Estimating Vertical Permeability
Based on Responses to Barometric Pressure Fluctuations in the Lesueur Formation

Project Report

*prepared for*

Australian National Low Emissions Coal Research and Development Ltd.
(ANLEC)
ACN 135 762 533
PO Box 3391
Manuka, ACT 2603
Australia

*prepared by*

Dr. Yingqi Zhang
Dr. Barry Freifeld
Class VI Solutions
711 Jean St.
Oakland, California 94610 USA

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Executive Summary

The vertical permeability of CO₂ storage formations and specifically those of confining layers are key parameters affecting the effectiveness of structural CO₂ trapping or the risk of leakage. As an potentially attractive method to examine the integrity of a large CO₂ storage site, long-term, passive, accurate monitoring of pressure variations in response to barometric pressure fluctuations and Earth tide effects may provide a means to assess the continuity of the confining units and their hydraulic properties. A scoping study of such responses and their suitability for determining vertical permeability is ascertained by numerical modelling combined with notional inversions and data-worth analyses.

One- and two-dimensional numerical models were developed to analyse the pressure response to Earth-tide and barometric fluctuations within and across different CO₂ storage formations and associated confining units. The models simulate fluid flow and pressure propagation triggered by the imposed loading effects and associated fluid pressure changes. The two-dimensional models include hydrogeological and geomechanical variabilities, which represent the presence of elongated facies (such as floodplain paleosols and vertisols) that may act as local confining layers. Heterogeneity within a given facies is also included in the geostatistical model.

The analyses suggest that the pressure fluctuations observed in deep boreholes may be used to infer hydrogeological and geomechanical properties. However, because the pore pressures induced by barometric and Earth-tide loading and the dissipation of these pressure perturbations are controlled by the local hydrogeomechanical properties rather than the large-scale hydrostratigraphic features of the CO₂ storage system (including medium-scale heterogeneity due to the deposition of high- and low-energy facies as well as small-scale heterogeneities within facies), it appears unlikely that reliable estimates of vertical permeability and/or continuity of the confining layer can be obtained by analysing pressure fluctuation data.

Accurate pressure data may be useful, however, to detect the presence and track the migration of a CO₂ plume during the operational and monitoring phase of a carbon storage project.
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1. Background

1.1 Problem Description

The vertical permeabilities of CO$_2$ storage formations and specifically those of confining layers are key parameters affecting the effectiveness of structural CO$_2$ trapping or the risk of leakage. Assessment of vertical permeability at the field scale is extremely challenging. Small-scale measurements on core plugs may not reflect the behaviour of a system that may consist of sand/shale baffles of variable lateral extent.

As an alternative, long-term, passive, accurate monitoring of pressure variations in response to barometric pressure fluctuations and/or Earth tide effects may provide a means to assess the continuity of the confining units and their large-scale, effective hydraulic properties.

As an illustration, Figure 1 shows land surface barometric pressure fluctuations and the response of a reservoir at a depth of 1500 m acquired at a well in Victoria, Australia. Clearly seen at reservoir depth are the impacts of the barometric fluctuations along with the response to solar and lunar Earth tides. Using passive forcing mechanisms, such as Earth tides and barometric pumping, to assess vertical permeability would greatly aid in the determining of site suitability for CO$_2$ sequestration.

![Figure 1](image.png)

Figure 1. Land surface barometric pressure fluctuations along with the reservoir response acquired from a reservoir at 1500 m depth in Victoria, Australia.
1.2 Objectives and Scope

The overall objective of this scoping study is to investigate the suitability and sensitivity of passive pressure monitoring for determining the large-scale vertical permeability of potential CO₂ storage formations and associated confining layers.

The investigation will be performed primarily by numerical modeling combined with notional inversions and data-worth analyses. The specific objectives of these modeling studies are to develop synthetic data to

1. predict the pressure below, in, and above a confining layer in response to synthetically generated atmospheric pressure fluctuations;
2. estimate the uncertainty of these predictions given uncertainty in key hydrological parameters and forcing terms;
3. examine the impact of Earth tides on the observed pressure responses;
4. calculate the approximate uncertainty with which vertical permeability could be estimated based on the calibration of a reservoir model against long-term pressure data; and
5. examine the relative worth of data collected at different depths in support of an initial design of a monitoring system.

The use of barometric pressure fluctuation and Earth tide signals for determining the continuity of permeability barriers will be examined using a simplified conceptual model. This model will include relevant features and conditions of the Lesueur site and be populated with known properties to the extent warranted by the model structure and objectives of the analysis.

1.3 Historical Remarks

Well water level measurements are routinely taken to determine hydraulic head and to infer groundwater flow conditions within an aquifer, either under ambient conditions or as part of a well test. Such measurements usually exhibit fluctuations in response to natural external stress changes, such as those imposed by barometric pressure changes, tidal or river-stage fluctuations, Earth tides, tectonic events, or recharge.

On the one hand, these fluctuations are often considered unwanted noise that needs to be filtered out from the water level data in order to avoid erroneous head calculations and misinterpretation of aquifer conditions.

On the other hand, since the tidal potential and barometric pressures at the land surface can be accurately calculated or measured, respectively, the downhole pressures (either measured as the absolute pressure or a water level in a well) can be analysed in the time or frequency domain to infer geomechanical and/or hydraulic properties. The interpretation of such data (and the parameters that can be estimated) depends on (1) the well conditions (open or closed, magnitude of wellbore storage, skin effects), (2) the measuring device (absolute or gauge pressure), (3) the formation properties themselves, and (4) the degree of aquifer confinement (confined, semi-confined, unconfined). Early investigations of confined
aquifer responses include those of Jacob [1940], Ferris [1963], Bredehoeft [1967] and Hsieh et al. [1987; 1988]; studies related to unconfined aquifers include Weeks [1979], Rojstaczer [1988] and Rojstaczer and Riley [1990].

In the current project, we are mainly interested in estimating large-scale vertical diffusivities of the confining layer overlying a potential CO2 storage formation. The behaviour of semi-confined aquifers and the determination of barometric response functions for property estimation have been summarized by Hussein et al. [2013]. Analytical models for predicting the borehole water level response to barometric pressure fluctuations have been developed and used to estimate degree of confinement, hydrostatic continuity of the confining layer, aquitard continuity, as well as confining layer and aquifer properties [Rasmussen and Crawford, 1997; Hare and Morse, 1997, 1999; Spane, 2001; Acworth and Brain, 2008; Butler et al., 2011]. Finally, Sato [2006] used changes in Earth-tide pressure responses as an indication of CO2 saturation changes. Wannell and Morrison [1990] estimated vertical permeability in an offshore hydrocarbon reservoir by measuring pressures across a gas-liquid interface as they respond to oceanic tides.

Various software packages related to Earth tides and barometric pressure fluctuations are available. They can be grouped into software for calculating ocean tides (e.g., SPOTL, NLOADF) or Earth-tide potentials or derived quantities, such as gravitational acceleration, as well as vertical, areal, or volumetric strains (e.g., ETGTAB, PREDICT, MT80W, ERTID). Other software packages have been developed specifically for the purpose of removing barometric and Earth-tide effects from measured data (e.g., BETCO [Toll and Rasmussen, 2007], TSOFT [van Camp and Vauterin, 2005]). BAYTAP is an example of a comprehensive tidal analysis software package.

Finally, the effects can also be calculated and analysed with an appropriate groundwater flow simulator, whereby the tidal forcing is included either as a source term or through a coupled simulation of hydromechanical processes. Moreover, barometric pressures can be imposed as time-dependent Dirichlet boundary conditions at the land surface. (An example of interpreting barometric forcing data in a multilayered formation to estimate hydraulic parameters can be found in a study performed at Yucca Mountain Nevada [Ahlers et al., 1999].) This last approach has the advantage of not being restricted to the simplified geometrical and hydrological conditions inherent in analytical approaches, or the limited explanatory power of purely data-driven correlations. Numerical simulation is thus the approach chosen for this project.

1.4 General Approach

Simulation of reservoir response to barometric and Earth tidal loading is carried out using the TOUGH2 non-isothermal multiphase flow and transport simulator [Pruess et al., 2012] as implemented in the iTOUGH2 simulation-optimization framework [Finsterle, 2004].

In our approach, transient fluid flow and fluid pressure diffusion in response to tidal and barometric forcing is calculated based on a finite-volume discretization of the mass-balance equations based on Darcy’s law. Estimation errors and data worth are
evaluated using linear uncertainty analysis; prediction errors are evaluated using either linear uncertainty propagation analysis or Monte Carlo simulations with Latin Hypercube sampling; correlations among the parameters can be taken into account. Depth-dependent property changes and correlations between porosity and permeability can be included. Earth-tide effects are simulated using a coupled mechanistic model of pore space compression or dilatation and fluid pressure diffusion; the approach is simplified by assuming that deformations are one-dimensional (see Section 2.2 for a detailed description).

Information available from the South West Hub drilling program (which has been used for formulating both the static and dynamic models of the South West Hub) serves as a starting point for development of an initial conceptual model as well as for the selection of representative property values for sensitivity and parameter estimation analyses.

The analysis presented in this report contains the following elements:

- A numerical model of a complexity appropriate for the given objectives is developed. Generic barometric pressure fluctuations at the land surface are applied, and the corresponding pressure response in the subsurface is simulated. Time lag and amplitude reduction as a function of depth and vertical permeability is examined.

- Uncertainty distributions of key input parameters are defined, and the corresponding uncertainty in predicted subsurface pressures is quantified.

- A method is developed to approximately represent pore-pressure fluctuations induced by Earth tide effects. Their magnitude relative to barometric pressure signals is examined.

- Using synthetically generated, fluctuating pressure data, notional inversions are performed to determine the uncertainty of estimated vertical permeability values using linear, Gaussian error analysis.

- An initial data–worth analysis is performed to determine the relative worth of pressure data measured at different depths for the estimation of vertical permeabilities.
2. Barometric and Earth Tide Effects in Well-Aquifer Systems

2.1 General Description of Processes

Barometric pressure fluctuations as well as the potential changes from Earth tides can be considered as uniform stress changes applied over a large area, leading to essentially one-dimensional, vertical deformations and pressure gradients inducing fluid pressure diffusion and potentially fluid flow. While changes in tidal and barometric loads act almost instantaneously everywhere within the Earth, barometric pressure changes also induce the flow of atmospheric gas in and out of the subsurface, leading to a dampened and delayed fluid pressure response as the fluctuations propagate through the unsaturated zone.

The way in which the well-aquifer system reacts to barometric pressure fluctuations and tidal loading effects depends on (1) the degree of aquifer confinement, (2) the hydraulic and geomechanical properties of the aquifer and overlying formations, and (3) the geometry and storage properties of the well.

In general, pressure fluctuations measured in response to tidal or barometric loading are the result of a combination of rock deformations and the propagation (or dissipation) of fluid pressure gradients. They are thus inherently a coupled hydrological-geomechanical problem. The solution to that problem is thus a function of hydrogeological, geomechanical, and fluid properties; the observable system response also depends on the frequency of the imposed fluctuations and local conditions (e.g., wellbore storage and skin effects). However, the analysis of tidal and barometric pressure effects are large in scale, as the tidal potential acts everywhere in the Earth, and atmospheric pressures act over a very large areal extent at the land surface. It is this aspect of tidal and barometric pressures that makes them potentially suitable for the identification of large-scale geologic features and their properties. Moreover, they are the result of naturally occurring phenomena, i.e., much cheaper than conducting large-scale field tests.

Following Rasmussen and Crawford [1997], we briefly describe the main mechanisms by which a change in barometric pressure is transmitted to the pore pressure in an aquifer, how this pressure is observed in a well, and to what extent the response depends on unknown or uncertain properties. It is useful to consider the extreme cases of a totally confined aquifer (i.e., an aquifer bounded by an impermeable cap rock), and an unconfined aquifer. The situation of interest to the current study is a semi-confined CO₂ storage formation, which can be expected to show a composite response.

For confined aquifers, the transmission of a change in load at the land surface to the pore pressure at depth is essentially instantaneous. For a compressible rock matrix, the increase in the aquifer’s pressure is a result of the compression/dilation of the pore space in response to an increase/decrease in the effective stress caused by loading/unloading at the land surface. However, the observable change in pore pressure represents only the fraction of the atmospheric pressure change that is not borne by the skeleton of the formation. By contrast, the atmospheric pressure is
fully and instantaneously transmitted to the water surface in an open well, inducing transient flow of water from the well into the aquifer as the two pressures equilibrate. This equilibration is akin to the pressure recovery from a slug test, providing the basis for the development of a water level response function to atmospheric loading [Box and Jenkins, 1976; Furbish, 1991].

The aquifer-well interaction described above is the topic of many publications related to the analysis of Earth tides and barometric pressure fluctuations. Such analyses may provide estimates of local, horizontal formation permeabilities in the vicinity of an open well. However, in this study we are concerned with the estimation of large-scale, vertical permeabilities by measuring pressure fluctuations in packed-off well intervals. Inference of large-scale properties may theoretically be possible because the pressure change induced by the cyclic compression and dilation of the pore space may dissipate vertically through a semi-confining layer, thus providing information about vertical hydraulic diffusivity. However, a vertical pressure gradient is only created if the poroelastic properties of adjacent formations are sufficiently different.

Finally, the atmospheric pressure perturbation travelling through the fluid phase from the land surface to a monitoring location also depends of the pneumatic and hydraulic diffusivities of the vadose and saturated zones, respectively. Whether such diffusivities can be estimated based on accurate measurements of pressure fluctuations in deep wells is the topic of this study.

The pressure at any given point in the subsurface is not only responding to Earth tide and barometric effects. In fact, such effects are generally much smaller than pressure changes induced by water table fluctuations in response to infiltration and recharge/discharge events, long-term changes in regional hydrologic boundary conditions (e.g., climate-change impacts on precipitation, evaporation, river stages and seal levels) as well as anthropogenic activities, specifically pumping of fluids for water resources and energy production (oil, gas, geothermal) or waste disposal (e.g., carbon dioxide, waste water, liquid wastes), irrigation and water banking, open-pit mining and tunneling, and other activities that directly interfere with the subsurface or the hydrologic boundary conditions. As the magnitude of these pressure changes is relatively large, they may mask the subtle signals from Earth tides or atmospheric fluctuations.

While most of these processes can be included in a general-purpose reservoir simulator (such as TOUGH2), the prediction uncertainty most likely remains high compared to the Earth tide and barometric pressure fluctuations, making a quantitative analysis of these signals more challenging. However, a flexible trend-removal algorithm could be used to filter out the signal of interest from the data and the simulation results. The principles of the analysis of barometric and tidal pressure fluctuations as presented here thus remain valid.

2.2 Definitions, Assumptions and Mathematical Development

In this section, we develop the mathematical framework needed to simulate Earth tides and barometric pressure effects. At the same time, we introduce key assumptions. We use the definitions and notation of Doan et al. [2006].
Following Walsh et al. [2012], the effects of an external, one-dimensional, vertical stress change on porosity is added to the TOUGH2 non-isothermal multiphase flow and transport simulator. Such enforced stress and porosity changes result in pore-pressure changes and related fluid redistributions. The assumptions of one-dimensional, uniaxial strain is appropriate as both atmospheric pressure fluctuations and Earth tides are mechanical loads that occur over a large area. The related, secondary assumption that the geologic formation is horizontally bedded may also be considered appropriate given the scale of interest.

Hydrogeomechanical coupling under a homogeneous and laterally extensive load is implemented within the mass accumulation term. Porosity (φ) in TOUGH2 is not constant, but is updated at the end of each iteration to account for changes in pressure. The expression for the updated porosity for the current time step (φₜ), including hydro-geomechanical effects, is

\[
φₜ = φₜ₋₁ + φₜ₋₁ \cdot cₚ \cdot dp - φₜ₋₁ \cdot S_{S₁D} \cdot ζ \cdot dσ_{zz}
\]  

where

- \(φₜ₋₁\) : porosity (\(\cdot\)) at previous time step
- \(cₚ\) : pore compressibility (Pa⁻¹)
- \(dp\) : pressure change (Pa) during the time step
- \(S_{S₁D}\) : one-dimensional specific storage coefficient (Pa⁻¹)
- \(ζ\) : one-dimensional loading efficiency (\(\cdot\))
- \(dσ_{zz}\) : change in vertical loading (Pa) during the time step (positive for increased load)

The second term on the right-hand side of Eq. (1), i.e., \(φₜ₋₁ \cdot cₚ \cdot dp\), represents the change in porosity due to the change in pore pressure during a time step; this term is implemented in standard TOUGH2. The third term, \(φₜ₋₁ \cdot S_{S₁D} \cdot ζ \cdot dσ_{zz}\), is the hydromechanical term that represents the change in porosity due to the change in vertical load applied during a time step. The variables that are unique to the hydromechanical formulation are the one-dimensional loading efficiency (\(ζ\)), the change in vertical load (\(dσ_{zz}\)), and the one-dimensional (uniaxial) specific storage coefficient (\(S_{S₁D}\)). The hydromechanical capability requires the one-dimensional loading efficiency to be defined for each material type. This parameter is used to determine what percentage of the applied vertical stress is borne by the pore-fluids; it is defined as:

\[
ζ = \frac{β(1 + ν)}{3(1 - ν) - 2αβ(1 - 2ν)}
\]

where

- \(α\) : Biot-Willis coefficient (\(\cdot\))
- \(β\) : Skempton coefficient (\(\cdot\))
- \(ν\) : Poisson ratio (\(\cdot\))

The Biot-Willis coefficient \(α\) quantifies how an expansion in volume of the whole porous medium results in an expansion of the pore volume:
\[ \alpha = \frac{\partial (V_{\varphi}/V)}{\partial \varepsilon} = 1 - \frac{K}{K_s} \]  \hspace{1cm} (3)

where

\( \varepsilon \): volumetric strain (-)
\( K \): drained bulk modulus (Pa)
\( K_s \): solid grain bulk modulus (Pa)

Consistent with the assumption made by Schlumberger [2013], we take the solid matrix to be rigid, i.e., any deformation of the porous medium is entirely due to the compression or dilation of the pore space, i.e., \( \alpha = 1 \).

The Skempton Coefficient \( \beta \) is defined as the ratio of the induced pore pressure to the change in applied stress for undrained conditions:

\[ \beta = -\frac{\partial p}{\partial \sigma} \]  \hspace{1cm} (4)

\( \beta \) is a measure of how the applied stress is distributed between the skeletal framework and the fluid. It tends toward one for saturated soils and unconsolidated rocks, because mainly the fluid supports the load. It tends toward zero for gas-filled pores and for saturated consolidated rocks because the framework supports the load.

The Skempton coefficient can be related to geomechanical parameters as follows:

\[ \beta = \frac{1}{\left( \frac{1}{K} - \frac{1}{K_s} \right)} \left( \frac{1}{\left( \frac{1}{K} - \frac{1}{K_s} \right) + \phi \left( \frac{c_w}{K_s} - \frac{1}{K_s} \right)} \right) \]  \hspace{1cm} (5)

where

\( \phi \): porosity (-)
\( c_w \): water compressibility (Pa\(^{-1}\)) = \( 1/K_w \)

The three-dimensional specific storage coefficient is given by:

\[ S_{S-3D} = \left( \frac{1}{K} - \frac{1}{K_s} \right) + \phi \left( \frac{c_w}{K_s} - \frac{1}{K_s} \right) \]  \hspace{1cm} (6)

The one-dimensional specific storage coefficient is given by:

\[ S_{S-1D} = S_{S-3D} (1 - \lambda \beta) \]  \hspace{1cm} (7)

where
\[
\lambda = \frac{2\alpha(1-2\nu)}{3(1-\nu)} \tag{8}
\]

The product of the one-dimensional loading efficiency and the specific storage coefficient, \( S_{s-1D} \zeta \), is independent of fluid composition and can be approximated as

\[
S_{s-1D} \zeta = \left( \frac{1 - \frac{1}{K_i}}{1} \right) \frac{(1 + \nu)}{3(1-\nu)} = \phi \left( c_\phi + c_w \right) \tag{9}
\]

where

\[ c_\phi : \text{pore compressibility} \]

The pore compressibility is chosen judiciously as:

\[
c_\phi = \frac{S_{s-1D}}{\phi} - c_w \tag{10}
\]

This one-dimensional hydrogeomechanical model has been implemented into the TOUGH2 forward simulator and integrated into the iTOUGH2 simulation-optimization framework, so the observable pressure response due to barometric and Earth tide fluctuations can be examined as part of sensitivity and uncertainty analyses as well as inverse modeling. In this implementation, the one-dimensional loading efficiency \( \zeta \) is directly entered as a known material property, or it can be considered an unknown or uncertain parameter to be estimated by inverse modeling.

Additional assumptions include:

- Tidal and barometric load changes are transmitted instantaneously to depth through the skeleton of the rock matrix; in reality, load changes are transmitted with the speed of sound.
- Tidal and barometric loading induces only vertical strains; in reality, heterogeneity in mechanical properties may lead to more complex strain patterns.
- Oceanic tides are neglected; in reality, if the site is relatively close to an ocean, loading from oceanic tides (which have a different mode than Earth tides) will need to be accounted for. However, this does not affect a study that is based on synthetic tidal loading.
3. Numerical Model Analyses

We reviewed information collected from the Harvey 1 stratigraphic well and other data from the Southern Perth Basin (specifically Schlumberger [2013]) and developed a highly simplified, albeit representative conceptual stratigraphic model of a potential CO₂ storage site and associate property values and ranges. This initial conceptual model is used to demonstrate and examine the relation between imposed barometric and Earth-tide effects on the pressure response that is potentially observable in deep boreholes. Moreover, sensitivity analyses and notional inversions provide insights into the influence of unknown and uncertain properties, the sensitivity of observations, and the identifiability of the parameters of interest.

The initial conceptual model is then refined to more realistically represent the conditions expected at the South West Hub site, and to examine the impact of heterogeneity on the observed pressure signal, and – conversely – whether these signals can be used to identify potential discontinuities in the confining layers.

3.1 Simplified, One-Dimensional Stratigraphic Model

3.1.1 Introduction

Based on the fundamental assumption that barometric pressure fluctuations and Earth tides are large-scale loading and unloading effects that result in predominantly vertical compression and dilation of the pore space, it is appropriate to consider a one-dimensional vertical column as the initial conceptual model. Only the main stratigraphic units are represented, each assumed to be homogeneous. The purpose of this highly simplified model is to understand the general system behavior in response to atmospheric and Earth tide loading. Furthermore, an initial sensitivity analysis will identify influential parameters.

3.1.2 Model Setup

A 2945 m long vertical column (representative of the stratigraphic well Harvey 1) is considered and discretized into 2945 one-meter thick elements. The column is subdivided into main stratigraphic units according to the data record for Harvey 1, as summarized in Table 1.

An atmospheric element is attached at the top of the column; no-flow boundary conditions are applied at the bottom of the column. The initial pressure and saturation distribution is obtained by running the column to steady state, establishing near the land surface an approximately 20 m thick unsaturated zone, which is at capillary-gravity equilibrium, and a hydrostatic pressure profile in the saturated zone. Temperature effects are not considered significant for this initial scoping calculation and are thus ignored.

Time-dependent Dirichlet boundary conditions are established in the top element to simulate atmospheric pressure fluctuations. Figure 2a shows the one-month long pressure transient, which is taken from an arbitrary weather station in the United States. The signal exhibits a similar pattern (in terms of frequency and amplitude) as that shown in Figure 1; it is thus believed to represent realistic barometric pressure
perturbations. A synthetic Earth-tide loading signal was generated as a superposition of the four strongest, sinusoidal lunar and solar modes (referred to as the O1, K1, M2, and S2 modes, Doan et al. [2006]). Frequencies, lags, and amplitudes (based on the volumetric strains $\varepsilon$ induced by changes in gravitational strengths) are summarized in Table 3. The composite synthetic Earth-tide signal is shown in Figure 2b. The pressure response due to hydrogeomechanical effects consists of the combined barometric and Earth-tide loadings shown in Figure 2c.
Table 1. Stratigraphy and Key Hydrologic and Mechanical Input Parameters

<table>
<thead>
<tr>
<th>Formation</th>
<th>Depth* [m]</th>
<th>$\phi$ @ [-]</th>
<th>$k_v$ % [mD]</th>
<th>$K$ &amp; [GPa]</th>
<th>$\nu$ * [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guildford</td>
<td>24</td>
<td>0.20</td>
<td>100</td>
<td>14</td>
<td>0.26</td>
</tr>
<tr>
<td>Leederville</td>
<td>-11</td>
<td>0.12</td>
<td>1</td>
<td>14</td>
<td>0.26</td>
</tr>
<tr>
<td>Eneabba</td>
<td>-225</td>
<td>0.12</td>
<td>1</td>
<td>14</td>
<td>0.26</td>
</tr>
<tr>
<td>Basal Eneabba</td>
<td>-600</td>
<td>0.10</td>
<td>$10^{-4}$</td>
<td>2</td>
<td>0.26</td>
</tr>
<tr>
<td>Yalgorup</td>
<td>-679</td>
<td>0.23</td>
<td>250</td>
<td>8</td>
<td>0.21</td>
</tr>
<tr>
<td>Wonnerup</td>
<td>-1335</td>
<td>0.14</td>
<td>2</td>
<td>20</td>
<td>0.25</td>
</tr>
<tr>
<td>Sabina</td>
<td>-2870</td>
<td>0.10</td>
<td>1</td>
<td>14</td>
<td>0.26</td>
</tr>
</tbody>
</table>

* True vertical depth subsea [Delle Piane et al., 2013]
@ Porosity [Schlumberger, 2013; Zhang et al., 2015]
% Vertical permeability, taken as 10% of reported permeabilities [Schlumberger, 2013; Zhang et al., 2015]
& Bulk modulus [Schlumberger, 2013; Zhang et al., 2015]
* Poisson ratio [Schlumberger, 2013; Zhang et al., 2015]

Table 2. Stratigraphy and Derived Hydrologic and Mechanical Formation Parameters

<table>
<thead>
<tr>
<th>Formation</th>
<th>$\beta$ # [-]</th>
<th>$\zeta$ @ [-]</th>
<th>$S_{S3D}$ % [GPa$^{-1}$]</th>
<th>$S_{S1D}$ &amp; [GPa$^{-1}$]</th>
<th>$D_H$ * [m$^2$ s$^{-1}$]</th>
<th>$c_s$ &amp; [GPa$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guildford</td>
<td>0.44</td>
<td>0.31</td>
<td>0.16</td>
<td>0.13</td>
<td>$7.8\times10^{-2}$</td>
<td>0.20</td>
</tr>
<tr>
<td>Leederville</td>
<td>0.57</td>
<td>0.43</td>
<td>0.13</td>
<td>0.10</td>
<td>$1.1\times10^{-3}$</td>
<td>0.34</td>
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<tr>
<td>Eneabba</td>
<td>0.57</td>
<td>0.43</td>
<td>0.13</td>
<td>0.10</td>
<td>$1.1\times10^{-3}$</td>
<td>0.34</td>
</tr>
<tr>
<td>Basal Eneabba</td>
<td>0.92</td>
<td>0.86</td>
<td>0.55</td>
<td>0.33</td>
<td>$3.1\times10^{-8}$</td>
<td>2.84</td>
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<tr>
<td>Yalgorup</td>
<td>0.54</td>
<td>0.38</td>
<td>0.23</td>
<td>0.17</td>
<td>$1.5\times10^{-1}$</td>
<td>0.27</td>
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<tr>
<td>Wonnerup</td>
<td>0.45</td>
<td>0.31</td>
<td>0.11</td>
<td>0.09</td>
<td>$2.9\times10^{-3}$</td>
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<tr>
<td>Sabina</td>
<td>0.61</td>
<td>0.47</td>
<td>0.12</td>
<td>0.09</td>
<td>$1.2\times10^{-3}$</td>
<td>0.41</td>
</tr>
</tbody>
</table>

# Skempton coefficient, Eq. (5)
@ One-dimensional loading efficiency, Eq. (2)
% Three-dimensional specific storage coefficient, Eq. (6)
& One-dimensional specific storage coefficient, Eq. (7)
* Vertical hydraulic diffusivity, $k_v/(\mu S_{S3D})$
& Pore compressibility, Eq. (10)

Table 3. Synthetic Earth Tides

<table>
<thead>
<tr>
<th>Mode</th>
<th>Period [h]</th>
<th>Lag [h]</th>
<th>Gravity Amplitude [mm s$^{-2}$]</th>
<th>Pressure Amplitude [Pa]</th>
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<tr>
<td>O1</td>
<td>25.82</td>
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</tr>
<tr>
<td>K1</td>
<td>23.94</td>
<td>5.98</td>
<td>434</td>
<td>282</td>
</tr>
<tr>
<td>M2</td>
<td>12.42</td>
<td>3.11</td>
<td>332</td>
<td>216</td>
</tr>
<tr>
<td>S2</td>
<td>12.00</td>
<td>3.00</td>
<td>154</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 2. (a) Atmospheric pressure fluctuations specified as time-dependent Dirichlet boundary conditions at the top of the column; (b) Earth tide loading, comprised of two lunar and two solar modes; (c) total surface loading, consisting of atmospheric pressure fluctuations and Earth tides.
3.1.3 Reference Simulation

Simulations of two-phase flow of water and air coupled to one-dimensional hydrogeomechanics according to the concepts outlined in Section 2.2 are performed using an extended version of TOUGH2 as implemented in the iTOUGH2 simulation-optimization framework [Finsterle, 2015]. This reference simulation is based on the approximate layering as observed in well Harvey 1, assuming homogeneity within each stratigraphic unit. The input parameters are given in Table 1.

3.1.3.1 Pressure fluctuations with time

The simulated pressure responses for each unit are shown Figure 3. In general, the numerically simulated responses exhibit similar characteristics as the observed reservoir pressures shown in Figure 1.

The topmost panel of Figure 3 shows the combined barometric and Earth-tide loading pressure change (see also Figure 2c). Note that the reference pressure is arbitrary and irrelevant, as only changes in the load induce deformations. The barometric component of the imposed loading (see Figure 2a) is also applied as a time-dependent Dirichlet boundary condition for the gas phase at the top of the model. The responses will be discussed for each stratigraphic unit from the land surface to the bottom of the well.

Guildford Formation

The responses in the upper parts of the Guildford formation (light-green dashed and dash-dotted lines) solely reflect the barometric pressure as it propagates through the unsaturated zone. Even though barometric and Earth-tide loading cause very small compressions and dilations of the pore space, these pore-volume changes do not lead to a perceptible pressure change due to the high compressibility of the gas phase. The pressure in the unsaturated zone shows the expected time lag and amplitude reduction with respect to the imposed barometric pressure fluctuations. This pneumatic signature can be analyzed for the estimation of gas diffusivity in the vadose zone. Upon entering the saturated zone of the Guildford formation (light-green solid line), the sinusoidal Earth-tide effects start to appear. The strong atmospheric pressure decline observed around Day 9 is further delayed and damped. It is a combination of the pressure propagation from the land surface through the unsaturated and saturated zones, and the emerging response due to instantaneous pore-volume changes induced by changes in both the barometric and Earth-tide load.

Leederville Formation

Two pressure transients are shown for the Leederville formation. The dark-green dashed line is taken near the top of the Leederville formation. It exhibits the same characteristics as the light-green solid line of the Guildford formation, with a slightly different contribution from the loading-induced pressure changes, which is due to different rock mechanical properties. However, the pressure diffusion component is essentially the same as the two monitoring locations are very close to each other. The pressure perturbation from the land surface does not reach the deeper section of the Leederville formation (dark-green solid line). Consequently, the fluctuations
solely reflect the loading induced pressurization and depressurization, as evidenced by the relatively stronger presence of the Earth-tide component and the fact that barometric pressure changes are seen instantaneously, i.e., without the time lag characteristic of a pressure diffusion process.

Eneabba, Basal Eneabba, Yalgorup, Wonnerup, and Sabina Members

The pressure fluctuations in the deeper units are devoid of the pressure diffusion component observed in the unsaturated zone of the Guildford formation and the shallow saturated zone near the water table. Consequently, the pressure fluctuations track those of the imposed loading without a lag. In the absence of significant fluid pressure diffusion, the amplitudes in each unit are proportional to each other, where the factor of proportionality is given by the ratios of the loading efficiencies, which in turn are functions of the geomechanical parameters and porosity. The Basal Eneabba Shales has the highest loading efficiency (see Table 1), and thus exhibits the strongest pressure fluctuations. The surrounding units are stiffer, specifically the Yalgorup member; their responses to barometric loading and Earth-tide effects are correspondingly weaker. These contrasts in geomechanical properties between stratigraphic units lead to local pressure gradients that induce the spreading of fluid expansion or contraction waves. The highly attenuated fluid pressure diffusion process partially equilibrates the pressure differences across interfaces.
Figure 3. Simulated pressure response to barometric and Earth-tide loading along Harvey 1 stratigraphic well.
### 3.1.3.2 Pressure and flow rate profiles

The question arises whether pressure equilibration between units is significant enough and can be used to estimate the vertical permeability of a confining layer. Figure 4a shows profiles of the pressure change (with respect to the initial hydrostatic profile) at approximately 6 and 9 days (representing a period of high and low loading, respectively). As discussed in Section 3.1.3.1, pressures in the near-surface layers are influenced by both (1) the local pressurization and depressurization caused by, respectively, compression and dilation of the pore space due to changes in barometric and Earth-tide loading, and (2) pressure propagation through the gas and liquid phases due to atmospheric pressure changes imposed at the land surface. Deeper in the subsurface, however, the diffusive pressure perturbation from the land surface dissipates, and only the first effect remains relevant. As a result, the profiles show distinct pressure changes for each stratigraphic unit, reflecting their respective loading efficiencies. Nevertheless, the pressure changes across interfaces between units of different geomechanical properties are somewhat smoothed out if sufficient permeability is available to allow for vertical fluid pressure diffusion to occur.

For example, the slightly higher pressure perturbation in the Yalgorup member (caused by a somewhat higher loading efficiency) gradually adjusts to the lower pressure change of the Wonnerup formations. This equilibration is facilitated by the relatively high permeabilities and thus fluid exchange between the two units, as illustrated in Figure 4b. A similar behavior can be observed at the interface between the Wonnerup and Sabina formation.

Conversely, the very low permeability of the Basal Eneabba Shales prevents any pressure equilibration with its adjacent layers (the Eneabba formation and Yalgorup member), resulting in a uniform pressure profile within the tight unit, and a step change to the lower pressure perturbations in the neighboring formations.

This initial analysis suggests that the ability to determine vertical permeability from barometric and Earth-tide effects is limited by permeability itself. Formations with very low permeabilities (e.g., the $10^{-19} \text{ m}^2$ permeability assumed for the Basal Eneabba Shale) only respond to the geomechanical processes, which are of secondary relevance as we are interested in flow and transport processes.

Figure 5 shows the pressure and flow rate profiles in the Basal Eneabba Shale and surrounding formations under the assumption that the permeability of the Basal Eneabba Shale is $10^{-16} \text{ m}^2$, i.e., significantly higher than assumed by Zhang et al. [2015], but still acting as a confining layer for the Yalgorup storage formation. The figure suggests that pressures would need to be monitored at multiple points within the formation, including very near the interfaces to the adjacent units, to be able to observe the pressure equilibration process that potentially contains information about vertical permeability. This concept will be further examined in subsequent sections.
Figure 4. Simulated profiles of pressure change and flow rates induced by barometric and Earth-tide effects along Harvey 1 stratigraphic well.

Figure 5. Excerpt of simulated profiles of pressure change and flow rates induced by barometric and Earth-tide effects along Harvey 1 stratigraphic well for a Basal Eneabba Shale permeability of $10^{-16} \text{ m}^2$. 
3.1.4 Sensitivity Analysis

A sensitivity analysis of the downhole pressure responses with respect to permeabilities, porosities, and drained bulk moduli was performed to identify influential parameters and sensitive observations. The sensitivity analysis is considered local in that it examines scaled sensitivity coefficients only at the reference parameter set shown in Table 1. The elements of the \( m \times n \) scaled sensitivity matrix \( S \) are defined as:

\[
S_{ij} = \frac{\partial z_i}{\partial p_j} \frac{\sigma_{pi}}{\sigma_{zi}}
\]  

(11)

where \( z_i \) \((i = 1, \ldots ,m)\) is a pressure observation at a given point in space and time, \( p_j \) \((j = 1, \ldots ,n)\) is an element of the input parameter vector, \( \sigma_z \) is a measure of a model output variation that would be considered significant (here related to the expected pressure measurement error), and \( \sigma_p \) is a measure of the expected parameter variability or uncertainty. The scaled sensitivity coefficients are dimensionless and can thus be compared to each other. The expected pressure measurement error \( \sigma_z \) is taken to be 100 Pa; log-permeabilities and log-\( K \) values are assumed to be known to one order of magnitude, and porosity is given a \( \sigma_p \) of 0.1 (note that only the relative magnitude of these scaling factors impact the qualitative outcome of the sensitivity analysis). The partial derivatives in Eq. (11) are calculated numerically using a forward finite difference approximation.

Composite sensitivity measures are calculated to summarize the \( m \times n = 15,120 \times 21 = 317,520 \) scaled sensitivity coefficients. They consist of the sum of the absolute scaled sensitivity coefficients for a given column (yielding an approximate composite measure of parameter influence) and the sum of the absolute scaled sensitivity coefficients for each row belonging to a given pressure data set (yielding an approximate composite measure of this data set’s overall sensitivity).

Table 4 summarizes the results, focusing on the units of interest, namely the Basal Eneabba Shales (the potential caprock), and the Yalgorup and Wonnerup storage formations. Pressure observations are assumed to be made two meters above and below a formation contact.

The following observations can be made:

- Overall, pressures observed in packed-off borehole intervals in response to barometric and Earth-tide effects are mostly determined by rock mechanical parameters that affect the stiffness of the formation and the degree to which a change in load is transferred to the pore fluid. The drained bulk modulus \( K \) reflects this property. Note that porosity also enters the loading efficiency.

- Fluid flow across the Yalgorup-Wonnerup interface is sufficiently strong to equilibrate pressure changes induced by property changes; the sensitivity coefficients are thus nearly identical for measurement points immediately above and below that interface. This is likely to lead to strong parameter correlations and thus non-uniqueness when estimating these parameters by means of inverse modeling.
• The low permeability of the Basal Eneabba Shales prevents information to propagate to the Yalgorup member; parameter changes in the shales thus mainly affect observations in the shales themselves.
• Pressure measurements in each of the units contain approximately equal amounts of information about the parameters of interest.
• The bulk modulus in the Yalgorup member is the most influential parameter.
• Increasing the Basal Eneabba Shale permeability to 10^{-16} m^2 induces more flow to equilibrate the pressures among units, and thus increases the overall parameter influence, specifically that of the permeabilities; see Table 5.

### Table 4. Composite Sensitivity Measures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observation</th>
<th>Total Parameter Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Bottom Basal</td>
</tr>
<tr>
<td>Log (permeability)</td>
<td>Basal E.</td>
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</tr>
<tr>
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<td>Yalgorup</td>
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</tr>
<tr>
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<td>Wonnerup</td>
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</tr>
<tr>
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<td>Basal E.</td>
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<tr>
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<td>Yalgorup</td>
<td>115</td>
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<tr>
<td></td>
<td>Wonnerup</td>
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<tr>
<td>Total Data Set Sensitivity</td>
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<td>3757</td>
</tr>
</tbody>
</table>

### Table 5. Composite Sensitivity Measures, Enhanced Permeability for Basal Eneabba Shale

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observation</th>
<th>Total Parameter Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Bottom Basal</td>
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<tr>
<td>Total Data Set Sensitivity</td>
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<td>5168</td>
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</table>
3.1.5 Notional Inversion

Notional inversions are performed to evaluate the uncertainty of estimated parameters without actually having measured calibration data available, but by assuming that the final residuals of the inversion will – on average – be consistent with an explicit expectation (or notion), expressed by the covariance matrix $C_{zz}$. The covariance matrix of the estimated parameters, $C_{pp}$, is then evaluated as

$$C_{pp} = (J^T C_{zz}^{-1} J)^{-1}$$  (12)

Here, the Jacobian matrix $J$ holds the sensitivity coefficients

$$J_{ij} = \frac{\partial z_i}{\partial p_j}$$  (13)

The covariance matrix of the estimated parameters depends on:

1. Our assumption about the attainable goodness-of-fit;
2. The sensitivity of the observations, which can be interpreted as the information content of the data about the parameters of interest; and
3. The impact of correlations among all parameters that are concurrently estimated. The higher the overall correlations, the less independently a parameter can be estimated, and thus the higher is the estimation uncertainty, because uncertainty in an estimated parameter is increased due to the uncertainties in the other parameters.

For this study it is assumed that:

1. Absolute pressures are measured every hour at the top, middle, and bottom of each stratigraphic unit, and that these calibration data will be fitted with an average error of 100 Pa (i.e., $C_{zz}$ is a matrix with $\sigma_{zz}^2 = 100^2 = 10,000$ Pa$^2$ on its diagonal).
2. The sensitivities are given in Table 4 for the reference case, and Table 5 for the case with an enhanced permeability for the Basal Eneabba Shales; and
3. Correlations among 21 parameters are accounted for (i.e., for estimates of seven log-permeability, seven porosity, and seven logarithms of drained bulk modulus values, one set for each of the seven units). The overall parameter independence is measured by the ratio between the conditional standard deviation (the estimation uncertainty attainable for a given parameter assuming that all the other parameters are perfectly known), and the marginal standard deviation (the uncertainty attainable for a given parameter accounting for the uncertainty and correlation of all the concurrently estimated parameters); this independence measure is reported in the last column of Table 6 and Table 7. Note that in general permeability and porosity are positively correlated if data depending on hydraulic diffusivity are inverted. Moreover, porosity and bulk moduli are also correlated, albeit in a more complex fashion through their impact on the Skempton coefficient and thus loading efficiency and pore compressibility, which all affect the observed pressure response. All three parameters are
thus expected to be correlated if concurrently estimated in an inversion of pressure data.

The estimation uncertainties (marginal standard deviations) for the reference case are given in the last column of Table 6; those for the case of an increased permeability for the Basal Eneabba Shales are given in Table 7.

Table 6. Estimation Uncertainties and Overall Parameter Correlation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Estimation uncertainty $\sigma_p$</th>
<th>Independence*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log (permeability)</td>
<td>Guildford</td>
<td>-13.0</td>
<td>0.02</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Leederville</td>
<td>-15.0</td>
<td>0.04</td>
<td>0.39</td>
</tr>
<tr>
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<td>-15.0</td>
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<td>0.67</td>
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<tr>
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<td>0.36</td>
</tr>
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<td>-12.5</td>
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</tr>
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<td>0.05</td>
</tr>
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<td></td>
<td>Sabina</td>
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<td>1.49</td>
<td>0.04</td>
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<td>0.34</td>
</tr>
<tr>
<td></td>
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<td>0.03</td>
<td>0.04</td>
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<td></td>
<td>Basal Eneabba</td>
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<td>0.04</td>
<td>0.05</td>
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<td>Yalgorup</td>
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<td>0.01</td>
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<td></td>
<td>Wonnerup</td>
<td>0.14</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Sabina</td>
<td>0.10</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Log (bulk modulus)</td>
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<td>Sabina</td>
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<td>1.52</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* Ratio of conditional over marginal standard deviations; a value near 1.0 indicates that the respective parameter can be estimated independently; a value near 0.0 indicates that the estimation uncertainty is strongly affected by uncertainties in other, correlated parameters.

Table 6 suggests that both the hydrological and geomechanical parameters of the top three layers can be quite accurately identified. In particular, the fact that atmospheric pressure fluctuations propagate through the shallow unsaturated and saturated zones lead to relatively high sensitivities of the pressures in the Guildford formation with respect to permeability. As this pressure propagation depends on hydraulic diffusivity, and because the Earth tide signal is not present in the unsaturated zone, permeability and porosity are relatively strongly correlated. Conversely, the Earth tide signal observable at greater depth of the Guildford allow for a relatively independent estimation of the bulk moduli for this formation.

The parameters of the Leederville formation are mainly determined by its own properties (rather than by the properties of the neighboring formations). In this one-
dimensional, thus serial flow configuration, vertical flow in the upper part of the column is determined by the Leederville formation's lower permeability (in comparison to the Guildford formation), reducing its estimation uncertainty.

The Eneabba, while assumed to have properties identical to those of the Leederville formation, is bounded below by the essentially impermeable Basal Eneabba Shales. Fluid pressure diffusion approaches zero at this interface, reducing the sensitivity of the pressure data to permeability.

The very low permeability of the Basal Eneabba Shales effectively divides the column into almost independent upper and lower sections. This has two implications:

1. Properties above the Basal Eneabba Shales are uncorrelated to properties below this layer; and

2. Vertical fluid pressure diffusion in the entire column is significantly reduced, especially in the lower section, which is bounded by two impermeable layers.

While reduced correlations are generally desirable in that they reduce estimation uncertainty (see discussion of Eq. (12) above), the lower overall fluid flow is detrimental, specifically for the estimation of permeability, which relies on fluid pressure diffusion across stratigraphic interfaces to equilibrate the pressures that are used as calibration data. Nevertheless, if pressures are observed in the Basal Eneabba Shales very near its interfaces to the overlying and underlying formations, it appears that permeability – the key property of interest in this study – can be determined with acceptably low estimation uncertainty.

The relatively high permeabilities of the Yalgorup, Wonnerup and Sabina members, combined with the minor differences in geomechanical properties and thus relatively small pressure gradients between these units, yield smaller sensitivity coefficients (compared to the Basal Eneabba Shales) and – more significant – strong overall correlations, and thus very high estimation uncertainties; they cannot be estimated based on pressure fluctuation data alone.

To further examine the impact of the low permeability of the Basal Eneabba Shales on estimation uncertainties, its permeability was increased to $10^{-16}$ m$^2$, and the analysis was repeated; results are summarized in Table 7.
Table 7. Estimation Uncertainties and Overall Parameter Correlation, Enhanced Permeability for Basal Eneabba Shale

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Estimation uncertainty $\sigma_p$</th>
<th>Independence*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log (permeability)</td>
<td>Guildford</td>
<td>-13.0</td>
<td>0.02</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Leederville</td>
<td>-15.0</td>
<td>0.04</td>
<td>0.40</td>
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<td>0.07</td>
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<td>0.29</td>
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<tr>
<td></td>
<td>Sabina</td>
<td>-15.0</td>
<td>0.09</td>
<td>0.54</td>
</tr>
<tr>
<td>Porosity</td>
<td>Guildford</td>
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<td>0.01</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Leederville</td>
<td>0.12</td>
<td>0.01</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>Eneabba</td>
<td>0.12</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Basal Eneabba</td>
<td>0.10</td>
<td>0.02</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Yalgorup</td>
<td>0.23</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Wonnerup</td>
<td>0.14</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Sabina</td>
<td>0.10</td>
<td>0.02</td>
<td>0.13</td>
</tr>
<tr>
<td>Log (bulk modulus)</td>
<td>Guildford</td>
<td>10.1</td>
<td>0.03</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>Leederville</td>
<td>10.1</td>
<td>0.02</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Eneabba</td>
<td>10.1</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Basal Eneabba</td>
<td>9.3</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Yalgorup</td>
<td>9.9</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Wonnerup</td>
<td>10.3</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Sabina</td>
<td>10.1</td>
<td>0.11</td>
<td>0.13</td>
</tr>
</tbody>
</table>

* Ratio of conditional over marginal standard deviations; a value near 1.0 indicates that the respective parameter can be estimated independently; a value near 0.0 indicates that the estimation uncertainty is strongly affected by uncertainties in other, correlated parameters.

Increasing the permeability of the Basal Eneabba Shales leads to increased fluid pressure diffusion within the entire column, specifically across the interface between the Eneabba and Basal Eneabba Shales, and the Basal Eneabba Shales and the Yalgorup members (compare Figure 3 and Figure 4). Pressure measurements are thus significantly more sensitive to permeability (compare Table 4 and Table 5), leading to reduced estimation uncertainties despite generally increased overall correlations (i.e., lower independence measure; compare Table 6 and Table 7). Estimation uncertainties for porosity and drained bulk modulus are either increased or decreased, depending on the influence of the changed correlation structure and changes in sensitivity coefficients.

3.1.6 Data-Worth Analysis

A data-worth analysis is performed to examine the contribution of individual data sets to the solution of the inverse problem at hand. We focus here on the accuracy with which the vertical permeability of the Basal Eneabba Shales can be determined. Given this specific objective, the relative worth of each data set (i.e., a time series of pressure data collected at a given depth) is evaluated by calculating the amount by
which the estimation uncertainty would increase if the data set were removed from the set of calibration data. Equation (12) is used to calculate the estimation uncertainty of the vertical permeability, first for the full set of calibration data, and then for reduced sets, whereby appropriate rows of the Jacobian matrix, Eq. (13), are removed one at a time. The estimation uncertainty will invariably increase whenever a data set is removed. The relative increase (as measured by the trace of the resulting estimation covariance matrix $C_{pp}$) is then used as a measure of data worth, i.e., a data set that (when removed) dramatically increases estimation uncertainty has higher data worth than a data set that only marginally affects our ability to estimate the parameter of interest.

Note that while we focus on the estimation of vertical permeability of the Basal Eneabba Shales, the impact (through correlations) of all the other, concurrently estimated parameters is properly accounted for in this data-worth analysis.

Table 8 summarizes the results of the data-worth analysis. The data sets measured close to the interface between the Basal Eneabba Shales and its bound formations are most valuable, as expected. Measuring pressure fluctuations away from these formation contacts contributes little to the determination of the vertical permeability of the confining layer. (Note that the data worth measured at the top of the Eneabba formation is slightly higher than that measured in the middle of the formation, because this data set helps constrain the Eneabba formation permeability, which is correlated to the uncertainty of the Basal Eneabba Shales’ permeability.)

The results again strongly depend on the assumed value of the Basal Eneabba Shales permeability. As permeability of the Basal Eneabba Shales is increased, its barrier function weakens, leading to overall higher pressure diffusion rates within the column, and thus stronger influence of the properties of adjacent formations. Moreover, the correlation between closely spaced sensors (i.e., that at the bottom of the overlying formation and top of the confining layer, and that at the bottom of the confining layer and top of the underlying formation) increases, reducing their respective data worth, while measurements taken in the middle of each formation become both more sensitive and less correlated, increasing their data worth. Finally, if the permeability is relatively high (i.e., $10^{-16}$ m$^2$), it appears to be essential to determine the permeability of the Eneabba formation, as it strongly affects the permeability of the Basal Eneabba Shales’ permeability; the Eneabba permeability is best constrained by measuring the pressure response in the middle of the formation.

The strong dependence of the sensitivities, correlation structure, and data worth on the (unknown) permeability of the Basal Eneabba Shales suggests that a robust monitoring design should be based on measuring pressure fluctuations at multiple points along the profile, i.e., above, within, and below the formation of interest.
Table 8. Relative Worth of Measured Pressure Data for the Estimation of Vertical Permeability of the Basal Eneabba Shales

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Data Worth</th>
</tr>
</thead>
</table>
|                      | $k_{BES} =$ ...
|                      | 10^{-19} m² | 10^{-18} m² | 10^{-17} m² | 10^{-16} m² |
| Eneabba Formation    | T          | 3.5  | 4.5  | 6.5  | 7.2  |
|                      | M          | 2.6  | 7.1  | 17.6 | 20.1 |
|                      | B          | 13.9 | 19.0 | 21.8 | 4.5  |
| Basal Eneabba Shales | T          | 18.0 | 10.0 | 6.2  | 2.7  |
|                      | M          | 3.9  | 2.8  | 2.0  | 4.2  |
|                      | B          | 6.9  | 4.2  | 2.5  | 2.1  |
| Yalgorup Member      | T          | 5.9  | 5.9  | 2.0  | 3.1  |
|                      | M          | 3.7  | 4.1  | 1.9  | 1.9  |
|                      | B          | 3.1  | 3.0  | 1.9  | 2.0  |

3.2 Scoping Calculations for a Two-Dimensional Cross Section

3.2.1 Introduction

The purpose of the two-dimensional simulations present in this subsection is to examine the pressure response to Earth tides and barometric pressure fluctuations in a heterogeneous formation that exhibits a gap in the otherwise continuous confining layer. As discussed in Section 3.1, pressure dissipation near stratigraphic contacts or across entire layers depend on the permeability of the formation where the pressure sensor is located, as well as the permeabilities of nearby units. Discontinuities in the confining layer as well as smaller-scale heterogeneity are thus expected to impact the observed pressure response.

3.2.2 Model Setup

The numerical model represents a two-dimensional cross section that is 2000 m wide and 2942 m deep, discretized into uniform elements of 50 m and 5 m in horizontal and vertical directions, respectively. The stratigraphy is based on Harvey 1 and identical to the one used for the one-dimensional simulations discussed in Section 3.1; the layers are horizontal.

Heterogeneity is introduced using a geostatistical approach, in which a cumulative distribution function of log-permeability modifiers is defined such that three facies (consisting of fine, medium, coarse material) are represented in proportions of 50, 20, and 30%, respectively. (Note that for the Lesueur formation, these facies can be interpreted as related to shale, silt, and sand, respectively.) Within each facies, permeability modifiers are generated that follow a log-triangular distribution. The log-triangular cumulative distribution function within each facies is approximated by
five points (two additional points are added for probabilities of 0 and 1); the cut-off values are summarized in Table 9. A spatially correlated random property field of log-permeability-modifiers is generated using the sequential indicator simulation method SISIM of the geostatistical software library GSLIB [Deutsch and Journel, 1992]. A spherical semi-variogram model is used with a correlation length of 1000 m in horizontal and 10 m in vertical direction.

Heterogeneity in rock mechanical properties is introduced by imposing a correlation to the permeability modifiers. While such a correlation is unknown, it is essential to account for varying loading efficiencies and pore compressibilities to obtain a more realistic distribution of observable pressure fluctuations. We therefore multiply the reference value of the dry bulk modulus $K$ (see Table 1) by the third root of the permeability modifiers, resulting in heterogeneous distributions of Skempton coefficients, loading efficiencies, and pore compressibilities according to Eqs. (5), (2), and (10), respectively. The Poisson ratios and porosities are assumed uniform within each stratigraphic layer, with values as given in Table 1. It is noted that introducing heterogeneity leads to two-dimensional stresses and strains, i.e., the assumption of strictly one-dimensional hydrogeomechanics is violated; this effect, however, is considered insignificant for this scoping calculations. A 100 m wide discontinuity in the Basal Eneabba Shales is introduced by assigning the properties and the Eneabba formation to all elements in the interval $[950 \text{ m} < X < 1050 \text{ m}]$ and $[-679 \text{ m} < Z < -600 \text{ m}]$; the resulting permeability field is shown in Figure 6.
Table 9. Generation of Spatially Correlated Random Permeability Modifier Field using Sequential Indicator Simulations.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Cumulative Distribution Function</th>
<th>Permeability Modifier</th>
<th>Log-Permeability Modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine (shale)</td>
<td>0.00 0.01 0.07 0.25 0.43 0.49</td>
<td>0.01 0.05 0.09 0.16 0.28 0.50</td>
<td>-2.00 -1.30 -1.05 -0.80 -0.55 -0.30</td>
</tr>
<tr>
<td>Medium (silt)</td>
<td>0.51 0.53 0.60 0.67 0.69</td>
<td>3.00 4.82 7.75 12.45 20.00</td>
<td>0.48 0.68 0.89 1.10 1.30</td>
</tr>
<tr>
<td>Coarse (sand)</td>
<td>0.71 0.75 0.85 0.96 0.99 1.00</td>
<td>30.00 37.08 45.83 56.64 70.00 100.00</td>
<td>1.48 1.57 1.66 1.75 1.85 2.00</td>
</tr>
</tbody>
</table>

Figure 6. Spatially correlated, anisotropic, random permeability field with (a) continuous, and (b) discontinuous Basal Eneabba Shale layer.
3.2.3 Reference Simulation

Figure 7 shows the pressure-change distribution at 6 days (upper row), which coincides with a period of high barometric and Earth-tide loading, and at 9 days (lower row), which represents a period of low total loading. The pressure changes not only reflect the large-scale layering, but also show the structure of the smaller-scale heterogeneity, as each facies (and each point within a facies) has a different loading efficiency. Moreover, heterogeneity and anisotropy in permeability lead to different relaxation times as the imposed pressure perturbations dissipate due to fluid exchange between facies and layers. The pressure distribution without a discontinuity in the Basal Eneabba Shale (left column) and that with a discontinuity (right column) are indistinguishable even very close to the discontinuity.

Figure 8 shows the calculated flow rates during a period of loading (upper row) and unloading (lower row). For example, loading leads to overall pore-space compression and pressure increase. Low-permeability, clay-rich regions are assumed to be softer, i.e., have a higher loading efficiency and thus a stronger pressure perturbation compared to the surrounding sand materials, where more of the load is taken up by the solid skeleton. Consequently, during loading, water is compressed and fluid pressure diffuses from the low-permeability regions into the high-permeability regions, as shown in Figure 8a; the direction of fluid pressure diffusion is reversed during unloading. Diffusivities are higher in the high-permeability Yalgorup member, compared to the low-permeability Eneabba formation and tight Basal Eneabba Shales. Pressure diffusion is predominantly horizontal, aligned with the bedding of the facies; moreover, the materials have anisotropic permeabilities. Again, the pattern of vectors is essentially indistinguishable, whether the Basal Eneabba Shale is considered continuous (left column) or discontinuous (right column).

Figure 8 suggests that pressure dissipation is entirely controlled by local heterogeneity, rather than the large-scale structure of the storage formation and confining layer. It is therefore unlikely that pressure measurements outside the location of the discontinuity itself have the sensitivity needed to identifying whether the confining layer is continuous or not. This will be further examined below.

Figure 9 shows the simulated pressure responses to barometric fluctuations and Earth tides within as well as above and below the Basal Eneabba Shales, both with and without a discontinuity in the confining layer. The presence of the hole in the Basal Eneabba Shales is only evident in pressure sensors that are placed in the discontinuity itself. If the discontinuity is present, the pressure response shows the characteristics of the higher permeable Eneabba formation rather than that of the Basal Eneabba Shales. A slight impact can be seen in a sensor that is located at the very bottom of the Eneabba formation, i.e., at an elevation of -598 m, immediately above the confining layer, should it exist. Essentially no difference in the pressures can be observed in the Yalgorup member, even at an elevation of -683 m, i.e., immediately below the Basal Eneabba Shales. This confirms the hypothesis that the pressure responds to the local conditions around the sensor. Larger-scale structures, such as a discontinuity in the confining layer, can only be detected if the sensor in the observation hole happens to encounter the discontinuity. Nearby sensors – even those in close proximity to the discontinuity – fail to reveal its existence.
Figure 7. Pressure change in response to barometric fluctuations and Earth tide. Left column: continuous Basal Eneabba Shale; right column: discontinuous Basal Eneabba Shale; upper row: high loading at 6 days; lower row: low loading at 9 days.
Figure 8. Permeability field and flow vectors in vicinity of Basal Eneabba Shale. Left column: continuous Basal Eneabba Shale; right column: discontinuous Basal Eneabba Shale; upper row: high loading at 6 days; lower row: low loading at 9 days.
Figure 9. Simulated pressure response to barometric and Earth-tide above and below Basal Eneabba Shales, without (solid lines) and with (dashed lines) discontinuity in Basal Eneabba Shales.
4. Summary and Preliminary Conclusions

This report presents initial scoping calculations that examine the potential to estimate the vertical permeability of a confining layer overlaying a CO\textsubscript{2} storage formation using long-term pressure data that fluctuate due to barometric and Earth tide loading effects.

The numerical analyses presented here consider highly simplified one- and two-dimensional models. They approximately mimic the conditions and properties encountered in the Lesueur formations, specifically the stratigraphy near the Harvey 1 well. Different facies and variability within a given facies was incorporated into the two-dimensional model by generating spatially correlated heterogeneity in both hydrological and geomechanical properties. Specifically, this approach was used to represent the floodplain paleosols and vertisols at the contact between the basal Yalgorup and Wonnerup units, elongated structures that may act as confining layers.

Numerical errors are considered insignificant given the simplifications, approximations, and uncertainties inherent in such a scoping study.

An approach has been developed to numerically simulate the geomechanical loading effects from barometric pressure fluctuations and Earth tides, and the resulting transient pressure dissipation.

Synthetic barometric and Earth-tide forcing terms were created, and corresponding pressure observations were generated using the multi-phase flow simulator TOUGH2 and used in notional inversions to determine the uncertainty with which vertical permeabilities (along with other hydrological and geomechanical parameters) can be estimated. The analyses were consistent with the assumption that pressure fluctuations can be measured continuously with an accuracy of approximately 0.01% of a measurement range of 5000 psi (note that pressures can be measured in situ with a resolution on the order of a ppm).

The following conclusions can be drawn from the one-dimensional simulations described in Section 3.1:

- If the confining layer has a very low permeability, its estimation uncertainty is high, i.e., its value cannot be determined with confidence. Conversely, if the CO\textsubscript{2} storage formation is bounded by a semi-confining layer of relatively high permeability, its value can be reasonably well determined based on pressure fluctuation data.

- As expected in a system with non-linear relations between input parameters and output variables, the uncertainty with which a certain parameter of a given layer can be estimated depends on the parameter value itself. In this case, the higher the permeability of the semi-confining layer (here represented by the Basal Eneabba Shales), the better it can be determined, which is fortunate, as determining the potential absence of a confining layer is more crucial than confirming its presence.

- While the rather complex physical behavior is appropriately captured by the coupled hydrogeomechanical simulator, the model remains highly simplistic,
and the related inversion results are too optimistic, as the key assumption of one-dimensionality and homogeneity within a stratigraphic unit leads to an underestimation of estimation and prediction uncertainties. Some of these assumptions are relaxed in the two-dimension simulations.

The following conclusions can be drawn from the two-dimensional simulations described in Section 3.2:

- Accounting for two-dimensional heterogeneity in both hydrogeologic and geomechanical parameters leads to intricate loading effects, pressure responses, and flow fields.
- Observable pressure fluctuations are dominated by (1) the loading effects, which are governed by the local geomechanical properties, and (2) the pressure dissipation effects, which are controlled by the local hydrogeological properties.
- Pressure fluctuation data thus contain information about the local permeabilities.

In summary:

- Loading effects due to Earth tides and barometric pressure fluctuations are instantaneous everywhere in the subsurface (i.e., they are not the result of pressure propagation due to fluid flow and fluid pressure diffusion from the land surface across the confining layer to the reservoir).
- While barometric pressure changes and Earth tides are large-scale forcings on the subsurface, the induced pressure perturbations are controlled by the local geomechanical properties. Moreover, pressure dissipation (which is needed to estimate permeability) is also determined by local hydrogeological properties.
- Therefore, even if sensitive pressure sensors are employed and sufficient fluid pressure diffusion is induced by pressure gradients across regions with different hydrogeomechanical properties, the resulting permeability estimates reflect local conditions.
- Accurate long-term pressure measurements may be useful to estimate local permeabilities and local geomechanical properties if analyzed using a hydrogeomechanical forward simulator that is embedded in a robust inversion framework.
- However, even under near-ideal conditions, it is very unlikely that discontinuities in confining layers can be reliably detected by measuring barometric and tidal effects at a few observation wells, unless the well directly encounters such a discontinuity, a condition that counters the overall goal of assessing reservoir integrity on a large scale.
- This means that no reliable conclusions about the large-scale lateral extent of confining units can be made even if highly accurate pressure fluctuation data are collected at high temporal resolution. This conclusion applies to distinct
contacts between hydrostratigraphic units, but also to interfaces between facies within a given formation.

- Analyzing the diffusion of barometric pressure changes imposed at the land surface may be suitable to determine larger-scale discontinuities and effective vertical permeabilities; however, this method is limited to the shallow subsurface.
5. Recommendations

The following is a list of recommendations that are based on the preliminary analyses and conclusions described in this report.

- The strong dependence of the sensitivities, correlation structure, and data worth on the (unknown) permeability of the Basal Eneabba Shales suggests that a robust monitoring design should be based on measuring pressure fluctuations at multiple points along the profile, i.e., above, within, and below the formation of interest.

- The amplitude of Earth-tide effects seen in long-term pressure measurements strongly depends on the compressibility of the fluid present in the pore space (it is strongest in a low-permeability, fully saturated porous medium, and essentially absent if the pores are filled with a highly compressible gas). This suggests that observing Earth-tide effects may be used as a means to detect the presence or absence of injected CO$_2$ at a given location, and thus to monitor plume migration. Numerical analyses similar to those presented here could examine the viability of this method.
6. References


