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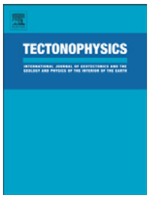

Stress evolution during 3D single-layer visco-elastic buckle folding: Implications for the initiation of fractures

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ABSTRACT

Buckle folds of sedimentary strata commonly feature a variety of different fracture sets. Some fracture sets including outer arc tensile fractures and inner arc shear fractures at the fold hinge zones are well understood by the extensional and compressional strain/stress pattern. However, other commonly observed fracture sets, including tensile fractures parallel to the fold axis, tensile fractures cutting through the limb, extensional faults at the fold hinge, and other shear fractures of various orientations in the fold limb, fail to be intuitively explained by the strain/stress regimes during the buckling process. To obtain a better understanding of the conditions for the initiation of the various fractures sets associated with single-layer cylindrical buckle folds, a 3D finite element modeling approach using a Maxwell visco-elastic rheology is utilized. The influences of three model parameters with significant influence on fracture initiation are considered: burial depth, viscosity, and permeability. It is concluded that these parameters are critical for the initiation of major fracture sets at the hinge zone with varying degrees. The numerical simulation results further show that the buckling process fails to explain most of the fracture sets occurring in the limb unless the process of erosional unloading as a post-fold phenomenon is considered. For fracture sets that only develop under unrealistic boundary conditions, the results demonstrate that their development is realistic for a perclinal fold geometry. In summary, a more thorough understanding of fractures sets associated with buckle folds is obtained based on the simulation of in-situ stress conditions during the structural development of buckle folds.

1. Introduction

Observations from various types of folds in nature show an abundance of folding related fractures, both shear and tensile. The location, type, extent, orientation, and likelihood of occurrence of these fractures are of importance in geomechanical analyses of folded strata both for fluid flow pathway and reservoir stability prediction. Numerous studies have been conducted to investigate the distribution and patterns of fractures associated with folds based on field observations (e.g. McQuillan, 1973; McQuillan, 1974; Groshong, 1975; Catherine et al., 1997; Hennings et al., 2000; Guiton et al., 2003; Bergbauer and Pollard, 2004; Florez-Nio et al., 2005; Bellahsen et al., 2006; Wennberg et al., 2006; Stephenson et al., 2007; Ismat, 2008; Ghosh and Mitra, 2009; Reber et al., 2010; Barbier et al., 2012; Iñigo et al., 2012; Vitale et al., 2012; Awdal et al., 2013; Watkins et al., 2015). The relation between the occurrence and development of the fracture systems and folding are dependent on a variety of parameters, such as layer thickness (McQuillan, 1973; Tavani et al. 2015), lithology (e.g. Catherine et al., 1997; Ericsson et al., 1998; Wennberg et al., 2006; Ghosh and Mitra, 2009; Watkins et al., 2015), curvature (e.g. Lisle, 1992, 1994; Hennings et al., 2000), the state of stress (Price, 1966; Ramsay, 1967; Stearns, 1968; Groshong, 1975; Price and Cosgrove, 1990; Lemiszki et al., 1994; Guiton et al., 2003; Reber et al., 2010; Eckert et al., 2014), interlayer slip (Chapple and Spang, 1974; Cooke and Underwood, 2001; Smart et al., 2009), their position in the fold system (e.g. Cloos, 1948; Price and Cosgrove, 1990; Bellahsen et al., 2006; Ismat, 2008; Jäger et al., 2008; Awdal et al., 2013; Eckert et al., 2014) and deformation history (Bergbauer and Pollard, 2004; Florez-Nio et al., 2005; Stephenson et al., 2007; Smart et al., 2010; Smart et al., 2012; Vitale et al., 2012). The often cited conceptual model by Price (1966) and Stearns (1968) suggests that there are 5 common fracture sets forming systematically with respect to the fold axis.

However, it is clear that the existence of fractures and the conditions for their initiation within fold structures can be attributed to various different, specific folding mechanisms (such as forced folding or buckle folding) and the stress evolution during either pre-folding, folding or post-folding (Price and Cosgrove, 1990; Eckert et al., 2014). Due to the several different types of forced folds, a generalized fold-fracture model does not exist and the fracture pattern strongly depends on the

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specific type of forced folding (Cooke et al., 1999; Cosgrove and Ameen, 2000a, 2000b; Couples and Lewis, 1999; Laubach et al., 1999; Smart et al., 2010; Smart et al., 2012).

For buckle folds, the relation of various fractures types and the fold geometry is discussed by Price and Cosgrove (1990) and a general comparison of fracture patterns associated with buckle folds and various types of forced folds has been established by Cosgrove and Ameen (2000a, 2000b). Fractures associated with buckle folding may result from the regional principal stresses, which are either parallel/subparallel or normal/subnormal to bedding during buckling of originally horizontal layers (Dieterich and Carter, 1969; Dieterich, 1969; Parrish et al. 1976). Fig. 1 shows the orientations of the various types of tensile and shear fractures associated with buckle folds, their locations and the stress conditions for their occurrence (after Price and Cosgrove, 1990). As stated by Price and Cosgrove (1990), different sets of tensile fractures (Fractures 1–4 in Fig. 1), and conjugate shear fractures (Fracture Sets 5–10 in Fig. 1) require different relations of the principal stresses, and thus these fractures develop at different times during the deformation history of the fold, including pre-folding and post-folding stages, as the stress state changes. It should be noted that these fractures represent various joint and fracture types including extensional faults (i.e. Fracture Sets 6 and 9), compressive faults (i.e. Fracture Set 5), conjugate shear fractures (i.e. Fracture Sets 7, 8 10 and 11) and dilational joints (i.e. Fractures 1–4).

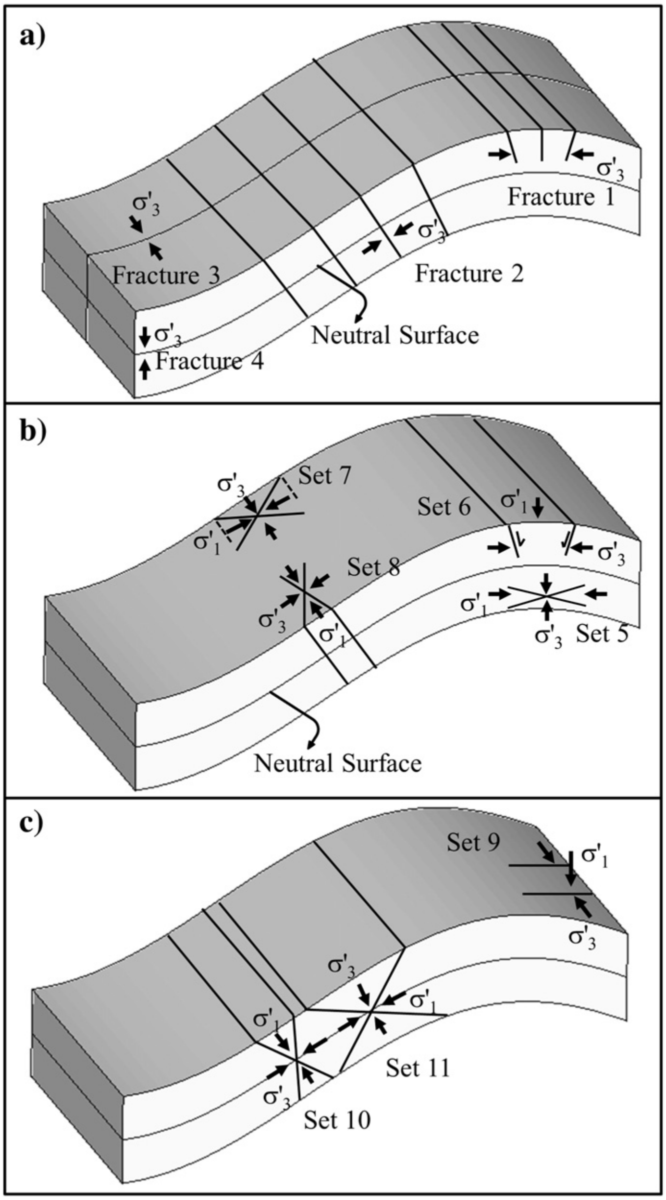

Fig. 1. Fracture sets commonly identified within fold structures, and the inferred orientations of the minimum and maximum principal stresses (σ'_3 and σ'_1) necessary to form them. a) 4 different tensile fractures commonly associated with buckle folds. b) Conjugate shear Fracture Sets 5 to 8 associated with buckle folds. c) Conjugate shear Fracture Sets 9 with 11 associated to buckle folds.

Amongst the most noticeable fractures associated with buckle folds are tensile fractures occurring at the outer hinges of the fold crest (Fracture 1), and shear fractures at the bottom of fold hinge zones (Set 5). The conditions for their occurrence are well understood and are related to the tensional and compressional strain/stress pattern developing in buckled elastic materials (Ramsay, 1967; Turcotte and Schubert, 2002) and also in the fold hinge zone of buckled rocks (e.g. Price and Cosgrove, 1990; Lemiszki et al., 1994; Reber et al., 2010; Frehner, 2011; Eckert et al., 2014). Shear fractures in the fold limb (Set 7) are frequently observed (e.g. Price and Cosgrove, 1990; Ismat, 2008) and attributed to the state of stress during the horizontal compression. Bedding parallel tensile failure (Fracture 4), i.e. bedding-parallel fibrous veins, also termed as “Beef” (Cobbold et al., 2013) can be attributed to fluid overpressure in combination with horizontal compression during buckling (Eckert et al., 2014).

There are fracture sets that are not intuitively linked to the stress regime occurring during buckling. These include layer penetrating tensile fractures parallel to the fold axis in the limb with various dip angles (Fracture 2 in Fig. 1; Engelder et al., 2009), layer penetrating tensile fractures perpendicular to the fold axis in the limb (Fracture 3 in Fig. 1, Price and Cosgrove, 1990; Bergabuer and Pollard, 2004; Lash and Engelder, 2007; Ismat, 2008), extensional (i.e. normal) faults at the fold hinge (Fracture Set 6 in Fig. 1, Price and Cosgrove, 1990), conjugate shear fractures with the acute bisector sub-parallel to the fold trend (Fracture Set 8 in Fig. 1; Price and Cosgrove, 1990), oblique faults (in the limb) or extensional faults (at the hinge) with steep dip angles (Fracture Set 9 in Fig. 1; Price and Cosgrove, 1990; Ismat, 2008), conjugate faults with the acute bisector sub-perpendicular to the bedding surface in the limb (Fracture Set 10 in Fig. 1; Ismat, 2008) and conjugate faults with the acute bisector sub-parallel to the bedding and perpendicular to the fold axis in the limb (Fracture Set 11 in Fig. 1, Price and Cosgrove, 1990; Lemiszki et al., 1994). In particular, shear factures Set 10 and Set 11 may separate the fold hinge from the limbs.

Of all these fracture sets identified, the association of Sets 8 and 10 to buckle folding is questionable since the maximum principal stress, σ'_1, is mostly parallel to the shortening direction during buckling (Eckert et al., 2014). Furthermore, tensile Fractures 2 remain difficult to explain since the necessary direction of the minimum principal stress, σ'_3, perpendicular to the fracture, is unlikely to be sub-parallel to the shortening direction at the fold limb during the buckling process. Hence this fracture is more likely to be influenced by either pre-folding deformation or post-folding deformation (Engelder et al., 2009).

In summary, the fractures shown in Fig. 1 are all based on observations from field studies (e.g. Price and Cosgrove, 1990; Cosgrove and Ameen, 2000a, 2000b) and any given fracture pattern is the result of some stage during the complete stress history undergone by the rocks, including the deformation history during buckle folding. In this regard, a distinction has to be made relative to the time of fracture development, i.e. if the fractures developed before, during or after buckle folding, since it is very unlikely that all these fracture sets are formed coevally or during a single buckling episode (Price, 1966). This becomes of particular interest for Fractures 2 and 3, as different studies (Price and Cosgrove, 1990; Twiss and Moores, 2007; Engelder, et al., 2009) have concluded that pre-existing bedding normal joint sets (i.e. Mode 1 fractures) play an important role in the distribution of fold related fractures. These observations support Casey and Butler (2004), who stated that the timing and evolution of fracture occurrence is not sufficiently understood. One of their main conclusions is that due to the complexity