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Predicting hydraulic tensile fracture spacing in strata-bound systems ☆

C.I. McDermott *, K. Edlmann, R.S. Haszeldine

Edinburgh Collaborative of Subsurface Science and Engineering (ECOSSE), School of Geoscience, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, Scotland, United Kingdom

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ABSTRACT

A model is presented which predicts the spacing of tensile-fractures due to fluid pressure increase in a multilayered sedimentary sequence comprising different typical sedimentary deposits such as mudstones, siltstones and sandstones. During normal burial and tectonic conditions, strata will undergo both extensional forces and an increase in fluid pressures. This model addresses the effects of the diffuse fluid pressure increase, and is useful for engineered applications such as the injection of fluid into a reservoir that may cause an increase of fluid pressure beneath a caprock, and for sedimentary sequences during normal digenetic processes of burial and fault activation. Analytical and numerical elastic stress strain solutions are compared to provide a robust normalised standard relationship for predicting the spacing of fractures. Key parameters are the local minimum horizontal stress, variability of the tensile strengths of the layers of a sedimentary sequence and the thickness of the beds. Permeability and storage are also shown to affect the fracture spacing. The model predicts many of the field observations made regarding strata-bound fracture systems, and should also prove useful in consideration of the impact of raised reservoir fluid pressures on caprock integrity.

1. Introduction

In the evaluation of the integrity of caprocks, and of analogue seals, the fracture spacing is of vital importance. In proposed CO2 storage sites, it is not the intact matrix of the caprock that causes concern for the retention of the injected CO2 rich fluids, or pure dense phase CO2. Rather, it is the presence of fractures at a series of scales which need to be quantified and analysed in terms of their connectivity and transport properties. During the characterisation of a reservoir for storage, the fluid pressure history and digenetic analysis of the caprock play an important role in understanding how the caprock will react to the presence of increased chemically aggressive fluid pressure loading beneath it. Indeed, the results of Rutqvist et al. [1] illustrate that hydraulic fracturing can be expected in the lower layers of a caprock after a relatively short period of time of fluid injection if the pressure is not controlled properly. It is generally accepted that hydro-fracturing will occur when the pore fluid pressure below the top seal equals or exceeds the minimum horizontal stress plus the tensile strength of the caprock [2].

Here we present a model that examines the impact of increased fluid pressure in multilayered sedimentary systems, the physical requirements for fluid driven fracturing of the strata in these layered systems, and the horizontal spacing between vertical fractures these systems could show. The model emphasises the importance of the local stress distributions on the formation of the fractures. It can be used to predict the likely fracture patterns of fluid driven (hydro-fracturing) in strata bound systems. A caveat to the model is that the presence of pre-existing fracture sets will influence the distribution of fluid pressure and impact on the predicted spacings. However, the model can be used for a first-order assessment.

1.1. Controls on fracture geometry

Several authors discuss joint formation mechanisms. Here we concentrate on opening mode fractures. The work of Price [3] discusses joint/fracture development wherever the effective tensile stress exceeds the tensile strength of the rock. Possible causes being a result of fluid overpressure, expansion of the rock mass under uplift and erosion, pull apart due to tension induced by a regional extension, salt diapirism and folding.

There are obviously several mechanisms that will lead to the formation of fractures. The dominant mechanism at any particular time, and the characteristics of the deposit (the packet of sediment and hard rock, including any existing fracturing) will influence the

* Corresponding author. Tel.: +44 131 650 5931; fax: +44 131 650 5738.
E-mail address: cmcdermo@starffmail.ed.ac.uk (C.I. McDermott).

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nature of the response of the deposit to the formation of fractures. Depending on the cause of fracturing, the fractures formed will exhibit different geometrical characteristics and be scale dependent.

Bonnet et al. [4] review several methods of scaling fracture systems, including the lognormal distributions, exponential distributions and gamma law distributions, and indicated a recent preference for the fractal approach. They point out that recent studies indicate lithological layering, from the scale of a single bed to the whole crust, is reflected in fracture system properties. This layering influences the scale range over which individual bed specific or fracture system specific scaling laws are valid. The above named distributions are mathematical fits of probability distributions, and to understand the cause of fracturing it is necessary to reference the mechanical constraints and drivers. In certain cases one model, with certain limiting factors, fits better than another, but there is no ubiquitous law to match the whole population of fractures.

In a typical geological deposit, several sets of fractures will be present. To understand the spacing of the fractures it is important to understand the mechanisms that have led to the development of the different fracture sets. The observation that lithological layering is reflected in the fracture systems suggests that a process operating at the scale of the lithological bed size is important in controlling the development of the fractures. Identifying the key processes behind fracturing as creating “separate fracture packets” or end members, will help in the analysis of the fracture spacing and the nature of the process leading to the fracturing.

Here we concentrate on strata bound fractures as opposed to fractures which cut across several formations, and hypothesise that hydraulic fracturing provides an important controlling mechanism for the development of strata bound fractures. Particularly the stress field developed during dynamic fluid fracturing significantly influences the location of the development of further fractures.

Bai et al. [5] summarised work from many authors to make the observation that “the fracture spacing in layered sedimentary rocks is roughly proportional to the thickness of the fractured layer, with a ratio of thickness's from less than 0.1 to greater than 10.” They developed a finite element model describing fracture spacing as a result of a pull-apart model, and a transition of stress from one bed to another bed. From the results of this model, they subdivided the fracture spacing to bed thickness ratios into four categories, whereby they could explain two categories with their extensional model and the further two categories where the joint spacing was too tight to have been caused by the extensional mechanism explained. They concluded that the other sets of joint spacing ratios required flaws and fluid pressure to produce the spacing. They note that as the tensile stress increases between two existing fractures, eventually a fracture will be initiated. The location of this new fracture will be dependent on a result of a local heterogeneity, such as a pre-existing zone of weakness, or due to the increase in fluid pressure overcoming compressive strength. Bai et al. [6] note that experimental and field results indicate fracture spacing decreases approximately as the inverse of the applied strain in the direction perpendicular to fractures, by fractures forming between earlier formed fractures. Gross [7] used the term “sequential infilling” to describe this process. Bai et al. [5] developed the concept of a maximum fracture saturation distance, being related to the stress distribution caused by the presence of a fracture leading to an area of “stress shielding” and thereby setting a lower limit to possible fracture spacing. The stress shielding is caused by the compressive stress due to vertical shortening of the fractures and the horizontal constraint in the central area between two fractures.

Addressing multiple layer sequences, Schöpfer et al. [8] examined the role of the transfer of extensional stress between different layers, and focussed on the relationship between the tensile strength of an individual bed and the amount of stress that can be transmitted into that bed from adjoining beds as a function of the interface shear strength. The larger the tensile strength, the more tensional stress needs to be transmitted to cause fracturing which is satisfied either through wider fracture spacing or through a higher interface shear strength. Following [8], and the references therein, this is described as Price's model [3]. They show that different extensional models are applicable depending on the ratio of the tensile strength of the bed to the interfacial shear strength; however, the influence of fluid pressure is not addressed.

Boutt et al. [9] investigated both experimentally and numerically the formation of natural hydraulic fractures. By reducing the external fluid pressure in sandstone samples more rapidly than the internal pressure could equilibrate, they were able to generate hydraulic fractures considered to be a consequence of both the internal fluid pressure exceeding the confining pressure and tensile strength of the rock, and also to be a consequence of a strong pressure gradient existing within the sample. Numerically they were able to simulate this type of depressurisation of the sample and the density of the in filled fractures. The rate of pressure release within the samples is a function of the permeability and storage of the samples. They conclude that the processes they have observed are very important in the natural hydro fracture process found within the earth's crust.

Odling et al. [10] examined several high-quality data sets of fracture systems from four reservoirs and identified two end member types of fracturing, named as “strata bound” and “non strata bound”. They suggest that in strata bound systems there is little mechanical coupling between the layers. The individual joints are confined to single layers, and there is a clear relationship between bed thickness and joint spacing. Such sequences are found in systems with strongly developed interbedded weak and strong layers, e.g. interbedded sandstones, limestones, mudstones and shales. They describe the system as having weak adhesion between the layers. Odling et al. [10] describe strata bound fracture systems as confined to single layers, the sizes are scale restricted and the spacing is regular. We note also from the observation of typical caprock analogues (unpublished in house) that fracturing may at times go slightly beyond the limits of the bed and into more plastic layers, and also that fractures extending only a partial distance in the fractured bed (half fractures) are also present.

The role of increased pore fluid pressure within the crust and the link to the development of natural hydraulic fracturing has long been accepted, (e.g. [11,12]), and there are several examples in the literature of natural fracture systems which are interpreted as being a consequence of hydraulic fracturing. The focus of this paper is on strata bound systems and the role of fluid overpressure, and we suggest that it plays a more significant role than previously acknowledged in the formation of strata bound systems.

1.2. Parametric controls on hydraulic fracturing

There is a large body of literature particularly from the hydrocarbon industry examining the parametric controls on the development of hydraulic fractures in layered sequences. They deal particularly with a localised increase in fluid pressure due to fluid injection in a borehole, as opposed to a more regional increase in fluid pressure as would be the case in burial or a generic build up of pressure under a caprock. The key area of interest of this literature is the prediction of the length of the fractures generated and containment within different layers. There is some discussion as to the transfer of stress between different geological layers, key parameters being addressed include the contrast of the elastic modulus and Poisson's ratio between beds. Simonson [13] showed