PORE PRESSURE DEVELOPMENT WITHIN UNDERTHRUST SEDIMENTS AT THE
NANKAI SUBDUCTION ZONE: IMPLICATIONS FOR DÉCOLLEMENT
MECHANICS AND SEDIMENT DEWATERING

A Thesis in
Geosciences

by
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ABSTRACT

Pore pressure is a primary control on the hydrologic and mechanical behavior of subduction complexes, and directly influences the strength and sliding stability of faults. Despite its importance for plate boundary fault processes, quantitative constraints on pore pressure – especially within fault zones - are rare. In this paper, we combine laboratory measurements of permeability for core samples taken from Ocean Drilling Program (ODP) Leg 190 with a model of loading and pore pressure diffusion to examine the evolution of pore fluid pressure within underthrust sediment at the Nankai accretionary complex. Constraints based on recent estimates of pore pressure up ~20 km from the trench, borehole data, and permeability measurements made over a wide range of stresses and porosities allow us to make projections of pore pressure within the underthrust section to greater depths and distances from the trench than in previous studies, and to directly quantify pore pressure within the fault zone itself, which acts as the upper boundary of the underthrusting section. Our results suggest that excess pore pressure ($P^*$) along the décollement ranges from 1.7 – 2.1 MPa at the trench to 30.2 – 35.9 MPa by 40 km landward, corresponding to pore pressure ratios of $\lambda_b = 0.68 – 0.77$ ($\lambda^*_b = 0.30 – 0.60$). For friction coefficients of 0.30 - 0.40, the resulting shear stress along the décollement remains < 12 MPa over the front 40 km of the accretionary complex. When non-cohesive critical taper theory is applied using these values, the required pore pressure ratios within the wedge are near hydrostatic ($\lambda_w = 0.41 - 0.59$), implying either that pore pressure throughout the wedge is low, or that the fault slips only during transient pulses of elevated pore pressure. In addition, simulated downward migration of minima in effective stress during drainage provides a simple, quantitative explanation for observed down-stepping of the décollement that is consistent with observations at Nankai.
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Chapter 1

Introduction

At subduction zones, porous sediments on the incoming plate are incorporated into an
overriding accretionary wedge, or are subducted with the underthrust plate. The rate of loading
via burial and tectonic stresses generally outpaces the rate of pore fluid diffusion, generating
pore pressures in excess of hydrostatic [e.g., Screaton et al., 1990; Neuzil, 1995]. The resulting
elevated fluid pressures are a primary control on both fault strength and sliding stability [Davis et
al., 1983, Moore and Vrolijk, 1992; Scholz, 1998]. In particular, the conditions within
underthrust sediments are important because they directly influence the shear strength of the
découllement, the taper angle of the accretionary wedge, and their dewatering potentially controls
the location of the updip limit of the seismogenic zone [e.g., Davis et al., 1983; Moore and
Saffer, 2001; Saffer, 2003; Bangs et al., 2004; Tobin et al., 2006]. Several studies have indicated
that elevated pore pressures may also control down-stepping of the découllement [Westbrook et
al., 1983; Byrne and Fisher, 1990; Le Pichon et al., 1993; Saffer, 2003]. Although pore pressure
is a key control on faulting mechanics, direct measurements and quantitative estimates of this
important parameter within active fault zones are scarce, both at subduction zones and in other
geologic settings. Thus, the in situ state and physical properties of active fault zones is one
primary objective of several major drilling efforts [e.g., Hickman et al., 2004; Tobin and
Kinoshita, 2006].

Previous studies have constrained pore pressure in the sediments underthrust beneath the
plate boundary découllement at several active subduction margins, including Southwest Japan
(Nankai) [e.g. Saffer and Bekins, 1998; Saffer, 2003], Costa Rica [e.g. Saffer et al., 2000;
Screaton and Saffer, 2005; Spinelli et al., 2006], and Barbados [e.g. Bekins et al., 1995]. These
studies have used a variety of approaches, including consolidation testing to estimate in situ
effective stress and pore pressure [Saffer et al., 2000]; inversion of porosities (or void ratios)
obtained from drilling data or predicted from seismic reflection interval velocities to compute
effective stress [Cochrane et al., 1996; Screaton et al., 2002; Saffer, 2003; Tobin et al., 2006];
and numerical modeling of fluid flow in one, two, and three dimensions [e.g., Screaton and Ge,
1997; Screaton and Saffer, 2005; Screaton, 2006]. Two overarching similarities of these studies
are that (1) they consistently predict pore fluid pressures significantly in excess of hydrostatic,
and (2) pore pressures and flow patterns indicate dominantly vertical (upward) dewatering of the underthrust section to the décollement.

In this paper, we focus on the well-studied Nankai margin (Figure 1-1). Previous studies of overpressures at Nankai have focused primarily on the area within a few kilometers of the trench where borehole data are available. For example, Screaton et al., [2002] used porosity-depth profiles from two boreholes penetrating the underthrust section and from a reference site to estimate depth-averaged excess pore pressure; their results imply that the underthrust sediments have insufficient permeability to accommodate dewatering at rates comparable to those of sedimentation and tectonic loading. Using a similar approach, Saffer [2003] combined laboratory consolidation test results with logging-while-drilling (LWD) data and shipboard measurements of porosity to estimate downsection variations in pore pressure, predicting partly drained conditions at the top of the section and nearly undrained conditions at the base. Tobin et al. [2006] used seismic reflection data to compute porosity and invert for effective stress and pore pressure within the underthrust section beneath the outermost ~20 km of the accretionary wedge, and predicted excess pore pressures (pressure above hydrostatic) of ~5 – 32 MPa, with values increasing systematically with distance landward of the trench. Gamage and Screaton [2006] incorporated laboratory permeability measurements into a one-dimensional loading model to study the evolution of pore pressure within the toe of the accretionary complex. They found that their measured values of permeability were low enough to generate modest excess fluid pressures, but were not sufficiently low to generate those inferred from porosity data, even when including additional pore pressure generation within the overriding wedge. Notably, in all of these studies, and in previous investigations of porosity, seismic reflection velocity, amplitude, and reflection polarity [e.g., Moore et al., 1991; Hyndman et al., 1993; Bangs et al., 2004], underconsolidation and elevated pore pressure within the underthrust sediment is speculated to somehow reflect elevated pore pressure at the décollement itself, but this idea has not been rigorously quantified.

Here, we combine new laboratory permeability measurements on sediment obtained from drilling at the Nankai margin with a numerical model of loading and pore pressure diffusion, to evaluate pore pressure development. We extend previous work on this topic in three important ways. First, we make projections of pore pressure within the underthrust section and along the plate boundary décollement zone to considerably greater depths and distances from the trench,
constrained by permeability measurements attained over an appropriate range of stresses and porosities, borehole data, and newly available estimates of pore pressure to \( \sim 20 \) km from the trench inferred from seismic reflection interval velocities [Tobin et al., 2006; Saffer, 2007]. Second, we explicitly evaluate the link between fluid pressure at the décollement itself and the drainage state of underthrust sediment, providing the first and most spatially extensive quantitative constraints on fault zone pore pressure obtained from a physically based model driven by tectonic loading. This differs from previous modeling studies, which have produced regional estimates of pore pressure within entire accretionary complexes but have neither been as tightly constrained as this study, nor explicitly focused on defining the pore pressure at the fault zone [e.g., Bekins et al., 1995; Saffer and Bekins, 1998]. Finally, we investigate the implications of our results for dewatering of the underthrust section, the strength of the décollement, and the taper angle of the accretionary wedge. We report simulated and inferred pore pressures in three ways: (1) excess pore pressure \( P^* = P_f - P_h \), where \( P_f \) is the pore fluid pressure and \( P_h \) is hydrostatic fluid pressure; (2) the pore pressure ratio \( \lambda = P_f / \sigma_z \), where \( \sigma_z \) is the vertical stress; and (3) the modified pore pressure ratio defined as \( \lambda^* = (P_f - P_h)/(\sigma_z - P_h) \). All variables in our analysis, and their definitions and units, are summarized in Table 1-1.

1.1 Geologic Setting

Located near the juncture of the Philippine Sea Plate, the Eurasia Plate, and the Pacific Plate (Figure 1-1), the Nankai accretionary complex is forming by subduction of the Shikoku Basin on the Philippine Sea Plate beneath the Eurasian Plate at \( \sim 40-65 \) km Myr\(^{-1} \) [Seno et al., 1993; Miyazaki and Heki, 2001]. The accretionary complex has been extensively studied by drilling, seafloor geophysical and geological surveys, and seismic reflection studies along two transects: the Muroto transect (offshore Cape Muroto) and the Ashizuri transect (\( \sim 100 \) km SW of Muroto offshore Cape Ashizuri) (Figure 1-1a). We focus our study on the Muroto transect, where drilling has penetrated the entire underthrust sediment section at several sites and pore pressure has been inferred from both porosity and seismic reflection data. Along this transect, the average surface slope (\( \alpha \)) is \( \sim 1.5^\circ \) and the décollement dip (\( \beta \)) is \( \sim 2.6^\circ \) [Taira et al., 1991]. The relatively low overall taper angle has been interpreted to reflect low strength along the décollement, most likely caused by elevated pore pressure [Davis et al., 1983; Moore et al., 1991; Moore et al., 2001].
The incoming sediment on the Philippine Plate includes four main units (Figure 1b). A basal volcaniclastic facies (37 m thick) of Middle Miocene age overlies oceanic basement and is composed of variegated siliceous claystone [Shipboard Scientific Party, 2001]. Above the volcaniclastic facies, the Mid-Miocene to Pliocene Lower Shikoku Basin facies (LSB) (344 m) is composed of homogeneous, clay-rich, hemipelagic mudstone interbedded with altered ash layers [Shipboard Scientific Party, 2001]. Overlying the LSB, the Upper Shikoku Basin facies (USB) (242 m) is Pliocene to Quarternary in age and consists of hemipelagic mudstone with abundant interbedded altered ash [Shipboard Scientific Party, 2001]. The Quaternary trench-wedge facies (TW) (102 m) is composed of slity and sandy turbidites interbedded with hemipelagic muds [Taira and Ashi, 1993; Shipboard Scientific Party, 1991]. The décollement forms entirely within the LSB, such that the underthrust section is composed entirely of homogeneous, hemipelagic mudstones of the LSB facies and the lower volcaniclastic facies [Moore et al., 2001].

Data and samples used in this study were collected on Ocean Drilling Program (ODP) Legs 131 and 190, during which several sites were drilled along the Muroto Transect (Figure 1-1b). These include a reference site ~10 km seaward of the trench (Site 1173), and two sites that penetrated the décollement and the underthrusting sediment section at ~1.5 km (Site 1174) and ~3.6 km (Site 808) arcward of the trench [e.g., Moore et al., 2001]. The décollement was identified as a fractured zone within uniform hemipelagic muds of the LSB between 945 and 964 mbsf at Site 808 [Shipboard Scientific Party, 1991], and between 808 and 840 mbsf at Site 1174 [Shipboard Scientific Party, 2001]. The age equivalent projection of the décollement zone at Site 1173 is within the LSB between 390 and 420 mbsf [Shipboard Scientific Party, 2001].

Porosity profiles from Sites 808 and 1174 exhibit a marked increase across the décollement zone (Figure 1-2). At Site 1174 porosity increases from ~0.33 at the base of the accretionary wedge to ~0.36 at the top of the underthrust section. At Site 808 porosity increases from ~0.31 at the base of the accretionary wedge to ~0.37 at the top of the underthrust section. The porosity increase has been interpreted to represent both increased mean stress above the décollement as a result of tectonic compression, and delayed compaction of the underthrust sediment associated high with pore pressure [e.g., Morgan and Karig, 1993; Screaton et al., 2002; Flemings, 2002; Saffer, 2003; Saffer, 2007].
1.2 Estimations of Pore Pressure

Two of the primary constraints on our model are (1) pore pressures inferred from porosity at Sites 1174 and 808, which are derived as described below [e.g., Screaton et al., 2002; Saffer, 2003]; and (2) pore pressures from the trench to ~20 km landward, computed using porosities estimated from well-constrained seismic reflection interval velocities together with a transform relating porosity to effective stress, and which are reported by Tobin et al. [2006] and Saffer [2007]. Estimates of pore pressure at boreholes relies primarily on determining the effective stress $\sigma_z$ [Pa] and calculating fluid pressure $P_f$ [Pa] by:

$$P_f = \sigma_z - \sigma_z'$$  \hspace{1cm} (1)

where the total vertical stress $\sigma_z'$ is calculated by downward integration of bulk density values from shipboard or logging measurements. The effective stress can be estimated in a variety of ways, including laboratory consolidation tests, and inversion of porosity data [e.g. Hart and Flemings, 1995; Screaton et al., 2002; Saffer, 2003; Saffer, 2007]. Here, we use an approach similar to that of Hart and Flemings [1995] and Saffer [2003] to define effective stress at Sites 1774 and 808 by inverting porosity data.

It is commonly assumed that porosity varies exponentially with depth [Athy, 1930]:

$$\phi = \phi_0 \exp(-bz)$$  \hspace{1cm} (2)

where $\phi_0$ is the porosity of material at the surface, $b$ is a constant dependent on the lithology and geologic setting, and $z$ is the depth [m], [Bray and Karig, 1985]. By differentiating equation (1), the change in effective stress with depth may be written as:

$$\frac{d\sigma_z'}{dz} = g(\rho_s - \rho_f)(1 - \phi)$$  \hspace{1cm} (3)

where $g$ is the gravitational constant [m s$^{-2}$], and $\rho_s$ and $\rho_f$ are the solid grain and fluid densities [kg m$^{-3}$], respectively. Differentiating equation (2) and using the chain rule along with equation (3) provides an expression for the change in porosity with effective stress:
\[ \frac{d\phi}{d\sigma_z'} = \frac{d\phi}{dz} = \frac{-b\phi}{g(\rho_s - \rho_f)(1 - \phi)} \] (4)

Integrating equation (4) and using the boundary condition, \( \phi(\sigma_z' = 0) = \phi_0 \) [e.g., Mello et al. 1994] yields:

\[ \ln \phi - \phi = \frac{-b\sigma_z'}{g(\rho_s - \rho_f)} + \ln \phi_0 - \phi_0 \] (5)

which can be rearranged to solve for effective stress as a function of porosity. Determining \( \phi_0 \) and \( b \) defines a unique relationship between effective stress and porosity, allowing porosity data to be inverted for effective stress (and thus pore pressure) at sites where they are unknown (i.e. Sites 1174 and 808). We define such a relationship for the LSB facies using data from the reference Site 1173, under the assumption that the pore pressure there is hydrostatic [e.g., Screaton et al., 2002; Saffer, 2003]. The assumption of hydrostatic pore pressure throughout the section at the reference site is justified by the large distance from the trench (~10 km), low sedimentation rates for most of the section (27-37 m/Myr), and consolidation test results which indicate that sediments at Site 1173 are normally consolidated [Shipboard Scientific Party, 2001; Moore et al., 2001; Saffer, Unpublished Data]. At Site 1174, the estimated excess pore pressure ranges from ~2.7 MPa at the top of the underthrust section (840 mbsf) to ~4.5 MPa at the base (1100 mbsf) (Figure 1-3). Estimated excess pore pressure at Site 808 increases from ~5.0 MPa at the top of the section (960 mbsf) to nearly undrained conditions, ~6.0 MPa, at the base (1124 mbsf) (Figure 1-3).
<table>
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<th>Symbol</th>
<th>Description</th>
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<td>$A$</td>
<td>cross-sectional area of core sample</td>
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<td>fluid pressure</td>
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<td>$\Gamma$</td>
<td>Source term representing loading processes</td>
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<td>m³ yr⁻¹ m⁻¹</td>
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<tr>
<td>$\dot{e}$</td>
<td>strain rate of core sample</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>pore pressure ratio ($P_f / \sigma_z$)</td>
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</tr>
<tr>
<td>$\lambda_b$</td>
<td>basal pore pressure ratio</td>
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</tr>
<tr>
<td>$\lambda_w$</td>
<td>wedge pore pressure ratio</td>
<td>unitless</td>
</tr>
<tr>
<td>$\lambda^*$</td>
<td>normalized pore pressure ratio ($P_f - P_h)/(\sigma_z - P_h$)</td>
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</tr>
<tr>
<td>$\lambda_b^*$</td>
<td>normalized, basal pore pressure ratio</td>
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</tr>
<tr>
<td>$\lambda_w^*$</td>
<td>normalized, wedge pore pressure ratio</td>
<td>unitless</td>
</tr>
<tr>
<td>$\mu_b'$</td>
<td>effective basal coefficient of friction</td>
<td>unitless</td>
</tr>
<tr>
<td>$\mu_b$</td>
<td>basal coefficient of friction</td>
<td>unitless</td>
</tr>
<tr>
<td>$\mu_w$</td>
<td>wedge coefficient of friction</td>
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</tr>
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<td>$\nu$</td>
<td>dynamic viscosity</td>
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<td>$\rho_f$</td>
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</tr>
<tr>
<td>$\rho_s$</td>
<td>solid density</td>
<td>kg m⁻³</td>
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<td>$\sigma_z$</td>
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</tr>
<tr>
<td>$\sigma_z'$</td>
<td>effective vertical stress</td>
<td>Pa</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
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<td>$\chi$</td>
<td>fluid compressibility</td>
<td>Pa$^{-1}$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Parameter controlling the top boundary condition</td>
<td>unitless</td>
</tr>
</tbody>
</table>
Figure 1-1: (a) Map of study area in the Nankai Trough. Ocean Drilling Program (ODP) drill sites are indicated by solid circles. EP refers to the Eurasian Plate, PP to the Pacific Plate and PSP to the Philippine Sea Plate. (b) Seismic cross-section at the toe of the Muroto transect showing the location of drill sites.
**Figure 1-2:** Porosity profiles at Sites 808, 1174, and 1173. Porosities were calculated using bulk density data collected during ODP Legs 131 and 190. Shading indicates the location of the décollement zone at each site. TW = Trench Wedge Facies; USB = Upper Shikoku Basin Facies; LSB = Lower Shikoku Basin Facies.
Figure 1-3: Excess pore pressure at Sites 808 (a) and 1174 (b) inferred from porosity, as described in text. Shading indicates the expected value of pore pressure under undrained conditions.
Chapter 2

Methods

2.1 Laboratory Permeability Measurements

Sediment permeability is one of the most important parameters controlling the evolution of pore pressure [Saffer and Bekins, 1998; Saffer and Bekins, 2002, 2006; Gamage and Screaton, 2006]. In particular, reliable projections of permeability with increased burial depend upon defining permeability over a wide range of porosities and effective stresses. We conducted permeability measurements on core samples from Site 1173 at effective stresses from ~1 to 90 MPa (corresponding to porosities from 12 – 60%), in order to extend the range of experimental conditions for which permeability data are available beyond mean effective stresses of ~1 MPa (corresponding to porosities >26%) [Gamage and Screaton, 2006]. For each individual test, we trimmed core samples into cylinders 20 mm in height and 25 – 38 mm in diameter, depending on the amount of material available. Experiments were performed in a fixed ring consolidation cell, in which a sample is placed and then back pressured to 300 kPa for 24 hr to ensure saturation and to dissolve any gasses present. The permeability of each sample is determined by one of two methods: 1) constant rate of strain (CRS) experiments; or 2) steady state flow through experiments [e.g., Saffer and McKiernan, 2005].

In a CRS test, the sample is subjected to a constant rate of strain using a computer controlled loading frame. Drainage is allowed at the top boundary of the sample, which is open to the back pressure; no drainage is allowed at the bottom boundary [e.g., Olsen, 1986]. The sample height $H$ [m], axial stress $\sigma_z$, and basal excess pore pressure $U_b$ [Pa], are monitored continuously. As the sample is progressively loaded and compressed, pressure builds at its base, allowing the permeability to be calculated continuously as a function of consolidation state by:

$$k = \frac{\nu \cdot \dot{\varepsilon} \cdot H \cdot H_0}{2 \cdot U_b}$$

(6)

where $\nu$ is the dynamic viscosity of water [Pa s], $\dot{\varepsilon}$ is the strain rate [s$^{-1}$], and $H_0$ is the sample height at the start of the test [ASTM International, 2006; Long et al., 2008]. The strain rate is chosen for each test so that the excess pore pressure is much lower than the effective stress (typically, $U_b$ is $\sim$1-5% of $\sigma_z$) (Figure 2-1).
For flow through tests, the sample is subjected to a prescribed axial stress and allowed to equilibrate over a 24 hr period. Permeability is measured by either: 1) imposing and maintaining a flow rate through the sample using high precision pumps connected to ports at the top and base of the sample; or 2) imposing a pressure gradient across the sample. In both cases permeability is calculated after steady-state flow is achieved by Darcy’s Law:

\[ k = \nu \frac{Q}{A} \frac{dl}{dP} \]  \hspace{1cm} (7)

where \( Q \) is the flow rate \([m^3 s^{-1}]\), \( A \) is the cross-sectional area of the sample \([m^2]\), \( P \) is pressure \([Pa]\), and \( dl \) is the sample height \([m]\). (The symbol “\( \mu \)” is typically used to denote dynamic viscosity; however, in this paper it is used to denote the coefficient of friction. Therefore to avoid confusion we have opted to use the symbol “\( \nu \)” to denote dynamic viscosity.) In all tests, porosities were calculated by comparing the saturated weight of a sample at the end of a test with its dry weight after oven-drying at 100 °C for 24 hr.

2.2 Modeling Methods

2.2.1 Governing Equation and Constitutive Relations

We simulated the evolution of pore pressure and compaction of sediment in a vertical column using a one-dimensional model which allows for variation of sediment physical and hydraulic properties in time and space (Figure 2-2). Our approach is similar to that of Gamage and Screaton [2006]; however, we explicitly incorporate the role of a pressure “cap” at the décollement boundary (e.g., as suggested by Moore et al., [1991]), and evaluate fluid pressure development to considerably greater depths and distances from the trench by utilizing additional constraints on pore pressure derived from seismic reflection data [Tobin et al., 2006]. One advantage of this modeling approach compared with previous studies [e.g., Saffer and Bekins, 1998; Screaton, 2006] is that it does not require assumptions about either fluid sources or fault zone permeability, neither of which is well constrained a priori. Past studies have indicated that at many subduction zones dewatering of the underthrusting layer is primarily vertical, especially as distance from the trench increases; thus, a one-dimensional model is sufficient to simulate the
process of interest [von Huene and Lee, 1982; Screaton and Saffer, 2005; Saffer and McKiernan, 2005; Gamage and Screaton, 2006].

The governing equation for one-dimensional, transient fluid flow is [Bear, 1972]:

\[
\frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial z^2} + \Gamma
\]  

(8)

where \( t \) is time [s], \( K \) is hydraulic conductivity [m s\(^{-1}\)], \( S_s \) is specific storage [m\(^{-1}\)], and \( \Gamma \) is a source term representing loading processes [m s\(^{-1}\)]. Hydraulic conductivity is related to permeability by:

\[
K = g \rho_f k / \nu
\]  

(9)

The specific storage is defined as:

\[
S_s = g \rho_f (m_v + \phi \chi)
\]  

(10)

where \( m_v \) is the bulk compressibility of the solid matrix and \( \chi \) is the compressibility of the interstitial fluid [Pa\(^{-1}\)] (normally the term \( \beta \) is used to denote fluid compressibility; however we have already used \( \beta \) to denote the décollement dip, hence the change in terminology; see Table 1-1).

The evolution of porosity and permeability with effective stress is an important parameter affecting both the drainage and the consolidation of sediment. Rather than describe the evolution of sediment porosity based on burial depth or as an exponential function of effective stress [e.g., Hart et al., 1995; Gordon and Flemings, 1998, Gamage and Screaton, 2006] we use an expression relating porosity to effective stress (equation 5) based on equation (2), the derivation of which is described in Section 1.2. All that remains is to solve equation (5) for porosity as a function of effective stress, which may be accomplished using what is known as Lambert’s \( W \) function, defined to be the function satisfying the equation:
\[ We^w = x \] (11)

[Corless et al.; Hayes, 2005]. Equation 5 may be put into a form similar to that of equation (11):

\[ \phi \exp(\phi) = \exp\left(\frac{-b\sigma_z'}{g(\rho_s - \rho_f)} + \ln \phi_0 - \phi_0\right) \] (12)

Straightforward calculations then yield the solution to equation (5):

\[ \phi = -W\left\{-\exp\left[\frac{-b}{g(\rho_s - \rho_f)}\sigma_z' + \ln \phi_0 - \phi_0\right]\right\} \] (13)

We make the assumption that sediment grains are incompressible, which leads to an expression for bulk compressibility in terms of porosity:

\[ m_c = -\frac{1}{z} \frac{\partial \tau_z}{\partial \sigma_z'} = -\frac{1}{z} \frac{\partial}{\partial \sigma_z'} \left( \frac{z}{1-\phi} \right) = \frac{1}{1-\phi} \frac{\partial \phi}{\partial \sigma_z'} = \frac{b}{g(\rho_s - \rho_f)} \frac{\phi}{(1-\phi)^2} \] (14)

Bulk compressibility as determined by equation (14) depends on the exponential coefficient \( b \) in equation (2), as well as the porosity determined by equation (13). Therefore we parameterize equation (14) using data from the reference Site 1173 rather than using experimental consolidation data, in order to maintain the internal consistency of our model and to avoid complications caused by substantial differences between compression behavior observed over short timescales in the laboratory and that occurring over the considerably longer timescales relevant to loading in subduction zones. Sediment permeability is then defined from porosity using relations based on our laboratory experimental data as described below (Section 3.1).
2.2.2 Solution of 1-D Problem

We initiate our model at Site 1173 and assume that the sediments beneath the age-equivalent projection of the décollement zone (~420 mbsf) are hydrostatically pressured, such that the initial condition is zero head throughout the sediment column:

$$h(z, t)|_{t=0} = 0$$

(15)

At each subsequent time step, head is incremented throughout the column based on the incremental change in overburden $\Delta \sigma_z$:

$$\Gamma(t) = \frac{\Delta \sigma_z - \Delta P_h}{\Delta t \rho_f}$$

(16)

Because we solve the fluid flow problem in terms of hydraulic head, the incremental change in hydrostatic pore pressure $\Delta P_h$ must be subtracted from the change in overburden in equation (16).

Head is updated by solving equation (8) using a Crank-Nicolson method derived for an arbitrarily spaced grid. At the end of each time step the updated values of head are converted to pressures and used to update the effective stress in the column using equation (1). The porosities and compressibilities are updated at each node using equations (13) and (14), respectively. These values are then used to update the permeability, specific storage, and hydraulic diffusivity (Figure 2-2).

The incremental change in the overburden $\Delta \sigma_z$ is a function of the burial rate, which in turn depends on the plate convergence rate $v_p$ and the wedge geometry. We define the burial rate in four phases. First, between Site 1173 and the trench we assign the burial rate a constant value to account for the deposition of approximately 300 m of trench wedge turbidites [Moore et al., 2001]. Second, borehole data allow the overburden to be determined accurately at the base of the décollement zone at Sites 1174 and 808. Thus the burial rates from the trench to Site 1174 and from Site 1174 to Site 808 are based on the detailed data from drilling. Third, seismic reflection data between ~0-25 km landward of the trench provides detailed definition of the wedge geometry. Rather than assuming a simple triangular geometry in which the taper angle is
assigned a constant value throughout the wedge [e.g., Screaton et al., 1990; Saffer and Bekins, 1998], we use seismically determined depths to the décollement to calculate incremental variations in the taper angle. Lastly, arcward of the extent of the seismic data we assume that the décollement dip maintains its average value and define a constant value of the surface slope in three broad regions based on bathymetric data.

Underlying the LSB at Sites 1173, 1174, and 808 is an approximately 40 – 55 m layer of altered ash which appears to act as a hydrological “seal” [Shipboard Scientific Party, 1991; Shipboard Scientific Party, 2001]. Screaton et al., [2002] and Saffer [2003, 2007] found that there is no apparent drainage at the base of the sediment column at Sites 1174 and 808. Accordingly, we specify that the bottom of the simulated sediment column is a no-flow boundary:

\[
\frac{\partial h(z,t)}{\partial z} \bigg|_{z=\text{Basement}} = 0
\]  

In order to investigate the role that pore pressure at the décollement plays in controlling drainage and consolidation of the subjacent sediment, we define the top boundary condition by requiring that the head there is a fraction \( \psi \) of the total pressure head generated in the rest of the underthrust column by burial beneath the overriding wedge.

\[
h(z,t) \bigg|_{z=\text{décollement}} = \psi \Gamma(t) = \psi \frac{(\Delta \sigma_z - \Delta P_h)}{g \rho_f}
\]  

Values of \( \psi \) apply only at the top boundary and are similar, but not identical, to the modified pore pressure ratio \( \lambda^* = (P_f - P_h)/(\sigma_z - P_h) \). The difference arises because a finite sediment thickness initially overlies the stratigraphic projection of the décollement and the proto-underthrust section at the start of the model, but does not contribute to pore pressure generation. The top boundary of the model space simulates the décollement zone and, along with sediment permeability, the condition imposed here has a large effect on pore pressure diffusion within the underthrust section. The value of \( \psi \) reflects the time-averaged pressure at this boundary, which ultimately controls consolidation and dewatering of the subjacent sedimentary section as
manifested in its porosity and P-wave velocity. It is important to note that although previous studies have suggested qualitatively that the underthrust section is in hydrologic communication with the décollement - and therefore that pore pressure within the underthrust is mechanically important [e.g. Saffer, 2003; Screaton and Saffer, 2005; Tobin et al., 2006] - the link between pore pressure within the underthrust section and in the décollement itself has not been directly or quantitatively investigated.

We evaluate model sensitivity to three parameters: sediment permeability ($k$), plate convergence rate ($v_p$), and the top boundary condition ($\psi$). Our laboratory results (described below in section 3.1) indicate that permeability varies log-linearly with porosity and can be described by a relation of the form [Bryant et al., 1975; Neuzil, 1994]:

$$\log(k) = \log(k_0) + \gamma \phi$$  \hspace{1cm} (19)

where $\log(k_0)$ is the projected permeability at zero porosity and $\gamma$ is a parameter describing the rate of permeability change with porosity [e.g., Bekins et al., 1995; Saffer and McKiernan, 2005; Gamage and Screaton, 2006]. Based on the range of our experimental results, we investigated values of $-21.47 \leq \log(k_0) \leq -19.94$ and $\gamma = 6.93$. We considered two reported values of the plate convergence rate: $v_p = 6.5$ km Myr$^{-1}$ and $v_p = 4$ km Myr$^{-1}$ [Miyazaki and Heki, 2001; Seno et al., 1993]. We explored the full range of values possible for the top boundary condition (i.e. $0 \leq \psi \leq 1$). Additionally, we explored the role of clay dehydration as a fluid source by including it in the model source term $\Gamma$ [e.g. Bekins et al., 1995]. In the investigation of model sensitivity to the parameter space defined above, all model runs are referred to a “base case,” in which $\log(k_0) = -20.45$, $\psi = 0.5$, and $v_p = 6.5$ km Myr$^{-1}$. To conduct the sensitivity analysis we vary one parameter and keep the others fixed to the base case values.
Figure 2-1: Example of data from a constant rate of strain (CRS) test on a sediment core sample from Site 1173. Solid line is effective axial stress, the dashed line is excess pore pressure at the base of the sample.
Figure 2-2: (a) Schematic of the model space and boundary conditions as described in text. At time $t_{\text{initial}}$ underthrust sediment is undeformed. Progressive loading as sediment is subducted beneath the overriding plate results in compression of the model coordinates as porosity is lost and assuming conservation of solid mass. (b) Flow chart showing conceptual model for one-dimensional pore pressure simulation in an underthrust sediment column.
Chapter 3

Results

Our experimental data define a relationship between permeability and porosity of the form of equation (19), as noted above. Values of permeability measured using flow through tests are consistent with those determined using CRS tests (Figure 3-1), and both data sets are also consistent with flow through data from Gamage and Screaton [2006], although they extend to considerably lower porosities and higher effective stresses. We determined values of $\gamma$ and $\log(k_0)$ over a porosity range of 12 - 60 % using data from CRS and flow through experiments for six sediment samples taken from the reference Site 1173 (Figure 3-1; Table 3-1). Values of $\gamma$ range from ~5 to 9, and values for $\log(k_0)$ range from ~ -20 to -21. The data are well bounded by the functions:

- upper bound: $\log(k) = -19.94 + 6.93\phi$
- lower bound: $\log(k) = -20.96 + 6.93\phi$

We define an overall best fit to the data described by:

- middle fit: $\log(k) = -20.45 + 6.93\phi$

The $\log(k_0)$ axis intercepts of our permeability-porosity relationships are similar to those determined by Saffer and Bekins [1998] by inverse modeling ($\log(k_0) = -20 + 5.25\phi$), and by Gamage and Screaton [2006] ($\log(k_0) = -19.82 + 5.39\phi$) for sediment from Nankai. The larger slope of our function means that we predict a higher rate of change of sediment permeability as porosity is lost than in either of those studies. Well defined relationships between permeability and porosity also allow a computation of the variation of bulk compressibility and hydraulic diffusivity over the range of relevant porosities. Values of bulk compressibility calculated using equation (14) range from $\sim1.1 \times 10^{-8}$ to $1.7 \times 10^{-7}$ m$^2$ kg$^{-1}$; values of diffusivity $K/S_c$ [m$^2$ s$^{-1}$] range from $\sim6 \times 10^{-9}$ to $6 \times 10^{-6}$ m$^2$ s$^{-1}$. 
3.2 Modeling Results

We investigate model sensitivity to the parameters \( \log(k_0) \), \( \psi \), and \( v_p \) by comparing simulated values of excess pore pressure between each model run and the base case. We then compare modeled excess pore pressures with values of excess pore pressures inferred from porosity data at Site 1174 (Figure 3). For the base case model run, \( P^* \) ranges from 2.6 MPa at the top of the column to 3.5 MPa at its base, with an average excess pore pressure of 3.1 MPa (corresponding to an average pore pressure ratio \( \lambda = 0.80 \) and an average modified pore pressure ratio \( \lambda^* = 0.50 \)) (Figure 7). We also investigate model sensitivity to \( \psi \) and \( \log(k_0) \) by reporting pore pressure as a function of distance landward from the trench, and then compare simulation results with pore pressures reported by Tobin et al. [2006] and Saffer [2007] to ~20 km landward. Additionally, we explored the role of clay dehydration as a fluid source by including an additional source term in equation (8) following Bekins et al. [1995] and Saffer and Bekins [1998], and we find that the contribution is negligible when compared to the compactive fluid source due to tectonic loading.

3.2.1 Sensitivity Analysis

We tested model sensitivity to the range of permeability relationships determined from the experimental data (Figure 3-2a). Average simulated excess pore pressures at Site 1174 range from 2.8 MPa to 3.6 MPa, corresponding to average pore pressure ratios of \( \lambda = 0.78 - 0.83 \) (\( \lambda^* = 0.45 - 0.58 \)) as \( \log(k_0) \) is decreased from -19.94 to -20.45. The excess pore pressure at the top of the column for each run corresponds to that of the base case, 2.6 MPa (defined by \( \psi = 0.5 \)). Excess pore pressure at the base of the column ranges from 3.0 MPa to 4.1 MPa. Setting \( \psi = 0.5 \) yields simulated excess pore pressures in good agreement with those inferred throughout most of the sediment column at Site 1174; however, even the lower bound permeability-porosity relation slightly underestimates inferred excess pore pressures of ~4.5 MPa at the base of the column. Using a fourth, “extra-low” permeability-porosity function of the form:

\[
\log(k) = -21.47 + 6.86\phi
\]

which provides an absolute lower bound to our experimental porosity data (Figure 3-1), simulated excess pore pressure at the base of the column is 4.8 MPa (Figure 3-2a). The average
excess pore pressure in the column using this permeability-porosity relationship is 4.2 MPa, corresponding to $\lambda = 0.86$ ($\lambda^* = 0.68$).

In contrast, simulated pressures are relatively insensitive to values of $v_p$ over the range of reported plate convergence rates (Figure 3-2b). Setting $v_p = 6.5$ km/Myr corresponds to the base case, described above. Setting $v_p = 4.0$ km/Myr yields an average excess pore pressure of 3.0 MPa (only 0.1 MPa lower than the base case), ranging from 2.6 MPa at the top of the column to 3.2 MPa at the base and corresponding to an average pore pressure ratio of $\lambda = 0.79$ ($\lambda^* = 0.47$).

Our results also indicate that pore pressure throughout the underthrust section is highly sensitive to the value of $\psi$ (Figure 3-2c, Figure 3-3). Setting $\psi = 0.25$ yields an average pore pressure of 2.2 MPa at Site 1174, ranging from 1.3 MPa at the top of the column to 2.7 MPa at the base and corresponding to an average pore pressure ratio of $\lambda^* = 0.73$ ($\lambda^* = 0.35$). Setting $\psi = 0.5$ corresponds to the base case. Setting $\psi = 0.75$ yields an average pore pressure of 4.1 MPa, ranging from 3.9 MPa at the top of the column to 4.3 MPa at its base and corresponding to an average pore pressure ratio of $\lambda = 0.86$ ($\lambda^* = 0.66$). Simulated pore pressures at Site 1174 are lower than those inferred from porosity data for all values of $\psi < ~0.5$.

3.2.2 Best Fit Models, Pore Pressure and Effective Stress at the Décollement

Although our model simulates a one-dimensional sediment column, two-dimensional cross sections of the pressure distribution along the Muroto Transect can be created by translating time into distance from the trench. In order to find the model parameters which best reproduce pore pressures in the underthrust section inferred from both borehole data [Screaton et al., 2003; Saffer, 2003] and seismic data [Tobin et al., 2006], we modeled pore pressure evolution within the underthrust section by varying the top boundary condition across the full range of possibilities for each of the three permeability relations (Figure 3-3a). Each simulation produces a pore pressure profile throughout the underthrust column up to 40 km landward of the trench. The pore pressures inferred by Tobin et al. [2006] from seismic interval velocity were taken at a depth of 75 m below the décollement. Therefore we extract the value of pore pressure at this depth from each model run for comparison to the seismically inferred pressures. We determine a best fit model by calculating the root-mean-squared value of the error between modeled and inferred pore pressures for the full range of model simulations (Figure 3-3b).
This process was repeated using each of the three permeability relations, yielding a suite of décollement (top) boundary conditions that are consistent with pore pressures estimated from the seismic reflection interval velocity data, falling within the range $\psi = 0.53 – 0.63$. These correspond to values of $P^*$ at the décollement itself increasing from 1.7 – 2.1 MPa at the trench to 30.2 – 35.9 MPa by 40 km landward, and equivalent to a range of pore pressure ratios of $\lambda_b = 0.68 – 0.77$ ($\lambda^*_b = 0.30 – 0.60$) (Figure 3-4a). These values of $\psi$ result in excess pore pressure 75 m below the décollement increasing from $\sim$2.1 to 37.0 MPa, from the trench to 40 km landward (Figure 3-3c). The best fit values of excess pore pressure and pore pressure ratio $\lambda$ along the décollement increase with the value of $\log(k_0)$, because increased sediment permeability allows more efficient drainage of the underthrust section, thus requiring a higher value of $\psi$ at the top boundary (i.e. a larger pressure “cap”) to match inferred pore pressures in the subjacent section. A marked increase in the simulated excess pore pressure at $\sim$27 km landward of the trench results from an increase in the wedge surface slope, imposed to reflect observed bathymetry. Even though simulated pore pressures are high overall and increase landward, partial drainage results in a $\sim$30% decrease in the total thickness of the underthrusting sediment column.

For models that match inferred pore pressures within the underthrust section, the effective stress at the décollement increases from $\sim$3.8 – 4.1 MPa at the trench to $\sim$23.7 – 29.4 MPa by 40 km landward (Figure 3-4b). Values of the effective stress then allow a calculation of the shear strength along the décollement:

$$\tau = \mu_b \sigma_b' + C$$ (20)

where $\tau$ is the shear strength [Pa], $\mu_b$ is the coefficient of friction for the décollement [unitless], and $C$ is cohesive strength [Pa]. Based on measurements that define the frictional strength of sediment from the LSB [Brown et al., 2003] and a range of clay-rich gouges [Saffer and Marone, 2003], we assume a friction coefficient of $\mu_b = 0.30$-0.40 and that the fault itself is cohesionless ($C = 0$ MPa). The resulting values of shear strength along the décollement range from 1.1 – 1.7 MPa at the trench to 7.1 – 11.8 MPa by 40 km landward from the trench.
Table 3-1. Laboratory Measured Permeabilities for Samples From ODP Leg 190, Site 1173. Indicates for each sample: the depth from which it was taken, the sample’s initial $\phi_{initial}$ and final $\phi_{final}$ porosities, the maximum value of effective stress which the sample felt during experimental compression, and parameters describing the evolution of permeability with porosity as measured in the laboratory, $\log(k_0)$ and $\gamma$.

<table>
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<tr>
<th>Sample</th>
<th>Depth [mbsf]</th>
<th>$\phi_{initial}$</th>
<th>$\phi_{final}$</th>
<th>max $\sigma_v'$ [MPa]</th>
<th>$k_0$</th>
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</table>
Figure 3-1: (a) Permeability of hemipelagic sediments from Site 1173 as a function of porosity, obtained from CRS tests (black dots), and flow through tests (open squares). Tests conducted by Gamage and Screaton [2006] are shown for comparison (open circles). The solid lines are fits used in this study corresponding to the functions: 1. upper bound: $\log(k) = -19.94 + 6.93\phi$; 2. middle fit: $\log(k) = -20.45 + 6.93\phi$; 3. lower bound: $\log(k) = -20.96 + 6.93\phi$; 4. extra low: $\log(k) = -21.47 + 6.93\phi$. The dashed line is the permeability-porosity function used by Gamage and Screaton, [2006]: $\log(k) = -19.82 + 5.39\phi$; the dot-dashed line is that used by Saffer and Bekins, [1998]: $\log(k) = -20 + 5.25\phi$. 
Figure 3-2: Results of sensitivity analysis showing a comparison of inferred pore pressure at Site 1174 with model output, for varying: (a) the permeability-porosity relationship used in the model, showing the lower bound relation (dashed line), middle fit (solid line), upper bound relation (dotted line), and the extra low relation (dot-dashed line); (b) plate convergence rate, showing $v_p = 4.0 \text{ cm/yr}$ (dotted line) and the base case (solid line); and (c) the top (i.e. décollement) boundary condition, showing $\psi = 0.25$ (dotted line), the base case (solid line), and $\psi = 0.75$ (dashed line).
Figure 3-3: (a) Comparison of pore pressures at 75 m below the décollement inferred from seismic interval velocity by Tobin et al. [2006] (solid black circles) and those simulated for the full range of possible top boundary conditions. 0% corresponds to a hydrostatic pressure boundary at the décollement, 100% corresponds to excess pore pressure equal to that of the added overlying lithostatic load. The solid yellow circles show values of excess pore pressure inferred at Sites 1174 and 808 for comparison. (b) Example of a calculation to minimize the error between model output and inferred pore pressures, shown here for the “Middle Fit” permeability relationship. The value of $\psi$ which minimizes the rms-error corresponds to the best fit run for that permeability relationship. (c) Results for the upper bound permeability-porosity function (dotted line, $\psi = 0.63$), the middle fit permeability function (solid line, $\psi = 0.59$), and the lower bound permeability function (dashed line, $\psi = 0.53$), showing pore pressures extracted from the model at 75 m below the décollement. We consider the lower bound permeability relation to be our preferred model (see text for discussion).
Figure 3-4: Excess pore pressure (a) and effective stress (b) at the décollement as a function of distance from the trench for the best-fit model runs shown in Figure 3-3c. The shaded area in (b) shows the range of shear strength at the décollement for all three runs assuming $\mu_b = 0.3 - 0.4$. Lines correspond to same parameters in Figure 3-3c.
Chapter 4

Discussion

4.1 Pore Pressure Development

The distribution and magnitude of simulated excess pore pressure depends on both the permeability-porosity relation and on the boundary condition at the top of the draining section (i.e. at the décollement). With higher sediment permeabilities (as \( \log(k_0) \) increases), the pore pressure at the décollement must be increased to match pore pressures within the underthrust section inferred from borehole and seismic data. Our results suggest that the pore pressure ratio along the décollement falls within the range \( \lambda_b = 0.68 - 0.77 \) (\( \lambda_b^* = 0.30 - 0.60 \)). These values are similar to those predicted by Saffer and Bekins [1998] near the trench (\( \lambda_b^* = 0.56 \) at Site 808), but are considerably lower than those landward of 20 km from the trench (\( \lambda_b^* = 0.82 \)). However, it is important to note that our model is focused specifically on constraining the excess pore pressure along the décollement using a physically based model of loading, whereas Saffer and Bekins [1998] investigated regional fluid pressure and flow patterns using a model driven by assumed fluid sources within the accreted and underthrust sections. Our results reinforce the notion that pore pressure within the underthrust section at subduction zones depends not only on the hydraulic properties of the sediment [Gamage and Screaton, 2006], but is also strongly dependent on the conditions at the décollement [e.g., Moore et al., 1991]. We show explicitly that because the underthrust section and the décollement are in hydrologic communication, pressures within the underthrust section have hydrologic and mechanical significance for conditions at the plate boundary above.

It is notable that the lower bound or extra low bound to our permeability-porosity data are needed to reproduce the vertical pore pressure profile inferred from porosities at Site 1174. In the case of vertical (upward) flow, the lowest permeability layer will control fluid flow [e.g., Bear and Verruijt, 1987], hence these two permeability-porosity relations are probably the most appropriate of the functions that we considered. Recent work by Hüpers and Kopf [2008] shows that when temperature effects on the consolidation state of underthrust sediments at Nankai are taken into account, excess pore pressure estimates are lower than previously reported by ~0.7 – 1.3 MPa. If that is the case, the inferred excess pore pressure profile shown in Figure 3-3a would be shifted to the left, resulting in an improved fit to modeled pressure profiles for the lower
bound permeability relation. Furthermore, it is likely that sediment permeability will decrease with increasing temperature due to processes such as mineral dissolution of precipitation sealing [e.g., Kato et al., 2004], although these effects are not included in our laboratory permeability measurements. On the basis of these observations, we consider the simulations using the lower bound and extra low permeability-porosity relations as our preferred models. However, we report the full range of our model results in Figures 3-3, 3-4 and subsequent discussion, because without information about the vertical distribution of pore pressure in the underthrust section landward of the drill sites, the available constraints down-dip of the boreholes can be matched equally well by any of the permeability-porosity relations shown in Figure 3-1; as noted above, with lower sediment permeability, the pressure at the top boundary required to match the inferred pressures is also lower.

4.2 Dewatering

As part of our analysis, we examine the dewatering rate of the underthrust sediments. We calculate the amount of cumulative fluid production in our model from the simulated porosity loss and height change of the section, and report the resulting fluid source as a function of distance from the trench, in terms of total fluid volume per unit width along strike [e.g. Saffer, 2003]:

\[ \Omega_{\text{compaction}} = v_p \Delta H \]  

(21)

where \( \Omega_{\text{compaction}} \) is the fluid source \([m^3 \text{ yr}^{-1} \text{ m}^{-1}]\), and \( \Delta H \) is the change in height. Using \( v_p = 6.5 \text{ km/Myr} \), the total simulated fluid production from the underthrust section between Sites 1173 and 1174 is 2.0 \( m^3 \text{ yr}^{-1} \text{ m}^{-1} \), and between Sites 1173 and 808 it is 2.7 \( m^3 \text{ yr}^{-1} \text{ m}^{-1} \) (Figure 4-1). These values correspond to fluid sources of \( 3.5 \times 10^{-14} \text{ s}^{-1} \) and \( 5.3 \times 10^{-15} \text{ s}^{-1} \) between the trench and Site 1174, and Sites 1174 and 808, respectively. Screamton et al. [2002] estimated dewatering rates of 1.3 \( m^3 \text{ yr}^{-1} \text{ m}^{-1} \) and 1.4 \( m^3 \text{ yr}^{-1} \text{ m}^{-1} \) within the same intervals based on differences in the average porosity of the section, and assuming, a plate convergence rate of \( v_p = 4.0 \text{ km Myr}^{-1} \). If converted to account for a plate velocity of \( v_p = 6.5 \text{ km Myr}^{-1} \), the values reported by Screamton et al. [2002] are equivalent to 2.1 \( m^3 \text{ yr}^{-1} \text{ m}^{-1} \) at Site 1174 and 2.3 \( m^3 \text{ yr}^{-1} \text{ m}^{-1} \) at Site 808; thus we
predict a nearly equivalent amount of dewatering up to Site 1174 and a slightly greater amount of fluid loss between Site 1174 and Site 808 than their study.

Our modeling results indicate that most of the dewatering occurs early; the rate of fluid loss is highest within the first ~5-10 km from the trench, and begins to taper off beyond ~10 km landward of the trench before increasing again at a distance of ~30 km due to the increased loading rate there (Figure 4-1). We attribute the decrease in dewatering rate to decreasing sediment permeability and compressibility accompanying progressive consolidation. For comparison, fluid loss in the outer 3.5 km at Barbados amounts to ~1.1 m$^3$ yr$^{-1}$ m$^{-1}$ and at Costa Rica to ~8 m$^3$ yr$^{-1}$ m$^{-1}$ by 1.6 km landward from the trench [Zhao et al., 1998; Saffer 2003]. When considered within the context of these values, our results for Nankai are consistent with low permeability expected for a clay rich underthrust section, and with the fact that initial burial to ~400 mbsf prior to underthrusting results in lower overall porosity (and thus lower permeability) than at non-accretionary margins like Costa Rica where the entire section is underthrust [see discussion in Saffer, 2003; Saffer and McKiernan, 2005].

4.3 Mechanical Implications

4.3.1 Strength Along the Décollement

If the underthrust section were freely draining, the effective stress at the décollement would increase from ~6 MPa at the trench to ~60 MPa by 40 km landward, corresponding to shear strength increasing from of ~2.1 to ~21 MPa. Our best fit models (Figure 8) indicate that shear strength along the décollement remains < 12 MPa within the frontal 40 km of the Muroto transect (Figure 3-4b). For comparison, by assuming that effective stress within the underthrust section is equivalent to that along the plate boundary, Tobin et al. [2006] estimated that shear strength at 20 km from the trench is 4.2 ± 0.5 MPa; we predict a shear strength of 3.2 – 5.1 MPa at this distance. The values of shear strength we report are equivalent an effective friction coefficient $\mu_b^*$ of 0.07 – 0.13, where $\mu_b^* = \mu_b (1 - \lambda_b)$. This result is consistent with the conclusions drawn from mechanical modeling studies, which indicate that $\mu_b$ is ~0.09 or less [Wang and He, 1999].

In contrast to our results and those of Tobin et al. [2006], Brown et al. [2003] estimated that shear strength remains less than ~4 MPa as far as 50 km from the trench, based on values of
effective stress along the décollement taken directly from the regional modeling results of Saffer and Bekins [1998]. This discrepancy arises from the considerably higher pore pressures predicted by Saffer and Bekins [1998] than reported here for the region beyond ~20 km from the trench. As noted above, our study explicitly quantifies pore pressure – and thus effective stress - along the décollement, using a model that directly incorporates loading to drive pore pressures, and which is well-constrained by drilling and seismic data to large distances from the trench (i.e. ~22 km). This contrasts with the regional modeling studies upon which Brown et al.’s [2003] analysis depends [e.g., Saffer and Bekins, 1998], in which pore pressure is driven by assumed fluid source terms. Despite these differences, we come to the same general conclusion that pore pressures along the décollement are significantly above hydrostatic. In detail however, we predict lower values of pore pressure along the décollement than previously reported; our results indicate that the mechanical strength of the plate boundary should be low relative to that expected under drained conditions, approximately twice as strong as suggested previously.

4.3.2 Implications for Taper Angle

Our constraints on the value of $\lambda_b$, in addition to constraints on the friction coefficient along the décollement and within the wedge, have implications for the taper angle and stability of the wedge. Dahlen [1984] gave an exact solution for the surface slope and décollement dip of a critically tapered, non-cohesive wedge as a function of the pore pressure ratios and coefficients of friction within the wedge ($\lambda_w$ and $\mu_w$) and along the base ($\lambda_b$ and $\mu_b$). At Nankai the values of the surface slope and the décollement dip are known, $\alpha = 1.6^\circ$ and $\beta = 2.5^\circ$ [Taira et al., 1991]. We used an iterative method to solve the critical taper equations numerically (see equations (9), (17), and (19) in Dahlen [1984]) for values of $\lambda_w$ which are consistent with the values of $\lambda_b$ determined from our modeling and using wedge and basal coefficients of friction ($\mu_w$ and $\mu_b$) constrained by laboratory studies [Brown et al., 2003; Saffer and Marone, 2003]. We find that values of $\lambda_w = 0.41 – 0.59$ are needed to satisfy the observed taper angle along the Muroto transect (Figure 4-2, Tables 4-1, 4-2), even when allowing for values of $\mu_b$ as low as 0.20, which are at the lower end of the range determined from laboratory experiments. Notably, the lower bound relation between permeability and porosity defined by our data, which best fits the inferred pore pressure profile at Site 1174, results in the lowest values of $\lambda_b$ and thus $\lambda_w$. 
If these values of $\lambda_w$ are correct, it implies, perhaps surprisingly, that pore pressure within the wedge must be near hydrostatic to maintain the observed taper angle of $\sim 4.1^\circ$ along the Muroto Transect (i.e. the wedge must be relatively strong). Overpressures are commonly inferred at large depths within accretionary wedges and it seems unlikely that hydrostatic pore pressures exist throughout the wedge, particularly far arcward of the trench where the wedge thickness becomes greater than a few kilometers [Dahlen, 1990]. However, ACORK measurements at Site 808 have recorded approximately hydrostatic pore pressures, which support our indirect estimates of $\lambda_w$, at least near the toe of the wedge [Davis et al., 2006]. It may also be that the frictional strength along the décollement is even lower than the range we considered here, which would allow pore pressure in the wedge to be somewhat higher and still be consistent with the observed taper angle. However, this would require $\mu_b < \sim 0.14$.

Another possibility is that critical deformation of the wedge occurs during pulses of elevated pore pressure along the décollement [e.g., Wang and Hu, 2006; Bourlange and Henry, 2007]. In this scenario, our constraints on $\lambda_b$ would represent the long-term average pore pressure along the base of the wedge, which controls drainage from the underthrust sediment, but would not reflect the value of $\lambda_b$ during slip. Thus, our constraints on $\lambda_b$ would under-predict the values at the time of slip and lead to underestimation of pore pressure within the wedge ($\lambda_w$) from critical taper theory.

4.3.3 Décollement Down-stepping

At Nankai, the décollement is observed to down-step through the underthrust sedimentary section [Bangs et al., 2004]. Downstepping occurs initially at $\sim 25$ km from the trench, and by $\sim 45$ km the entire underthrust section has been underplated [Bangs et al. 2004]. Several studies have suggested that down-stepping of the décollement may occur if drainage causes changes in effective stress that result in migration of zones of minimum mechanical strength [e.g., Wesbrook and Smith, 1983; Saffer 2003]. A simple calculation indicates that the point of minimum effective stress within the sediment column will coincide with the point where the pressure gradient $\partial P/\partial z$ is equal to the gradient of the lithostat $\partial \sigma_z/\partial z$. Differentiating (1) and setting it equal to zero yields:
Our three best-fit models yield very different vertical hydraulic gradients across the sediment column. The best-fit model for the upper bound permeability-porosity relation generates a maximum gradient of 4 kPa m\(^{-1}\) across the entire sediment column and does not generate sufficient curvature of the gradient to initiate downward migration of the depth of the minimum effective stress. The best-fit model for the lower bound permeability-porosity relation results in a maximum gradient of 46 kPa m\(^{-1}\), and generates enough curvature to initiate a gradual, continued downward migration of the zone of minimum effective stress, beginning at the trench and reaching the bottom of the section by ~23 km arcward (Figure 4-3). This is in contrast to the sudden onset of down-stepping interpreted from seismic reflection data [e.g. Bangs et al., 2004]. However, if a small amount of cohesion (\(C = 1 – 2\) MPa) is assumed for the unfaulted underthrusting section, the minimum in mechanical strength migrates down section in a discrete step, in a manner similar to the observed down-stepping of the décollement at Nankai. For \(C = 1\) MPa, no downward migration occurs until ~23 km from the trench, at which point the effective stress minimum jumps nearly to the bottom of the underthrust section (Figure 4-3). Similarly, for \(C = 2\) MPa, no migration is observed until ~30 km from the trench, where the jump is again to the bottom of the section. The fact that setting \(C = 0\) MPa in our analysis does not produce down-stepping in discrete, while setting \(C = 1 – 2\) MPa does, indicates that the sediments in the underthrust section must possess some small amount of cohesion and that this cohesion plays an important role in the location and onset of down-stepping. Furthermore, the observation that setting a single, constant value for cohesion in our analysis produces only one discrete down-step, whereas the décollement is observed in the seismic reflection data [e.g Bangs et al., 2004] to undergo two discrete down-steps, leads to the likely conclusion that cohesion in the underthrust sediments varies laterally.

Our results are in good agreement with the observed location of the onset of down-stepping at Nankai, ~25-35 km landward from the trench [Bangs et al., 2004], and indicate that drainage and cohesion of the underthrust section likely mediate décollement down-stepping. It is important to note that arcward of the point of downstepping, our model would no longer simulate...
realistic drainage distances or loading rates, because the drainage path length (height of the remaining underthrust section) would be decreased, and the uppermost underplated sediment would be incorporated into the accretionary wedge and subjected to higher mean and differential stresses [e.g., Karig, 1990]. Because of the decreased flow path length, the net effect of downstepping would be to increase the efficiency of drainage, thereby potentially leading to lower pore pressures – and higher effective stresses and shear strengths - than reported here. This is consistent with the hypothesis that downstepping is associated with increased shear strength along the décollement.
Table 4-1: Values of $\lambda_w$ which satisfy the critical taper equations ((9), (17), and (19) in Dahlen [1984]) for a given values of $\mu_b$ and $\lambda_b$. The value of $\mu_w$ is set at 0.4. “N/A” indicates cases for which $\lambda_w$ would be sub-hydrostatic.

<table>
<thead>
<tr>
<th>$\mu_b$</th>
<th>$\lambda_b = 0.70$</th>
<th>$\lambda_b = 0.74$</th>
<th>$\lambda_b = 0.75$</th>
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<td>0.20</td>
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<tr>
<td>0.26</td>
<td>N/A</td>
<td>N/A</td>
<td>0.41</td>
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</table>

Table 4-2: Values of $\lambda_w$ which satisfy the critical taper equations for a given values of $\mu_w$ and $\lambda_b$. The value of $\mu_b$ is set at 0.2. “N/A” indicates cases for which $\lambda_w$ would be sub-hydrostatic.

<table>
<thead>
<tr>
<th>$\mu_w$</th>
<th>$\lambda_b = 0.70$</th>
<th>$\lambda_b = 0.74$</th>
<th>$\lambda_b = 0.75$</th>
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</thead>
<tbody>
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<td>0.30</td>
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<td>N/A</td>
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</tr>
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<td>0.38</td>
<td>0.43</td>
<td>0.52</td>
<td>0.56</td>
</tr>
<tr>
<td>0.4</td>
<td>0.47</td>
<td>0.55</td>
<td>0.59</td>
</tr>
</tbody>
</table>
Figure 4-1: Cumulative volume of fluid expelled from the underthrust section as a function of distance from the trench. Lines correspond to best fit simulations for each permeability – porosity relationship (dashed line: upper bound; solid line: middle fit; dotted line: lower bound).
Figure 4-2: Example of solutions to the critical taper equations using a best fit value for the pore pressure ratio along the décollement, determined from simulations using the Middle Fit permeability-porosity relation. The box marks the observed geometry along the Muroto transect. The value $\lambda_w = 0.48$ satisfies the equations for the observed wedge geometry.
Figure 4-3: (a) Simulated depth of the effective stress minimum within the underthrust section as a function of distance from the trench for the lower bound permeability-porosity function and best-fit conditions ($\psi = 0.53$). Depth has been referenced to the base of the column. The solid line indicates the location of effective stress minimum, and thus shear strength minimum, for $C = 0$ MPa. The dashed lines indicate the location of minimum shear strength for cohesion values of $C = 1$ MPa and $C = 2$ MPa, illustrating abrupt downstepping.
at 23 and 30 km from the trench, respectively. (b) Effective stress profiles within the underthrust section extracted at three locations landward from the trench. Dashed line in each panel indicates the zone of minimum effective stress.


Chapter 5

Conclusions

In this study, we have combined laboratory-derived values of permeability with numerical modeling to evaluate the generation of pore pressure within the underthrust section along the Muroto transect of the Nankai accretionary complex. Specifically, we have incorporated new constraints on the pressure state of underthrust sediment in order to project drainage and pore pressure to considerably greater depths than previous studies, and we have explicitly quantified the role of a pore pressure “cap” at the décollement in controlling drainage of the subjacent sediments. Sensitivity analyses show that the evolution and generation of pore pressure within the underthrusting section is highly dependent upon both sediment permeability and the pore pressure at the décollement. We find that pore pressures along the décollement that are consistent with the drainage state of the subjacent section range from 1.7 – 2.1 MPa at the trench to 30.2 – 35.9 MPa by 40 km landward, corresponding to values of $\lambda_b = 0.68 – 0.77$. Such elevated pore pressures would result in low shear strength (< 12 MPa) along the décollement up to 40 km from the trench, although the values are not as low as some previous studies have suggested on the basis of pore pressure predictions that are less well constrained than those reported here [e.g., Brown et al., 2003].

Permeability-porosity functions defined in our study are consistent with previously published relations, but span a larger range of porosities (12 – 60 %) and effective stresses (0 – 90 MPa). Simulations incorporating our "Middle Fit" relation to experimental permeability data were not able to reproduce the high pore pressures observed at Site 1174, indicating that the least permeable sediment in the underthrust section probably play a dominant role in controlling vertical fluid flow. However, recent work has indicated that the consideration of thermal effects on consolidation would yield predicted pore pressures at the boreholes that are ~1 MPa lower than in previous studies [Hüpers and Kopf, 2008], which would lead to improved agreement with model results for the lower bound permeability-porosity relation.

The excess pore pressure along the décollement also has implications for pore pressure in the accretionary wedge ($\lambda_w$). We use non-cohesive critical taper theory to constrain values of $\lambda_w$ based on model-derived constraints of the basal pore pressure ratio ($\lambda_b$) and using measured values of the coefficient of friction for LSB sediments. We estimate values of $\lambda_w = 0.41 – 0.59$, which correspond to near hydrostatic pore pressures. An alternative scenario is that the values of
\lambda_b\), we predict reflect the time-averaged pore pressure at the décollement, which controls drainage from underthrust sediment in between periods of increased pore pressure when the fault is slipping. This would allow pore pressure in the wedge to be higher. Finally, for the lower bound and extra low permeability relations used in our models, the simulated evolution of the vertical pore pressure profile in the underthrusting section, along with the inclusion of a finite amount of cohesion, results in downward migration of the shear strength minimum. This offers a simple explanation for down-stepping of the décollement, and is consistent with the location of downstepping at \(~25\) km from the trench observed in seismic reflection data.
References


Appendix A

Experimental Data

Appendix A contains data compiled from constant rate of strain tests used in this study (see Table 3-1). For each separate experiment, a table showing the sample name, depth below the sea floor from which it was cored, the in situ stress that the sample felt, values of preconsolidation stress (determined using the Casagrande and Becker methods), and parameters describing the evolution of permeability with porosity ($\log(k_0)$ and $\gamma$) are shown. Four plots for each test are included:

One showing the evolution of effective stress and excess pore pressure with time, to illustrate that the excess pore pressure at the base of the sample was at no time a significant fraction of the effective stress. The second showing the sample’s void ratio plotted against the effective stress on a logarithmic scale. This type of plot is often referred to as an $e$-$\log(p)$ plot, and shows the sample’s transition from elastic to plastic deformation. The third plot describes the evolution of permeability, calculated using Equation 6, with effective stress. The fourth plot describes the evolution of permeability with porosity. A log-linear line of the form of Equation 19 is fit to this plot, yielding the parameters $\log(k_0)$ and $\gamma$. 
<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (mbsf)</th>
<th>In Situ Stress (kPa)</th>
<th>Casagrande Stress (kPa)</th>
<th>Becker Stress (kPa)</th>
<th>log($k_0$)</th>
<th>$\gamma$</th>
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<td>1173-12H</td>
<td>107.14</td>
<td>538</td>
<td>660.46</td>
<td>591.56</td>
<td>-20.3614</td>
<td>7.9317</td>
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</table>

![Graph showing Effective Stress and Excess Pore Pressure](chart.png)
1173-12H-CRS; depth = 107.14 mbsf; $dz/dt = 0.00408$ mm/min

**Effective Stress (kPa)**

**Void Ratio**

**Permeability ($m^2$)**
1173-12H-CRS; depth = 107.14 mbsf; dz/dt = 0.00408 mm/min

Porosity

Permeability (m²)

10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹

0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65

Porosity
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<th>Sample</th>
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<th>In Situ Stress (kPa)</th>
<th>Casagrande Stress (kPa)</th>
<th>Becker Stress (kPa)</th>
<th>log($k_0$)</th>
<th>γ</th>
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<td>1173-19H</td>
<td>178.13</td>
<td>977</td>
<td>1384.89</td>
<td>1316.58</td>
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<td>6.8111</td>
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1173-19H; depth = 178.13 mbsf; dz/dt = 0.00093 mm/min
<table>
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<th>Casagrande Stress (kPa)</th>
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</table>

Graph: 1173-34X, depth = 321.58 mbsf, dz/dt = 0.00262 mm/min

- Effective Stress
- Excess Pore Pressure
1173-34X, depth = 321.58 mbsf, \( \frac{dz}{dt} = 0.00262 \) mm/min

![Graph 1](image1)

1173-34X, depth = 321.58 mbsf, \( \frac{dz}{dt} = 0.00262 \) mm/min

![Graph 2](image2)
1173-34X; depth = 321.58 mbsf; dz/dt = 0.00262 mm/min
<table>
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<tr>
<th>Sample</th>
<th>Depth (mbsf)</th>
<th>In Situ Stress (kPa)</th>
<th>Casagrande Stress (kPa)</th>
<th>Becker Stress (kPa)</th>
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<td>1173-36X</td>
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<td>3980.8</td>
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<td>6.8643</td>
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1173-36X; depth = 339.95 mbsf; $dz/dt = 0.00392$ mm/min
1173-36%, depth = 339.95 mbsf, dz/dt = 0.00392 mm/min

Permeability (m^2)

10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13}

Porosity

0.35 0.4 0.45 0.5 0.55 0.6
<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (mbsf)</th>
<th>In Situ Stress (kPa)</th>
<th>Casagrande Stress (kPa)</th>
<th>Becker Stress (kPa)</th>
<th>log($k_0$)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1173-45X</td>
<td>427.1</td>
<td>2745.473</td>
<td>5784.23</td>
<td>5640.04</td>
<td>-21.49</td>
<td>9.224</td>
</tr>
</tbody>
</table>

$U-09-1173-45X$; depth = 427.1 mbsf; $dz/dt = 0.00085$ mm/min
<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (mbsf)</th>
<th>In Situ Stress (kPa)</th>
<th>Casagrande Stress (kPa)</th>
<th>Becker Stress (kPa)</th>
<th>log($k_0$)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1173-49X</td>
<td>464.71</td>
<td>3110</td>
<td>5938.44</td>
<td>4265.12</td>
<td>-21.3015</td>
<td>8.2476</td>
</tr>
</tbody>
</table>

$1173-49X$; depth = 464.71 mbsf; $dz/dt = 0.00116$ mm/min

Effective Stress

Excess Pore Pressure
1173-49%, depth = 464.71 mbsf, dz/dt = 0.00116 mm/min

Void Ratio

Effective Stress (kPa)

1173-49%, depth = 464.71 mbsf, dz/dt = 0.00116 mm/min

Permeability (m²)

Effective Stress (kPa)
1173-49%; depth = 464.71 mbsf; dz/dt = 0.00116 mm/min
Appendix B
Numerical Model Code

%Simulation of pore pressure development in the underthrust section along
%the Muroto transect at the Nankai Trough. Input the boundary condition at
%the decollement (TopHead), the total run time of the simulation (RunTime),
%the time step (TimeStep) and an index value controlling the
%permeability-porosity relation to be used (PermIndex = -1, 0, 1, or 2).

function [DepthC, DistanceC, HeadC, HeadODP, DepthODP, EffectiveStressC,...
    EffStressMin, EffStressMinDepth, OverburdenB, PorosityC, YearsT, z_Dec1,...
    z_Dec2, DistanceODP, EffectiveStressODP, OverburdenODP, PorosityODP,...
    SourcePressure, FluidFluxC]...
    = AutoCRS(TopHead_0, RunTime, TimeStep, PermIndex)

%Load seismic data: inferred pore pressure and wedge geometry.
load Nankai_Seismic_Taper.mat;
%Load clay dehydration source data.
load Nankai_Sources.mat;

z_column = 730;  %depth to the base of the column.
z_dec = 420;     %depth to the decollement at start.
dz = 2;         %length step spacing.
Depth = (z_dec:dz:z_column)';   %Depth referenced to the decollement.
Depth_seaflr = (0:dz:z_column)';   %Depth referenced to the sea floor.
SubDepth = 0;               %SubDepth is the amount of subduction depth.
m = (z_column-z_dec)/dz;  %number of nodes.

%Times step in seconds.
dt = 365*24*3600*TimeStep;
%Initialize model time to zero.
Time = 0;
%Calculate the total number of iterations, N.
N = round((RunTime*365*24*3600)/dt);

%Specific weight of water.
gamma = 9810;                                              %[kg/m^3]%
%Volumetric compressibility of water.
beta = 4.6e-10;                                            %[1/Pa]%

%Calculate the initial lithostat based on MAD data at Site 1173.
[Lithostatic_seaflr, Lithostatic, Porosity] = ...
    Initial1173(z_dec, dz, m, Depth, Depth_seaflr);
EffectiveStress = Lithostatic - 9.81*1024.*Depth;  %[Pa]
InitialPorosity = Porosity;

%Hydraulic properties.
%Experimentally derived permeability relations
if (PermIndex == -1)
    k = 10^(-3.0523/0.1457)*10.^(Porosity./0.1457);
elseif (PermIndex == 0)
    k = 10^(-2.9771/0.1457)*10.^(Porosity./0.1457);
elseif (PermIndex == 1)
    k = 10^(-2.9019/0.1457)*10.^(Porosity./0.1457);
elseif (PermIndex == -2)
    k = 10^(-3.1275/0.1457)*10.^(Porosity./0.1457);
end

%Determine the effective diffusivity between nodes in the control space.
Temp = 70.*ones(m+1,1); %[degrees Celsius]
mu = (239.4*10^(-7)).*10.^(248.37./(Temp+133.15)); %[Pa*s]
%Volumetric compressibility [1/Pa]
alpha = (Porosity./(1-Porosity).^2).*((0.001112/(9.81*(2650-1035))));
Diffusivity = (k.*(gamma./mu))./(1024*9.81*(alpha + Porosity.*beta));
for q = 1:m
    DiffusivityEffective(q,1) = 2*Diffusivity(q)*Diffusivity(q+1)/...
        (Diffusivity(q)+Diffusivity(q+1));
end
r = DiffusivityEffective.*(dt/dz^2);

%Initialize output variables.
DepthC = zeros(numel(Depth),round(N/100));
DistanceC = zeros(round(N/100),1);
EffectiveStressC = zeros(numel(Depth),round(N/100));
SourcePressure = zeros(round(N/100),1);
FluidFluxC = zeros(round(N/100),1);
HeadC = zeros(numel(Depth),round(N/100));
OverburdenB = zeros(round(N/100),1);
PorosityC = zeros(numel(Depth),round(N/100));
SubDepthC = zeros(round(N/100),1);
YearsT = zeros(N,1);
EffStressMin = zeros(round(N/100),1);
EffStressMinDepth = zeros(round(N/100),1);
z_Dec1 = zeros(round(N/100),1);
\( z_{\text{Dec2}} = \text{zeros(round(N/100)},1); \)

\[
\begin{align*}
\text{HeadODP} &= \text{zeros(numel(Depth)},2); \\
\text{DepthODP} &= \text{zeros(numel(Depth)},2); \\
\text{DistanceODP} &= \text{zeros(1,2)}; \\
\text{EffectiveStressODP} &= \text{zeros(numel(Depth)},2); \\
\text{OverburdenODP} &= \text{zeros(1,2)}; \\
\text{PorosityODP} &= \text{zeros(numel(Depth)},2); \\
\end{align*}
\]

\%Initialize Crank-Nicolson matrix coefficients.
\[
\begin{align*}
\text{H} &= \text{zeros(m+1,1)}; \\
\text{A} &= \text{ones(m+1,1)}; \\
\text{DZ2} &= \text{zeros(m,1)}; \\
\end{align*}
\]

\%Loading.
\[
\begin{align*}
\beta_T &= 2.6*\pi/180; \quad \%\text{decollement dip angle.} \\
v_{\text{plate}} &= 0.065/(365*24*3600); \quad \%\text{plate convergence velocity [m/s].} \\
\text{Overburden} &= \text{Lithostatic_seafloor(z_{\text{dec}}/dz+1)}; \quad \%[\text{Pa}] \\
\text{StressV} &= 0; \quad \%\text{StressV is the change in stress due to applied overburden.} \\
\text{TopHead} &= 0; \quad \%\text{Head at the decollement due to excess pore pressures [m].} \\
\text{Dist} &= -10450; \quad \%\text{Location of the underthrust column landward of the trench.} \\
\text{InstantSource} &= 0; \quad \%\text{Head source due to clay dehydration [m].} \\
\text{FluidFlux2} &= 0; \quad \%\text{Amount of fluid leaving the column [m^2/s].}
\end{align*}
\]

\[
\begin{align*}
\text{ww} &= 0; \\
\text{EE} &= \text{numel(EffectiveStress)}; \\
\end{align*}
\]

\[
\text{for w = 1:N}
\begin{align*}
\%\text{Time and overburden.}
\end{align*}
\]

\[
\begin{align*}
\text{Time} &= \text{Time} + \text{dt}; \\
\text{Years} &= \text{Time}/(3600*365*24); \\
\text{EffectiveStress}_i &= \text{EffectiveStress}; \\
\text{Porosity}_i &= \text{Porosity}; \\
\text{Depth}_i &= \text{Depth}; \\
\end{align*}
\]

\[
\begin{align*}
\%\text{Loading calculations}
\end{align*}
\]

\[
\begin{align*}
\text{[Dist,SubDepth,Overburden,StressV,dPressureHead,TopHead,...}
\text{ dTopHead,v_x]} &= \text{NankaiLoading_1D(Dist,DistanceSeismic,Alpha2000,...}
\text{ v_plate,betaT,SubDepth,z_{\text{dec}},dt,Overburden,StressV,TopHead,TopHead_0);}
\end{align*}
\]

\[
\begin{align*}
\%\text{Add a fluid source due to clay dehydration}
\end{align*}
\]

\[
\begin{align*}
\%\text{if (Dist > 12)} \\
\%\quad \text{InstantSource} &= \text{spline(DistanceDehydration,SourceDehydration,Dist);} \\
\%\quad \%\text{else} \\
\%\quad \text{InstantSource} &= \text{SourceDehydration(1);} \\
\%\quad \%\end
\end{align*}
\]

\[
\begin{align*}
\text{SourceTerm} &= \text{dPressureHead + dt*InstantSource;}
\end{align*}
\]
% Set up and solution of Crank-Nicolson equations for a nonuniform grid spacing
H = CrankNicFlowSource(A,m,r,TopHead,dTopHead,SourceTerm,H);

% Update constitutive properties: effective stress, permeability, diffusivity, etc.
[EffectiveStress,Porosity,k,Temp,A,r,DZ2] = ConstitutiveUpdate(...
Lithostatic_seafloor,Porosity,z_dec,dz,m,Depth,StressV,H,SubDepth,EE,...
EffectiveStress_i,Porosity_i,PermIndex,InitialPorosity,Temp,...
dt,DZ2,beta,gamma);

% Updated depth.
   Depth(1) = z_dec;
   for J = 2:m+1
      Depth(J) = Depth(J-1) + DZ2(J-1);
   end
% Dewatering.
   FluidFlux2 = FluidFlux2 + (Depth(end)-Depth_i(end))*v_x;

% Record data every one hundred time steps.
if (mod(w,round(N/round(N/100))) == 0)
   ww = ww + 1;
   DepthC(:,ww) = Depth;
   DistanceC(ww,1) = (Dist/1000);
   EffectiveStressC(:,ww) = EffectiveStress;
   HeadC(:,ww) = H;
   PorosityC(:,ww) = Porosity;
   OverburdenB(ww) = Overburden;
   SubDepthC(ww) = SubDepth;
   [e EffMinDepth] = min(EffectiveStress);
   EffStressMin(ww) = e;
   EffStressMinDepth(ww) = Depth(EffMinDepth);
   z_Dec1(ww) = z_dec + SubDepth;
   z_Dec2(ww) = SubDepth + Depth(EffMinDepth);
   SourcePressure(ww,1) = dPressureHead/(dt*Depth(end));
   FluidFluxC(ww,1) = FluidFlux2;
end
% Record Data at the location of Site 1174 from the trench.
if (1799.8 <= Dist) && (Dist <= 1800.2)
   HeadODP(:,1) = H;
   DepthODP(:,1) = Depth + SubDepth;
   DistanceODP(:,1) = Dist./1000;
   EffectiveStressODP(:,1) = EffectiveStress./1000000;
   OverburdenODP(:,1) = Overburden./1000000;
end
PorosityODP(:,1) = Porosity;

% Record Data at the location of Site 808 from the trench.
elseif (3399.6 <= Dist) && (Dist <= 3400.4)
    HeadODP(:,2) = H;
    DepthODP(:,2) = Depth + SubDepth;
    DistanceODP(:,2) = Dist./1000;
    EffectiveStressODP(:,2) = EffectiveStress./1000000;
    OverburdenODP(:,2) = Overburden./1000000;
    PorosityODP(:,2) = Porosity;
end
end
function [Lithostatic_seafhr,Lithostatic,Porosity] = Initial1173(z_dec, dz, m, Depth, Depth_seafhr)

%First compute the lithostat at Site 1173 referenced to the seafloor.
%One
Lithostatic = 9.81*(2650.*Depth_seafhr + (2650-1024)*... 
(0.76749/0.001112).*(exp(-0.001112.*Depth_seafhr) - 1));

Hydrostatic = 9.81*1024*Depth_seafhr;
EffectiveStress = (Lithostatic - Hydrostatic);

%Porosity = 0.65627*exp(-0.00000011452.*EffectiveStress);
C = -(0.001112/(9.81*(2650-1024))).*EffectiveStress + log(0.76749) - 0.76749;
Porosity = -lambertw(0,-exp(C));

Lithostatic_seafhr = Lithostatic;
Porosity_seafhr = Porosity;

%Second, compute the lithostat at Site 1173 referenced to the decollement depth.
%One
Lithostatic = 9.81*(2650.*Depth + (2650-1024)*... 
(0.76749/0.001112).*(exp(-0.001112.*Depth) - 1));

Hydrostatic = 9.81*1024*Depth;
EffectiveStress = (Lithostatic - Hydrostatic);

%Porosity = 0.65627*exp(-0.00000011452.*EffectiveStress);
C = -(0.001112/(9.81*(2650-1024))).*EffectiveStress + log(0.76749) - 0.76749;
Porosity = -lambertw(0,-exp(C));

%Two
Lithostatic(1,1) = Lithostatic_seafhr(z_dec/dz+1);
for W = 1:20
    BulkDensity = 2650 - (2650-1024).*Porosity;
    for i = 2:m+1
        Lithostatic(i,1) = 9.81*(Depth(i) - Depth(i-1))*BulkDensity(i)... 
        + Lithostatic(i-1);
    end
    EffectiveStress = (Lithostatic - Hydrostatic);
    %Porosity = 0.65627*exp(-0.00000011452.*EffectiveStress);
    C = -(0.001112/(9.81*(2650-1024))).*EffectiveStress + log(0.76749) - 0.76749;
    Porosity = -lambertw(0,-exp(C));
end
%This file is the loading program for one dimensional fluid flow at Nankai.

function [Dist,SubDepth,Overburden,StressV,dPressureHead,TopHead,...
    dTopHead,v_x] = NankaiLoading_1D(Dist,DistanceSeismic,Alpha2000,...
    v_plate,betaT,SubDepth,z_dec,dt,Overburden,StressV,TopHead,TopHead_0)

%Compute wedge geometry based on seismic data.
    if (Dist > 3400) && (Dist < 20000)
        [deltaDist, I] = min(abs(DistanceSeismic-Dist./1000));
        if Dist >= DistanceSeismic(I)
            minDist = [DistanceSeismic(I);DistanceSeismic(I+1)];
            minAlpha = [Alpha2000(I);Alpha2000(I+1)];
        else
            minDist = [DistanceSeismic(I-1);DistanceSeismic(I)];
            minAlpha = [Alpha2000(I-1);Alpha2000(I)];
        end
        alphaT = spline(minDist,minAlpha,Dist./1000)*(pi/180);
    elseif (Dist > 20000) && (Dist <= 28550)
        alphaT = 0.0175;
    elseif (Dist > 28550) && (Dist <= 37270)
        alphaT = 0.1249;
    else
        alphaT = 0.0247;
    end
    v_z = v_plate*sin(alphaT+betaT)/cos(alphaT);
    v_x = v_plate*cos(betaT);

%Burial rates calculated to account for turbidite deposition.
    if (Dist < 0)
        v_z = 3.35*10^-11; %v_plate = 4 cm/yr
        v_z = 5.4467e-11;
        v_x = v_plate;
    elseif (Dist >= 0) && (Dist <= 1800)
        v_z = (840-696)/(1800/v_plate*cos(betaT));
        v_x = v_plate*cos(betaT);
    elseif (Dist >= 1800) && (Dist <= 3400)
        v_z = (960-840)/(1600/v_plate*cos(betaT));
        v_x = v_plate*cos(betaT);
    end

%Update current location and depth of underthrust column.
dDist = v_x*dt;
Dist = Dist + dDist;
dSubDepth = v_z*dt;
SubDepth = SubDepth + dSubDepth;

%Integrate bulk density to calculate total overburden to to overlying wedge
%and the resulting pressure added to the underthrust column.

BulkDensity_L = 2650 - 0.99.*exp(-0.0024.*(SubDepth+z_dec)).*(2650-1024);
dSigmaV = 9.81*BulkDensity_L*dSubDepth;
Overburden = Overburden + dSigmaV;
StressV = StressV + dSigmaV;
dPressureHead = (dSigmaV - 9.81*1024*dSubDepth)/(1024*9.81);
dTopHead = TopHead_0*dPressureHead;
TopHead = TopHead + dTopHead;
%This CrankNicFlow accounts for the harmonic mean of the transmissivity. As well as source terms.

function H = CrankNicFlowSource(A,m,r,TopHead,dTopHead,SourceTerm,H)

    a_0 = zeros(m,1);
    a_left = zeros(m-1,1);
    a_right = zeros(m-1,1);
    B = zeros(m,1);

%Crank-Nicolson matrix coefficients.
    for j = 1:m-1
        a_0(j,1) = 8/((A(j)+A(j+1))*(A(j+1)+A(j+2)));
    end
    a_0(m,1) = 2*(A(m-1)+3*(A(m)))/((A(m)+A(m+1))*(A(m-1)+2*A(m)+A(m+1)));

    a_leftTop = 8/((A(1)+A(2))*(A(1)+2*A(2)+A(3)));
    for j = 1:m-2
        a_left(j,1) = 8/((A(j+1)+A(j+2))*(A(j+1)+2*A(j+2)+A(j+3)));
    end
    a_left(m-1,1) = 2*(A(m-1)+2*A(m)-A(m+1))/((A(m-1)+A(m))*(A(m)+A(m+1)));

    for j = 1:m-1
        a_right(j,1) = 8/((A(j+1)+A(j+2))*(A(j)+2*A(j+1)+A(j+2)));
    end

%Crank-Nicolson matrix for non-uniform grid.
    F = diag(2+r(1:m).*a_0) + diag(-r(1:m-1).*a_right,1) +... 
        diag(-r(2:m).*a_left,-1);

%No flow boundary.
    a_0B = 2*(A(m-1)+3*(A(m)))/((A(m)+A(m+1))*(A(m-1)+2*A(m)+A(m+1)));
    a_left1 = 2*(A(m-1)+2*A(m)-A(m+1))/((A(m-1)+A(m))*(A(m)+A(m+1)));
    a_left2 = 2*(A(m)-A(m+1))/((A(m-1)+A(m))*(A(m-1)+2*A(m)+A(m+1)));

    F(m,m) = A(m)+r(m)*a_0B;
    F(m,m-1) = -r(m)*a_left1;
    F(m,m-2) = r(m)*a_left2;

%Solution vector.
%Top node.
    B(1) = r(1)*a_leftTop(1)*(2*H(1) + dTopHead) + (2-r(1)*a_0(1))*H(2)...
        + r(1)*a_right(1)*H(3) + 2*SourceTerm;
%Interior nodes.
   for I = 2:m-1
       B(I) = r(I)*a_left(I-1)*H(I) + (2-r(I)*a_0(I))*H(I+1)...
           + r(I)*a_right(I)*H(I+2) + 2*SourceTerm;
   end
%Bottom node.
   B(m) = (A(m+1)-r(m)*a_0B)*H(m+1) + r(m)*a_left(m-1)*H(m) - ...
       r(m)*a_left2*H(m-1) + SourceTerm;

%Solve matrix equation.
   H = F\B;
   H = [TopHead;H];
function [EffectiveStress,Porosity,k,Temp,A,r,DZ2] = ConstitutiveUpdate(...
    Lithostatic_seaflr,Porosity,z_dec,dz,m,Depth,StressV,H,SubDepth,EE,...
    EffectiveStress_i,Porosity_i,PermIndex,InitialPorosity,Temp,...
    dt,DZ2,beta,gamma)

%Calculate bulk density and lithostat within the underthrust column and the %resulting effective stress due to the updated pressure.
    BulkDensity = 2650 - (2650-1024).*Porosity;
    Lithostatic(1,1) = Lithostatic_seaflr(z_dec/dz+1);
    for i = 2:m+1
        Lithostatic(i,1) = 9.81*(Depth(i) - Depth(i-1))*BulkDensity(i)...        + Lithostatic(i-1);
    end
    Lithostatic = Lithostatic + StressV;
    PorePressure = 1024*9.81.*(H + Depth + SubDepth);
    EffectiveStress = Lithostatic - PorePressure;

%Calculate porosity based on derived function.
    C = -(0.001112/(9.81*(2650-1024))).*EffectiveStress + log(0.76749) - 0.76749;
    Porosity = -lambertw(0,-exp(C));
    %Porosity = 0.65627*exp(-0.00000011452.*EffectiveStress);
    %Patch to prevent the column from expanding, which might not work.
    for k = 1:EE
        if (EffectiveStress(k) - EffectiveStress_i(k) < 0)
            Porosity(k) = Porosity_i(k);
        end
    end

%Hydraulic properties.
%Experimentally derived permeability relations
    if (PermIndex == -1)
        %low 36X
        k = 10^(-3.0523/0.1457)*10.^((Porosity./0.1457));
    elseif (PermIndex == 0)
        %mid
        k = 10^(-2.9771/0.1457)*10.^((Porosity./0.1457));
    elseif (PermIndex == 1)
        %high
        k = 10^(-2.9019/0.1457)*10.^((Porosity./0.1457));
    elseif (PermIndex == -2)
        %LowLow, non fit to experimental data.
    end

%Update dynamic viscosity based on empirically as a function of temperature.
\[ Temp = Temp + \frac{110}{(1000000 \times 365 \times 24 \times 3600)} \times dt; \]
\[ mu = (239.4 \times 10^{-7}) \times 10^{\frac{248.37}{Temp+133.15}}; \]
%Calculate volumetric compressibility of solid matrix (alpha) and update %diffusivity.
\[ alpha = \frac{(Porosity \times (1-Porosity)^2)}{(0.001112/(9.81 \times (2650-1035)))}; \]
\[ Diffusivity = \frac{k \times (gamma/mu)}{(1024 \times 9.81 \times (alpha + Porosity \times beta))}; \]

%Calculate current size of each node.
\[ DZ1 = \frac{(1-InitialPorosity) \times dz}{1-Porosity}; \]
%Calculate spacing between each node.
\[
\text{for } j = 1:m
\]
\[ DZ2(j) = 0.5 \times (DZ1(j)+DZ1(j+1)); \]
\text{end}
%Update compression coefficients needed for Crank-Nicolson equations.
\[ A = \frac{DZ1}{dz}; \]
%Calculate effective diffusivity between adjacent nodes.
\[
\text{for } q = 1:m
\]
\[ \text{DiffusivityEffective}(q,1) = 2 \times DZ2(q) \times \text{Diffusivity}(q) \times \text{Diffusivity}(q+1) / \]
\[ (DZ1(q+1) \times \text{Diffusivity}(q)+DZ1(q) \times \text{Diffusivity}(q+1)); \]
\text{end}
%Second order term in the diffusion equation.
\[ r = \text{DiffusivityEffective} \times (dt/dz^2); \]