Porosity loss within the underthrust sediments of the Nankai accretionary complex: Implications for overpressures

Elizabeth Screaton Department of Geological Sciences, University of Florida, Gainesville, Florida 32611, USA
Demian Saffer Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071-3006, USA
Pierre Henry Département de Géologie, École Normale Supérieure, Paris Cedex 05 75231, France
Sabine Hunze Geowissenschaftliche Gemeinschaftsaufgaben-GGA, Stilleweg 2, 30631 Hannover, Germany
Leg 190 Shipboard Scientific Party*

ABSTRACT

Subduction complexes provide an opportunity to examine the interactions of deformation and fluid flow in an active setting. Ocean Drilling Program Leg 190 investigated the relationship between deformation, physical properties, and fluid flow in the toe of the Nankai Trough accretionary complex. With three sites (two from Leg 190, one from a previous leg) penetrating the décollement zone at various stages of development along the same transect, it is now possible to examine the change in porosity during rapid loading by trench turbidites and subsequent underthrusting. Results indicate inhibited dewatering and probable overpressure development seaward of the frontal thrust. Comparison of a reference site porosity versus depth curve to data from a site located within the protothrust zone indicates an overpressure ratio, λ*, of ~0.42, where λ* = [(pore pressure − hydrostatic pressure)/(lithostatic pressure − hydrostatic pressure)]. These overpressures suggest that the hemipelagic sediments have insufficient permeability for fluid escape to keep pace with the rapid loading by turbidite deposition within the trench. At a site 1.75 km farther arcward, an excess pore pressure ratio of λ* = ~0.47 was estimated, reflecting the additional loading due to recent thickening by the frontal thrust.

Keywords: accretionary prism, Nankai Trough, overpressure, compaction, porosity.

INTRODUCTION

Fluids within subduction complexes play an important role in deformation, geochemical and thermal transport, and the behavior of seismogenic zones. The Nankai subduction complex is characterized by accretion of a thick turbiditic sequence over hemipelagic sediments. Because these hemipelagic sediments appear homogeneous, it has been suggested that variations in pore-fluid pressures near the deformation front control the location of the décollement zone, the plate boundary faults that separate accreted from subducted sediment (Le Pichon et al., 1993).

Porosity data collected at Site 808 during Ocean Drilling Program (ODP) Leg 131 indicated a sharp increase in porosity below the décollement zone. However, without a reference site, it was not possible to distinguish whether the underthrust sediments were overpressured, or whether the downward increase in porosity primarily reflected enhanced dewatering of the overlying accretionary prism due to lateral stresses.

During ODP Leg 190, two additional sites were drilled through the décollement zone along the same transect as Site 808. Site 1173 was located seaward of the deformation front to provide information on the properties of incoming sediments. Site 1174 examined the sediments within the protothrust zone, seaward of Site 808. In this study we examine the evolution of porosity near the toe of the accretionary prism and investigate the implications for pore pressures.

BACKGROUND

The Nankai accretionary complex is forming where the Shikoku Basin on the Philippine Sea plate subducts under the southwest Japan arc on the Eurasian plate (Fig. 1) at a rate of 4 cm/yr (Seno et al., 1993). This study focuses on the Muroto transect (Fig. 1). Along this transect, the prism toe has a taper angle of 4°–5° (Shipboard Scientific Party, 2001). The low taper angle along the Muroto transect has been inferred to represent either high décollement pore pressures or low intrinsic décollement strength.

Previous drilling on the Muroto transect during ODP Leg 131 consisted of a single site, Site 808. This site penetrated the frontal thrust and the décollement zone and reached oceanic basement at 1290 m below seafloor (mbsf) (Shipboard Scientific Party, 1991). The upper 560 m are primarily turbidites, deposited rapidly in the trench. Below the turbidites, sedi-

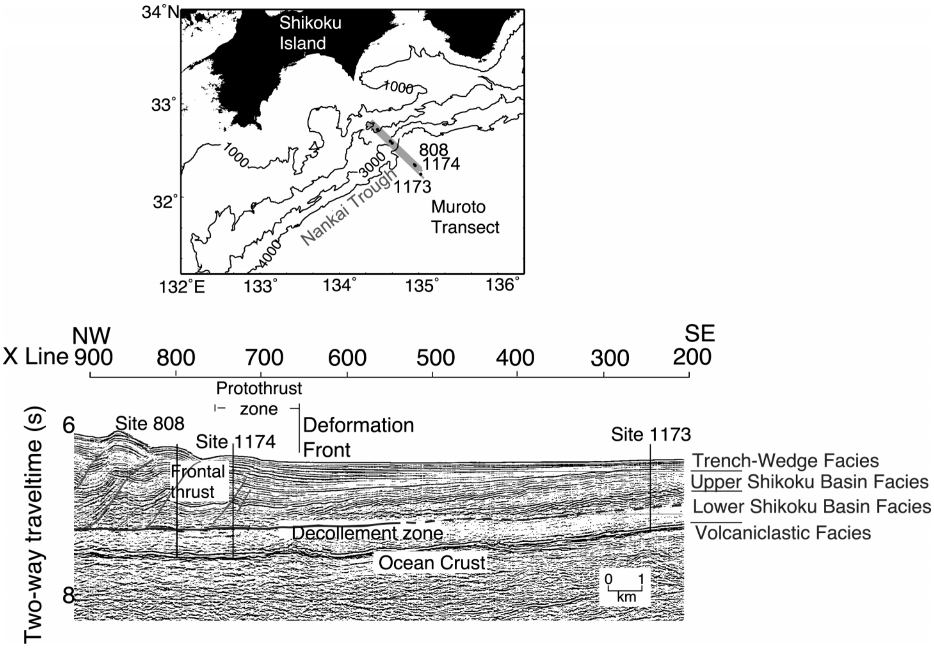

Figure 1. Location map and cross section showing drilling sites. Based on bathymetric and seismic reflection data from Moore et al. (2001).

*Gregory F. Moore, Asahiko Taira, Adam Klaus, Keir Becker, Luann Becker, Babette Boeckel, Barry A. Cragg, Allison Dean, Christopher L. Fergusson, Satoshi Hirano, Toshio Hisamitsu, Miriam Kastner, Alex J. Maltman, Julia K. Morgan, Yuki Murakami, Mario Sanchez-Gomez, David C. Smith, Arthur J. Spivack, Joan Steurer, Harold J. Tobin, Kohtaro Ujiie, Michael B. Underwood, Moyra Wilson.

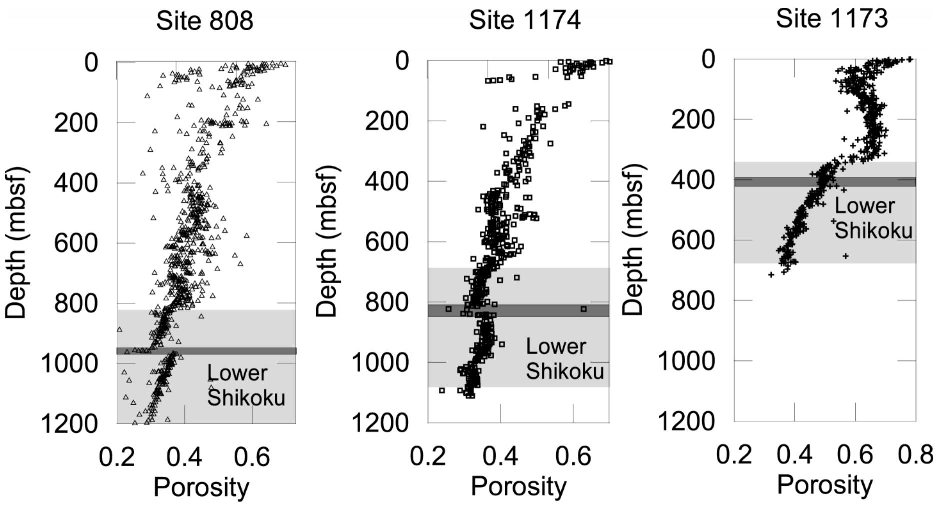

Figure 2. Porosity profiles of Sites 808 (triangles), 1174 (squares), and 1173 (plus signs). Light shading shows lower Shikoku Basin facies. Darker shading shows décollement zone. At Site 1173, this depth is chosen at age-equivalent level of Site 1174 décollement zone. For consistency with Leg 190 data, Site 808 porosities were based on measured wet bulk densities, dry bulk densities, and dry volume. Previously reported porosities (Shipboard Scientific Party, 1991) used wet volume estimates.

ments of the upper and lower Shikoku Basin facies are primarily hemipelagic muds.

At Site 808, the frontal thrust was observed between 357 and 395 mbsf and repeats ~145 m of turbidites (Shipboard Scientific Party, 1991). On the basis of reversals in geochemical profiles, recent movement (<20 ka) was inferred for the fault (You et al., 1993; Kastner et al., 1993). The décollement zone at Site 808 was observed as a fractured zone between 945 and 964 mbsf, within the apparently monotonous hemipelagic sediments of the lower Shikoku Basin facies.

During ODP Leg 190, Site 1174 was drilled ~1.75 km seaward of Site 808 (~1.5 km landward of the deformation front). This site was selected to penetrate the décollement within the protothrust zone. Drilling penetrated 431 m of trench turbidites before entering a transitional horizon and hemipelagic muds of the upper and lower Shikoku Basin facies. The décollement zone was identified between 808 and 840 mbsf, within the lower Shikoku Basin facies (Shipboard Scientific Party, 2001).

To provide an undeformed reference section of the incoming sedimentary sequence, Site 1173 was drilled 11 km seaward of the deformation front. Because of the distance seaward of the trench, a much thinner (102 m) sandy turbidite layer was penetrated. The upper and lower Shikoku Basin facies extend to 688 mbsf. The age equivalent of the Site 1174 décollement zone occurs at 390–420 mbsf within the lower Shikoku Basin facies (Shipboard Scientific Party, 2001).

At the reference site (Site 1173), there is a slight variation in porosity around the age equivalent of the décollement zone (Fig. 2). In general, however, Site 1173 porosities decrease smoothly through the lower Shikoku Basin facies. Site 1174 exhibits a porosity increase across the décollement zone, from ~0.33 at the base of the accretionary prism to ~0.36 within the underthrust sediments. The porosities from Site 808 indicate a greater increase across the décollement zone, from ~0.31 at the base of the accretionary prism to ~0.37 at the top of the underthrust sequence. The lesser porosities directly beneath the décollement at Site 1174 than at Site 808 indicate that there are some lateral variations in the initial sediment properties or their drainage and compaction history. However, average porosities of the underthrust (or equivalent) sediments of the lower Shikoku Basin facies decrease from 0.42 at Site 1173 to 0.34 and 0.33 at Sites 1174 and 808, respectively.

METHODS

We focus our comparison of porosities at Sites 1173, 1174, and 808 on the lower Shikoku Basin facies, in which the décollement zone has propagated. The rate of porosity loss within the underthrust sediments is controlled by the rate at which pore fluid can escape relative to the rate of loading. Initially, during loading of unconsolidated, highly compressible sediments, the overburden weight is transmitted primarily to the pore-fluid pressure. The elevated pore pressures drive fluid expulsion, transferring the load to the sediment framework and reducing porosity.

The porosity data provide a means to estimate the volume of pore fluid incoming at Site 1173 and the volumes of fluid expelled between Site 1173 and Sites 1174 and 808. Assuming that solid volume is constant, the volume change, dV, is related to the porosity change, dn, by

$$dV = \frac{dn}{(1 - n)}V. \tag{1}$$

This approximation assumes that Site 1173 porosities provide a reasonable proxy for conditions of the Site 1174 and 808 sediments when they were seaward of the trench and that the original lithology and sediment thickness were generally uniform between these sites. Shipboard description did not note any significant variation in lower Shikoku Basin facies lithology or its degree of cementation between the sites (Shipboard Scientific Party, 2001). The comparison will be affected by errors in laboratory-measured porosity due to rebound effects or due to smectite dehydration during oven drying of samples, if these errors do not affect the sites' samples equally.

Comparison of porosity data also provides a means to estimate overpressures at Sites 1174 and 808. The total stress, σ_t, is partitioned between the pore-fluid pressure, P, and the effective stress, σ_e, carried by the matrix:

$$\sigma_t = \sigma_e + P. \tag{2}$$

For underthrust sediments and the reference site, σ_t is assumed to be equal to the weight of overlying sediments or lithostatic pressure, P_L. This assumption requires that the compaction of the underthrust sediments at Sites 1174 and 808 is essentially vertical, as has been suggested for underthrust sediments in this and other accretionary complexes (Bruckmann et al., 1993; Housen et al., 1996; Saffer et al., 2000). We subtract out the hydrostatic pressure, P_H,

$$P_L^* = \sigma_e + P^*, \tag{3}$$

where the excess lithostatic pressure is $P_L^* = P_L - P_H$ and the excess pore pressure is $P^* = P - P_H$. We assume that porosity will decrease exponentially with depth as is generally observed for sediments (e.g., Athy, 1930). We fit a curve to Site 1173 porosity data from the lower Shikoku Basin facies (Fig. 3):

$$n = 0.77 \times \exp(-0.0011 \times z), \tag{4}$$

where z = depth below seafloor.

Under conditions of hydrostatic pore pressure at Site 1173, $P_L^* = \sigma_e$, allowing the porosity versus depth relationship from Site 1173 to be used to establish a porosity versus effective stress relationship. This curve was compared to porosity versus excess lithostatic pressure for Sites 1174 and 808 (Fig. 4). The excess lithostatic pressure, P_L^*, at those sites was calculated from the bulk-density profile for each site. Because no core was recovered from the turbidites between ~55 and 143 mbsf at Site 1174, bulk-density data from Site 808 were used for these depths at Site 1174.

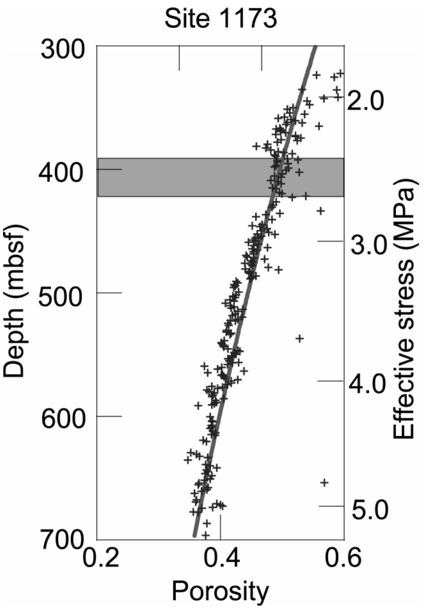

Figure 3. Exponential porosity vs. depth (meters below seafloor, mbsf) relationship fitted to Site 1173 porosities (plus signs). Shading indicates décollement zone. Right axis indicates effective stress calculated from exponential porosity vs. depth relationship and assuming hydrostatic pore pressures.

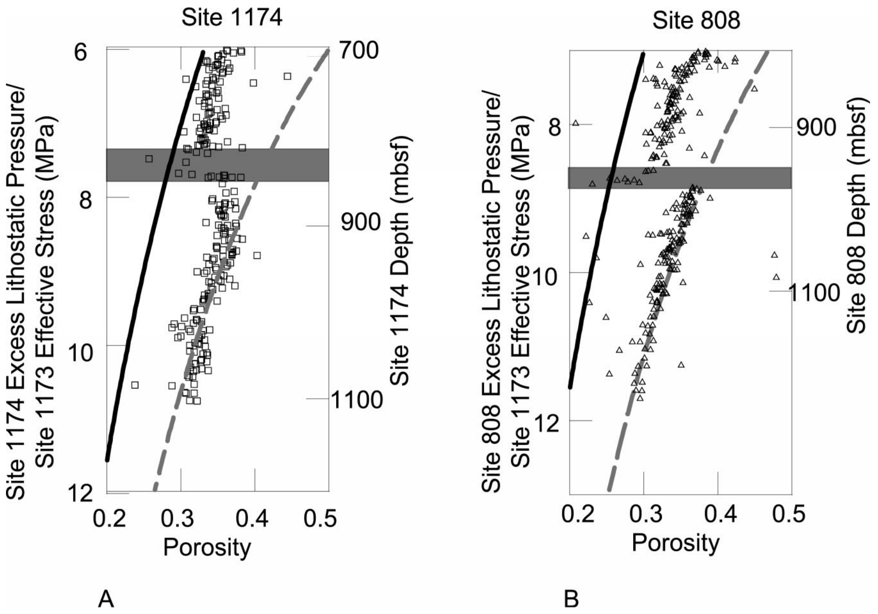

Figure 4. A. Comparison of Site 1174 porosities (squares) as function of excess lithostatic pressure to Site 1173 porosity vs. effective stress relationship (solid curve). Dashed curve shows Site 1173 porosity vs. effective stress relationship with 3.6 MPa shift. B. Comparison of Site 808 porosities (squares) as function of excess lithostatic pressure to Site 1173 porosity vs. effective stress relationship (solid curve). Dashed curve shows Site 1173 porosity vs. effective stress relationship with 4.2 MPa shift. Shading indicates décollement zone.

If excess pore-fluid pressures exist at Site 1173, overpressures at Sites 1174 and 808 will be underestimated. We note that Site 1173 underwent turbidite deposition under high sedimentation rates of 450–650 m/m.y. (Shipboard Scientific Party, 2001). Therefore, overpressures are possible, although their magnitude will be limited because the total turbidite thickness is only ~100 m. Lower sedimentation rates of 72–77 and 27–37 m/m.y. were determined for the upper and lower Shikoku Basin facies, respectively (Shipboard Scientific Party, 2001).

The use of the Site 1173 porosity curve to analyze overpressures assumes that the relationship observed at Site 1173 continues to depths equivalent to those at Sites 1174 and 808. As with the estimate of fluid-expulsion rates, the overpressure estimates will be affected by discrepancies between laboratory and in situ porosity, if these offsets are not consistent between sites.

Error will also be introduced if there is lateral inflow of fluid from deeper in the underthrust sediments. Saffer and Bekins (1999) suggested that budgetary constraints require that flow be episodic or spatially focused. Because porosity loss is only partially reversible, episodic or recent pressure increases due to lateral fluid influx would not be fully reflected in the porosity profile. As a result, pore pressures could be higher than those estimated based on porosity profiles, and accurate determination will require in situ measurements.

RESULTS

For a convergence rate of 0.04 m/yr, the total fluid volume entering the system at Site 1173 in the stratigraphic equivalent of the underthrust sediments is 4.5 $m^3 \cdot yr^{-1} \cdot m^{-1}$ along strike. Between Sites 1173 and 1174, the average porosity of the underthrust (or proto-underthrust) sediment decreases from 0.42 to 0.34, suggesting expulsion of 0.12 m^3 per unit bulk volume due to porosity loss, or 1.3 $m^3 \cdot yr^{-1} \cdot m^{-1}$ along strike for the entire underthrust thickness of the lower Shikoku Basin facies. Between Site 1173 and 808, the average porosity decreases from 0.42 to 0.33, indicating expulsion of 0.13 m^3 per unit bulk volume of sediments due to porosity loss, or 1.4 $m^3 \cdot yr^{-1} \cdot m^{-1}$ along strike for the entire underthrust thickness of the lower Shikoku Basin facies.

Despite this fluid expulsion, porosities at Sites 1174 and 808 indicate an underconsolidation relative to the relationship shown by the Site 1173 profile (Fig. 4). Directly below the décollement zone at Site 1174, porosities are ~0.08 higher than those of the adjusted Site 1173 curve, and this difference increases slightly as P_L* approaches 8.6 MPa (920 mbsf). At Site 808, porosities of the lower Shikoku Basin facies exceed the Site 1173 relationship by ~0.10.

By shifting the reference site porosity versus effective stress curve to match the porosity versus excess lithostatic pressure data from Sites 1174 and 808, we can approximate the magnitude of overpressures within the underthrust lower Shikoku Basin sediments by the magnitude of the shift. The pore pressure ratio, λ*, was calculated as P^*/P_L^*. The match between the Site 1173 porosity–effective stress relationship and the Site 1174 porosity–excess lithostatic pressure data for $P_L^* > 8.6$ MPa is good if we shift the Site 1173 relationship by 3.6 MPa, yielding a λ* of ~0.42 (Fig. 4A). For $P_L^* < 8.6$ MPa, the porosity points fall below the curve, suggesting some upward drainage. For Site 808, the shift due to excess pore pressures is 4.2 MPa (Fig. 4B). At the top of the underthrust sequence, where P_L* is 8.9 MPa (970 mbsf), λ* is ~0.47.

Porosities above the décollement zone at Sites 808 and 1174 also indicate overpressures (Fig. 4). Because accreted sediments have been subjected to lateral compression in addition to overburden, an analysis based on reference-site porosities would underestimate the excess fluid pressures.

DISCUSSION

Comparison of porosity data from the lower Shikoku Basin sequence at Sites 1174 and 808 to those at the reference Site 1173 indicates that although some fluid is expelled during trench sedimentation and initial prism development, pore pressures are rapidly elevated near the toe of the accretionary complex. Below the décollement zone at Site 1174, sediments are underconsolidated, with an estimated overpressure ratio λ* of 0.42. A likely cause of the overpressures is rapid loading by trench turbidites. At a convergence rate of 4 cm/yr, transit from the location of Site 1173 to Site 1174 would have taken 0.3 m.y. Between these sites, the thickness of turbidites increases from ~100 to ~430 m (Shipboard Scientific Party, 2001), yielding an extremely high average sedimentation rate of ~1100 m/m.y.

Comparison of average porosity values of the sediments at Sites 1173 and 1174 indicates fluid expulsion of ~12% of the initial bulk volume (~28% of the initial fluid volume) during underthrusting. Although some fluid has escaped, the estimated overpressure of 3.6 MPa ($\lambda^* = 0.42$) indicates that the sediments have insufficient permeability for fluid expulsion to keep up with loading. This evidence of overpressures supports the suggestion by Le Pichon et al. (1993) that a minimum in effective stress results at depth below the base of the turbidites because of their rapid deposition. Le Pichon et al. (1993) further suggested that this minimum may control the depth of décollement development and, as a result, the amount of sediment accreted.

At Site 808, excess pore pressures average 4.2 MPa ($\lambda^* = \sim 0.47$) in the underthrust sediments. In addition to rapid turbidite loading, the section at Site 808 has thickened because of movement along the frontal thrust within the past ~20 k.y. In accordance with the greater loading rate, estimated overpressures at Site 808 are greater than those at Site 1174. The magnitude of overpressure within the hemipelagic sediments at Site 808 is consistent with one-dimensional modeling by Le Pichon and Henry (1992). In the model, representative sedimentation rates, compressibilities, and permeabilities were assigned to the hemipelagic and turbiditic sediments. Results indicated λ^* values of ~0.5 in the underthrust sediments, suggesting that sedimentation rates are sufficiently high to explain the overpressures estimated in this investigation without requiring input of additional fluids from deeper in the accretionary complex.

If sediments at Site 1173 are already underconsolidated due to ~102 m of rapid turbidite deposition, overpressures at Sites 1174 and 808 will be higher than estimated in this investigation. An approximate upper bound of Site 1173 overpressures can be made by assuming that the excess pore fluid pressures at that site are equal to the entire excess lithostatic pressure applied by the 102 m of turbidities, or ~0.6 MPa. More detailed modeling of overpressure development at Sites 1173 and 1174 will be possible following laboratory permeability and consolidation tests on core samples.

The observed porosity discontinuity at the décollement zone of Sites 1174 and 808 likely reflects a change in total stress crossing the décollement. Lateral stresses within the accretionary prism would cause a greater total stress above the décollement than below (Morgan and Karig, 1995). In addition, if the décollement provides a barrier to vertical fluid flow at the top of the underthrust sediment, there may be a steep pore-pressure gradient across the décollement zone. Permeability measurements of clay-rich sediments during shearing indicate a significant permeability reduction perpendicular to the direction of shearing (Brown et al., 1994).

The question remains as to the fate of the fluids trapped within the underthrust sediment. Results from upslope sites drilled during Leg 190 indicate very recent development (younger than 2 Ma) of the 40-km-wide prism toe (Shipboard Scientific Party, 2001), which would further contribute to overpressure development. From the observed rapid development of overpressures at Sites 1174 and 808, it is apparent that intergranular permeability in the lower Shikoku Basin facies is insufficient to allow fluid escape to keep pace with loading. Therefore, it is likely that fluid escape will primarily occur through fractures or other conduits. Ultimately the fluids retained in the underthrust sediments will escape when either the décollement downsteps into these sediments, thrusts coming up from the décollement zone allow fluid expulsion, or pore pressures become sufficient to create hydrofractures.

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