Journal of Natural Gas Science and Engineering 30 (2016) 295–304

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Effects of gas generation on stress states during burial and implications for natural fracture development

Yang Luo [a], Hongping Liu [a], Yanchao Zhao [a, *], Guochang Wang [b]

[a] Key Laboratory of Tectonics and Petroleum Resource of Ministry of Education, China University of Geosciences, Wuhan, China
[b] Petroleum and Natural Gas Engineering, Saint Francis University, Loretto, PA, United States

A R T I C L E I N F O

Article history:
Received 28 September 2015
Received in revised form
15 February 2016
Accepted 15 February 2016
Available online 18 February 2016

Keywords:
Gas generation
Stress state
Coupling
Burial process
Natural fracture

A B S T R A C T

The complexity of fracture networks in shale gas reservoirs may result from the superimposition of several fracture sets forming in temporally modified stress states during burial. In addition to tectonic evolution, this modification can also be caused by the overpressure generated by gas generation. Compared with undercompaction, gas generation shows a different overpressuring process and may cause different effects on stress states. This paper addresses these effects during burial in terms of pore pressure stress coupling. A series of finite element simulations for this investigation are designed with different tectonic stress regimes using a simplified model with a homogeneous poroelastic medium. The results show that during burial, gas generation not only significantly decreases effective stresses but also changes differential stress by decreasing it in the normal faulting regime and increasing it in the thrust faulting regime compared with undercompaction. Furthermore, gas generation during burial may locally transform the given tectonic stress regime from normal faulting to strike slip or even thrust faulting regimes. The investigation implies that gas generation rather than undercompaction in burial history can significantly diversify the patterns of natural fractures by affecting the differential stress and even the local stress regime in addition to influencing their spatial distribution due to its spatial heterogeneity and its different effects on stress states in different stress regimes. As a result, the contribution of gas generation to overpressures should be differentiated from that of undercompaction before analysing the effects of overpressures on natural fracture development.

1. Introduction

The development of natural fractures in shale gas reservoirs has become a fertile field of investigation due to the rising interest in shale gas exploration (Curtis, 2002; Gasparrini et al., 2014; Gale et al., 2014, 2007). Generally, natural fractures show higher complexity in shale reservoirs than in conventional fractured sandstone, carbonate or igneous reservoirs (Aydin, 2014). The complexity of a fracture network in conventional fractured reservoirs usually results from the superimposition of different fracture sets forming during multi-phase fracturing events (Spence et al., 2014). These sets may have different intensities, orientations or patterns, including tensile and shear fractures, which can usually be caused by the temporal modification of stress states (Ferrill et al., 2014; Laubach et al., 2009; Lianbo and Xiang-Yang, 2009) or even the change of the local tectonic stress regime (Lash and Engelder, 2005). However, in shale formations, in addition to the reasons above, the complexity can also be caused by the prevailing overpressure during burial (Gale et al., 2014; Lash and Engelder, 2005; Rozhko et al., 2007), partially because of its significant impacts on stress states, such as the reduction of effective stresses (Cosgrove, 2001). Among several mechanisms for overpressure generation, two main ones are gas generation and undercompaction (Osborne and Swarbrick, 1997; Tingay et al., 2013). Compared with undercompaction, gas generation is the main mechanism for high overpressure (Bowers, 2002) and should not be ignored when analysing natural fracture formation in burial history. This paper mainly concentrates on the effects of gas generation on stress states during burial to help us further understand natural fracture development in shale gas reservoirs.

The effects of overpressures, due to undercompaction or gas generation, on stress states have always been considered in fracture analysis. They used to be described by Terzaghi's effective stress principle, assuming that total stresses are independent of pore pressure (Cosgrove, 2001; Terzaghi, 1943). In fact, total stresses and pore pressure are coupled (Hillis, 2001, 2000; Engelder and Fischer,

* Corresponding author.
E-mail address: ychzhao2008@163.com (Y. Zhao).

http://dx.doi.org/10.1016/j.jngse.2016.02.023

1994), i.e., the so-called pore pressure stress coupling (Hillis, 2001; Altmann et al., 2010; Mourgues et al., 2011), which has been widely proved using stress measurement data observed for hydrocarbon reservoirs (Goulty, 2003; Segall and Fitzgerald, 1998; Addis, 1997; Segura et al., 2011) or sedimentary basins (Yassir and Bell, 1994; Hillis, 2003; Binh et al., 2007). The coupling effect has been considered in the analysis of stress states (Altmann et al., 2010; Segall and Fitzgerald, 1998; Altmann et al., 2014; Yassir et al., 2002) and rock failure (Lash and Engelder, 2005; Rozhko et al., 2007; Mourgues et al., 2011, 2012; Hillis, 2003). Studies have shown that homogeneous overpressure usually reduces differential stress in addition to effective stresses because of its coupling with minimum horizontal stress (Hillis, 2000; Mourgues et al., 2011; Hillis, 2003), whereas overpressures with a point or limited width source may affect the stress states depending on the location with respect to the source (Mourgues et al., 2011; Altmann et al., 2014) due to their additional coupling with vertical stress. Moreover, the in situ tectonic stress regime may also be changed by overpressures (Altmann et al., 2014; Yassir et al., 2002). As a result, the stress states changed by overpressures will cause natural fractures to form in a manner different from the prediction based on conventional effective stress methods (Lash and Engelder, 2005; Luo et al., 2015). In many cases, overpressures can convert a potential fracture pattern from shear to extension by reducing differential stress and thus stabilize rocks (Hillis, 2001; Mourgues et al., 2011; Hillis, 2003).

However, two points may be valuable to increase attention for the analysis of natural fractures that form in burial history. The first is that the overpressures generated by undercompaction and gas generation may have different effects on stress states and then the natural fracture development. It is well known that undercompaction and gas generation cause different overpressuring processes (Osborne and Swarbrick, 1997), leading to the different mechanical and compaction behaviours of rocks, such as differences in the loading curve and the unloading curve (Bowers, 2002, 1995; Tingay et al., 2009). This may result in different changes in stress states. This idea was supported by Miller's analysis of natural hydraulic fractures (Miller, 1995), which showed the different stress paths between undercompaction without fluid draining and fluid addition without depth change. The other point is that depth change is accompanied by overpressuring during burial. The current work about pore pressure stress coupling usually assumes a nearly constant burial depth during overpressuring, e.g., stress changes in reservoirs caused by fluid injection (Altmann et al., 2014) and trap integrity evaluation associated with overpressuring (Mourgues et al., 2011). The analysis of natural fractures associated with overpressures also usually overlooks the effects of depth change (Gasparrini et al., 2014; Zanella et al., 2015, 2014). In fact, if the stress paths for undercompaction and gas generation are considered in the burial history, the depth change during burial should be inevitable because of the consequent change in vertical stress.

This paper tries to determine some effects of overpressure due to gas generation on stress states, considering the change in the burial depth. It is noted that the effects can be influenced by many factors of fluid, rocks and other geological elements. This paper focuses on the obviously different mechanical effects between gas generation and undercompaction, which are simplified by overlooking some factors, such as temperature change and the complex mechanism of gas generation. The whole investigation is implemented by using a general finite element program, i.e., ABAQUS software. A numerical model of poroelastic medium is designed to simulate the stress state evolution for gas generation, as well as normal compaction and undercompaction, accompanied by the change in the burial depth. Furthermore, the model also considers the factor of tectonic stress regimes, including normal faulting, strike slip and thrust faulting regimes. The results should help to distinguish the effects of gas generation and undercompaction on in situ stress states in the burial history. This will have positive implications for further work related to natural fracture characterization in shale gas reservoirs.

2. Description of the numerical method

In this study, our focus is the change in stress states during overpressuring due to gas generation. It is mainly a geomechanical analysis. Thus, it was implemented using a simplified homogeneous model to represent subsurface shale formation, which will undergo normal compaction and overpressuring generated by undercompaction or gas generation. The numerical simulations were performed using a finite element program (ABAQUS Software).

2.1. Model properties

A simplified model is prepared for the following numerical simulations. Its geometry is cuboid, being 4 m × 4 m × 4 m, as denoted in Fig. 1. Eight-node hexahedral displacement and pore pressure elements are used to mesh the model. A homogeneous structural mesh is adopted, with an average mesh cell of 0.1 m. Then, the homogeneous poroelastic medium, saturated by water, is set for the model. The rock mechanical properties mainly refer to those used by Altmann et al. (2010). Note that the Biot-Willis coefficient equals one here; that is, the assumption of non-compression of grains and pore fluid is adopted. Table 1 presents the material properties used in the model.

2.2. Simulations of compaction procedures

The simulations involve three compaction procedures: normal compaction, undercompaction overpressuring and gas generation overpressuring. All of these procedures simulate the changes of stress states with simulation time, which represents the burial process. The model is assumed to meet the depth for complete fluid retention at a certain time: normal compaction occurs before that time, whereas overpressure occurs after (Fig. 2).

Some strategies are adopted here to simplify the simulations. First, the suitable expressions of pore pressure and stress are separately used in the normal compaction and overpressuring procedures. A special excess pore pressure (Δp in Fig. 2) is used to represent the pore pressure during the whole simulation, by which the absolute pore fluid pressure is avoided. However, the baselines for the excess pore pressure are different in the two procedures, as is the expression of overburden stress. Second, the burial history is simplified by increasing the value of overburden stress with time. According to the different compaction behaviours mentioned

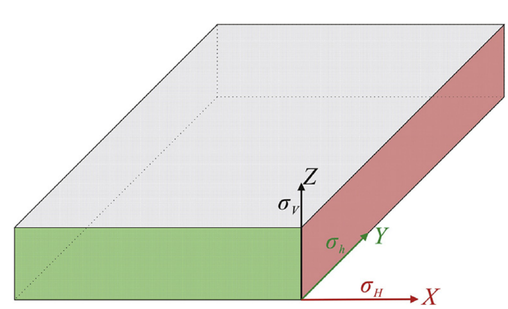

Fig. 1. 3D model of hypothetical shale formation.