial stress induces a localization of the deformation in the form of subhorizontal bands again with respect to the main stress direction. In this second regime, focal mechanisms of the acoustic emissions reveal an important number of compression events suggesting pore collapse mechanisms. Microstructural observations confirm this assumption. Similar compaction structures are usually obtained for porous sedimentary rocks (20–25%). However, the investigated basalt has an initial total porosity of only about 10% so that compaction structures were not expected. The pore size and the ratio of pore to grain size are likely to be key factors for the particular observed mechanical behavior.

1. Introduction

Basaltic rocks are the main component of the oceanic upper crust. During cooling, the basalt lava flow is highly fractured. Thus, at shallow depth they can host fluids (Geoffroy and Dorbath, 2008; Adelinet et al., 2011a, 2011b). This is of potential interest in water resources (D'Ozouville et al., 2008) or in CO_2 storage issues (Matter et al., 2007; Goldberg et al., 2008). Elastic properties of basalt have been investigated in the laboratory through different experiments: (i) evolution of elastic parameters during increasing confining pressure (Vinciguerra et al., 2005; Stanchits et al., 2006; Adelinet et al., 2010; Fortin et al., 2011) and (ii) differential stress cycling (Vinciguerra et al., 2005; Heap et al., 2009) and also (iii) evolution related to increasing temperature (Pinkerton and Norton, 1995; Lore et al., 2000; Kato et al., 2003; Violay et al., 2010, 2012). In addition, in order to constrain the behavior of natural volcanic systems (during pre- and post-eruptive time intervals notably), some experimental studies of rupture have also been performed on volcanic rocks (Rocchi et al., 2002, 2004; Balme et al., 2004; Smith et al., 2009).

Beyond a defined stress threshold, rock deformation becomes irreversible. Then the increasing differential stress can induce a non-elastic deformation of the rock. Different deformation regimes are possible. Dilatancy and brittle faulting typically result in shear bands characterized by stress softening (Paterson, 1978). A fundamentally different failure mode develops if a porous rock is stressed under relatively high confinement and low temperature. The pore space compacts and ductile failure develops. In this ductile regime, characterized by strain hardening, damage can be distributed in non-localized manner (Handin and Hager, 1963; Wong et al., 1997) or can be localized, i.e. under the form of compaction bands. Compaction bands are areas of material which extend perpendicular to the main compressive stress. From microstructural observations, a compaction band appears as a crushed zone of reduced porosity. Such structures have only been observed up to now in the laboratory in porous sedimentary rocks (Klein et al., 2001; Wong et al., 2001; Baud et al., 2004; Fortin et al., 2006, 2009) or in porous material like honeycombs (Papka and Kyriakides, 1998) or aluminum foams.

These different regimes correspond to specific stress conditions characterizing the yield envelope of the rocks in the (P,Q) plane, where P is the mean effective pressure and Q the differential stress. Laboratory conditions allow sometimes to describe the full yield envelope of a rock, as for some limestones or sandstones (Wong et al., 1997; Baud et al., 2004; Vajdova et al., 2004; Fortin et al., 2005, 2006, 2009). At low confining pressure, these rocks exhibit a brittle behavior. At higher confining pressure, increasing axial stress induces the formation of compaction bands. However, at room temperature

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only brittle regime has been observed on basalts (Stanchits et al., 2006; Benson et al., 2007, 2008; Heap et al., 2011). Note that Violay et al. (2012) shows that basalt submitted to high temperature exhibits a ductile behavior even at low confining pressure.

Deformation in rocks is not only controlled by the differential stress *Q* but also by the effective pressure *P* and is consequently related to the fluid pressure (Secor, 1965), as the effective pressure is defined by the mean stress minus the pore pressure. Note that pore pressure is one of the most variable parameter in the earth crust. The role of pore fluid in the mechanics of the crust has been extensively studied in the past (Rocchi et al., 2002; Kato et al., 2003; Balme et al., 2004; Ramsey and Chester, 2004). More recently, a specific fluid-induced rupture experiment was performed on a Fontainebleau sandstone recording acoustic emissions (Schubnel et al., 2007).

This paper presents the results of triaxial experiments performed on an Icelandic basalt. Depending on the confining and fluid pore pressure values, different deformation modes have been evidenced. Strain and elastic wave velocities have been measured. Simultaneously, we recorded acoustic emissions to monitor and analyze the failure processes. Microstructure analysis of deformed samples has also been conducted and correlated to acoustic emissions locations.

2. Samples and experimental methods

2.1. The Reykjanes basalt

2.1.1. Description of investigated basalt

The basaltic block was extracted on a road outcrop in the Reykjanes peninsula (southwestern part of Iceland), in the vicinity of the road connecting the cities of Keflavik and Vogar. Due to its particular geological context, Iceland is the ideal natural laboratory to study interplays between fluid, basalt and deformation. Extracted samples were fresh and young (less than 10,000 years; Sigurdsson et al., 2000). The studied rock is a microlitic alkali basalt containing mm-sized phenocrysts of pyroxene and albite (identified with X-ray method, see Fig. 1B) and also microliths of feldspar (thin section in Fig. 1A). We also investigate the microstructure and the chemical composition of an intact Reykjanes sample through a Scanning Electron Microscope (SEM) installed at the Laboratoire de Géologie of École Normale Supérieure (Paris, France). The chemical composition of the microlitic matrix is presented in Table 1 in oxide weight percentage. Fig. 2 present a large scale view of the microstructure (top figure) and a detail of a pore where we the microlitic texture (bottom figure) can be identified. The mean size of grains is about 100 μm. At the resolution of optical and electron microscopes, neither phenocrysts of pyroxen and albite nor feldspar microliths appear cracked.

2.1.2. Porosity analysis

Based on mercury intrusion porosimetry data, the sample presents a bimodal distribution of porosity. Initial porosity is about 8% made up of 1% crack porosity and 7% equant pores. This bimodal distribution confers some interesting properties to the rock in terms of elastic wave velocity dispersion for instance (Adelinet et al., 2010). Note that more details on mercury porosimetry results are presented in Adelinet et al. (2010). The average inclusion entry diameters are 0.1 and 100 μm, respectively for cracks and pores. The porosity accessible to helium gas of the Reykjanes basalt has been investigated by He-pycnometry (equipment installed at IFP Energies Nouvelles). The porosity value is 10.3 ± 1%. Note that the porosity values of the Reykjanes basalt range is typical for basaltic rocks coming from lava flows (Saar and Manga, 1999). Around 2% of the porosity is unconnected to mercury but connected to helium gas. The difference can be explained by the different sizes of helium and mercury molecules according to surface tension. Very thin cracks accessible to helium are not accessible to mercury. Furthermore volatile exsolution during magma ascent can lead to isolated vesicles which are not accessible to gases or liquids. Additional processes such as thermal cooling can induce thin cracks to the magma eventually connecting some of these isolated vesicles. Consequently, depending on their aperture, cracks are accessible to gas only or gas and liquid leading to a difference in porosity measurements.

2.2. Experimental set-up

Cylindrical specimens of 80 mm in length and 40 mm in diameter were cored into the Reykjanes basalt block. The experiments were performed in a triaxial cell installed at the Laboratoire de Géologie of École Normale Supérieure (Paris, France) and exhaustively described in Ougier-Simonin et al. (2011) and Brantut et al. (2011). A schematic diagram of the setup is presented in Fig. 3. This apparatus allows for hydrostatic and differential stresses to be applied independently on the cylindrical sample. The hydrostatic and differential stresses are servo-controlled with an accuracy of 0.01 MPa. The confining medium is oil. Pore pressure is driven by one precision volumetric pump. Pore fluid is introduced into the sample through hardened steel end pieces placed on the top and bottom of the rock sample. Maximum pore pressure in the system is 100 MPa. Axial strain is measured by three gap sensors

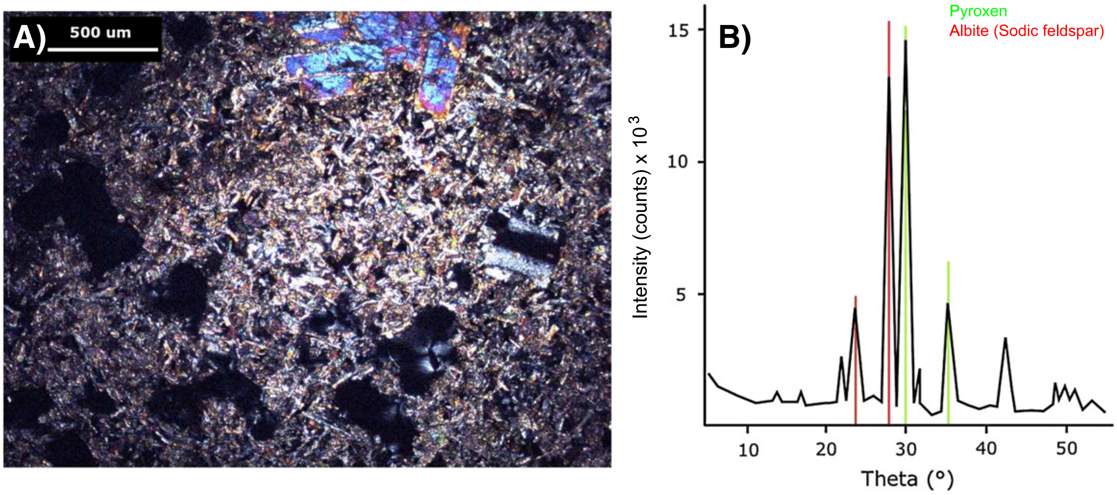

Fig. 1. Petrographical description of the Reykjanes basalt: A) thin section picture showing the microlithic texture with phenocrystals of pyroxen and the equant porosity, B) X-ray diffractogram.