Thermal Consolidation with Chemical Dehydration Reactions: Pore Pressure Generation in the Slow Slip Region of Subduction Zones

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ABSTRACT

Slow slip and tremor in subduction zones take place where there is abundant evidence for elevated, near lithostatic pore pressures along the plate interface. In Japan and Cascadia, these depths (∼30-45 km) are such that the main source of fluids must be attributed to chemical dehydration reactions. Here we model the condsolidation of low porosity (∼5%) oceanic crust subducting through the slow slip and tremor zone, in the presence of pressure and temperature-dependent dehydration reactions. We use parameters consistent with the geometry of the Cascadia subduction margin, and bulk rock permeabilities in the range $10^{-25} \leq k_0 \leq 10^{-21}$ m^2. The generation of pore pressures in excess of lithostatic values, and hence negative effective stresses, is a robust feature of our simulations. These results indicate that hydraulic fracturing likely occurs at relevant depths, and have implications for the generation mechanism of non-volcanic tremor in subduction zones.

INTRODUCTION

In subduction zones, fluids escaping from down-going oceanic crust and sediment play an important role in governing the mode of fault behavior (e.g. seismic, creeping, slow slip) by controlling the effective stress along the plate interface. Slow slip and related nonvolcanic tremor occur at depths where the main source of fluids to the plate interface must be attributed to chemical dehydration reactions in the subducting fault material and underlying oceanic crust, rather than from porosity loss due to compaction (e.g. *Obara*, 2002; *Shelly et al.*, 2006, *Liu and Rice*, 2007; *Peacock*, 2009; *Audet et al.*, 2009; *Fagereng and Diener*, 2011). While oceanic sediments may have porosities of ∼50% near the trench, by ∼10 km depth the porosity of subducted sediments is reduced by an order of magnitude, to the point where mechanical compaction is no longer a significant fluid source (*Moore and Vrolijk*, 1992). Thus, the role of chemical dehydration reactions as a source of overpressures is critical.

Multiple lines of evidence indicate that the pore pressures along subduction plate interfaces are near lithostatic at depths where slow slip and tremor are observed

(*Kodaira et al.*, 2004). Several studies have argued for the triggering of slow slip by small stress perturbations from climatic loading, a mechanism that would require a low effective stress (*Shen et al.*, 2005; *Lowry*, 2006). Similarly, other studies have found that tremor is sensitive to stress changes induced by tidal loading and passing surface waves (e.g. *Rubinstein et al.*, 2008). Observations of anomalously high V_p/V_s ratios also support the presence of high pore pressures (*Shelly et al.*,2006; *Audet et al.*, 2009). Moreover, fault mechanics models that reproduce slow-slip behavior seem to require high pore pressures as well (e.g. *Liu and Rice*, 2007; *Segall et al.*, 2010; *Skarbek et al.*, 2012).

To maintain near-lithostatic pore pressures at relevant depths, permeabilities must be relatively low given estimated rates of fluid release due to metamorphic dehydration reactions (*Audet et al.*, 2009; *Peacock*, 2009; *Peacock et al.*, 2011). As an example, it is instructive to consider conditions along the Cascadia subduction margin, where slow slip and tremor occur at depths of $\sim$35 to 45 km. At these depths, *Hyndman and Peacock* (2003) estimate a fluid production rate due to dehydration of 10^{-4} $\mathrm{m}^3/(\mathrm{m}^2\mathrm{yr})$. Using this fluid production rate along with Darcy's law, *Audet et al.* (2009) suggest that the plate interface acts as a low permeability seal, with permeability values of 5×10^{-25} to 5×10^{-22} m^2. *Peacock et al.* (2011) perform a similar calculation and estimate a permeability of 10^{-24} to 10^{-21} m^2, assuming a fluid production rate twice that obtained by *Hyndman and Peacock* (2003). *Peacock et al.* (2011) also point out that high pore pressure could be maintained if the entire layer of subducted oceanic crust has a low permeability, rather than just the plate interface. In this case, he estimates that the subducted crust has a permeability of $< 3 \times 10^{-20}$ m^2, corresponding to crystalline rocks with a fluid filled porosity of 2.7% to 4.0%, in which the pore pressure is nearly lithostatic (*Peacock et al.*, 2011).

Here, we use a model for consolidation of porous media in the presence of pressure and temperature-dependent dehydration reactions, to examine the hydrologic and mechanical properties of subducting oceanic crust in the slow-slip region. While it seems well established that fluids play a first-order role, questions remain as to the failure mechanism involved in producing slow slip and tremor. Models generally suggest that slow slip and tremor occur either as a frictional process where rupture of a through-going fault takes place at aseismic slip speeds, or as a result of fluid migration and fracture generation (see *Rubinstein et al.*, 2010 and references therein). We consider fluid flow through the entire subducting layer and use parameters consistent with the Cascadia subduction margin to examine the evolution of pore pressure. Our results predict that pressures significantly greater than lithostatic are generated under a broad range of conditions; this may have implications for hydrofracturing and tremor generation.

MODEL OVERVIEW

We simulate the evolution of pore pressure due to progressive burial and chemical dehydration reactions in a vertical column of subducting oceanic crust. We include dehydration reactions explicitly as a fluid source based on published thermodynamic simulations relevant to the Cascadia subduction zone. Accordingly, the concentration of bound fluid within the solid constituent $c_s = c_s(\sigma, T)$ is treated as a known function of stress σ and temperature T. *Fagereng and Diener* (2011) have shown that for relevant depths in Cascadia, c_s is mainly controlled by water release due to the breakdown of chlorite and glaucophane to form hornblende and epidote. Thermodynamic models indicate that $\sim$1 wt% H_2O is released due to these reactions, with the rocks containing $\sim$2 wt% H_2O initially (*Hacker et al.*, 2003; *Peacock*, 2009; *Fagereng and Deiner* (2011). We use the results of *Fagereng and Deiner* (2011) to estimate changes in water content, which we accommodate over a narrow range of temperature and pressure conditions ($1\,^\circ$C, $0.7\,$GPa) using $\partial c_s/\partial\sigma = -1.4 \times 10^{-10}$ Pa^{-1} and $\partial c_s/\partial T = -5 \times 10^{-4}$ °C^{-1}. Thus, in our model we control the value of c_s based on the subducting column's location relative to a single boundary in pressure–temperature space. At each point, the pressure is approximated by the total overburden $\sigma = \int g\rho_b \,\mathrm{d}z$, where g is acceleration of gravity and ρ_b is bulk density. For simplicity, we assume that temperature varies linearly with depth within the column, and that the evolution in temperature T_0 at the top of the column depends on the vertical component of the subduction velocity, according to a fixed temperature gradient of $0.02\,^\circ$C/m (*Peacock*, 2009).

Considering an Eulerian coordinate system for a fluid-filled, porous subducting column, we enforce conservation conditions for total mass, water content, and fluid momentum – the latter, in the form of Darcy's law with a permeability $k(\phi)$ that depends on porosity ϕ. For illustration, we adopt an exponential dependence for these constitutive functions, so that

$$k = k_0 \exp(\gamma\phi) \ , \quad \phi = \phi_0 \exp(-\beta\sigma') \ ,$$

where γ and β are material-dependent parameters that control the diffusivity of the subducting material, and σ' is the effective stress. The inertia of solid and fluid constituents is negligible, and we assume that chemical dehydration reactions do not significantly alter the bulk density. However, fluid release does act as an important source term m_f, of the form

$$m_f = \rho_s \frac{\partial}{\partial t} \left[(1-\phi)c_s\right] \ .$$

Denoting the solid and fluid densities as ρ_s and ρ_f, and the fluid viscosity as μ, we obtain a a single governing equation for the evolution of excess pore pressure u, which

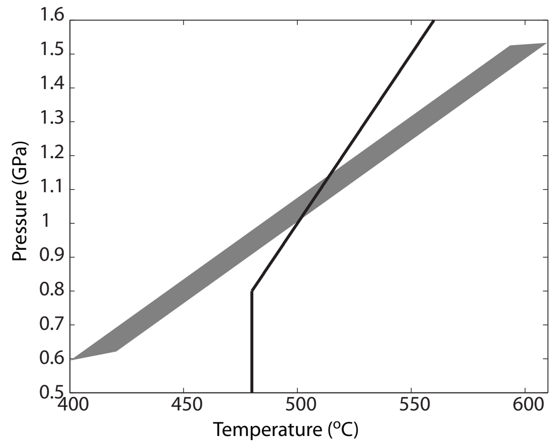

Figure 1. Pressure-temperature space showing the location of the reaction boundary (black line) and the subducting column's path (grey shaded region). The upper (lower) boundary of the column corresponds to the left (right) edge of the shaded region.

satisfies

$$\begin{aligned}\frac{\partial u}{\partial t} &= \left[1-\frac{\rho_s}{\rho_f}\left(c_s-\frac{\partial c_s}{\partial \sigma}\frac{\mathrm{d}\sigma'}{\mathrm{d}\phi}\right)\right]^{-1}\left\{\frac{k(\phi)}{\mu}\frac{\mathrm{d}\sigma'}{\mathrm{d}\phi}\frac{\partial^2 u}{\partial z^2}\right.\\ &+ \frac{1}{\mu}\left[\frac{\mathrm{d}k(\phi)}{\mathrm{d}\phi}-k(\phi)\right]\left(\frac{\partial u}{\partial z}\right)^2+g(\rho_s-\rho_f)\frac{1}{\mu}\left[\frac{\mathrm{d}k(\phi)}{\mathrm{d}\phi}-k(\phi)\right]\frac{\partial u}{\partial z}\\ &+ \left.\frac{\rho_s}{\rho_f}\frac{\partial c_s}{\partial T}\frac{\mathrm{d}\sigma'}{\partial \phi}\frac{\mathrm{d}T}{\mathrm{d}t}\right\}+\frac{\mathrm{d}\sigma_o}{\mathrm{d}t}\,, \qquad (1)\end{aligned}$$

where σ_0 is the lithostatic stress at the top of the column, whose rate of increase is determined by the dip angle and convergence velocity of the subducting plate. Equation (1) is subjected to a constant pressure condition at the upper boundary of the subducting column, where that pressure is set to some fraction of the overburden at any given time. At the column's base, a zero flux condition is applied. Finally, equation (1) is integrated using a fourth-order Runge-Kutta method in MATLAB.

RESULTS AND DISCUSSION

We ran simulations for values of the initial permeability in the range $10^{-25} \leq k_0 \leq 10^{-21}$ m^2 (excluding $k_0 = 10^{-24}$ m^2), covering the scope of estimated permeabilities for subducting material at slow slip depths in Cascadia. For each value of k_0 we set the upper boundary pressure condition to values of 0%, 50%, 75%, 90%, and 100% of the overburden. All other parameters were kept constant throughout the suite of simulations. Each simulation was initiated at a depth of 20 km, within the frictional transition zone at Cascadia (*Burgette et al.*, 2009), with an initial porosity of 5%. Under these conditions, the permeability at any point in the subducting column does not vary substantially from its initial value.

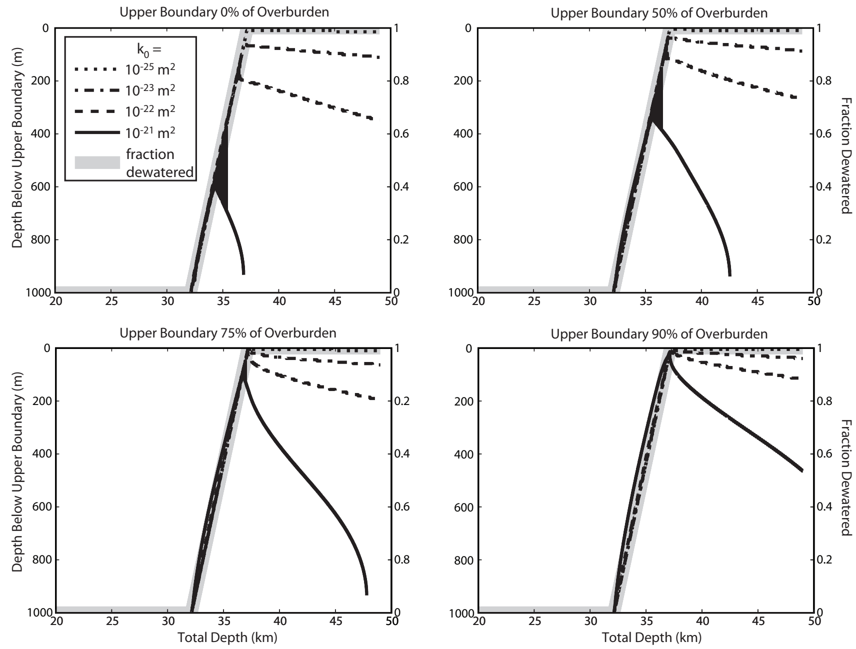

Figure 2. Results for simulations with the upper boundary condition set to 0%, 50%, 75%, and 90% of the total overburden, for the range of permeability k_0 values shown in the legend. Black lines show the minimum depth below the upper boundary to negative effective stress within the subducting column. The grey shaded region shows the fraction of the column that has crossed the reaction boundary and dewatered.

The subducting column's path through the pressure-temperature phase space (grey shaded region) and the location of the dewatering reaction boundary (solid line) are shown in Figure 1. When any node crosses the reaction boundary, its value of c_s is changed from 2 wt% to 1 wt% while the source term is activated. Under these conditions our model commonly predicts the generation of pore pressures in excess of lithostatic. Negative effective stresses are a robust and important feature of these results.

Figure 2 shows the minimum depth at which negative effective stresses are predicted for a range of permeabilities and upper boundary conditions. Below this depth the entire column is in a state of negative effective stress. Each panel in Figure 2 also shows the fraction of the subducting column that has crossed the reaction boundary. Since the temperature increases with depth, the reaction begins at the base of the subducting column and procedes smoothly upward until the entire column has crossed the boundary.

Although not shown, all tested values of k_0 produced negative effective stresses that reach to the upper boundary in simulations with the upper boundary condition set at 100% of the overburden. This is to be expected, since in this case no drainage of excess pressures is allowed. A notable result is that permeabilities $\leq 10^{-21}$ m^2 produce negative effective stresses for all of the boundary conditions. This suggests that if the bulk permeability of the subducting rock is less than 10^{-21} m^2, then hydrofracturing can occur regardless of the permeability at the plate interface. For $k_0 = 10^{-25}$ m^2, negative effective stresses reach to within 5 m of the upper boundary, to within 40 m of the upper boundary for $k_0 = 10^{-23}$ m^2, and to within 100 m for $k_0 = 10^{-22}$ m^2. In simulations with $k_0 = 10^{-21}$ m^2, the negative effective stress front reaches to within 30 – 400 m of the upper boundary before steadily decreasing. In these cases there is sufficient permeability to allow significant drainage of excess pore pressures. The simulations with $k_0 \neq 10^{-21}$ m^2 show similar trends, with the magnitude of the decrease dependent on the value of k_0.

CONCLUSION

The common occurence of negative effective stresses in our simulations suggests the presence of hydraulic fracturing. In these cases the fluid pressure generated due to dehydration reactions is greater than the least principle stress. Thus, hydraulic fractures should form, oriented perpindicular to the least principle stress, which in the simplest scenario would be oriented horizontally, parallel to the strike of the subducting slab. The creation of such fractures would be expected to greatly alter the bulk permeability of the subducting material, ongoing work aims to incorporate this effect into the model presented here. When non-volcanic tremor was discovered it was suggested that tremor radiated as result of dehydration reaction-induced hydraulic fracturing (*Obara*, 2002). Although some models for slow slip and tremor indicate that tremor is produced by frictional slip (e.g. *Ide et al.*, 2007; *Shelly et al.*, 2007), our results indicate that the generation of hyraulic fractures is highly likely, and point to the need for more detailed modeling efforts that incorporate changes to rock permeability due to fracturing, as well as for experimental work to better constrain the constitutive properties of oceanic crustal rocks.

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