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Exploring the relative contribution of mineralogy and CPO to the seismic velocity anisotropy of evaporites

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ABSTRACT

We present the influence of mineralogy and microstructure on the seismic velocity anisotropy of evaporites. Bulk elastic properties and seismic velocities are calculated for a suite of 20 natural evaporite samples, which consist mainly of halite, anhydrite, and gypsum. They exhibit strong fabrics as a result of tectonic and diagenetic processes. Sample mineralogy and crystallographic preferred orientation (CPO) were obtained with the electron backscatter diffraction (EBSD) technique and the data used for seismic velocity calculations. Bulk seismic properties for polymineralic evaporites were evaluated with a rock recipe approach. Ultrasonic velocity measurements were also taken on cube shaped samples to assess the contribution of grain-scale shape preferred orientation (SPO) to the total seismic anisotropy. The sample results suggest that CPO is responsible for a significant fraction of the bulk seismic properties, in agreement with observations from previous studies. Results from the rock recipe indicate that increasing modal proportion of anhydrite grains can lead to a greater seismic anisotropy of a halite-dominated rock. Conversely, it can lead to a smaller seismic anisotropy degree of a gypsum-dominated rock until an estimated threshold proportion after which anisotropy increases again. The difference between the predicted anisotropy due to CPO and the anisotropy measured with ultrasonic velocities is attributed to the SPO and grain boundary effects in these evaporites.

1. Introduction

Although the anisotropic elastic properties of evaporite crystals have long been acknowledged (Kupfer, 1989; Sun et al., 1991; Aptukov et al., 2010), potential interactions between them as contributors to the bulk seismic anisotropy of evaporite rocks are poorly documented. Halite is the dominant mineral in evaporite rock sequences. As such, the study of seismic properties of evaporites has mostly focused on pure crystalline halite (Raymer et al., 2000a,b). However, chlorides (e.g., halite, sylvite, carnallite), sulphates (e.g., anhydrite, gypsum, polyhalite) and carbonates (e.g., dolomite, calcite), are often found interlayered with halite or in minor amounts as secondary phases or solid inclusions. Furthermore, evaporite crystals can align along preferential directions induced by either tectonic deformation or diagenetic processes. This can produce strong fabrics and induce bulk seismic velocity anisotropy (Raymer et al., 2000b,a; Hildyard et al., 2009; Trippetta et al., 2010).

Among the microstructural factors that cause seismic velocity anisotropy are crystallographic preferred orientation (CPO), shape preferred orientation (SPO), variation in mineral and grain distribution, aligned pores, cracks, and fractures, and thin layering (Wenk and Van Houtte, 2004). In polycrystalline rocks, bulk seismic properties result from the combination of the individual anisotropic elastic properties, modal content and geometrical arrangement of grains of the individual mineral constituents. Standard averaging methods are commonly used to determine the azimuthal distribution of compressional and shear wave velocities (V_P and V_S) from averaged elastic properties, based on the availability of single-crystal elastic properties, the volume fraction of mineral constituents and their CPO (Mainprice and Humbert, 1994; Mainprice and Nicolas, 1989; Lloyd and Kendall, 2005). Electron backscatter diffraction (EBSD) technique is now the standard technique to

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quantify CPO accurately (Prior et al., 1999). This methodology has been extensively applied to determine seismic properties of a wide range of rock types and geological settings (Mainprice and Nicolas, 1989; Burlini and Kunze, 2000; Valcke et al., 2006; Tatham, 2008; Tatham et al., 2008; Healy et al., 2009; Lloyd et al., 2009; Dempsey et al., 2011; Lloyd et al., 2011b,a; Ward et al., 2012; Almqvist et al., 2013). Studies on sedimentary rocks that have used this methodology are fewer and include works in clastic rocks (e.g., Louis et al., 2005; Valcke et al., 2006), polycrystalline synthetic and natural halite (e.g., Sun et al., 1991; Raymer et al., 2000a,b; Urai et al., 2008; Desbois et al., 2010), and on polycrystalline anhydrite (e.g., Boeyens and Ichhram, 2002; Hildyard et al., 2009). Other works consider calcite mylonite and micaceous carbonates (e.g., Burlini and Kunze, 2000; Wenk and Van Houtte, 2004); all of which have found that fabrics and elastic properties of individual minerals contribute to the seismic character of a rock.

In this study, we explore 1) the influence of CPO development in evaporites, 2) the effects of mineralogy, e.g., halite, anhydrite, and gypsum, and 3) the effects of extrinsic structural factors, such as initial porosity, open aligned cracks, and SPO, on the resulting seismic velocity anisotropy of natural and hypothetical polymineralic evaporites. We used a suite of natural evaporite samples of three main lithologies (halite-, anhydrite-, and gypsum-dominated) with strong fabrics, which were collected from a single diapiric province in Nova Scotia. Our objective is to identify and separate the controlling factors on the distribution of seismic velocities from both microstructural analysis on thin sections and ultrasonic tests on cube shaped samples of the same rock specimens. Our results provide insights into the microstructural factors controlling seismic velocities of polymineralic evaporites to better understand the relationship between intrinsic and extrinsic sources of these characteristics.

2. Location of study

A suite of 20 samples, consisting of evaporites rich in halite, anhydrite and gypsum, was collected from a single diapiric province in Nova Scotia, Canada (Fig. 1a). Here, salt diapirs are prominent under the Gulf of St. Lawrence, along the Hollow Fault and onshore in Cape Breton Island. These thick (c. 1 km) evaporitic deposits correspond to the lower Windsor Group, of Visean age. Such evaporites are believed to have migrated from depths of 4 km and today are found tens to hundreds of metres below the ground level and exposed along the western shores of Nova Scotia (Howie, 1986).

Exposures of salt diapirs occur in continuous across-strike cliff sections, and have been previously documented by Alsop et al. (2000). They consist predominantly of gypsum mylonite and comprise the Broad Cove diapir (BC), Coal Mine Point diapir (CMP), Finlay Point diapir (FP) and Port Hood diapir (PH) (Fig. 1a). Outcrops are characterised by steep salt-siliciclastic contacts and a wide variety of fabrics that steepen progressively towards the subvertical diapiric contacts. As an example, the CMP salt diapir is shown in Fig. 1b–c, which exhibits strong deformation, distinctive foliation and fracturing. Several samples were taken to study a variety of fabrics within the same outcrop Fig. 1b–c. Additionally, several samples were taken from the Pugwash salt mine (PM), which contains strongly deformed, interlayered deposits of halite and anhydrite.

3. Sample description and preparation

Both the FP and PH salt diapir outcrops preserve fabrics and are characterised by light grey to orange, highly folded and strongly deformed bands of nodular gypsum, interlayered with thin clay seams (Fig. 2a–c). The BC diapir outcrop is characterised by distinctive lozenges of weakly deformed, bitumen-stained gypsum (Fig. 2d–e). The strongest foliation and deformation were observed at the CMP outcrop where a tightly folded mylonitic fabric, parallel to the diapiric margin, is cross-cut by strongly deformed, thin gypsum veins (Fig. 2f). Gypsum mylonites from the CMP outcrop are generally medium to dark grey, are denser than the other gypsum samples, and are interpreted to have larger anhydrite

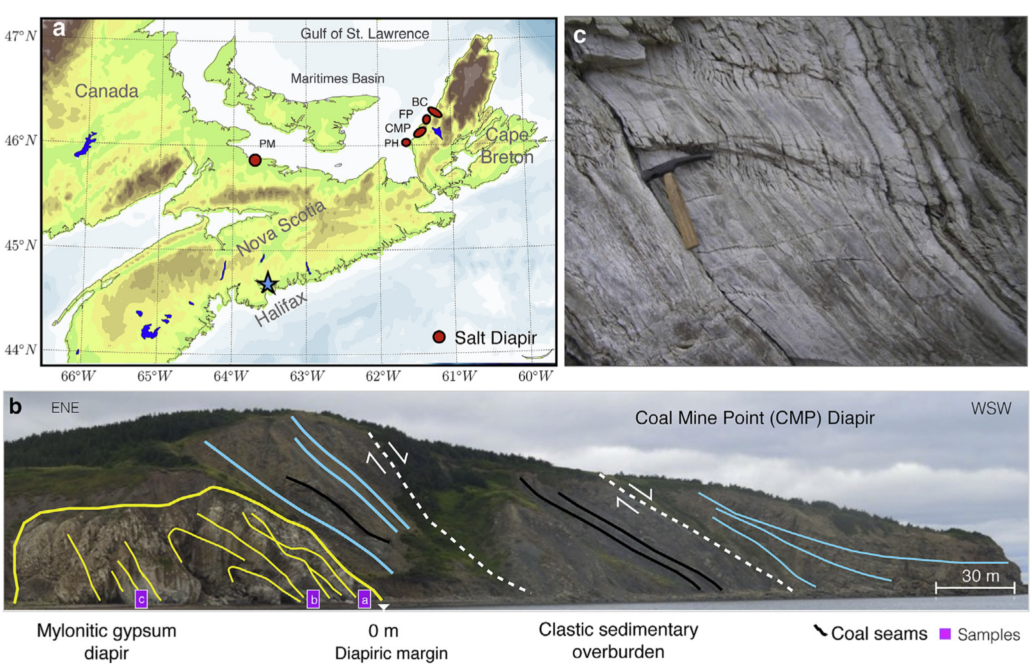

Fig. 1. a) Map of the Gulf of St. Lawrence and western Cape Breton showing the localities where we sampled evaporites. b) Simplified cross-section of the salt diapir and its drag zone exposed at Coal Mine Point (CMP), modified from Alsop et al. (2000). Samples were taken from three different places within the diapir (indicated by squares). c) Detail of the intense mylonitic fabric that characterises this gypsum diapir outcrop. Note that foliation is parallel to the diapiric flank. Hammer of 30 cm length for scale.