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A rock physics simulator and its application for CO_2 sequestration process

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Key Words: rock physics, seismic response, CO_2 sequestration

ABSTRACT

Injection of CO_2 into underground saline formations, due to their large storage capacity, is probably the most promising approach for the reduction of CO_2 emissions into the atmosphere. CO_2 storage must be carefully planned and monitored to ensure that the CO_2 is safely retained in the formation for periods of at least thousands of years. Seismic methods, particularly for offshore reservoirs, are the primary tool for monitoring the injection process and distribution of CO_2 in the reservoir over time provided that reservoir properties are favourable. Seismic methods are equally essential for the characterisation of a potential trap, determining the reservoir properties, and estimating its capacity. Hence, an assessment of the change in seismic response to CO_2 storage needs to be carried out at a very early stage. This must be revisited at later stages, to assess potential changes in seismic response arising from changes in fluid properties or mineral composition that may arise from chemical interactions between the host rock and the CO_2. Thus, carefully structured modelling of the seismic response changes caused by injection of CO_2 into a reservoir over time helps in the design of a long-term monitoring program. For that purpose we have developed a Graphical User Interface (GUI) driven rock physics simulator, designed to model both short and long-term 4D seismic responses to injected CO_2. The application incorporates CO_2 phase changes, local pressure and temperature changes, chemical reactions and mineral precipitation. By incorporating anisotropic Gassmann equations into the simulator, the seismic response of faults and fractures reactivated by CO_2 can also be predicted.

We show field examples (potential CO_2 sequestration sites offshore and onshore) where we have tested our rock physics simulator. 4D seismic responses are modelled to help design the monitoring program.

INTRODUCTION

Theories and empirical models developed in rock physics provide essential tools for the seismic analysis of porous media. They relate the micro-structure of a porous rock to its seismic response. Widely used theories and formulations have been discussed by numerous researchers in this field (Gassmann, 1951; Wyllie et al., 1958; Mavko et al., 1998). To make these models readily accessible to a wider geophysical community, we have developed a user-friendly GUI-driven rock physics simulator, for fluid substitution in generalised media. Specifically for CO_2 sequestration objectives, we also include computations of CO_2 and CH_4 properties under variable temperature and pressure regimes (Rowe and Chou, 1970; Span and Wagner, 1996; Angus and Reuck, 1976). Moreover, variation in CO_2/CH_4 mixtures under variable pressure and temperature conditions is also incorporated into the calculations (Duan et al., 1992). Fluid-substitution modelling can then be performed to assess the 4D seismic response to CO_2 injection.

During a long-term CO_2 sequestration process, the composition of fluid in the pore space may change, accompanied by chemical reactions, change in minerals composition, precipitation of new minerals, and often changes in reservoir pressure and porosity (Johnson et al., 2001). Such changes will produce different seismic responses over time, depending on the type of the host rock (lithology and mineral composition of the reservoir), its porosity, permeability, injection rate, pressure at the well, and the CO_2 state-of-phase. Our simulator transforms such changes into equivalent seismic responses.

COMPUTATION OF ELASTIC PARAMETERS OF A RESERVOIR

At low frequencies, Gassmann (1951) and Biot (1956) predicted the effective bulk modulus $K_{saturated}$ and shear modulus $\mu_{saturated}$ of saturated porous rocks. The equations are as follows:

$$K_{saturated} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{grain}}\right)^2}{\frac{\phi}{K_{fluid}} + \frac{1-\phi}{K_{grain}} - \frac{K_{dry}}{K_{grain}^2}}, \quad (1)$$

$$\mu_{saturated} = \mu_{dry}. \quad (2)$$

Here, K_{grain} and μ_{grain} are the bulk modulus and shear modulus for grain minerals, while K_{dry}, μ_{dry} are for dry frame rocks. K_{fluid} is the bulk modulus for the saturating fluid, and ϕ represents the porosity value. From equations (1) and (2), we need the values of K_{grain}, μ_{grain}, K_{dry}, K_{fluid}, μ_{dry}, ϕ, to estimate the effective bulk and shear moduli of fluid-saturated porous rocks. Then we can compute the P- and S-wave velocities using:

$$v_p = \sqrt{\frac{k_{saturated} + \frac{4}{3}\mu_{saturated}}{\rho}}, \quad (3)$$

$$v_s = \sqrt{\frac{\mu_{saturated}}{\rho}}. \quad (4)$$

Here, ρ is the density for the fluid-saturated porous rocks.

From well logs, core sample analysis, and a priori geological knowledge of the local basin conditions, porosity, density, pressure, temperature, permeability, mineral composition, P- and S- wave velocities may be estimated with various proposed fluids or their mixtures occupying the pore space. However, the evaluation of

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elastic moduli for grain minerals and the dry rock frames is not exact and in general may be prone to errors. Widely used theories and formulations have been discussed by numerous researchers in this field (Wyllie et al., 1958; Krief et al., 1990; Mavko et al., 1998). These theories and empirical models developed in rock physics enable us to utilise Gassmann's equation (Gassmann, 1951) for computation of the properties of fluid-saturated rocks. In practice an optimum approach has to be evaluated for any specific sedimentary basin. To help such processes, we have devised several utilities, which enable the user to make the right choice, particularly when either computing dry moduli or modelling them from log data. The final stage of the simulator provides a full short- and long-term prediction of the 4D seismic response to a CO_2 injection process.

FSM_SIMULATOR

FSM_SIMULATOR is a program manager for launching simulations of seismic property changes in fluid-saturated porous rocks. There are three major components:

- Computation of fluid properties for a single or multiple constituents under reservoir conditions
- Computation of elastic properties of porous rocks containing different fluids or fluid mixtures
- 4D seismic response prediction for generalised porous rocks containing CO_2 or fluid mixtures

The FSM_SIMULATOR control box is shown in Figure 1. While each module can be used independently, the computation of fluid properties is normally conducted first.

Fluid property calculation

The calculation of the physical properties of a fluid saturating a reservoir is an essential step for fluid-substitution modelling. For different fluid types such as brine, oil, live oil, and gas, the density and bulk modulus are calculated from the Batzle and Wang (1992) equations. For a fluid mixture we use Wood's formula (Wood, 1955). The Voigt (1890) average could be used for a patchy saturation when the fluid phases are mixed more heterogeneously relative to the seismic wavelength. For CO_2 sequestration objectives we also include computations of the properties of a CO_2/CO_2 saturated brine and CH_4/CH_4 saturated brine under variable temperature and pressure regimes (Rowe and Chou, 1970; Span and Wagner, 1996; Angus and Reuck, 1976; Duan et al., 1992).

Computation of dry and saturated moduli

To utilise the Gassmann equation for fluid-substitution modelling, we must estimate the elastic moduli of the grain mineral and the dry rock frame. For a heterogeneous rock, Hashin-Shtrikman bounds, the Kuster-Töksöz formula, and the Reuss average can be used to predict average grain moduli K_{grain} and μ_{grain} (Mavko et al., 1998). There are also several theoretical and empirical models that estimate the dry frame moduli K_{dry} and μ_{dry} for dry rock frames. They are: the Krief empirical formula, the Nur model, the Geertsma model, the Hertz-Mindlin model, the Walton model for infinitely rough grains, smooth grains, and their average values, the uncemented sand model with cement deposited within the pore spaces away from the grain contacts, and the cemented sand model with cement deposition evenly across the grain surfaces and only at the contacts between grains (Mavko et al., 1998; McKenna, 2002). With the estimated values of bulk and shear moduli for the grain and skeleton frame, combined with the fluid moduli, the effective moduli for the fluid-saturated porous rocks can be computed via the Gassmann-Biot equations. The velocities for P- and S-waves, Poisson's ratio, and other elastic properties can then be derived. Comparing the calculated with measured values, a suitable model for the local basin conditions can be determined. Apart from the existing models for the calculation of dry moduli, we may also directly compute the dry moduli from the logs using the Gassmann equation, provided that the elastic moduli for mineral constituents, pore fluid, and the porous rocks are known or modelled beforehand. Using the appropriate model, the seismic properties for the reservoir under different fluid saturation can be estimated.

The porous frame may be composed of two different types of solid constituent. For example, sandstone may contain a substantial part of clay in its pores. Assuming the relative change in volume of each constituent equals the volume changes of the equivalent medium, Berryman and Milton (1991) derived equations for the calculation of the elastic moduli for porous rocks with two constituents. Such a model is also incorporated into our rock physics simulator.

In practice, the measured input parameters always have errors to some degree. It is important that the input errors should not influence the calculation results of the elastic moduli to the point that the calculation is unreliable. For that reason we designed the Sensitivity Analysis module to analyse the uncertainty of the final results if one of the input parameters is estimated with error of up to ±10%. While it is unlikely that error exists in only one input parameter, this type of analysis provides an estimate of the potential error involved in computation of elastic moduli, for a particular case.

After selecting an optimum model for computation of elastic moduli and performing sensitivity analysis, further fluid-substitution modelling is performed, typically within the reservoir interval. In some cases accurate information about mineral grain moduli under reservoir conditions may not be available. Consequently, the values assumed may result in inaccurate velocity estimations. A best-fit iterative approach is then used at this stage to find the most suitable values from the log data for the selected computational model.

Anisotropy and fracture density

Another feature of the simulator is the computation of elastic moduli for saturated fractured porous rock and prediction of its 4D seismic response. In terms of CO_2 sequestration, such an analysis is important for an early detection of fault and fracture reactivation caused by CO_2 upward migration (buoyancy effect) or increased pore pressure. CO_2 migration along existing fractures will also be important in predicting long-term CO_2 flow. For a fractured porous

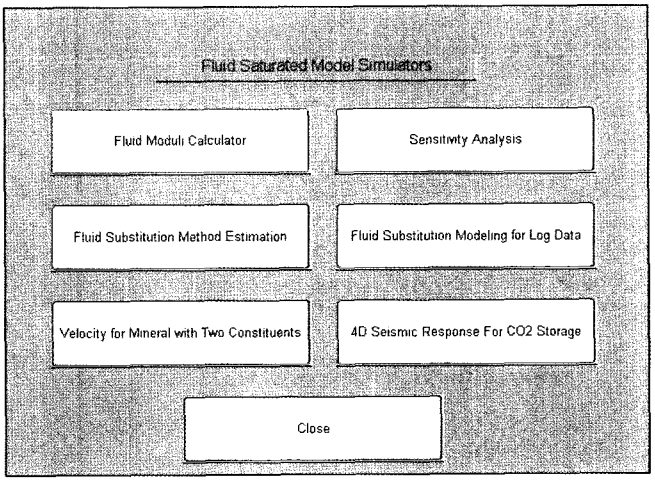


Fig. 1. The user interface for the FSM_SIMULATOR program.

reservoir the anisotropic Gassmann equation (Gurevich, 2003) is utilised for fluid substitution and included in the simulator.

Prediction of seismic response to a long-term CO_2 sequestration

After injection of CO_2 in a shallow aquifer, CO_2 will typically migrate as an immiscible fluid and start replacing formation water in the reservoir. CO_2 is trapped beneath a seal and this is often referred to as structural trapping (McKenna, 2004). After a substantial time in which CO_2 is structurally trapped within the reservoir, solubility trapping will occur as CO_2 dissolves in the formation water. Gradually, CO_2 will interact with the host-rock frame (by exchange of minerals, or precipitation). This final stage is known as mineral trapping and the reservoir will involve petrophysical alterations (McKenna, 2004). During these CO_2 storage stages, changes in fluid type, porosity, and pressure, chemical reactions, mineral precipitations, and other processes may cause a detectable change in the seismic response. Our simulator can be used to estimate the time-lapse or 4D change in the seismic response and assess the feasibility of seismic monitoring.

To examine the free CO_2 effect, a numerical simulation is implemented first for the seismic response of brine with different CO_2 saturations. The reservoir rock frame is composed of quartz and clay with 20% porosity. Pore pressure is 14.48 MPa, the overburden pressure is 33.44 MPa, and temperature is 92°C. Figure 2 shows the density and bulk moduli of the fluid mixture with different CO_2 saturations. The velocities and velocity ratio for the fluid-saturated rocks are also displayed by using the Krief model to calculate the bulk and shear moduli for the dry rock frame. As the arrows indicate in the figure, even a very small amount of CO_2 will dramatically change the fluid properties, and hence, cause large changes in the porous rock properties. These changes can be used to assess the feasibility of seismic monitoring.

The methodology described above has been applied to the Otway Basin and the Perth Basin, which are two potential CO_2 sequestration sites in Australia.

OTWAY BASIN 4D SIMULATION

A depleted gas field in the Otway Basin is considered a potential test site for CO_2 sequestration. The Naylor 1 well at this site was available for the analysis and simulation of the seismic response. Before production, a sonic log and surface seismic data were acquired (Figure 3). Core samples of the reservoir Waarre Sandstone were also tested in the CSIRO Petroleum laboratory (Siggins, 2006). This work established the following relations

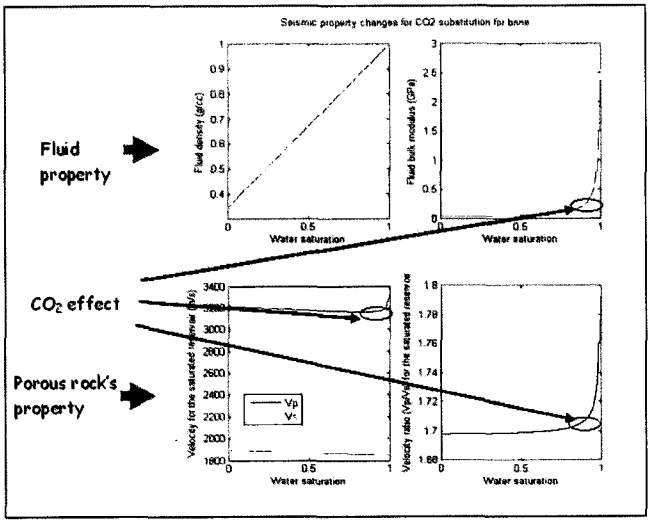
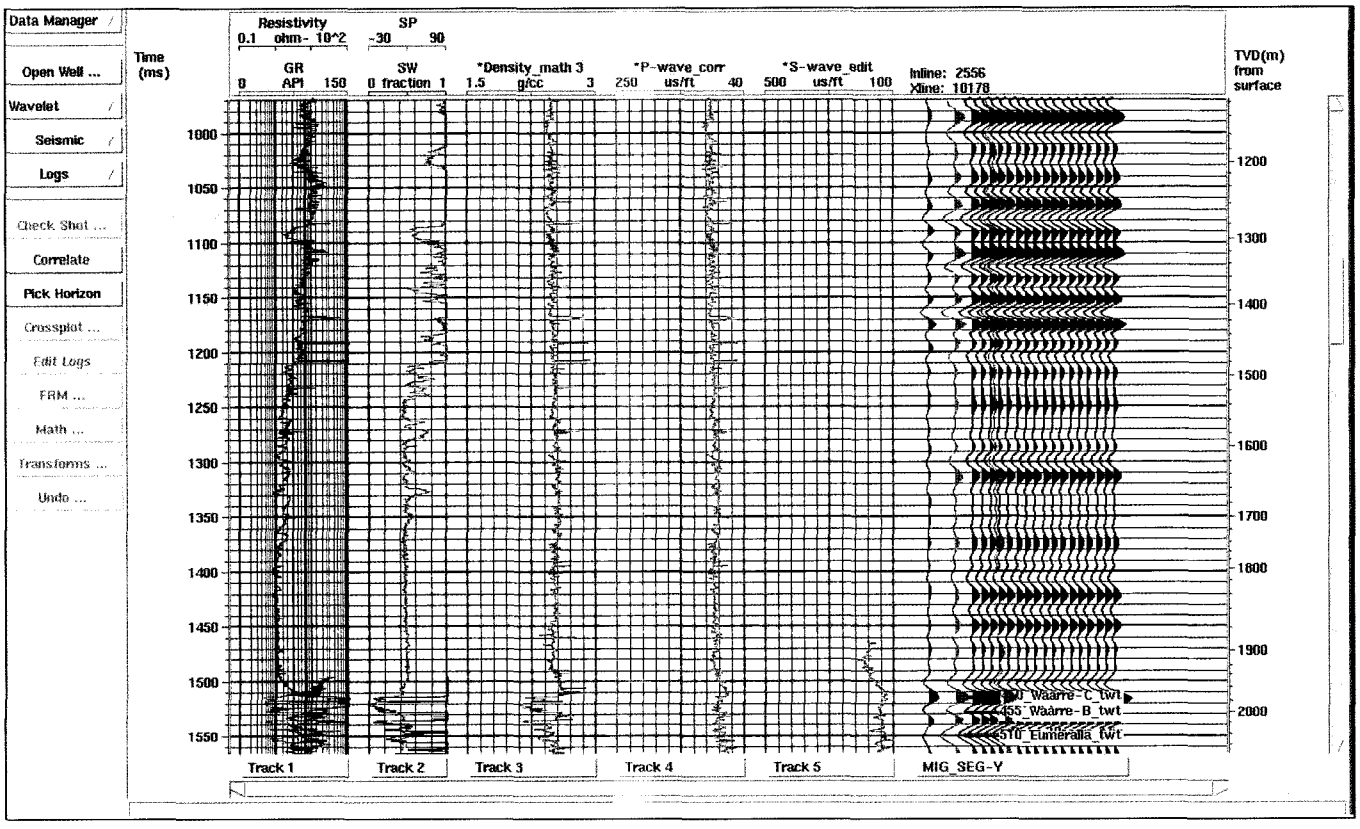


Fig. 2. The effect of free CO_2 gas on elastic moduli for different saturation levels.



linking seismic velocities and density for the dry Waarre Sandstone to varying effective pressure:

$$v_{p\text{dry}} = 1922.5 P_{\text{eff}}^{\ 0.1678} \text{ (m/s)}, \quad (5)$$

$$v_{s\text{dry}} = 1007.5 P_{\text{eff}}^{\ 0.0961} \text{ (m/s)}, \quad (6)$$

$$\rho_{\text{dry}} = 1966.3 \text{ kg.m}^{-3}. \quad (7)$$

The laboratory measurements were also carried out for the Waarre Sandstone saturated with CO_2 in various phase states. The laboratory measurements established that the Gassmann equation can predict velocities for Waarre Sandstones for different CO_2 saturations and effective pressures provided that effective pressures are relatively high. Effective pressures must be sufficiently high so that compliant pore space is compressed and doesn't contribute to the bulk modulus and influence seismic wave propagation. This justified the use of our simulator for the prediction of 4D seismic response at this site.

The fluid and mineral moduli are derived from petrophysical data obtained for the reservoir before gas production. Dry bulk and shear moduli at each reservoir depth are then derived from the measured logs by using the Gassmann equation. A cross-check between mineral and dry frame moduli shows that in this case inversion for dry moduli from log data works reasonably well (Figure 4). By using subscript 0 to represent the physical property for pre-production values, the dry bulk and shear moduli under different effective pressures can be recovered by the use of equations (5) and (6), as follows:

$$\mu_{\text{dry}} = \mu_{\text{dry}\,0}\left(\frac{P_{\text{eff}}}{P_{\text{eff}0}}\right)^{0.1922}, \quad (8)$$

and

$$k_{\text{dry}} + \frac{4}{3}\mu_{\text{dry}} = (k_{\text{dry}} + \frac{4}{3}\mu_{\text{dry}})_0\left(\frac{P_{\text{eff}}}{P_{\text{eff}0}}\right)^{0.3356}. \quad (9)$$

After gas production, the pore pressure decreased from 26.37 MPa to 14.48 MPa, and the reservoir is saturated with brine and methane with the saturation ratio 0.7:0.3. We assume the injected CO_2 will substitute part of the brine and the saturation ratio for brine, CO_2, and CH_4 is 0.09:0.61:0.3, while the pore pressure increased to 15.86 MPa due to the CO_2 injection. The predicted seismic response after CO_2 injection for reservoir depth between 2041 m and 2049 m, is shown in Figure 5a. The percentage changes for the density and velocities after the CO_2 injection are shown in Figure 5b. This example considers only one of several possible scenarios that could happen after CO_2 injection. For example, the CO_2 could fill the space between the methane cap and water saturated sand, instead of being mixed with the methane. If that is the case, the seismic responses will show different characteristics. By seismic monitoring, such changes should be measured and compared to the predicted response. This will enable us to understand the fluid distribution, reservoir pressure, and saturation amount.

PERTH BASIN MODELLING STUDY

A similar feasibility study was conducted in offshore Perth Basin. The main objective at this site was to assess the potential of 4D seismic measurements for monitoring the distribution of a CO_2 plume.

There are measured data from 17 petroleum exploration wells, and extensive seismic surveys allow us to construct a detailed structural section across the Southern Perth Basin (Figure 6). The offshore basin (the Vlaming Sub-basin) has previously been identified as an Environmentally Sustainable Site for CO_2 Injection (ESSCI), relatively close to potential sources in the Kwinana area approximately 40 km distant. The Gage Sandstone is the potential reservoir for the injected CO_2. We use the log data from well Mullaloo 1 to study the seismic response changes resulting from the CO_2 injection process.

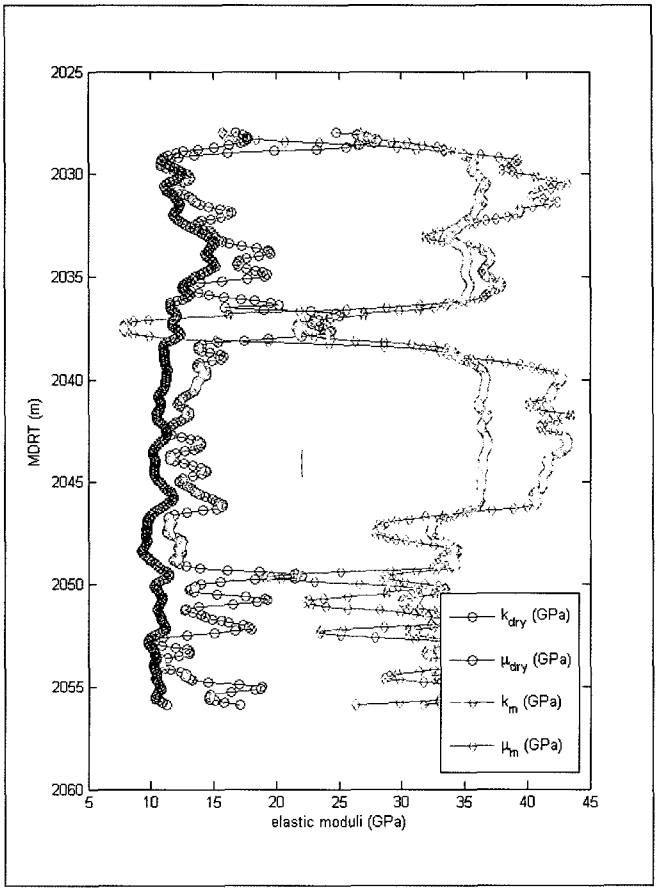


Fig. 4. Dry moduli at each depth from log data, derived using the Gassmann equation. The computed grain moduli are also shown. In this case inversion for dry moduli from log data works reasonably well.

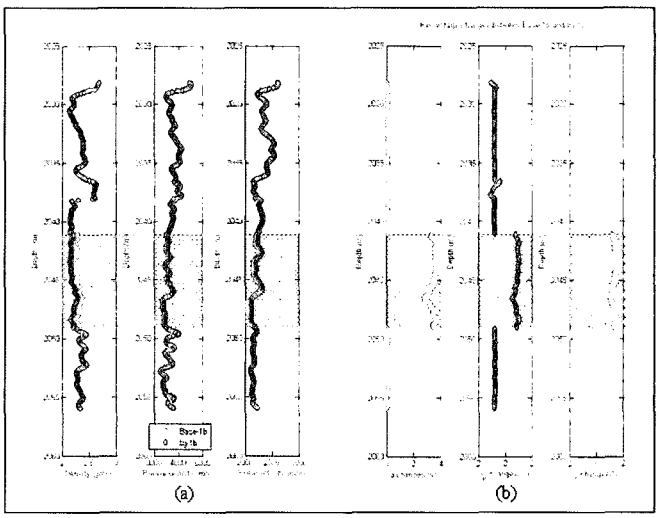


Fig. 5. Fluid-substitution results for CO_2 injection. After CO_2 injection, CO_2 is assumed to replaced 61% of its original fluid in the shaded area between depth 2041 m and 2049 m. (a) The density and velocities before and after CO_2 injection. (b) The percentage changes for the density and velocities after the CO_2 injection.

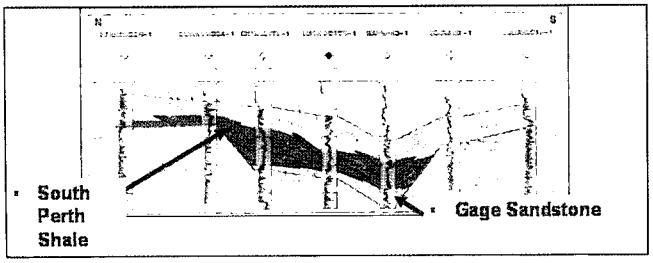


Fig. 6. The structure section for the Gage Sandstone in Perth Basin.

South Perth Shale dominates the interval between 1200 m and 1500 m depth, while Gage Sandstone is present between 1500 m and 1650 m. Gage Sandstone is composed of quartz and clay. Overburden pressure is 33.75 MPa and pore pressure is 15 MPa, and temperature is 60°C. As an example we represent 4D seismic response changes (post- minus pre-injection) in the form of 3D plots (Figure 7), modified from the initial research by McKenna et al. (2003). Changes in seismic velocities, density, v_P/v_S ratio, $\lambda\rho$, and $\mu\rho$ attributes are computed here as functions of pressure (or depth), saturation, and temperature. Noticeable 4D effects are observed for assumed different saturations of immiscible CO_2. This clearly shows that 4D seismic methods are technically feasible, based on reservoir and fluid properties, and could be a primary monitoring tool at this site.

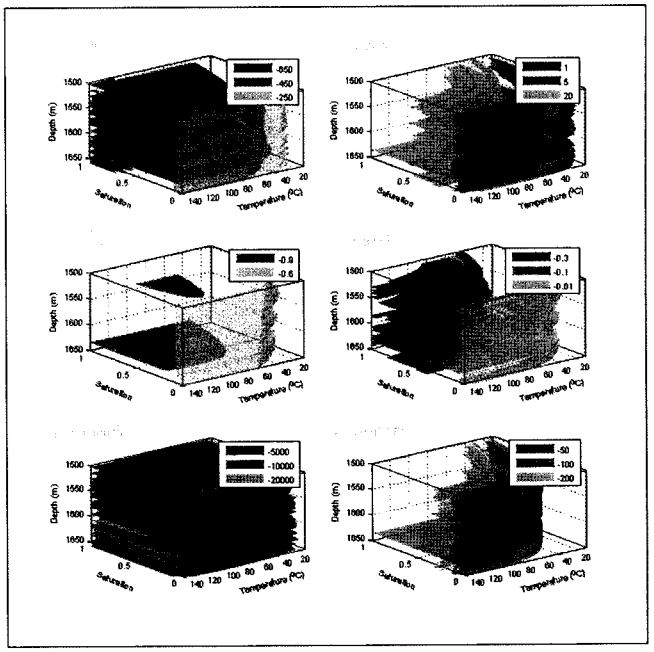


Fig. 7. Fluid-substitution modelling for Perth Basin. 4D seismic response changes (post- minus pre-CO_2 injection) are displayed for different saturations (immiscible CO_2).

CONCLUSIONS

A rock physics simulator has been developed for evaluation of the elastic moduli for a generalised porous medium. The software enables a quick selection of the optimum approach for computation of elastic moduli. The inclusion of an anisotropic Gassmann equation into the simulator made it more versatile and applicable to any reservoir condition. Computed changes can be shown in a variety of ways including 3D plots, log-type, or block diagrams.

The rock physics simulator has been successfully applied to the Perth Basin and Otway Basin, to model 4D seismic response changes caused by CO_2 injection, and will help assess the feasibility of seismic monitoring at these sites. The simulator can also be used to assess the feasibility of seismic monitoring to detect leakage into overlying formations. The use of the simulator is not limited to a CO_2 sequestration process. It can be conveniently used for a generalised AVO analysis in hydrocarbon exploration.

ACKNOWLEDGMENTS

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岩石物性シミュレータと CO_2 地層貯留処理への応用

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要 旨： 地下塩水層への CO_2 の圧入は、その容量の大きさがゆえに、大気中への排出二酸化炭素の減少の方策として最も有望視されている。CO_2 が地層内で少なくとも数千年間安全に貯留されることを保証するには、CO_2 貯留は慎重に計画・監視しなければならない。貯留層の諸条件が好都合な場合、地震探査法による特に海底貯留層探査は、貯留層の注入過程と貯水層中の CO_2 の分布の経時変化をモニタリングする最良の手法である。地震探査法は潜在的トラップ、貯水層特性、およびその容量の算定にもまた不可欠である。したがって、CO_2 貯留層に対する地震波の応答は、プロジェクトの初期段階に調査する必要がある。また、流体特性の変化や母岩と CO_2 との化学反応から起りうる鉱物構成の変化に起因する地震波応答の変化を評価するために、後に再利用する必要がある。CO_2 を貯留層に圧入することにより生じる、地震波応答の経時変化を、慎重にモデリングすることは、長期モニタリング・プログラムの設計に役立つ。そのために、筆者らは CO_2 圧入後の短期・長期の 4D 地震波応答をモデル化するための、グラフィカルユーザインタフェイス(GUI)つき岩石物性シミュレータを開発した。 このアプリケーションには CO_2 相変化、局所的圧力・温度変化、化学反応、および鉱物析出が組み込まれている。異方性を考慮した Gassmann 方程式を組み入れることによって、このシミュレータは CO_2 圧入により”再活性化”された断層・破砕に対する地震波応答をも予測する事ができる。

本論文では、筆者らの岩石物性シミュレータを実フィールドデータに用いた例(陸上と海底の CO_2 地層処理候補地)を示す。モニタリング・プログラムを設計する一助とするために、4D の地震波応答のモデリングを実施した。

キーワード：岩石物性、弾性波応答、CO_2 地層処分

CO_2 격리 처리를 위한 암석물리학 모의실험장치와 그 응용

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요 약： 지하 염수층의 CO_2 주입은 큰 저장 능력으로 인하여 대기 중으로의 CO_2 방출을 감소시키기 위한 가장 유망한 방법일 것이다. CO_2 저장은 적어도 수 천년 간 CO_2 가 지층 안에 안전하게 남아있도록 주의깊게 계획되고 모니터링되어야 한다. 특히 해양 저류층에 대한 탄성파 탐사 방법들은 알맞은 저류층 특성이 제공된다면 CO_2 의 주입공정과 분산을 모니터링하기 위한 일차적인 수단이다. 탄성파탐사 방법은 잠재적인 트랩, 저류층 특성, 저류층 저장능력의 규명에 또한 필수적이다. 따라서 CO_2 저장에 대한 탄성파 반응의 변화에 대한 평가는 매우 초기 단계에 이루어져야 한다. 이것은 모암과 CO_2 사이의 화학적 작용에 의해 일어날 수 있는 유체의 특성이나 광물 조성의 변화에 따른 탄성파 반응에서의 잠재적 변화를 평가하기 위해 나중 단계에 다시 고려될 필요가 있다. 따라서 저류층에 일정시간 이상의 CO_2 주입에 의한 탄성파 반응 변화에 대해 섬세히 구축된 모형은 장기간의 모니터링 프로그램 설계에 도움을 준다.

그러한 목적으로 주입된 CO_2 에 대한 단기간과 장기간의 4 차원 탄성파 반응을 모델링하도록 설계된, 그래픽 사용자 인터페이스(GUI)를 채택한 암석물리학 모의실험장치를 개발했다. 적용분야는 CO_2 위상 변화, 국부적인 압력과 온도 변화, 화학 반응 및 광물의 침전을 포함한다. 이방성 가스만(Gassmann) 식을 모의실험장치에 고려시킴으로써 단층과 파쇄대를 재활성화 시키는 CO_2 의 탄성파 반응 또한 예측될 수 있다.

이 논문에서는 암석물리학 모의실험장치를 적용했던 현장(해상과 육상의 잠재적 CO_2 격리 지역)의 사례를 보여주고 있다. 4 차원 탄성파 반응들이 모니터링 프로그램의 설계를 돕기 위하여 만들어 졌다.

주요어： 암석물리학, 탄성파 반응, CO_2 격리

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