Targeted 3-D prestack depth imaging at Legs 190-196 ODP drill sites (Nankai Trough, Japan)

Patrizia Costa Pisani,[1] Moshe Reshef,[2] and Gregory Moore[1]

Received 25 July 2005; revised 6 September 2005; accepted 19 September 2005; published 25 October 2005.

[1] Target-oriented 3-D prestack depth migration (PSDM), tied to known depths of key reflections at three ODP drill sites in the Nankai Trough, provides an improved representation of the subsurface depths and P-wave velocities around the drill holes. The resulting velocity volume is representative of the "in situ" velocities and allows us to extend the 1-D logging and core velocity data from the drill sites to the entire seismic transect. The PSDM velocity gradients closely match those at the drill sites, although the absolute values of the velocity curves are somewhat different. The average PSDM vertical velocity gradient above the décollement decreases from 0.99 s^{-1} seaward of the trench axis to 0.87 s^{-1} landward in the proto-thrust and frontal thrust zone, with a velocity inversion of about 50–150 m/s at the décollement. Below the décollement, the vertical gradient in the underthrusting section decreases from 0.97 s^{-1} in the basin to 0.72 s^{-1} beneath the frontal thrust. The lateral velocity gradient in the underthrusting section between the basin and the deformation front is 0.02 s^{-1}, corresponding to $\sim$10% thinning in the direction of subduction.
Citation: Costa Pisani, P., M. Reshef, and G. Moore (2005), Targeted 3-D prestack depth imaging at Legs 190-196 ODP drill sites (Nankai Trough, Japan), *Geophys. Res. Lett.*, *32*, L20309, doi:10.1029/2005GL024191.

1. Introduction

[2] Integration of core, log and seismic reflection data requires accurate depth images of the reflection data, which in turn requires an excellent knowledge of the seismic interval velocity. Interval velocity estimation based on prestack depth migration (PSDM) can yield geologically meaningful velocities [*Guo and Fagin*, 2002] but additional constraints provided by depth ties to well data are needed to enable accurate velocity modeling at the drill sites. In order to establish better ties between a 3-D seismic reflection data volume and physical properties and logging data collected on ODP Legs 131, 190 and 196 in the Nankai Trough, we conducted a 3-D PSDM imaging study targeted at Sites 808, 1173 and 1174. This study builds on the 3-D prestack time migration performed by *Bangs et al.* [2004] and was designed to provide the basis for a full 3-D PSDM of the entire seaward portion of our data volume.

[1]Department of Geology and Geophysics, University of Hawaii, Honolulu, Hawaii, USA.
[2]Department of Geophysics and Planetary Sciences, Tel Aviv University, Ramat Aviv, Israel.

0094-8276/05/2005GL024191$05.00

2. Background

[3] Our study area is located in the Nankai Trough, the plate boundary where the Philippine Sea plate is subducting beneath the Eurasian plate [*Karig and Angevine*, 1986; *Seno et al.*, 1993]. A joint Japan-U.S. group collected the 3-D seismic reflection survey along 81 lines, each 80 km long, with 100 m spacing between lines. Seismic signals were generated by a tuned array of 14 air guns with a total volume of 70 L (4276 in^3) fired at a 50-m interval and were received by a single 6 km streamer with 240 channels at 25-m group spacing. We sorted the data into 25 m inline $\times$ 50 m crossline common mid-point (CMP) bins before 3-D PSDM [*Moore et al.*, 2001; *Bangs et al.*, 2004].

[4] Site 1173 (Figure 1) is a seaward reference site, Site 1174 is located in the protothrust zone, and Site 808 is above the frontal thrust. The holes all penetrated the décollement (or proto-décollement) and the entire subducting section [*Taira et al.*, 1991; *Moore et al.*, 2001, 2005]. The drilled section consists of Quaternary trench turbidites, Pleistocene trench-to-basin transition facies (TBF), the Upper Shikoku Basin (USBF) and Lower Shikoku Basin (LSBF) hemipelagic facies, volcaniclastic facies (VF) and basalt basement.

[5] Logging data were collected using either wireline logging [*Taira et al.*, 1991; *Moore et al.*, 2001] or logging-while-drilling (LWD) [*Mikada et al.*, 2002; *Goldberg et al.*, 2005]. A vertical seismic profile (VSP) was also acquired in the upper part of Hole 808E [*Moore*, 1993].

3. Velocity Model Building and Updating Procedures

[6] We first generated detailed velocity models at the three drill sites based on the two-ship split-spread velocity profiles of *Stoffa et al.* [1992] with velocities interpolated along interpreted horizons. We applied an iterative "top-down" procedure to refine the velocities at each drill site to fix shallow layers on early iterations, with deeper layers being modified on subsequent iterations. The criteria for the correctness of the updated velocities is based on the assumptions that when the velocity model used for migration is correct, the events in the depth migrated Common Image Gathers (CIGs) should be flat [*Faye and Jeannot*, 1986].

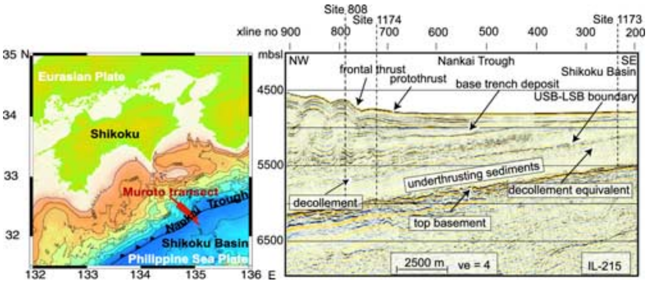

Figure 1. Location map of Muroto Transect and depth section inline 215, showing the main features of the Nankai Trough margin, and the Drill Site positions.

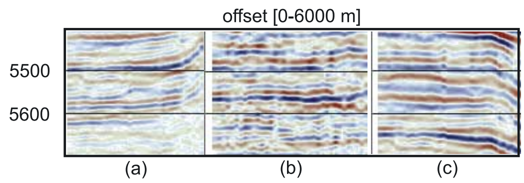

Figure 2. Velocity model sensitivity, calculated at ODP Site 1174 (CMP 734 of inline 215) around the décollment: (a) final velocity model −5%, results in undermigrated reflections; (b) final velocity model, results in correctly migrated reflections; (c) final velocity model +5%, results in overmigrated reflections.

[7] We used ProMAX3D PSDM software based on a Kirchhoff-summation algorithm [*Reshef*, 1991]. The imaging condition of the migration is kinematic and is calculated by a direct solution of the 3-D eikonal equation [*Reshef*, 1991]. This prestack shot migration [*Reshef and Kosloff*, 1986] produces a final image that is the result of summing the contribution of each input trace at all the subsurface image points that comprise the migrated volume. ProMAX3D performs migrations in a target-oriented mode, in which partial 3-D PSDM is based on a travel time grid to allow the use of smaller portions of the prestack dataset, with a drastic decrease in run times.

[8] We modified the starting velocity field based on the depths of first-order features such as the frontal thrust, décollement and top of oceanic crust, as determined at the drill sites for the first PSDM iteration. We updated the velocity model after every iteration, calculating the residual move out corrections (RMO) along picked horizons. We used the RMO values of the depth CIGs to perform horizon-based tomography to update the interval velocity model [*Stork and Clayton*, 1992].

[9] The iterative migrations are run using two different types of CIGs [*Reshef*, 1997, 2001]. In the first type (original-offset gathers), the data are binned with respect to the shot-to-receiver distance and used as input to the RMO and the following tomography processes. In the second type (imaging-offset gathers), the data are binned with respect to the sum of the surface distances from the source to the CIG surface location, and the CIG surface location to the receiver. The maximum offset of the imaging-offset gathers depends on the migration aperture. We performed the analysis on these gathers because of their higher sensitivity to velocity errors compared to the corresponding original-offset gathers. The analysis of the imaging-offset CIGs can also be used to discriminate reflections from dipping versus flat horizons, to emphasize velocity anisotropy, and to produce stacked sections with a higher signal-to-noise ratio.

[10] We estimate that the final velocity model has an error of about ±5% based on the velocity sensitivity shown in the CIGs (Figure 2). We calculated the error by adding and subtracting increments of 1% to/from the total velocity model, from the seafloor to the décollement to visually determine the maximum departure from perfectly flat gathers. Because the velocity error is lower than the sensitivity of velocity-porosity relationships [e.g., *Hoffman and Tobin*, 2004], the interval velocity model, even when affected by error, is still representative of rock physical properties.

4. Results

[11] Depths to key horizons in our 3-D depth images tie very well to depths of reference horizons at the drill sites. The interval velocity trends obtained from our PSDM work also compare very well with the velocity trends obtained from wireline and LWD logging, and from measurements on core samples (Figures 3–5).

[12] Although the velocities obtained from core samples, wireline, LWD and PSDM show very similar trends, they are characterized by different vertical gradients. The core velocities have lower vertical gradients compared to the PSDM and log velocities. Porosity rebound of the samples is likely responsible for the different core velocity values

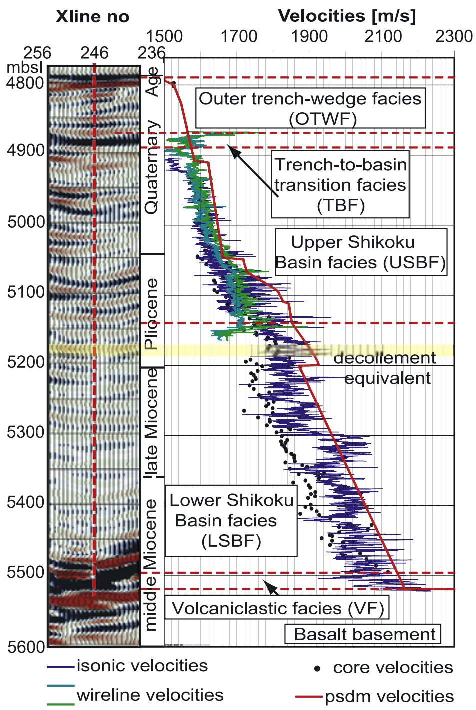

Figure 3. ODP Drill Site 1173: 3-D PSDM section, and comparison of ODP and PSDM velocities.

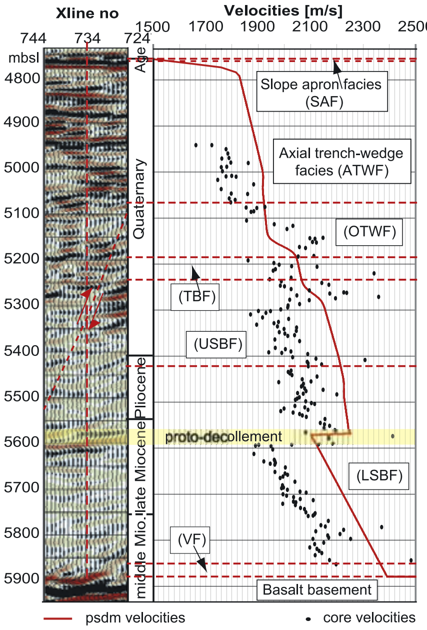

Figure 4. ODP Drill Site 1174: 3-D PSDM section, and comparison of ODP and PSDM velocities.

with respect to those measured "in-situ" and by seismic methods. Other variations can be attributed to rock properties (such as anisotropy), or to sampling bias produced by incomplete core recovery or by not sampling local deformed zones [*Goldberg et al.*, 2005]. The PSDM velocities show a higher vertical gradient at all the drill sites, which can be ascribed to transverse anisotropy [*Shultz*, 1999]. The difference between the vertical gradients of the log and PSDM velocities is, however, very slight. The only anomaly is recorded in the interval of Site 808 located between the seafloor and the top of the USBF (Figure 5). Here, while the interval velocities resemble very well both the wireline velocities and the VSP profile (measured at site 808B and 808E), they are offset about 60–260 m/s with respect to the LWD ISONIC velocities (measured at site 808I). *Goldberg et al.* [2005] have determined the difference between the seismic and the ISONIC velocities recorded in the same interval to be due to transverse anisotropy related with the frontal thrust deformation. In our case, the mismatch of the interval velocities occurs only in approximately the first 400 m of the ISONIC velocity curve, while a good correlation is maintained with the rest of log velocities and the VSP. In addition to the transverse anisotropy also documented by other studies [*Brueckmann et al.*, 1993; *Henry et al.*, 2003], the deformation of the frontal thrust might have differently affected the site where wireline (808B and 808E) and LWD (808I) velocities were measured, with the lower LWD vertical gradient produced by a more highly fractured interval.

[13] The velocities at Site 1173 (Figure 3) increase within the trench turbidites (1525–1580 m/s), the USBF hemipelagic unit (1580–1860 m/s), and the upper part of LSBF hemipelagic unit (1860–1920 m/s), although with different rates for each unit. The average vertical gradient of this upper 400 m interval is ~0.99 s^{-1}. About 50–60 m below the top LSBF, the velocity decreases sharply by about 50–60 m/s. This depth (~5200 mbsl) could be the stratigraphic equivalent of the décollement documented at Sites 1174 (proto-décollement) and 808. Below the interval velocity inversion zone, the P-wave velocity increases with depth again within the rest of the LSBF unit (1870–2160). The velocity trend is a single gradient (0.97 s^{-1}) because this interval does not have any distinctive reflection horizons that would allow a more detailed velocity analysis.

[14] Velocities at Sites 1174 and 808 (Figures 4 and 5) increase within the trench deposits (1525–2060 m/s), the TBF (2060–2140 m/s), the USBF unit (2140–2220 m/s, 824 mbsf), and the top of the LSBF unit (2220–2340 m/s), with the average vertical gradient being equal to 0.87 s^{-1}. Velocities decrease about 100–150 m/s at the décollement. Below the décollement, the velocities again show a normal trend of increase with depth (2340–2500 m/s), but the velocities represent a simple gradient (0.72 s^{-1}). The lateral velocity gradient calculated for the underthrusting section, between Site 1173 and Site 808, is equal to 0.02 s^{-1}. This corresponds to a thinning of the underthrusting sediments of ~10%, occurring in the direction of subduction.

5. Conclusions

[15] We applied targeted 3-D PSDM imaging constrained at three ODP drill sites in the Nankai Trough to achieve a

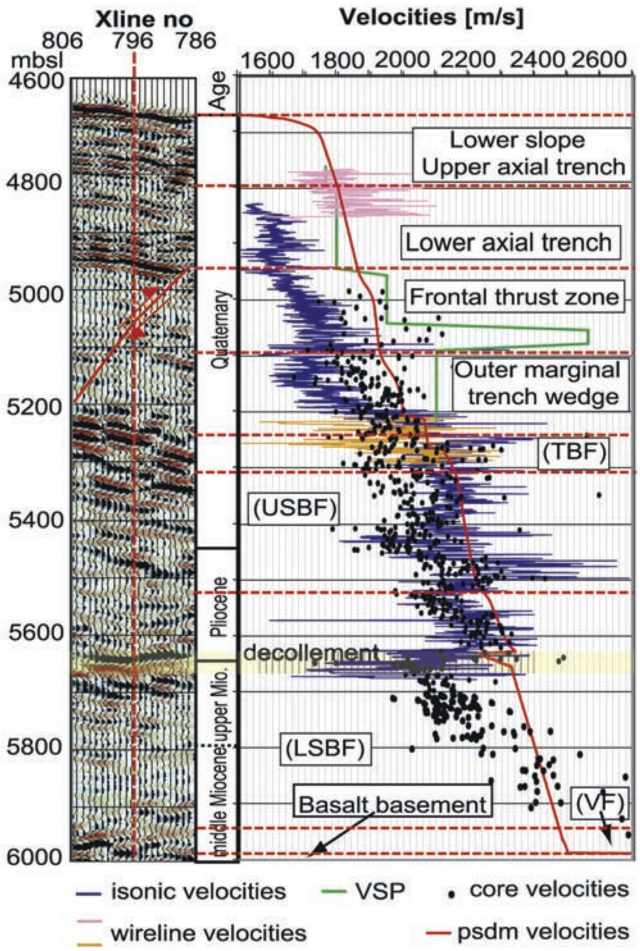

Figure 5. ODP Drill Site 808: 3-D PSDM section, and comparison of ODP and PSDM velocities.

geologically meaningful velocity/depth volume by combining standard PSDM velocity analyses with minimizing the misties between the drill hole depths and the corresponding seismic reflections. Our PSDM velocity gradients compare very well with the drill site logging and core velocities, although there are some differences in the absolute velocity values, inferred to be caused by porosity rebound, transverse anisotropy and local deformation. Hence, the PSDM velocity field can be considered representative of the "in-situ" velocities, and can be used to address rock physical properties and to produce accurate depth images suitable for structural interpretation. The décollement represents a velocity inversion of about 50–150 m/s, yielding the highest impedance contrast in the seismic volume. Above and below the décollement, the velocities increase normally versus depth. In the trench and accretionary prism the vertical gradient decreases landward from 0.99 to 0.87 s^{-1}, and in the underthrusting section the vertical gradient decreases from 0.97 to 0.72 s^{-1}. The lateral velocity gradient in the underthrusting section is 0.02 s^{-1}, corresponding to ~10% landward thinning.

[16] **Acknowledgments.** The 3-D seismic data set was collected with funds from NSF (U.S.) and MEXT (Japan). We used data provided by the Ocean Drilling Program, sponsored by NSF and participating countries under management of JOI, Inc. Funding was provided by NSF grant OCE-0241380 and a grant from the US Science Support Program.

References

Bangs, N. L., T. H. Shipley, S. P. Gulick, G. F. Moore, S. Kuromoto, and Y. Nakamura (2004), Evolution of the Nankai Trough décollement from the trench into the seismogenic zone: Inferences from 3-D seismic reflection imaging, *Geology*, *32*, 273–276.

Brueckmann, W., K. Moran, and E. Taylor (1993), Acoustic anisotropy and microfabric development in accreted sediment from Nankai Trough, *Proc. Ocean Drill. Program Sci. Results*, *131*, 221–233.

Faye, J. P., and J. P. Jeannot (1986), Prestack migration velocities from focusing depth analysis, paper presented at 56th Annual International Meeting, Soc. of Expl. Geophys., Tulsa, Okla.

Goldberg, D., A. Cheng, S. P. S. Gulick, J. Blanch, and J. Byun (2005), Velocity analysis of LWD sonic data in turbidites and hemipelagic sediments offshore Japan, ODP Sites 1173 and 808, *Proc. Ocean Drill. Program Sci. Results, 190/196*, 196SR-352.

Guo, N., and S. Fagin (2002), Becoming effective velocity model builders and depth imagers, part 1—The basics of prestack depth migration, *Leading Edge*, *21*, 1205–1209.

Henry, P., L. Jouniaux, E. J. Screaton, S. Hunze, and D. M. Saffer (2003), Anisotropy of electrical conductivity record of initial strain at the toe of the Nankai accretionary wedge, *J. Geophys. Res.*, *108*(B9), 2407, doi:10.1029/2002JB002287.

Hoffman, N. W., and H. J. Tobin (2004), An empirical relationship between velocity and porosity for underthrust sediments in the Nankai Trough accretionary prisms, *Proc. Ocean Drill. Program Sci. Results, 190/196,* 196SR-355.

Karig, D. E., and C. L. Angevine (1986), Geologic constraints on subduction rates in the Nankai Trough, *Initial Rep. Deep Sea Drill. Proj.*, *87*, 789–796.

Mikada, H., et al. (2002), *Proceedings of the Ocean Drilling Program*, *Initial Reports* [CD-ROM], vol. 196, Ocean Drill. Program, College Station, Tex.

Moore, G. F. (1993), Vertical seismic profile data, Hole 808E, Nankai Trough, *Proc. Ocean Drill. Program Sci. Results*, *131*, 417–423.

Moore, G. F., et al. (2001), *Proceedings of the Ocean Drilling Program*, *Initial Reports* [CD-ROM], vol. 190, Ocean Drill. Program, College Station, Tex.

Moore, G. F., H. Mikada, J. C. Moore, K. Becker, and A. Taira (2005), Legs 190 and 196 synthesis: Deformation and fluid flow processes in the Nankai Trough accretionary prism, *Proc. Ocean Drill. Program Sci. Results, 190/196,* 190SR-201.

Reshef, M. (1991), Prestack depth imaging of three-dimensional shot gathers, *Geophysics*, *56*, 1158–1163.

Reshef, M. (1997), The use of 3-D prestack depth imaging to estimate layer velocities and reflector positioning, *Geophysics*, *62*, 206–210.

Reshef, M. (2001), Some aspects of interval velocity analysis using 3-D depth-migrated gathers, *Geophysics*, *66*, 261–266.

Reshef, M., and D. Kosloff (1986), Migration of Common shot gathers, *Geophysics*, *51*, 324–331.

Seno, T., S. Stein, and A. E. Gripp (1993), A model for the motion of the Philippine Sea Plate consistent with NUVEL-1 and geological data, *J. Geophys. Res.*, *98*, 17,941–17,948.

Shultz, P. (1999), The seismic velocity model as an interpretation asset, 1999 Distinguished Instructor Short Course, Distinguished Instructor Series, 2, Soc. of Explor. Geophys., Tulsa, Okla.

Stoffa, P. L., W. T. Wood, T. H. Shipley, G. F. Moore, E. Nishiyama, M. A. B. Bothelo, A. Taira, H. Tokuyama, and K. Suyehiro (1992), Deepwater high-resolution expanding spread and split spread marine seismic profiles in the Nankai Trough, *J. Geophys. Res.*, *97*, 1687–1713.

Stork, C., and R. W. Clayton (1992), Using constraints to address the instabilities of automated prestack velocity analysis, *Geophys*, *57*, 404–419.

Taira, A., et al. (1991), *Proceedings of the Ocean Drilling Program*, *Initial Reports*, vol. 131, Ocean Drill. Program, College Station, Tex.

G. Moore and P. Costa Pisani, Department of Geology and Geophysics, University of Hawaii, Honolulu, HI 96822, USA. (patrizia@hawaii.edu)

M. Reshef, Department of Geophysics and Planetary Sciences, Tel Aviv University, Ramat Aviv, 69978 Israel.