Response of submarine hydrologic monitoring instruments to formation pressure changes: Theory and application to Nankai advanced CORKs

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1] We describe the response of a compressible submarine hydrologic monitoring instrument to formation pressure changes in low-diffusivity rock. The measured pressure depends on the frequency of the pressure signal, the hydraulic diffusivity, and the wellbore storage. The Nankai advanced circulation obviation retrofit kits (ACORKs) (offshore Japan) record tide-induced formation pressure changes with small amplitudes (<10% of seafloor amplitudes) and large phase shifts (>25°). The pressure measurements occur in thick, homogeneous, compressible, low-permeability sediment, where in situ tidal pressure responses should approximate the seafloor tidal signal. A wellbore storage of 2 × 10−8 m3 Pa−1 can explain many of the observed tidal responses, given the hydraulic diffusivities of the monitored intervals. A reduced permeability around the wellbore of 1000-fold and a wellbore storage of 10−11 m3 Pa−1 can also reconcile the data. Our analysis suggests that ACORK screens in the Lower Shikoku Basin facies have a critical frequency on the order of 5 × 10−8 Hz (equivalent to a period of 250 days); higher-frequency formation pressure signals will be distorted in the pressure record. Within the Lower Shikoku Basin facies the time for this monitoring system to record 90% of an instantaneous pressure change is on the order of 10 d. We suggest that the ACORK instrument compliance contributes to, but does not fully explain, the small tidal amplitudes and large phase shifts recorded at the least permeable monitoring intervals.


1. Introduction

2] Borehole monitoring of formation pressure changes requires that pressure in the instrument equilibrate with pressure in the formation. Consequently, large or compressible instruments filter formation pressure signals if the hydraulic diffusivity of the formation is sufficiently small. If formation pressure changes abruptly, the measured pressure asymptotically approaches the new formation pressure with time. If formation pressure oscillates with sufficiently high frequency, the measured pressure oscillation has a diminished amplitude and lags formation pressure. Numerous authors have presented this problem in open boreholes for both step [Gibson, 1963; Cooper et al., 1967; Papadopulos et al., 1973; Bredehoeft and Papadopulos, 1980] and cyclic [Cooper et al., 1965; Bredehoeft, 1967; Hsieh et al., 1987] pore pressure changes.

3] Circulation obviation retrofit kits (CORKs) have monitored pressures in tectonically active submarine settings for over a decade [Davis and Becker, 2001]. CORKs in the Barbados accretionary prism penetrate the décollement and record overpressures that are 30% to 60% of hydrostatic effective stress (the difference between hydrostatic and lithostatic pressure) [Becker et al., 1997; Foucher et al., 1997]. Barbados CORK data also indicate that décollement permeability is greater than surrounding sediment permeability [Screaton et al., 2000]. Davis et al. [2006] described abrupt pressure transients at Nankai Trough advanced CORKs (ACORKs) (offshore Japan), and suggested they represent earthquake-induced strain. In the Costa Rica prism, CORKs recorded transient pressure and temperature signals approximately two weeks after the onset of onshore strain events detected by a GPS network [Davis and Villinger, 2006]. CORKs in the Juan de Fuca Ridge recorded several pressure transients associated with seafloor spreading events [Davis et al., 2001, 2004].

4] In these studies, the measured pore pressure was assumed to equal the in situ pressure. Notably, recorded tidal pressure responses often had amplitude attenuations...
wellbore storage is too large to permit accurate measurement of in situ pressures at tidal frequencies in hemipelagic mud. Actions to improve pressure monitoring may include designing stiffer instruments with smaller volumes, conducting well tests, and increasing permeabilities near screens through the use of sand packs, hydraulic fractures, or conventional well development.

2. Instrument Response to Formation Pressure Changes

Consider a well, represented by a closed cylinder with screen radius \( r = a \), surrounded by an infinite homogeneous medium (Figure 1). Formation fluid enters the well through the cylindrical screen. The nondimensionalized cylindrical flow equation describes pressure in the formation:

\[
\frac{\partial^2 P_D}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial P_D}{\partial r_D} + S_D(t_D) = \frac{\partial P_D}{\partial t_D},
\]

where \( P_D \) is dimensionless pressure,

\[
P_D = \frac{P(r, t)}{P(\infty, t)},
\]

\( P(\infty, t) \) is the formation pressure far from the well’s sphere of influence; \( r_D \) is the dimensionless radius,

\[
r_D = \frac{r}{a},
\]

where \( a \) is the screen radius; \( t_D \) is dimensionless time,

\[
t_D = \frac{ct}{a^2},
\]

where \( c \) is the hydraulic diffusivity:

\[
c = \frac{k}{\mu S_v}
\]

\( k \) is intrinsic permeability, \( \mu \) is fluid viscosity, and \( S_v \) is specific storage, given by

\[
S_v = \rho g (m_v + n \beta_v).
\]

\( \rho g \) is specific weight of the pore fluid, \( m_v \) is formation compressibility, \( n \) is porosity, and \( \beta_v \) is the compressibility of the pore fluid (Table 1). \( S_D \) (equation (1a)) is a nondimensionalized time-varying fluid source term. Fluid volume is conserved between the formation and the well such that

\[
\frac{\partial P_D}{\partial \hat{t}_D} = \beta_D \frac{\partial P_D}{\partial r_D} \quad \text{at} \quad r_D = 1,
\]

where \( P_D \) is dimensionless pressure measured at the screen, normalized according to equation (1b), and \( \beta_D \) is the dimensionless formation-instrument compliance ratio:

\[
\beta_D = \frac{2\pi a^2 h m_v}{\beta_s V}.
\]
Table 1. Symbols, Definitions, and Dimensions of Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Dimension</th>
</tr>
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<tr>
<td>(A)</td>
<td>amplitude</td>
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<tr>
<td>(a)</td>
<td>screen radius</td>
<td>L</td>
</tr>
<tr>
<td>(c)</td>
<td>hydraulic diffusivity</td>
<td>L(^2) t(^{-1})</td>
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</tr>
<tr>
<td>(F)</td>
<td>imaginary pressure response parameter</td>
<td>-</td>
</tr>
<tr>
<td>(h)</td>
<td>screen height</td>
<td>L</td>
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<tr>
<td>(k)</td>
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<td>(L)</td>
<td>characteristic diffusion length</td>
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<tr>
<td>(L_t)</td>
<td>tubing length</td>
<td>L</td>
</tr>
<tr>
<td>(m_c)</td>
<td>formation compressibility</td>
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<tr>
<td>(n)</td>
<td>porosity</td>
<td>-</td>
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<tr>
<td>(P(r, t))</td>
<td>pressure</td>
<td>M L(^{-1}) t(^{-2})</td>
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<tr>
<td>(P_m^0)</td>
<td>dimensionless measured pressure</td>
<td>-</td>
</tr>
<tr>
<td>(P_D)</td>
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<td>-</td>
</tr>
<tr>
<td>(r)</td>
<td>radius</td>
<td>L</td>
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<tr>
<td>(r_D)</td>
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</tr>
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<td>(r_{c,i})</td>
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<td>L</td>
</tr>
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<td>(r_{c,o})</td>
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</tr>
<tr>
<td>(r_{s,i})</td>
<td>screen inner radius</td>
<td>L</td>
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<td>(r_{s,o})</td>
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<td>L</td>
</tr>
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<td>(r_{t,i})</td>
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<td>L</td>
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<tr>
<td>(r_{t,o})</td>
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<td>L</td>
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<tr>
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<tr>
<td>(t)</td>
<td>time</td>
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<td>(t_D)</td>
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<tr>
<td>(V)</td>
<td>system volume</td>
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<td>(\mu)</td>
<td>fluid viscosity</td>
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<td>degrees</td>
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<tr>
<td>(\rho_g)</td>
<td>specific weight</td>
<td>M L(^{-2}) t(^{-2})</td>
</tr>
<tr>
<td>(\Psi)</td>
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<td>Poisson’s ratio</td>
<td>-</td>
</tr>
<tr>
<td>(\omega)</td>
<td>radian frequency</td>
<td>t(^{-1})</td>
</tr>
<tr>
<td>(\omega_D)</td>
<td>dimensionless radian frequency</td>
<td>-</td>
</tr>
</tbody>
</table>

\(h\) is the cylindrical cavity height, \(\beta_s\) is the composite fluid and instrument compressibility, and \(V\) is the instrument volume (Figure 1 and Table 1). Equation (2b) assumes the specific storage approximates the product of formation compressibility and specific weight of the fluid, which is common for sediment. Small values of \(\beta_D\) represent a more compressible instrument relative to the formation. The fluid pressure in the instrument \((P_D^0)\) equals the formation pressure at the screen radius:

\[
P_D^0 = P_D \text{ at } r_D = 1 \text{ for } t_D > 0.
\]  

We first consider the case without a source term \((S_D = 0)\), where pressure is initially uniform in the formation, and pressure in the borehole instantaneously decreases by \(\Delta P\) at time zero (Figure 1, dashed line). Formation pressure is constant far from the borehole:

\[
P_D \to 1 \text{ as } r_D \to \infty \text{ for } t_D > 0.
\]  

\(Gibson\ [1963]\) and \(Bredehoeft\ and\ Papadopulos\ [1980]\) solved this problem in spherical coordinates and cylindrical coordinates, respectively. \(\beta_D\) (equation (2b)) is equivalent to \(2\alpha\) in the \(Neuzil\ [1982]\) correction to the \(Bredehoeft\ and\ Papadopulos\ [1980]\) solution. We plot pressure equilibration \((\varepsilon)\) versus the combined parameter \(\beta_D\) for different formation-instrument compliance ratios using Bredehoeft and Papadopulos’ [1980] solution (Figure 2).

\[
\varepsilon = \frac{P(\infty) - P(t)}{P(\infty) - P(0)}
\]  

For a given formation-instrument compliance ratio \((\beta_D)\), equilibration increases with time or hydraulic diffusivity (Figure 2 and equation (1d)). With increasing \(\beta_D\), equilibration occurs more rapidly (Figure 2 and equation (2b)).

\([9]\) To consider sinusoidal changes in formation pressure, we include a uniform, time-varying source term \((S_D)\) in equation (1a):

\[
S_D(t_D) = \omega_D \cos(\omega_D t_D).
\]  

\(\omega_D\) is the nondimensionalized radian frequency \((\omega)\):

\[
\omega_D = \frac{a^2 \omega}{c}.
\]  

The inner boundary condition is unchanged, and we assign a no-flow outer boundary:

\[
\frac{\partial P}{\partial r} \to 0 \text{ as } r \to \infty.
\]  

\(Hsieh\ et\ al.\ [1987]\) solved this problem for head change in an open well due to Earth tide dilation of the surrounding confined aquifer. We modify their solution to describe pressure in a closed monitoring instrument. \(A\), the measured amplitude in the instrument relative to amplitude in the far field, and \(\phi\), the phase shift, are given by

\[
A = \frac{1}{\sqrt{E^2 + F^2}},
\]  

\[
\phi = -\tan \left( \frac{E}{F} \right).
\]  

\(E\) and \(F\) are defined in Appendix A.

\([9]\) The measured pressure is a function of two dimensionless parameters: \(\beta_D\), the formation-instrument compliance ratio (equation (2b)), and \(\omega_D\), the dimensionless frequency (equation (6b)) (Figures 3a and 3b). An instrument with low compressibility relative to the formation (high \(\beta_D\)) records pressure signals with negligible amplitude attenuations and phase shifts \((A \sim 100\%, \phi \sim 0)\) over a wide range of frequencies (e.g., \(\beta_D = 100\), Figures 3a and 3b). However, all instruments have some frequency threshold above which measured pressures depart from formation pressures. We define the critical frequency for a given \(\beta_D\) as the frequency where \(A = 90\%\). For example, an instrument with \(\beta_D = 100\) has a critical dimensionless frequency of 250
Above this frequency, amplitude attenuation and phase shift of the measured signal increase rapidly. More compliant instruments (lower $\beta_D$) have lower critical frequencies.

3. A Case Study: Nankai ACORKs

We use our model to analyze the fidelity of pressure measurements at two long-term hydrologic observatories (ACORKs) installed offshore of Japan in the Nankai Trough in June 2001 [Mikada et al., 2002; Davis et al., 2006] (Figure 4). The Nankai Trough marks the shallow subduction of the Philippine Sea Plate beneath the Eurasian Plate (Figure 4). The plate boundary (décollement) separates offscraped and accreted sediment of the Nankai accretionary prism from underthrust sediment and basement [Taira et al., 1991] (Figure 5). At Ocean Drilling Program (ODP) Site 1173, the 16 Ma basement is successively overlain by volcanoclastics, a middle Miocene to mid-Pliocene hemipelagic mud (Lower Shikoku Basin facies), an upper Pliocene to lower Pleistocene hemipelagic mud with tephra layers (Upper Shikoku Basin facies), and a sequence of Pleistocene to Holocene interbedded turbidites and hemipelagic muds (Trench-Basin facies and Outer-Trench Wedge facies) [Mikada et al., 2002] (Figure 6).

ODP Site 808 penetrates the frontal thrust of the imbricate thrust zone and the décollement (Figure 5). The basaltic basement at ODP Site 808 is overlain by volcanoclastics, the Lower Shikoku Basin facies, Upper Shikoku Basin facies, Trench-Basin facies, and Outer Marginal Trench-Wedge facies (Figure 7). The stratigraphy at ODP Site 808 includes additional Pleistocene to Holocene sand and silt turbidite units not present at ODP Site 1173: Lower Axial Trench facies (thin-beded sand and silt turbidites), Upper Axial Trench facies (thick-beded sand turbidites), and Lower Slope facies (a thin, Quaternary hemipelagic
mud and turbidite unit) (Figure 7). The frontal thrust at ODP Site 808 displaces the Outer Marginal Trench-Wedge facies over the Lower Axial Trench facies [Mikada et al., 2002]. The Lower Shikoku Basin facies contains the décollement (Figure 7).

3.1. ACORK Design

Each ACORK consists of a 10.75" outside-diameter casing string with packers and monitoring screens suspended around it (Figures 6 and 7). A multiline hydraulic umbilical transmits screen pressures to sensors and data loggers at the seafloor. The hydraulic umbilical runs the length of the installation between the casing and borehole wall and passes successively through packers [Becker and Davis, 2005] (Figure 8). The inflatable packers consist of 3-m-long steel-reinforced rubber bladders. The screens, numbered sequentially from deepest to shallowest, are 7.6 m long and extend outward from the casing by 2 cm [Becker and Davis, 2005] (Figure 8). Because pressure sensors are located at the seafloor, the measurements for each screen share the same hydrostatic reference. Pumping valves, used for conducting well tests, are also located at the seafloor [Becker and Davis, 2005].

The ACORKs represent a fundamental design change from previous CORK installations [Becker and Davis, 2005]. CORKs are cased holes with a single seal at the seafloor. Pressure monitoring occurs at the CORK head. The original CORKs integrate pressure over the length of open borehole or perforated interval. They do not measure pressure in multiple isolated zones, and they have no tubing to connect the open hole with gauges at the seafloor [Becker and Davis, 2005].

The ACORK at ODP Site 1173 monitors pressures at five screens (Figure 8). A packer exists above each screen except screen 5 (Figure 6). A bridge plug, or hydraulic seal, was installed inside the casing to prevent flow to the seafloor. During deployment, the bridge plug set prematurely at approximately 466 m below seafloor (mbsf) [Mikada et al., 2002]. The ACORK at ODP Site 808 monitors pressures at six screens. Only two packers are present: one separates the shallowest screen from the seafloor and the other separates the two deepest screens [Mikada et al., 2002]. It is assumed that borehole collapse around screens provides hydraulic isolation for each monitoring interval [Mikada et al., 2003]. Owing to poor drilling conditions at ODP Site 808, the ACORK was emplaced 37 m above its intended position [Mikada et al., 2002]. A bridge plug could not be installed, so the open casing likely accommodates fluid flow between screen 1 and the seafloor [Mikada et al., 2002].

3.2. Lithology and Hydraulic Diffusivity

Four of the five screens at ODP Site 1173 lie in the Lower Shikoku Basin facies (Figure 6), which is composed of moderately bioturbated silty claystone to clayey siltstone. Porosity gradually decreases from approximately 55% at screen 5 (359 mbsf) to 40% at screen 2 (569 mbsf). Screen 1 spans volcanioclastics composed of silty claystone that...
overlay the oceanic basement (Figure 6) [Moore et al., 2001]. Because screen 1 is close to or in contact with the high-permeability basement, vertical fluid flow from the basement may be significant.

At ODP Site 808, screen 6 lies just above the frontal thrust in the Outer Marginal Trench-Wedge facies, and screen 5 lies below the frontal thrust in the Outer Marginal Trench-Wedge facies of the footwall (Figure 7). The composition of these intervals is bioturbated silty clay and silt turbidites. A thin silt to coarse sand layer occurs at screen 6 (370 mbsf) [Taira et al., 1991]. At screen 5, current-ripple laminated siltstone interbeds are present. Screen 4 lies within the Upper Shikoku Basin facies and spans silty claystone to clayey siltstone with tuff beds. Screens 1 through 3 lie in moderately bioturbated silty claystone to clayey siltstone of the Lower Shikoku Basin facies. Screen 1 is located approximately 10 m above the décollement.

We calculated hydraulic diffusivity at each screen based on estimates of permeability, temperature-dependent fluid viscosity, and formation compressibility (Appendix B and Table 2). At both ACORKs, sand and silt turbidites are less common and porosity generally decreases at greater depths. As a result, permeability decreases with depth by almost 1 order of magnitude at ODP Site 1173 and 4 orders of magnitude at ODP Site 808 (Table 2). Formation compressibility ($m_v$) varies little with depth, and we assume it equals $10^{-8}$ Pa$^{-1}$ [Bourlange et al., 2004; D. Saffer et al., unpublished data, 2007].

Because formation compressibility varies little, permeability most strongly influences hydraulic diffusivity at the ACORK screens (Figures 6 and 7). At ODP Site 1173, where four of five screens lie in the Lower Shikoku Basin facies, hydraulic diffusivities decrease slightly from the shallowest to deepest screen (Figure 6). At ODP Site 808, where two screens lie in the Outer Marginal Trench-Wedge facies, hydraulic diffusivities decrease by 4 orders of magnitude (Figure 7).

The small variation in formation compressibility also implies little variation in loading efficiency ($\gamma$), which describes the pore pressure response to undrained uniaxial loading. The loading efficiency represents the fraction of an applied load supported by the pore fluid. The loading

![Figure 6. Stratigraphy of ODP Site 1173, ACORK design, and tidal response: (left to right) 1, depth in meters below seafloor; 2, porosity from core samples; 3, logging-while-drilling gamma ray; 4, logging-while-drilling resistivity; 5, stratigraphic units; 6, position of ACORK elements (S, screen; P, packer; and BP, bridge plug); 7, hydraulic diffusivity; 8, tidal amplitude response for K$_1$ (diurnal) and M$_2$ (semidiurnal) frequencies; and 9, phase response (Table 3). Porosity, gamma ray, and resistivity data were collected during ODP Legs 190 and 196. Analysis of tidal pressure responses is based on an 80-day window that begins on 12 October 2003.](image-url)
efficiency depends on formation compressibility, porosity, and water compressibility [van der Kamp and Gale, 1983; Wang and Davis, 1996]:

\[
\gamma = \frac{m_v'}{m_v' + n b_w};
\]

(9a)

where

\[
m_v' = \frac{1 + \nu}{3(1 - \nu)} m_v;
\]

(9b)

\(\nu\) is Poisson’s ratio. The sediment at ODP Sites 808 and 1173 has a formation compressibility of 10^{-8} Pa^{-1} [Bourlange et al., 2004; D. Saffer et al., unpublished data, 2007], which is 2 orders of magnitude greater than that of water. For the ACORK monitoring intervals, where porosities range from 0.30 to 0.55, we calculate loading efficiencies between 0.95 and 0.99. This large loading efficiency implies that in situ pore pressure changes approximate changes in the undrained applied load.

3.3. Tidal Response Analysis

[20] We examined two 80-day windows of data: one at ODP Site 1173 (Figure 9) and the other at ODP Site 808 (Figure 10). An 80-day window allows resolution of \(S_2\) (12.00 hours), \(M_2\) (12.42 hours), \(K_1\) (23.93 hours), and \(O_1\) (25.82 hours) frequencies (Figure 11). We calculated the
Figure 8. ACORK design at ODP Site 1173. (left) Detailed view of packers and screens. Horizontal exaggeration is approximately 20:1 (screen height is actually 25 times the screen radius). (right) Hydraulic tubing connects screens with pressure sensors at the seafloor. The bridge plug at ODP Site 1173 set prematurely during installation at \( /C24 466 \) m below seafloor (mbsf).

Table 2. Permeability, Viscosity, and Compressibility Estimates Used to Calculate Hydraulic Diffusivity at ODP Sites 1173 and 808\(^a\)

<table>
<thead>
<tr>
<th>Screen</th>
<th>Depth, mbsf</th>
<th>( T, ^\circ C )</th>
<th>( \mu, \text{ Pa s} )</th>
<th>( k, \text{ m}^2 )</th>
<th>( m_c, \text{ Pa}^{-1} )</th>
<th>( c, \text{ m}^2 \text{s}^{-1} )</th>
<th>( \omega_{12} ) (12 hours)</th>
<th>( \omega_{24} ) (24 hours)</th>
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<tbody>
<tr>
<td>1173 S5</td>
<td>359</td>
<td>65</td>
<td>( 3.9 \times 10^{-4} )</td>
<td>( 8.5 \times 10^{-18} )</td>
<td>( 1.5 \times 10^{-8} )</td>
<td>( 1.4 \times 10^{-6} )</td>
<td>2.4</td>
<td>1.2</td>
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<tr>
<td>1173 S4</td>
<td>402</td>
<td>70</td>
<td>( 3.7 \times 10^{-4} )</td>
<td>( 7.6 \times 10^{-18} )</td>
<td>( 1.5 \times 10^{-8} )</td>
<td>( 1.4 \times 10^{-6} )</td>
<td>2.6</td>
<td>1.3</td>
</tr>
<tr>
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<td>445</td>
<td>78</td>
<td>( 3.3 \times 10^{-4} )</td>
<td>( 5.1 \times 10^{-18} )</td>
<td>( 1.5 \times 10^{-8} )</td>
<td>( 1.0 \times 10^{-6} )</td>
<td>3.5</td>
<td>1.7</td>
</tr>
<tr>
<td>1173 S2</td>
<td>569</td>
<td>92</td>
<td>( 2.9 \times 10^{-4} )</td>
<td>( 2.2 \times 10^{-18} )</td>
<td>( 1.5 \times 10^{-8} )</td>
<td>( 5.1 \times 10^{-7} )</td>
<td>6.9</td>
<td>3.5</td>
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<td>41</td>
<td>( 5.9 \times 10^{-4} )</td>
<td>( 5.0 \times 10^{-15} )</td>
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<tr>
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<td>54</td>
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</tr>
<tr>
<td>808 S1</td>
<td>922</td>
<td>83</td>
<td>( 3.1 \times 10^{-4} )</td>
<td>( 4.4 \times 10^{-19} )</td>
<td>( 1.5 \times 10^{-8} )</td>
<td>( 9.3 \times 10^{-8} )</td>
<td>38</td>
<td>19</td>
</tr>
</tbody>
</table>

\(^a\)See Appendix B; mbsf is meters below seafloor. To calculate \( \omega_{12} \) for semidiurnal and diurnal frequencies, we used the ACORK screen radius of 0.156 m.
and tidal components. We only plot phase and amplitude of the M2 tidal component since it has the highest signal-to-noise ratio (Figure 11).

### 3.3.1. ODP Site 1173 Tidal Responses

Tidal signals at ODP Site 1173 generally decrease in amplitude with depth (Figure 6 and Table 3). At screens 4 and 5, amplitudes approach 90% of tidal loading amplitudes, as predicted in the compressible Lower Shikoku Basin facies. In contrast, screens 1, 2, and 3 have small amplitudes (35%, 55%, and 20% of loading amplitudes, respectively). Screens 1 and 3 also have large negative phase shifts (~30°), while the other screens have small positive phases (~5°).

The M2 (12.42 hours) amplitudes and phases vary with time (Figure 12). During ACORK installation, valves for screens 3, 4, and 5 rotated open. In August 2002 when the first pressure data were recovered, the open pump valves were discovered and closed [Mikada et al., 2003]. Pressure at screen 1 inexplicably fell, though the valve for this screen was not disturbed. The elevated pressure, small amplitudes, and large phase lags at screen 1 indicate that either the bridge plug or borehole collapse isolates the screen from the seafloor. The slow pressure recovery after valve closure at screen 3 may suggest the permeability is especially low. The small amplitudes and large phase lags also imply a reduced permeability at screen 3.

### 3.3.2. ODP Site 808 Tidal Responses

Tidal signals at ODP Site 808 also decrease in amplitude with depth. Amplitudes at screens 2 and 3 (in low-permeability hemipelagic mudstone) are less than 15% of tidal loading amplitudes. However, amplitudes at screens 5 and 6 (in silty hemipelagic turbidites) approach 90% of tidal loading amplitudes, as predicted for compressible sediment (Figure 7). Phase lags increase with depth from screen 6 (~25°) to screen 4 (~40°). However, screens 2 and 3 have large phase leads (Figure 7 and Table 3).

The M2 tidal signals at ODP Site 808 also vary through time. The pump valve for screen 3 was the only valve found closed at ODP Site 808 in August 2002 [Mikada et al., 2003]. As a result, all other screens recorded hydrostatic pressures, zero phase shifts, and no amplitude attenuation prior to valve closure (Figure 13). After valve closure, mean pressures at screens 1 and 2 (Lower Shikoku Basin facies) rose (Figure 13a). Screen 4 (Upper Shikoku Basin facies) and screens 5 and 6 (Outer Marginal Trench-Wedge facies) all maintained hydrostatic pressures from 2002 to 2004.

### 3.4. Formation-Instrument Compliance Ratio ($\beta_D$)

One interpretation of small amplitudes and large phase shifts in measured tidal pressure responses is that the instrument is sufficiently compliant, given the hydraulic diffusivity of the formation, to impact the fidelity of the measurements. To evaluate this interpretation, we estimated the formation-instrument compliance ratio for the ACORKs through three approaches.

#### 3.4.1. Formation-Instrument Compliance Ratio ($\beta_D$) From Tidal Response

We used observed amplitude attenuations and phases to estimate $\beta_D$. We represent K1 (diurnal) and M2 (semidiurnal) tidal amplitudes and phases at each screen as horizontal bars (Figure 3). Solid bars indicate K1 (diurnal) frequencies, and dashed bars indicate M2 (semidiurnal) frequencies. The vertical position of each bar corresponds

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#### Figure 9.
Typical pressure record at ODP Site 1173. Pressure is slightly elevated above hydrostatic (<0.1 MPa) at every screen. Screens 1, 2, and 3 have visibly diminished amplitudes.

#### Figure 10.
Typical pressure record at ODP Site 808. Pressure is slightly elevated above hydrostatic (<0.2 MPa) at screens 2 and 3. Inset shows mean-removed pressures over the 2-day window A–B. Screens 2, 3, and 4 have visibly diminished amplitudes and large phase shifts.
to the amplitude (Figure 3a) or phase (Figure 3b) measured at that screen (Table 3). Each bar spans a 1-order-of-magnitude range in $\omega_D$, which corresponds to a 1-order-of-magnitude uncertainty in our permeability estimates (Table 2). We used vertical permeability estimates to calculate hydraulic diffusivity and $\omega_D$ (Table 2). Horizontal permeability may be up to ten times greater [Yang and Aplin, 2007]. We excluded ODP Site 808 screen 1 and ODP Site 1173 screen 1 from our analysis because of the potential for drainage to the seafloor and basement, respectively.

All but one of the screens lie along an amplitude response curve with characteristic $\beta_D$ between 0.1 and 1 (Figure 3a). Three of the nine analyzed screens also lie on a phase shift curve with characteristic $\beta_D$ between 0.1 and 1 (Figure 3b). We did not plot screens with positive phases on Figure 3b, as our model does not predict positive phases. We used equation (2b) to estimate $\beta_* V$ (wellbore storage) from our estimate of $\beta_D$, the ACORK screen dimensions ($a$ and $h$) (Appendix B), and formation compressibility ($m_v$) (Table 2). Because $a$, $h$, and $m_v$ are similar for all screens, so is the wellbore storage. If $\beta_D = 0.5$, $\beta_* V$ is $2 \times 10^{-8} \text{ m}^3 \text{ Pa}^{-1}$ at both ACORK sites (equation (2b)).

### 3.4.3. Formation-Instrument Compliance Ratio ($\beta_D$) From Well Test Analysis

On 6 August 2002 (4 d after valve closure in Figure 13), a remotely operated vehicle opened and promptly closed the pump valve for ODP Site 808 screen 2 [Mikada et al., 2003] (Figure 14a). The pressure at screen...
2 immediately dropped to hydrostatic and then asymptotically approached a new pressure approximately 100 kPa above hydrostatic. In an ideal slug test, instrument pressure is instantaneously offset from formation pressure and then allowed to recover. Formation pressure should be uniform near the screen prior to the slug test [Neuzil, 1982]. Unfortunately, at ODP Site 808 screen 2, open flow from 2001 to 2002 had likely reduced formation pressures around the screen (Figure 14a).

[31] Nonetheless, we interpret this pressure response as a traditional slug test, since it is the closest approximation to a well test conducted at either ACORK. The data match a type curve with characteristic $\beta_D$ of 0.01 (Figure 14b). This $\beta_D$ implies a wellbore storage ($\beta V$) of $2 \times 10^{-6}$ m$^3$ Pa$^{-1}$, given the screen geometry and formation compressibility of $1.5 \times 10^{-8}$ Pa$^{-1}$. The match between the data and type curve also establishes $ca^2$ as 0.0026 s$^{-1}$ (Figure 14b). Given an ACORK screen radius ($a$) of 0.156 m, $c$ is thus $6.3 \times 10^{-7}$ m$^2$ s$^{-1}$. Using our $ca^2$ value, we determined $\omega_D$ for a semidiurnal tidal frequency to be 0.056 (equation (6b)). We indicate the tidal pressure response for the slug test-derived $\beta_D$ and $\omega_D$ estimates in Figure 3 (solid stars).

4. Discussion

[32] At ODP Sites 808 and 1173, tidal amplitudes and hydraulic diffusivities generally decrease with depth (Figures 6 and 7). Most of the measured amplitudes in the Lower Shikoku facies are much smaller than amplitudes predicted for the formation ($\sim 95\%$ of seafloor amplitudes). Phase shifts also become large (nonzero) as diffusivity decreases. We interpret that small amplitudes and large phase shifts result from hydraulic impedance at the screens. A formation-instrument compliance ratio ($\beta_D$) of 0.5, and consequently a wellbore storage ($\beta V$) of $2 \times 10^{-8}$ m$^3$ Pa$^{-1}$, will reconcile most of the tidal measurements, given our hydraulic diffusivity estimates (Table 2). This $\beta_D$ value implies a dimensionless critical frequency of 0.07 (Figure 3a). In the Lower Shikoku Basin facies ($c \sim 10^{-7}$ m$^2$ s$^{-1}$), the dimensionless critical frequency equates to $5 \times 10^{-8}$ Hz, or a period of 250 days. Measured pressure signals with shorter periods will theoretically have attenuated amplitudes and phase shifts, given our wellbore storage estimate. For example, at the Nyquist frequency ($\sim 10^{-3}$ Hz), our model predicts an amplitude response near 1% and a phase lag near $-45^\circ$ in the Lower Shikoku Basin facies.

[33] In spite of their low critical frequencies, the ACORKs will record a rapid pressure change in response to a nearly instantaneous formation pressure change. The pressure response follows the step load solution (Figure 2). For $\beta_D \sim 0.5$, measured pressures will equilibrate to within 90% of the formation pressure change ($\epsilon = 0.1$) at a dimensionless time ($t_D$) of approximately 12 (Figure 2, $\beta_D = 6$). At ODP Site 1173, this dimensionless time is equivalent to three days at screen 5, where diffusivity is greatest, and seven days at screen 1, where diffusivity is least (equation (1d) and Table 2). This calculation agrees well with rapid pressure changes observed at ODP Site 1173 following VLF earthquake activity in 2003 [Davis et al., 2006, Figure 4]. Pressures declined at ODP Site 1173 screens 2, 4, and 5 over approximately 5 days, while pressure at screen 1 increased over approximately 6 d.

[34] Our wellbore storage estimate from tidal responses lies between two other independent estimates. The slug test (Figure 14b) implies a very compressible instrument with $\beta V \sim 10^{-8}$ m$^3$ Pa$^{-1}$ and $\beta_D \sim 10^{-2}$. Most likely, this apparent compressibility results from significant pressure drawdown around the wellbore prior to the test. The cone of depression causes a slower pressure recovery than predicted and thus an apparently high wellbore storage value.

### Table 3. Measured Tidal Pressure Responses at ODP Sites 1173 and 808, Based on an 80-Day Window That Begins on 12 October 2003

<table>
<thead>
<tr>
<th>Screen</th>
<th>$O_1$ (25.82 hours)</th>
<th>$K_1$ (23.93 hours)</th>
<th>$M_2$ (12.42 hours)</th>
<th>$S_2$ (12.00 hours)</th>
<th>Amplitude, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1173 SF</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1173 SS</td>
<td>88.99</td>
<td>90.04</td>
<td>90.13</td>
<td>90.35</td>
<td>0.00</td>
</tr>
<tr>
<td>1173 S4</td>
<td>83.96</td>
<td>85.26</td>
<td>87.91</td>
<td>88.74</td>
<td>0.00</td>
</tr>
<tr>
<td>1173 S3</td>
<td>25.09</td>
<td>21.42</td>
<td>20.19</td>
<td>20.44</td>
<td>0.00</td>
</tr>
<tr>
<td>1173 S2</td>
<td>55.72</td>
<td>55.53</td>
<td>56.65</td>
<td>57.15</td>
<td>0.00</td>
</tr>
<tr>
<td>1173 S1</td>
<td>42.28</td>
<td>40.34</td>
<td>33.25</td>
<td>33.60</td>
<td>0.00</td>
</tr>
<tr>
<td>808 SF</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>0.00</td>
</tr>
<tr>
<td>808 S6</td>
<td>101.18</td>
<td>94.68</td>
<td>75.94</td>
<td>76.53</td>
<td>0.00</td>
</tr>
<tr>
<td>808 S5</td>
<td>99.73</td>
<td>99.41</td>
<td>96.10</td>
<td>95.55</td>
<td>0.00</td>
</tr>
<tr>
<td>808 S4</td>
<td>51.20</td>
<td>47.78</td>
<td>27.56</td>
<td>27.27</td>
<td>0.00</td>
</tr>
<tr>
<td>808 S3</td>
<td>10.42</td>
<td>11.72</td>
<td>14.16</td>
<td>14.52</td>
<td>0.00</td>
</tr>
<tr>
<td>808 S2</td>
<td>8.21</td>
<td>9.43</td>
<td>11.74</td>
<td>12.29</td>
<td>0.00</td>
</tr>
<tr>
<td>808 S1</td>
<td>92.96</td>
<td>92.99</td>
<td>92.73</td>
<td>92.65</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 4. ACORK Engineering Specifications for Calculation of $\beta_D$ at ODP Site 808 Screen 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_c$</td>
<td>formation compressibility</td>
<td>$1.5 \times 10^{-8}$ Pa$^{-1}$</td>
</tr>
<tr>
<td>$r_{i,j}$</td>
<td>tube inner radius</td>
<td>0.0023 m</td>
</tr>
<tr>
<td>$r_{o,j}$</td>
<td>tube outer radius</td>
<td>0.0032 m</td>
</tr>
<tr>
<td>$\beta_{steel}$</td>
<td>steel compressibility</td>
<td>$5.0 \times 10^{-12}$ Pa$^{-1}$</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>fluid compressibility</td>
<td>$4.5 \times 10^{-10}$ Pa$^{-1}$</td>
</tr>
<tr>
<td>$r_{i,j}$</td>
<td>screen inner radius</td>
<td>0.136 m</td>
</tr>
<tr>
<td>$r_{o,j}$</td>
<td>screen outer radius</td>
<td>0.156 m</td>
</tr>
<tr>
<td>$h$</td>
<td>screen height</td>
<td>7.6 m</td>
</tr>
<tr>
<td>$r_{c,j}$</td>
<td>casing inner radius</td>
<td>0.126 m</td>
</tr>
<tr>
<td>$r_{c,o}$</td>
<td>casing outer radius</td>
<td>0.136 m</td>
</tr>
<tr>
<td>$L_t$</td>
<td>tubing length</td>
<td>878 m</td>
</tr>
</tbody>
</table>

*See Appendix C.*
In contrast, our calculation of wellbore storage from the ACORK design (Appendix C) implies a very stiff instrument with $\beta^* \approx 10^{-10} \text{ m}^3 \text{ Pa}^{-1}$ and $\beta_D \approx 10^2$. This calculation likely underestimates the system compressibility.

Closed monitoring systems often have unexpectedly large system compressibilities due to instrument parts and connections [Neuzil et al., 1981; Neuzil, 1982]. Potential sources of ACORK compliance that we ignored in our calculation include the screens and packers, as well as numerous connections in the hydraulic lines that transmit screen pressures to the gauges (Figure 8). Leaky hydraulic connections are common in experimental systems [Neuzil et al., 1981; Neuzil, 1982]. Free gas in the tubing or screens would also increase $\beta^*$, although the effect would be small at confining pressures near 50 MPa [Wang et al., 1998].

Alternatively, if hydraulic diffusivities are 1000 times less than our estimates (Table 2), tidal analysis will predict the same $\beta_D$ as our calculation from ACORK design because tidal responses will plot further to the right (at higher $\omega_D$ values) in Figure 3. In mudstones, drilling can shear borehole walls to create a low-permeability zone (Figure 1, light shading) [d’Astous et al., 1989; Fisher et al., 1996; Fisher and Zwart, 1997]. The damaged zone permeability determines $\omega_D$ if the damaged zone is thicker than the penetration distance of a tidal pressure signal. The diffusion length ($L$) defines the penetration distance:

$$L = \sqrt{\varepsilon t}.$$  

For a 12-hour period in the undamaged Lower Shikoku Basin facies ($c \approx 10^{-7} \text{ m}^2 \text{ s}^{-1}$), $L$ is 6 cm. For a 1000-fold reduction in permeability within the damaged zone, $L$ is 2 mm. Therefore a thin zone of severe damage in combination with a stiff instrument can explain the observed amplitudes and phases.

We assumed horizontal flow into a cylindrical cavity from a homogeneous medium and did not consider the effect of flow contributions from above and below the screened interval. To evaluate the impact of vertical flow to the screen, we numerically modeled the same problem in spherical coordinates. We represented the cylindrical screen as a sphere with an equivalent surface area. The results approximated those of the cylindrical coordinate system, even for screens with a height-to-radius ratio as large as 25 (Figure 3, solid and open circles).

Our model is most appropriate for instruments that monitor pressures far from a drainage boundary such as the seafloor or high-permeability basement. Close to a drainage boundary (within the diffusive wavelength of a tidal signal), vertical fluid exchange across the drainage boundary influences the in situ tidal pressure response [van der Kamp and Gale, 1983; Rojstaczer and Riley, 1990; Wang and Davis, 1996]. The diffusive wavelength for the Lower Shikoku Basin facies is 6 cm. Even for the greatest hydraulic diffusivity we estimate ($\varepsilon \approx 10^{-4} \text{ m}^2 \text{ s}^{-1}$) the diffusive wavelength is only 5 m. All screens we included in our analysis are over 100 m from the seafloor or basement. Thus vertical drainage is negligible.

Our model cannot predict phase lags greater than $-90^\circ$ or phase leads of any form, yet we observe small phase leads at ODP Site 1173 screens 2, 4, and 5 and larger leads at ODP Site 808 screens 2 and 3. One-dimensional tidal loading models predict attenuated amplitudes and phase leads near a contrast in compressibility where the framework stiffness or pore fluid compressibility increases [van der Kamp and Gale, 1983; Wang and Davis, 1996].

Figure 13. (a) Mean pressure versus time since installation at ODP Site 808. (b) Amplitude response versus time for the $M_2$ (semidiurnal) tidal signal. (c) Phase versus time for the $M_2$ (semidiurnal) tidal signal. Open pump valves for screens 1, 2, 4, 5, and 6 were discovered and closed at approximately 400 days. Average pressures varied at screens 2 and 3 (Lower Shikoku Basin facies) over the 3-year record. Major transient pulses, interpreted as responses to deformation events [Davis et al., 2006], occurred at screens 2, 3, and 4 in the Lower Shikoku Basin facies during this period (~725 days).
Figure 14. (a) Pressure record at the seafloor and ODP Site 808 screen 2 during inadvertent slug test. The valve for screen 2 had been open prior to 2 August 2002 (labeled 1). The valve was closed (labeled 1), and pressure began to recover. Before pressure had fully equilibrated, the valve was quickly opened and closed again (labeled 2). Measured pressures recovered over days. (b) Shaded plot showing equilibration, \( \varepsilon \) (equation (5)), at ODP Site 808 screen 2 versus time, beginning after the second valve closure (labeled 2). The solid curves are dimensionless pressure response curves (Figure 2). The data match a type curve with characteristic \( \beta_D \) of 0.01. The offset between the \( t \) axis of the data plot and the \( \beta_D \) axis of the type curve plot establishes \( \varepsilon \) as 0.0026 s\(^{-1}\) (equation (1d)).

However, these models generally do not predict positive phase shifts greater than 20° or amplitudes as small as 10% in compressible sediment under high (>20 MPa) confining pressures (even near accumulations of free gas) [Wang et al., 1998]. Thus free gas cannot explain the recorded phase leads and amplitude attenuations in the ACORK data.

Davis and Becker [2007] recently suggested an alternate explanation for both tidal signals and transient pressure pulses at ODP Site 808. They proposed that tidal or tectonic forcing pumps warm formation fluid into and out of the bottom of the unsealed casing at ODP Site 808. The displacement of warm fluid inside the casing alternately warms the surrounding tubing and screens to produce a measurable pressure perturbation. This model is intriguing because it presents an alternate mechanism for amplitude and phase modulation of measured pressure signals and because it also relies on low hydraulic diffusivity at monitoring intervals. Moreover, the thermal compliance model can generate phase leads, unlike our mechanical compliance model. It may also explain the presence of coherent, high-frequency, low-amplitude signals at some of the ACORK screens (Figure 10, screens 2, 3, 4, and 6).

Our analysis of the Davis and Becker [2007] model suggests that phase is particularly sensitive to thermal forcing, and amplitude is less sensitive. This sensitivity might explain why amplitude responses cluster more closely along a characteristic \( \beta_D \) curve than phase shifts (Figure 3). Ultimately, thermal forcing cannot explain all amplitudes and phase shifts in the ACORK data [Sawyer, 2007]. A critical observation is that ODP Site 1173 screens 2 and 3 lie in the low-diffusivity Lower Shikoku Basin facies and have amplitude responses as small as 55% and 20%. Yet the bridge plug at ODP Site 1173 presumably seals the casing and prevents thermal pressure perturbations (Figure 8).

Direct experiments would clarify the contributions of thermal and mechanical compliance to the ACORK pressure response. Through slug tests, we could measure hydraulic diffusivity and wellbore storage in situ. Proper slug test procedure includes measuring the fluid volume added or removed during the test [Neuzil, 1982]. Late time analysis of slug test results determines two of three variables, given an assumption of the third: wellbore storage (\( \beta_D V \)), hydraulic diffusivity (\( c \)), and a measure of formation damage (\( S_w \)) [Sageev, 1986]. Additionally, we have hoped for several years to install a bridge plug at ODP Site 808. Sealing the annulus at ODP Site 808 would eliminate fluid flow in the casing and associated thermal perturbations.

We have presented a systematic approach to understand pore pressure measurements in low-diffusivity sediment. We have applied this approach to analyze data from the Nankai ACORKs. Ultimately, our analysis does not reconcile all the data but does suggest that where hydraulic diffusivities at monitoring intervals are low, mechanical compliance impacts the fidelity of measured pressures signals with high frequencies. Results from new slug tests may influence the design and experimental application of present and future marine pressure monitoring systems. Our analyses suggest that in hemipelagic mud, the ACORK wellbore storage is too large to permit accurate measurement of in situ pressures at tidal frequencies. Future actions to improve pressure measurements may include (1) designing well tests into CORK experimental plans to support interpretation of pressure data, (2) designing stiffer instrument systems with smaller volumes, or (3) increasing permeabilities near screens in future installations with sand packs, hydraulic fractures, or conventional well development.

5. Conclusions

In the Nankai ACORKs (offshore Japan), measured pressures have amplitudes as low as 10% of the amplitude of the tidal load and phase shifts of more than 25°. These measurements occur in thick, homogeneous, compressible,
low-permeability sediment, where in situ pressure signals should approximate the tidal load. To determine the fidelity of these pressure measurements, we used a quantitative model for the response of a closed monitoring instrument to formation pressure changes. The measured pressure response to a change in formation pressure depends on the formation-instrument compliance ratio ($\beta_D$), hydraulic diffusivity, and the frequency of the pressure signal. At the Nankai ACORKs, a wellbore storage of $2 \times 10^{-8}\, \text{m}^3\, \text{Pa}^{-1}$ can explain many of the observed tidal responses, given the hydraulic diffusivities of the monitored intervals. A reduced permeability around the borehole of 1000-fold and a wellbore storage of $10^{-11}\, \text{m}^3\, \text{Pa}^{-1}$ can also reconcile the data. Our analysis suggests that ACORK screens in the Lower Shikoku Basin facies have a critical frequency on the order of $5 \times 10^{-8}\, \text{Hz}$ (equivalent to a period of 250 days). Formation pressure signals with greater frequencies will be distorted in the pressure record. We also estimate that the time for the ACORKs to record 90% of an instantaneous pressure change in the Lower Shikoku Basin facies is on the order of 10 days.

We have presented an approach to quantify the impact of mechanical compliance and hydraulic diffusivity on pressure measurements at submarine hydrologic monitoring stations. Our analysis of the Nankai ACORKs illustrates that in low-diffusivity sediment, the fidelity of pressure measurements is sensitive to instrument compressibility when pressure signals contain high frequencies. We recommend conducting slug tests at submarine monitoring instruments installed in low-diffusivity sediment to aid quantification of instrument response.

Appendix A: Parameters for Sinusoidal Loading Equations

The amplitude and phase of a sinusoidal pressure change measured by a closed instrument (equation (8)) are dependent on imaginary parameters $E$ and $F$:

$$E = 1 - \frac{\omega_D}{\beta_D} (\Psi \text{Kei}(\sqrt{\omega_D}) + \Phi \text{Ker}(\sqrt{\omega_D})), \quad (A1)$$

$$F = \frac{\omega_D}{\beta_D} [\Phi \text{Ker}(\sqrt{\omega_D}) + \Psi \text{Kei}(\sqrt{\omega_D})]. \quad (A2)$$

$\text{Ker}(x)$ and $\text{Kei}(x)$ are Kelvin functions of order 0. $\Psi$ and $\Phi$ are given by

$$\Psi = -\frac{[\text{Ker}(\sqrt{\omega_D}) - \text{Kei}(\sqrt{\omega_D})]}{2\omega_D [\text{Ker}^2(\sqrt{\omega_D}) + \text{Ker}^2(\sqrt{\omega_D})]}, \quad (A3)$$

$$\Phi = -\frac{[\text{Ker}(\sqrt{\omega_D}) + \text{Kei}(\sqrt{\omega_D})]}{2\omega_D [\text{Ker}^2(\sqrt{\omega_D}) + \text{Ker}^2(\sqrt{\omega_D})]]. \quad (A4)$$

$\text{Ker}(x)$ and $\text{Kei}(x)$ are Kelvin functions of order 1.

Appendix B: Hydraulic Diffusivity Calculations

We estimated hydraulic diffusivity at each screen based on permeability, formation compressibility, and temperature-dependent fluid viscosity (equations (1e) and (1f) and Table 2). For screens in the Upper and Lower Shikoku Basin facies, we estimated permeability from laboratory measurements on samples with similar porosities [Gamage and Screaton, 2003, 2006]. We also calculated permeability using an empirical permeability-porosity relationship [Gamage and Screaton, 2003, 2006]:

$$\log k = -19.82 + 5.39n. \quad (B1)$$

[48] For screens in interbedded silts and muds, we used RAB images [Mikada et al., 2002] and core descriptions [Taira et al., 1991] to estimate total silt bed thickness at each screen. We then calculated weighted average screen permeabilities based on typical marine mudstone and siltstone permeabilities [Freeze and Cherry, 1979]. For example, ODP Site 808 screen 5 lies in hemipelagic mud interbedded with four very thin to thin normally graded silt layers [Taira et al., 1991]. We assumed mud and silt permeabilities of $10^{-18}\, \text{m}^2$ and $10^{-14}\, \text{m}^2$, respectively [Freeze and Cherry, 1979]. For a 7.6-m screen interval with four 5-cm-thick silt beds, the permeability is thus $2.6 \times 10^{-16}\, \text{m}^2$ (Table 2). For comparison, Adatia and Maltman [2004] estimated a similar permeability ($9.6 \times 10^{-17}\, \text{m}^2$) for an Outer Marginal Trench-Wedge facies core sample at ODP Site 1174.

[49] Formation compressibility ($m_s$) varies little with depth, according to the few estimates from laboratory tests on core samples. In Outer Marginal Trench-Wedge and Shikoku Basin facies sediment, $m_s$ is typically $10^{-8}\, \text{Pa}^{-1}$ [Bourlangue et al., 2004; D. Saffer et al., unpublished data, 2007]. If we assume the pore fluid is water, which has a compressibility of $4 \times 10^{-10}\, \text{Pa}^{-1}$, the storage coefficient approximates the product of specific weight and formation compressibility (equation (1f)).

[50] We calculated fluid viscosity ($\mu$) after Garling [1977]:

$$\mu = 16.687T^{-0.8987}, \quad (B2)$$

where $T$ is temperature in degrees Celsius. We used temperature projections from measurements above 400 mbsf at ODP Sites 808 and 1173 [Taira et al., 1991; Moore et al., 2001].

Appendix C: ACORK Wellbore Storage Calculation

We calculated the ACORK formation-instrument compliance ratio ($\beta_D$) from equation (2b). We assumed a formation compressibility ($m_s$) for the Lower Shikoku Basin facies to be $1.5 \times 10^{-8}\, \text{Pa}^{-1}$ (Appendix B). We calculated $V'$ and $\beta^*$ from ACORK specifications in Table 4 (equations (C1) and (C2)).

[52] The ACORK screens are cylindrical shells that surround the inner casing: each screen stands 7.6 m high and has a thickness of 2 cm (Figure 8). The ACORK volume, $V'$, is the volume of the screen (first term) and hydraulic tubing (second term):

$$V' = \pi (r_2^2 - r_1^2)h + \pi r_2^2 L_s, \quad (C1)$$
where $r_{x,i}$ is the screen outer radius, $r_{y,i}$ is the screen inner radius, $h$ is the screen height, $L_t$ is the tubing length to the seafloor, and $r_{z,i}$ is the inner tubing radius. At ODP Site 808 screen 2, the tubing length is 878 m. The total volume is 0.15 m$^3$.

[53] The ACORK system compressibility is the sum of the fluid compressibility ($\beta_f$), steel tubing compressibility (second term), and casing compressibility (third term):

$$\beta^* = \beta_f + \beta_{\text{steel}} \left( \frac{r_{x,i}}{r_{y,i} - r_{y,j}} + \frac{r_{y,j}}{r_{x,i} - r_{y,j}} \right).$$

We did not attempt to estimate additional sources of compressibility such as screens, hydraulic connections, and packers. For $\beta_f$, we assumed the compressibility of water $(4.5 \times 10^{-10} \text{ Pa}^{-1})$. The tubing compressibility is a function of the compressibility of steel ($\beta_{\text{steel}}$) and the tubing dimensions, while the inner casing compressibility is a function of the compressibility of steel and casing dimensions. $\beta^*$ is $5 \times 10^{-10} \text{ Pa}^{-1}$. Substituting $V$ and $\beta^*$ into equation (2b), we calculated $\beta_f$ to be ~200.

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