PREDICTING, MONITORING AND CONTROLLING GEOMECHANICAL EFFECTS OF CO_2 INJECTION

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ABSTRACT

Long-term subsurface containment of CO_2 is a key objective of geological CO_2 storage in porous rock. To avoid damage to reservoir seals and fault seals of storage sites during CO_2 injection, fault stability and maximum sustainable pore-fluid pressures should be estimated in geomechanical studies. Such analyses rely on predicting the evolution of effective stresses in rocks and faults during CO_2 injection. Geomechanical analyses often do not incorporate poroelastic behaviour of reservoir rock, as relevant poroelastic properties are hardly ever known. However, the knowledge of rock poroelastic properties would allow the use of seismic methods for the accurate measurement of the effective stress evolution during CO_2 injection. While it is known that not only effective stresses but also total stresses can change during fluid-pressure depletion in hydrocarbon fields, it is not clear whether fluid injection will have significant effects on total stresses on a reservoir scale. Repeated hydraulic-fracturing tests and extended leak-off tests could be used to detect changes of the total minimum horizontal stress during CO_2 injection in storage sites. Monitoring for induced microseismic activity with geophones during CO_2 injection can provide a mechanism for detecting unexpected effective stress changes. Such monitoring can also be used to detect accidental over-pressurization of the formation and for the real-time adjustment of injection pressures, if required.

INTRODUCTION

A key objective of geological storage of CO_2 is the long-term underground containment of CO_2 in order to assist in the effective reduction of greenhouse gas emissions. The quantities of stored CO_2 per unit volume of porous rock can be maximized by injecting CO_2 as a relatively dense phase and hence in supercritical state below approximately 800 m [1]. The injection of CO_2 requires the formation pressure to be exceeded as the injected fluid needs to displace or compress the existing fluid or compress the rock. The effects of such CO_2 injection on the storage reservoir, on its seals, and on the rock stresses in the storage area need to be predicted, monitored, and controlled in order to avoid injection-related damage. Brittle damage to reservoir and fault seals that would create or enhance fracture permeability could lead to unwanted CO_2 leakage from storage reservoirs [2]. Relevant pathways for fluid flow towards the earth's surface in sedimentary basins could be large-scale faults or connected fault-fracture networks.

The formation of substantial fracture and fault permeability is often attributed to seismic faulting (e.g. [3]). Fluid injection into boreholes can induce microseismic (MS) faulting, as has been shown in injection tests conducted in the drill holes of the German continental deep-drilling program [4] and the Cold Lake Oil Field, Alberta, Canada [5]. It has been suggested that deep-well injection of waste fluids has in some cases induced earthquakes with moderate local magnitudes (M_L), such as the 1967 Denver earthquakes ($M_L \leq 5.3$) [6] and the 1986/87 Ohio earthquakes ($M_L \leq 4.9$) [7]. To avoid injection-induced seismicity and damage to reservoir and fault seals, maximum sustainable injection pressures that will not induce brittle failure should be determined prior to CO_2 injection [2, 8].

Estimates of maximum sustainable fluid pressures in CO_2-storage sites are primarily based on predicted changes of effective stresses in rocks during CO_2 injection and associated pore-pressure increase. The techniques used for estimating fault and rock stability usually rely on Mohr-Coulomb criteria using effective stress defined as the total stress minus the pore-fluid pressure [2, 8]. It is known that not only the pore-fluid pressure, but also the total stress can change during pore-pressure depletion of hydrocarbon reservoirs [9]. In some cases this is attributed to poroelastic rock behaviour (e.g. [10]). Since little is known about such behaviour

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and its influence on effective stresses during the injection of fluid into reservoirs, this aspect needs to be investigated.

This article discusses key geomechanical effects of CO_2 injection into porous rock, and especially focuses on the effects that the poroelasticity of reservoir rocks and pore pressure/stress coupling have on effective stresses. While such effects are known from pressure-depletion scenarios, the discussion of their relevance to CO_2 storage is new. Since little is known about the poroelastic behaviour of entire reservoirs and injection-related pore pressure/stress coupling, relevant geophysical monitoring techniques are suggested herein. This article outlines how such techniques can be applied to measure stress changes related to poroelastic rock behaviour during CO_2 injection and to test the predictions of sustainable changes in effective stress in CO_2 storage sites. The suggested combination of predictive geomechanical techniques and application of geophysical monitoring techniques is a new concept for controlling and monitoring the geomechanical effects of CO_2 storage.

EFFECTIVE STRESS

Law of Effective Stress

Increasing pore-fluid pressures in rocks and faults can decrease their strength and lead to brittle failure. Brittle failure that is induced by high pore-fluid pressures in laboratory experiments is typically attributed to low effective stresses [11]:

$$\sigma' = \sigma - P_f \quad (1)$$

where σ' is the effective stress, σ is the total stress and P_f is the pore-fluid pressure. The effective principal stresses that are exerted on a rock resolve into shear and effective normal stresses acting on potential failure planes (Figure 1). Brittle failure on a fault can be described in a general form as:

$$\tau = C + \mu(\sigma_n - P_f) \quad (2)$$

where τ is the shear stress, σ_n is the normal stress, and μ is the coefficient of static friction. *C* is an inherent shear strength of the plane of shear failure and is negligibly small on pre-existing cohesionless faults that are gouge-lined [12]. Application of Eq. (1) and (2) to natural systems for the prediction of pore pressures that lead to failure requires knowledge of the *in situ* stresses. These can be used then to assess fault stability.

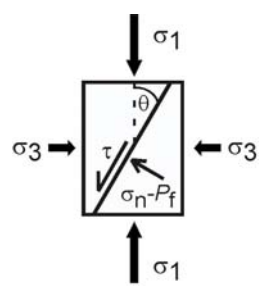

Figure 1: Stresses resolved on a fault plane which forms an angle θ with the maximum principal stress (σ_1). The intermediate principal stress (σ_2) is in the fault plane and σ_3 is the minimum principal stress.

FAULT STABILITY AND MAXIMUM SUSTAINABLE FLUID PRESSURES

Assessment of the fault stability and estimates of sustainable fluid pressures for CO_2 injection and storage require knowledge of *in situ* stresses, fault geometries and rock strengths. The work flow for such geomechanical analyses is schematically shown in Figure 2. The determination of *in situ* stresses in CO_2-storage sites from drilling data is detailed by Streit and Hillis [2] and Streit et al. [8]. The strength of faults, reservoir and seal rocks can determined in laboratory strength tests. Fault geometries are ideally determined from depth-converted 3D seismic surveys.

Methods that can be applied for assessment of fault stability and for estimating maximum sustainable fluid pressures in potential CO_2-storage sites are typically based on Mohr-Coulomb failure criteria (see Eq. (2)). The application of relevant methods, such as failure plots, the Fast technique, and fault-slip tendency, in the context of CO_2 storage are detailed elsewhere [2, 8]. Figure 3 gives an example for the slip tendency ($\tau/(\sigma_n - P_f)$) on a non-planar fault surface based on knowledge of the *in situ* stress tensor, pore-fluid pressure, and fault geometry. It was assumed that the fault is cohesionless and has Byerlee friction coefficients (μ = 0.6 to 0.85). In this case, a critically high slip tendency is attained when the resolved stress ratio ($\tau/(\sigma_n - P_f)$) is approximately μ. Examples for the geomechanical analysis of potential CO_2 storage sites in Australia are given by Gibson-Poole et al. [13].

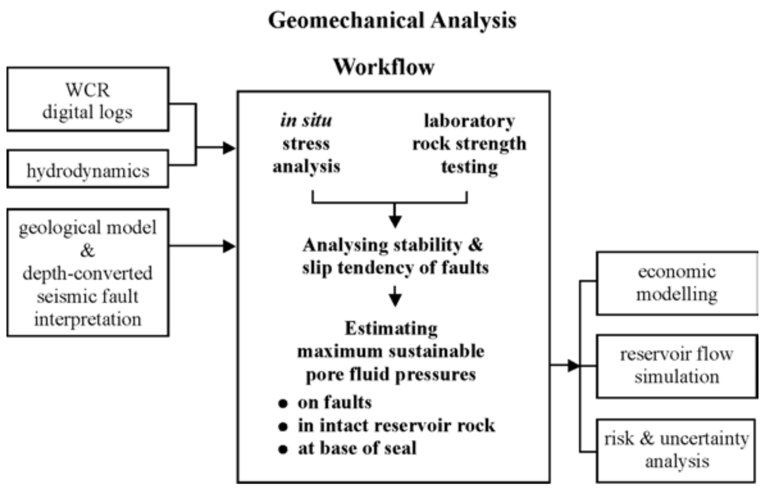

Figure 2: Schematic workflow for geomechanical analyses as described in detail by Streit and Hillis [2]. WCR denotes well completion report.

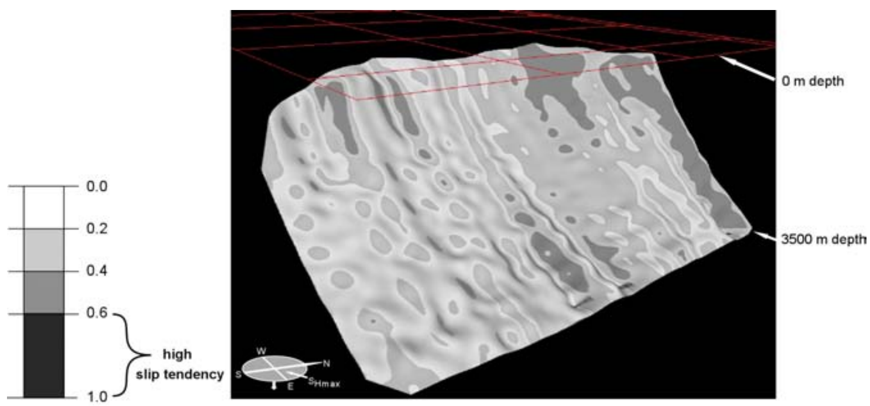

Figure 3: Slip tendency on a fault surface. Diagram from Streit and Hillis [2].

STRESS CHANGES

In conventional models, fault-stability assessments and estimates of maximum sustainable pore-fluid pressures are based on the simplistic law of effective stress given in Eq. (1). In this form, Eq. (1) does not account for the poroelastic behaviour of porous rock and any associated influence on effective stress.

Poroelasticity

The effective stresses in porous rocks such as reservoir rocks considered for CO_2 storage should ideally be calculated from an equation that incorporates Biot's poroelastic coefficient α (e.g. [14]):

$$\sigma' = \sigma - \alpha P_f \quad (3)$$

Experimental work by Nur and Byerlee [14] indicates that α is a function of the compressibility of the rock framework, the grain compressibility, and the applied pressures or stresses. While several authors report α

values substantially less than 1 [14, 15, 16], α is only known for few reservoir rocks and may be a function of effective stress.

Pore Pressure/Stress Coupling

Pore-pressure depletion over decades of production in oil fields can be associated with a decrease in the minimum horizontal stress [9, 10]. In the case of the Ekofisk Field, where the reservoir rocks are composed of medium- to high-porosity chalks, the pore pressure/stress coupling effect is probably related to both poroelastic and permanent compaction (= pore collapse) of the rock [17].

Severe pore-pressure depletion and associated changes of total stresses can have several corollaries that need to be considered in the context of CO_2 storage. In pressure-depleted reservoirs, *in situ* stresses need to be determined from post-production data in order to lead to realistic assessments of fault stability and maximum sustainable pore-fluid pressures [2, 8]. Where pore-pressure depletion has led to pore collapse, this will diminish the CO_2-storage capacity of the reservoir. Indeed pore-pressure depletion is known to have caused fault slip, MS activity, and well-bore casing failure (e.g. [9, 18, 19]). Such failure can compromise the integrity of reservoir and fault seals, and thus affect the suitability of severely pressure-depleted reservoirs for CO_2 storage or their storage capacity.

Streit and Hillis [20] have developed a method for the prediction of induced faulting during severe pore-pressure depletion. Their method can potentially be applied to retro-model the likelihood of production-induced fault-seal damage in cases where CO_2 storage in severely pressure-depleted reservoirs is envisaged.

Predicting Stress Changes during CO_2 Injection

Since the poroelastic behaviour of reservoir rocks is hardly ever known, predictions of stress changes resulting from fluid injection are associated with some uncertainty. Even if the poroelastic behaviour of reservoir rocks is known from laboratory experiments, it is difficult to predict how this exactly affects the local stresses. Based on the interpretation of field data, Santarelli et al. [21] argue that, in several cases, repressurization of a pressure-depleted field did not show any reversibility of the pore pressure/stress coupling seen during depletion. This appears to be consistent with results given by Hettema and de Pater [22] from their laboratory experiments on Felser sandstone. Their experiments, conducted at confining pressures of approximately 10 and 38 MPa, indicate that monotonously increasing pore-fluid pressure causes diminishing increases of pore volume, especially when pore-fluid pressures exceed 4 to 5 MPa. This could mean that grain compression or dilation of total rock volume becomes negligible at fluid pressures exceeding 4 to 5 MPa, thus not changing total stresses but eventually leading to brittle failure. However, given there is some contradiction between theoretical predictions of poroelastic behaviour of rocks and field and laboratory observations, effective stress changes should be measured in demonstration projects for CO_2 injection.

SEISMIC TECHNIQUES FOR MEASURING EFFECTIVE STRESS CHANGES

Departures of velocity or travel times from a normal compaction trend form the basis of many empirical methods of extracting pore pressure from velocity-depth relationship (e.g. [23]; [24]). However, a new method of calculating pore pressures directly from seismic data has recently been developed. The method by Ciz et al. [25] relies on extraction of instantaneous waveform attributes such as frequency content of the seismic signal. Calibration of the method was based on extensive laboratory experiments and has the potential to yield absolute values of pore pressure.

Velocity-Effective Stress Relationship

Central to the determination of pore pressure from seismic velocities is the velocity-effective stress relationship for a given lithology. Where such a relationship is well established and unique, a measured velocity will give an effective-stress value. However, there are a number of problems with this approach. There may not be a unique velocity-effective stress relationship for a given lithology, particularly if unloading due to fluid generation has occurred [26]. Microcracking or the opening of pre-existing cracks on core during retrieval from reservoir depths (typically 1.5 to 2.5 km), and hence due to unloading, provides problems for the laboratory calibration of the velocity-effective stress relationship. While core damage results in a higher velocity-effective stress sensitivity, the effects can be minimized if samples are measured under simulated *in-situ* stress conditions [27].

Another issue concerns the choice of effective stress. Harrold at al. [28] concluded that, rather than the vertical stress, the mean stress should be used to calibrate the velocity-effective stress relationship. Laboratory experiments on loading of shales under tectonic-stress conditions by Siggins et al. [29] have confirmed that the mean stress, rather than the vertical or horizontal stresses, has a systematic relationship to p-wave velocity.

Stress-Path Dependence of Velocity-Effective Stress Relationship

Poroelastic considerations indicate that changes in pore pressure are less effective in influencing volumetric strain, ε_v than are changes in confining pressure. This can be expressed in the following form,

$$\varepsilon_v = \frac{dV}{V} = C_{bc}\left\{dP_c - dP_f[1 - \frac{C_r}{C_{bc}}]\right\} \qquad (4)$$

where V is volume, C_{bc} and C_r are bulk and grain compressibilities (with units of Pa^{-1}) respectively and P_c is the confining pressure. The notation used is that of Zimmerman [30].

Equation 4 implies a form of hysteresis in that an increase in confining pressure will not be equivalent to an equal and opposite change in pore pressure. This further implies a stress-path dependence of the velocity-effective stress relationship. A pore-pressure increase equivalent to a confining-pressure reduction will not retrace the original curve but places the rock on a new velocity-effective stress path (Figure 4).

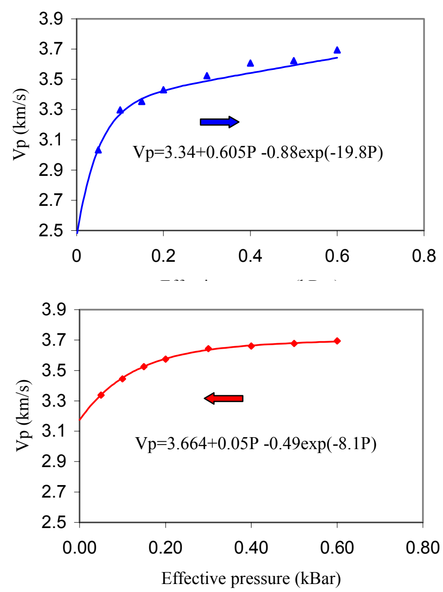

Figure 4: Velocity–effective stress data and Eberhardt-Phillips [31] curve fits for a typical sample under both loading, blue (via confining-pressure increase) and un-loading, red (via pore-pressure increase).

Pore-pressure changes in Eq. (4) are reduced in effect by the factor $[1-C_r/C_{bc}]$, which is equivalent to Biot's α. In cases where α is less than 1, this has several implications. Effective stresses estimated from velocity data will be under-estimated and pore pressures over-estimated. A knowledge of α allows the stress-path hysteresis effects to be reduced (particularly in sandstones) and a unique relationship between velocity and effective stress to be restored. Determining α from field data is a difficult task, although it has been attempted in thick shales where the over-pressure mechanism is known [32].

While a determination of α may reduce some ambiguity in the geophysical measurement of effective-stress changes, it is unclear whether poroelastic effects can significantly affect the effective stresses on a reservoir scale during fluid injection (see above). In any case, it appears prudent to conduct passive seismic monitoring during the injection of CO_2 to detect whether effective-stress changes induce seismic fault slip.

PASSIVE SEISMIC MONITORING

Monitoring for Induced Shear Failure

The brittle reactivation of pre-existing faults at relatively high slip rates will result in the generation of MS events. MS events can be monitored with geophysical instrumentation such as accelerometer, hydrophone or geophone arrays. In sedimentary hydrocarbon fields, there have been a number of recent reports of monitoring MS activity associated with fluid injection, particularly water flooding (e.g. [33]; [34]). MS activity may also occur in conjunction with CO_2 injection.

Although most MS monitoring has been performed in crystalline rock in support of hydraulic fracturing, long-term MS monitoring in sedimentary rocks in the context of CO_2 storage has the potential to indicate the advancement of fluid pressure fronts during injection. Since sedimentary rocks are usually of lower strength than the crystalline rocks encountered in many HDR fields, the event magnitudes will be lower and there may be problems with a low signal to noise ratio for relatively small slip events when using conventional geophones. While the Richter magnitude of induced events is typically between +1 and –2 in crystalline rock, in sedimentary rock, event magnitudes can be –2 to –4. It is recommended that high-sensitivity seismometer arrays be placed in the reservoir close to the origin of the MS activity to detect low-magnitude events. However, MS events above the noise floor of conventional geophones are of primary interest as they are more likely to cause significant damage to fault seals. The emphasis of monitoring will be to establish accurate source locations and to refocus MS event clouds in order to delineate fracture geometries, and to reveal fracture activation and fluid-flow paths.

Geomechanical Interpretation

Micoseismic activity follows injection of reservoir pore fluids at pressures which have approached the critical state for slip on fractures. These events most probably arise from faults and fractures that are optimally oriented for slip. It should be noted that the MS activity has been shown to be associated with the advancement of fluid pressure fronts [35] and these fluids may not necessarily be injected CO_2, but may be *in situ* pore fluids such as brines or hydrocarbons. In order to quantify the displacement on faults due to induced slip, it is desirable to calculate the fault-plane solutions from the first motions of the recorded seismograms. This requires a well calibrated seismic array using test firings to determine velocity models, possibly along with bore-hole imaging at reservoir depths. If there are sufficient events and a high degree of precision in the recording system is available, then fault-plane solutions can be performed which will give the moment tensor acting at the source. Spectral content of the MS events can yield parameters such as event radius (according to the Brune [36] model) and stress change at the event source. Furthermore, if the event-source radii are known, estimates of the area over which fluid may flow in the fractured zone can be made since the fractures become areas of increased permeability.

Nolen-Hoeksema and Ruff [33] describe moment tensor analysis of MS events following injection in a thick sandstone – shale sequence, the M-site in the Mesaverde sequence (Figure 5). They conclude from their analysis that slip planes from where the events originate are parallel to hyrdofrac surfaces but are rotated with respect to the regional stress field. If MS events arise in the CO_2-reservoir cap rock and shales, such analysis will be critical in monitoring reservoir-seal integrity.

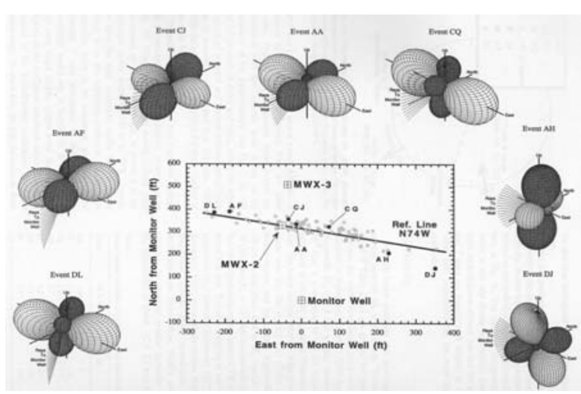

Figure 5: Moment tensor displays for seven events in the B-sand at the M-site. After Nolen–Hoeksema et al. [32].

DISCUSSION

This study has focused on effective-stress changes that can occur due to pore-fluid pressure increase during CO_2 injection. Effective-stress changes are of immediate relevance, as high pore-fluid pressures that lower effective stresses can cause brittle failure in rocks, which in CO_2 storage sites can damage the reservoir seal integrity.

Uncertainty in Predictions of Effective Stress

Predictions of effective-stress change as a consequence of pore-fluid pressure increase in conjunction with fluid injection are associated with some uncertainty for several reasons. The poroelastic behaviour of the porous reservoir rock is usually not known. Laboratory tests on some porous rocks indicate that the poroelastic coefficient is dependent on the confining pressure [15]. In cases where α <1, estimates of maximum sustainable pore-fluid pressures that are based on Eq. (1) may not be accurate. However, given the observations by Santarelli et al. [21] and Hettema and de Pater [22], it is not clear whether the poroelastic behaviour of reservoir rock during fluid injection would significantly affect effective stresses or total stresses on a reservoir scale. This remains to be investigated in CO_2-demonstration and -storage projects.

Monitoring for Effective Stress Changes in CO_2-Demonstration Projects

In CO_2-storage projects, monitoring should be conducted to test for pore pressure/stress coupling during CO_2 injection. One way is to repeatedly perform extended leak-off tests and hydraulic-fracturing tests over the injection period in order to determine the total horizontal stresses. Together with formation-fluid pressure measurements, this can indicate whether pore-pressure increases associated with CO_2 injection have changed the total horizontal stresses.

Monitoring for injection-induced MS events should be conducted during CO_2 injection to provide a mechanism to detect accidental over-pressurization of the reservoir formation. The detection of such events would allow real-time adjustment of injection pressures, if required [8]. Passive seismic monitoring will also provide a control mechanism against damage from a potential overestimation of maximum sustainable fluid pressures. In specific cases, MS events could be intentionally induced, such as in specially devised testing programs, to calibrate geomechanical predictions against the first occurrence of induced MS events.

CONCLUSION

This study has discussed the effects of pore-fluid pressure change on effective stresses in porous reservoir rock. While there is substantial information on pore pressure/stress coupling during pressure depletion in hydrocarbon fields, little is known about such effects during fluid injection. Thus, in cases where CO_2 storage in severely depleted reservoirs is envisaged, geomechanical methods that predict depletion-induced faulting, such as by Streit and Hillis [20], can be useful for estimating whether fault-seal damage was induced. In cases where Biot's α can be determined for reservoir rocks in CO_2-storage sites, velocity-effective stress relationships should be established to also measure effective-stress changes with seismic techniques in addition to direct fluid-pressure measurement in monitoring wells. To test for injection-related changes in total horizontal stresses in CO_2 storage or demonstration projects, extended leak-off tests and hydraulic-fracturing tests can be conducted. In storage sites with an identifiable risk of injection-related fault reactivation to produce events of noticeable magnitude, geophones and transducers should be installed for the monitoring of induced MS events. The monitoring can then be used to detect accidental over-pressurization of the formation as it is likely to allow for real-time adjustment of injection pressures, if required.

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