Origin of bottom-simulating reflectors: Geophysical evidence from the Cascadia accretionary prism

Mary E. MacKay Department of Geology and Geophysics, University of Hawaii, Honolulu, Hawaii 96822
Richard D. Jarrard Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112
Graham K. Westbrook School of Earth Sciences, University of Birmingham, Birmingham B15 2TT, United Kingdom
Roy D. Hyndman Pacific Geoscience Centre, Geological Survey of Canada, Sidney, British Columbia V8L 4B2, Canada
Shipboard Scientific Party of Ocean Drilling Program Leg 146

ABSTRACT

Vertical seismic profile (VSP) data from two drill sites on the Cascadia margin show low-velocity zones, indicative of free gas, beneath a bottom-simulating reflector (BSR). Offshore Oregon, at Ocean Drilling Program (ODP) Site 892, velocities drop from an average of 1750 m/s above the BSR to less than 1250 m/s below it. Sonic logs confirm that seismic velocity in the sediments adjacent to the borehole is less than that of water for at least 50 m beneath the depth of the BSR at this site. Similarly, at ODP Site 889 offshore Vancouver, velocities range from 1700 to 1900 m/s in the 100 m above the BSR and drop abruptly to 1520 m/s in the 15 m just beneath it. The low velocities observed beneath the BSR are strong evidence for the presence of 1%–5% free gas (by volume). The BSR at these two sites results from the contact between gas-free sediments containing a small quantity of hydrate above the BSR and a low-velocity free-gas zone beneath it. Although the BSR is associated with the base of the hydrate stability field, hydrate appears to account for relatively little of the velocity contrast that produces the BSR. Velocity above the BSR at Site 889 is only about 100 m/s greater than that expected for sediments of similar porosity. Sediments above the BSR at Site 892 appear to have normal velocity for their porosity and may contain little hydrate.

INTRODUCTION

Bottom-simulating reflectors (BSRs) broadly mimic the relief of the sea floor and, in many settings, are believed to mark the pressure- and temperature-dependent base of the methane-hydrate stability field (e.g., Shipley et al., 1979; Hyndman et al., 1992). Below this boundary, methane may be present as dissolved or free gas, but not as hydrate. Hydrate is an icelike substance, consisting of gas molecules within a lattice of water molecules, that is formed at high pressure and low temperature. Appropriate *P-T* conditions for methane-hydrate stability are widespread in the shallow sediments of the sea floor of continental margins, and BSRs are commonly observed in seismic reflection data from accretionary prisms (Shipley et al., 1979). Because hydrate may store large quantities of methane, an understanding of the origin of BSRs and the amounts of hydrate or free gas associated with them is important in assessing both their economic potential and their effect on global climate change (Kvenvolden, 1988). BSRs have also been widely used to estimate geothermal heat flow from the *P-T* conditions for hydrate stability, thereby providing constraints on determinations of fluid movements within accretionary prisms (Yamano et al., 1982; Minshull and White, 1989; Davis et al., 1990; and others).

BSRs are typically strong, negative-polarity reflectors. Reflection amplitude can be as great as that of the sea floor, and reflection polarity of BSRs is consistently opposite that of the sea floor, indicating a large decrease in acoustic impedance (velocity × density) below the reflector. In water-saturated sediments, the presence of either hydrate or small amounts of free gas will lower the density slightly. The presence of hydrate increases sediment velocity, although the relation of concentration to velocity is not well known (Stoll, 1974; Pearson et al., 1986); even very small amounts of free gas in a sediment will greatly reduce its velocity (Domenico, 1976). Consequently, the impedance contrast between sediment containing hydrate and sediment containing free gas (or non–hydrate-bearing sediments) is predominantly caused by the change in velocity.

The origin of this velocity contrast, and the relative importance of hydrate vs. free gas in the formation of the BSR, has remained controversial. Models for BSRs have, to date, been based almost exclusively on analysis of surface seismic data. In various locales, the BSR has been interpreted as either the base of a high-velocity layer due to hydrate above the BSR (Hyndman and Davis, 1992) or the top of a low-velocity zone due to free gas beneath the BSR (Bangs et al., 1993; Singh et al., 1993) or a combination of both (Dillon and Paull, 1983; Minshull and White, 1989; Miller et al., 1991). Although Deep Sea Drilling Project (DSDP) and ODP drilling has penetrated BSRs at several sites (Kastner et al., 1991), the rapid dissociation of hydrate and loss of gas during core recovery have thwarted attempts to determine the in situ concentrations of hydrate and free gas. Bangs et al. (1993) presented a partial suite of downhole logs that show good evidence for the presence of free gas despite poor borehole conditions. In this paper, we present velocity measurements from vertical seismic profiles (VSPs) and downhole logs that unambiguously document the presence of a surprisingly thick zone of free gas beneath the BSR.

GEOLOGIC SETTING

During ODP Leg 146 (Westbrook et al., 1993), we obtained in situ velocity measurements from VSPs and downhole logs at two sites that penetrated BSRs in the Cascadia accretionary prism, offshore Oregon and Vancouver Island. Oregon margin Site 892 is situated near the crest of a large ridge ~16 km behind the thrust front, at a water depth of 670 m (MacKay et al., 1992). Multichannel seismic (MCS) data show a strong BSR with few other coherent reflectors (Fig. 1). The site is located in the hanging wall of a minor thrust over which the BSR rises locally, presumably because of the movement of warm fluids along the fault (Moore et al., 1991). The structural and hydrologic setting of the Oregon margin in the vicinity of Site 892 has been examined by means of MCS data, Seabeam bathymetry, GLORIA and SeaMARC 1A side-scan data, and *Alvin* dives (Carson et al., 1991; Moore et al., 1991; MacKay et al., 1992). Nonetheless, the subsurface velocity structure at the site remains poorly determined because of the lack of coherent reflections for use in velocity analysis of the MCS data.

Vancouver margin Site 889 lies on a broad mid-slope terrace at a water depth of 1322 m. A veneer of slope sediment 130 m thick overlies the more deformed accreted sediments at the site (Fig. 1). The BSR is within the accreted sediments at Site 889, but in nearby regions it extends across both prism and slope-basin deposits (Hyndman and Spence, 1992). Based on detailed velocity analyses, estimates of heat flow, and modeling of the BSR, the hydrologic setting at Site 889 was inferred to be dominated by diffuse upward flow of

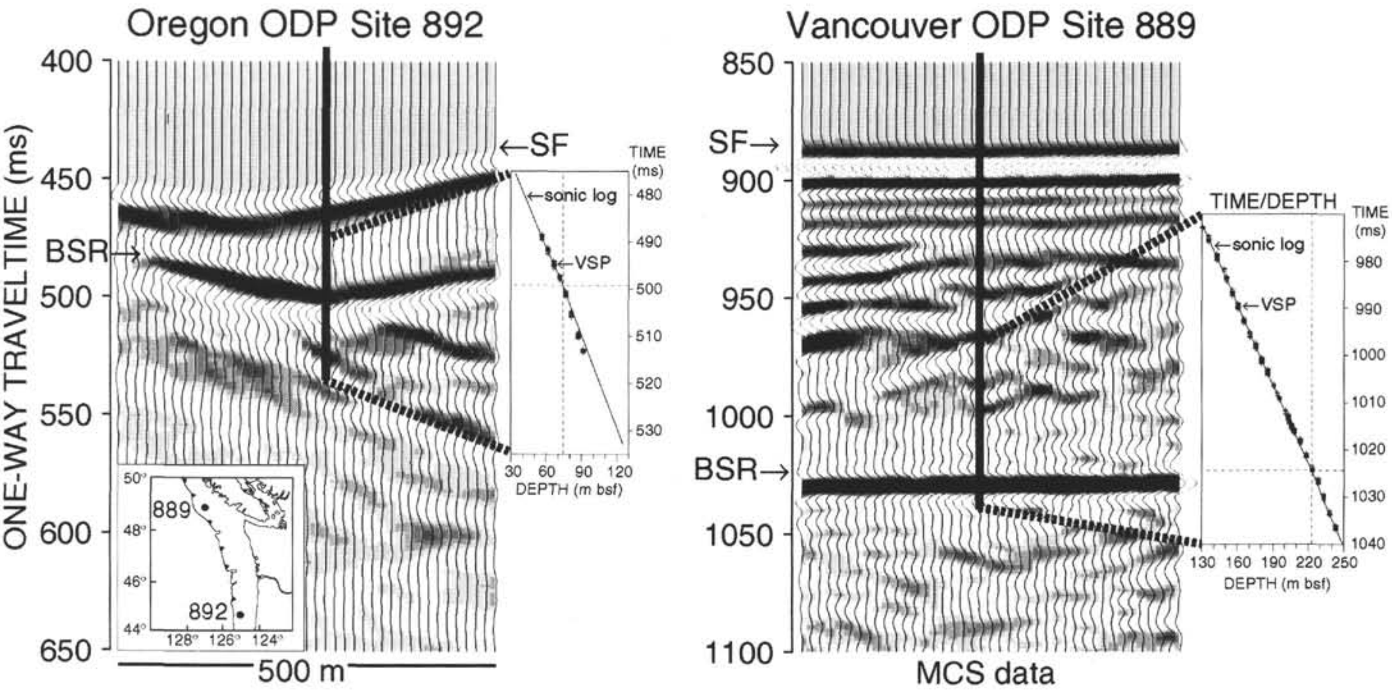

Figure 1. Time/depth relations between vertical seismic profile (VSP) and multichannel seismic (MCS) data. MCS data are plotted in one-way traveltime to correspond to VSP data. SF = sea-floor reflection. BSR = bottom-simulating reflector. MCS amplitudes are displayed as both wiggle traces and gray scale; positive amplitudes are dark, and negative amplitudes are light. Note that BSR has reversed polarity relative to sea-floor reflection. Vertical scale for VSP time vs. depth curve is twice that of MCS data; figures are aligned at time of BSR; depth is given in metres below sea floor (bsf). In graphs, points on line are first-arrival times for VSP data; solid line is integrated sonic-log values; dashed lines represent time vs. depth position of BSR. Inset shows location.

fluids (Davis et al., 1990; Hyndman and Davis, 1992; Hyndman and Spence, 1992), rather than by fault-dominated flow as seen at Site 892.

VSP DATA ACQUISITION AND VELOCITY ANALYSIS

VSP data differ from conventional seismic reflection data in that receivers are located at a series of stations in the borehole while shots are fired at the sea surface (Gal'perin, 1974). In a zero-offset VSP, the source is located almost directly above the borehole. Zero-offset VSPs were shot at Sites 892 and 889 with a 4.9 L airgun and a 6.5 L watergun, fired in alternate series of six to 20 shots at each receiver position, and received downhole by a single vertical-component geophone in a Schlumberger well-seismic tool. At Site 892, eight receiver stations were spaced at 5 m intervals from 56.5 m below sea floor (bsf) to 91.5 m bsf; sonic-log data extend from 34.3 m bsf to 125 m bsf. At Site 889, 23 receiver stations were located from 125.5 m bsf to 243.0 m bsf. Most receiver stations were spaced at 5 m intervals; a few spacings were as close as 2 m or as far apart as 7 m. Sonic-log data extend from 61.7 to 243 m bsf.

VSPs provide a time vs. depth relation from the direct arrival time of the compressional wave at each receiver depth (Fig. 1). The slope of the time-depth curve is the average velocity across a given depth interval. Although most of the VSP data were collected at 5 m receiver spacing, we cannot resolve velocity across such a short interval because of the limits of accuracy in determining time and depth measurements (0.1 ms and 0.1 m, respectively). The velocities shown in Figure 2 are mean values of slope obtained from linear regression of the time-depth values over overlapping 10 to 15 m intervals with an estimated error of ±30 m/s. Velocity was not averaged across the BSR, because the BSR clearly represents a strong discontinuity in both sonic-log and VSP-velocity data.

VELOCITY STRUCTURE OF THE BSR

At Oregon margin Site 892, the BSR lies 499 ms (one-way traveltime) below the sea surface. This traveltime corresponds to a depth of 73.9 m bsf on the time-depth curve (Fig. 1) and is marked by an abrupt downhole decrease in both VSP and sonic-log velocities (Fig. 2). Above the BSR, VSP and sonic-log velocities average 1774 and 1790 m/s, respectively, from 56.6 to 71.5 m bsf. A high-velocity interval seen in the sonic log from 61.5 to 66.5 m bsf has low neutron porosity, high density, and high resistivity (Fig. 2). We interpret the interval as an indurated or cemented zone rather than hydrate, because hydrate has high neutron porosity and low density, opposite to the observed variations. Beneath the BSR, VSP velocity drops to 1250 m/s at 71.5 m bsf, then increases slightly to 1320 m/s over the next 20 m; sonic-log velocity drops to 1510 m/s below 72.5 m bsf.

At Vancouver margin Site 889, the BSR lies 1024.5 ms below the sea surface, which corresponds to a depth of 223.5 m bsf on the time-depth curve (Fig. 1). Above the BSR, VSP and sonic-log velocities generally range from about 1700 to 1900 m/s for the interval from 130 m bsf to the BSR at 224 m bsf, with mean values of 1800 and 1770 m/s, respectively. High-velocity spikes, seen in the sonic log at 190 and 214 m bsf (Fig. 2), are low-porosity, high-resistivity zones, similar to those seen at Site 892. Beneath the BSR, VSP velocity drops abruptly to 1520 m/s for the interval 228–243 m bsf; sonic-log velocity drops by only 150 m/s in the vicinity of the BSR, and it reaches a minimum value of 1630 m/s at 231 m bsf.

Effect of Free Gas on Velocity

Free gas dramatically lowers velocity, particularly in poorly consolidated, high-porosity sediments. Theoretical and laboratory results indicate that as little as 1%–3% free gas can reduce normal sediment velocity to as low as 1200 m/s; further increases in gas

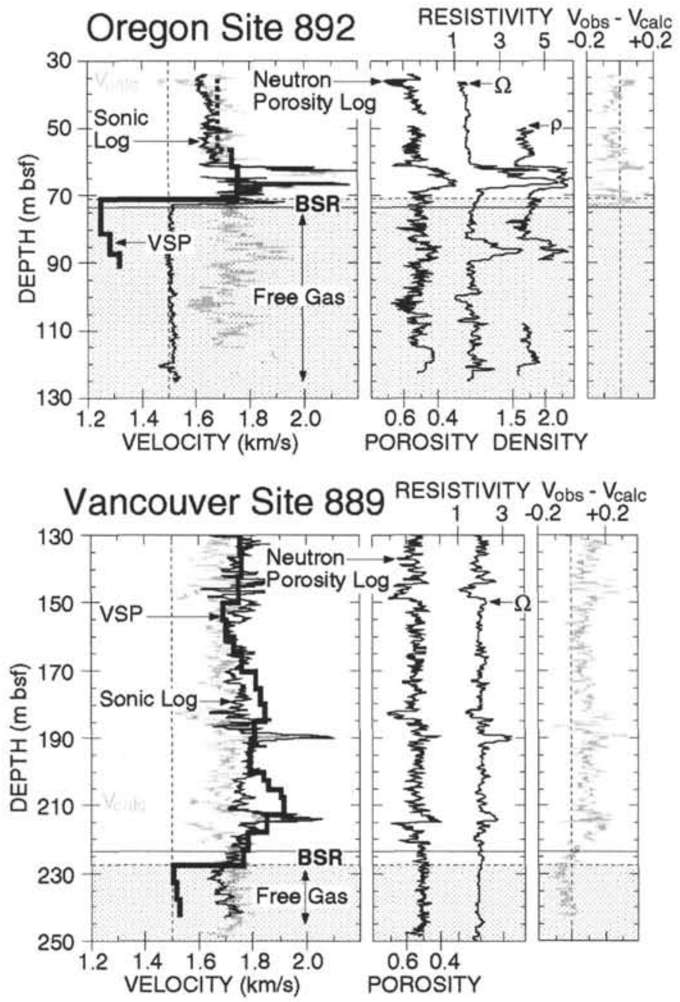

Figure 2. VSP velocity and well logs for ODP Sites 892 (top) and 889 (bottom); depth is given in metres below sea floor (bsf). On each panel, solid horizontal line marks position of BSR observed in MCS data; dashed horizontal line marks velocity drop in VSP data. Stipple indicates low-velocity free-gas region. Note that high-velocity intervals above BSR are low-porosity, high-resistivity "cemented" intervals, rather than high-velocity, low-porosity hydrate. Plots at left show VSP-derived velocity (heavy line), sonic-log velocity (thin line), and V_{calc} (shaded line) estimate of "normal" velocity for sediments of similar porosity. Center plots show neutron-porosity log (solid line), resistivity log (solid line labeled Ω, in ohm · m), and density log (solid line labeled ρ, in g/cm^3) for Site 892 only—no density log is available for Site 889. Increasing values are plotted to right with exception of porosity, which is plotted with high porosity values to left. Plots at right show V_{obs} − V_{calc} (shaded line) estimate of velocity anomaly due to hydrate.

concentration produce very little additional change in velocity (Domenico, 1976). Velocity values near or less than those of water (nominally 1500 m/s), as observed beneath the BSR at Sites 892 and 889, are a strong indication of at least small quantities of free gas (Serra, 1984). In sufficient concentrations, gas will also lower density and increase resistivity. Neither low density nor high resistivity is associated with the low-velocity intervals at Sites 889 and 892, indicating that the concentrations of free gas are low, probably a few percent.

At Site 892 sonic-log velocity beneath the BSR is near-constant at 1510 m/s (Fig. 2), equal to the velocity of sea water in the borehole. The borehole diameter below the BSR was sufficiently small (25–33 cm, except for 33–39 cm interval from 89 to 108 m bsf) to reliably measure formation velocities (Goetz et al., 1979); however, the sonic log cannot measure a formation velocity lower than that of the borehole fluid, indicating that the true formation velocity is less than or roughly equal to the velocity of the borehole fluid. This is strong evidence for free gas in the formation (Goetz et al., 1979; Serra, 1984).

At Site 889, sonic-log velocities decrease beneath the BSR, but are higher than VSP velocities for the same interval (Fig. 2). In gas-bearing sediments, borehole fluids may invade the formation and flush free gas away from the borehole wall; the sonic log thus measures only the high-velocity invaded zone or an intermediate value, depending on the depth of invasion (Serra, 1984). Vigorous downhole circulation of seawater was required at Site 889 to keep the borehole open for logging; if free gas were present in situ, there is a high likelihood that it would be at least partially driven from the near-borehole zone measured by the sonic log. The VSP measures velocity over several tens of metres adjacent to the borehole in contrast to sonic-log penetration of less than 0.3 m. Heterogeneity, whether naturally occurring or resulting from invasion of borehole fluids, will result in sonic-log velocities that differ from those measured by the VSP.

Evidence from Other Logs

Sonic-log velocity shows a strong correlation with both resistivity and neutron-porosity logs above the BSR (Fig. 2). To estimate the effect of hydrate or free gas on the observed velocities, we calculated velocity (V_{calc}) from the neutron-porosity log using the empirical relation of Hyndman et al. (1992), $P = -1.180 + 8.607(1/V) - 17.89(1/V^2) + 13.94(1/V^3)$. This relation provides a reasonable fit to data from the Vancouver reference site, Site 888, and to Site 889 above 130 m bsf; however, scatter of 100 m/s is common in velocity-porosity relations because of variation in lithology and cementation. Areas of anomalously high velocity ($V_{obs} - V_{calc} \gg 0$) indicate possible hydrate presence, whereas anomalously low velocity ($V_{obs} - V_{calc} \ll 0$) indicates the presence of free gas.

At Site 892, sediments above the BSR appear to have a normal velocity-porosity relation (Fig. 2, upper right panel); there is no indication of anomalously high velocity (relative to porosity), and sediments may contain very little hydrate. VSP velocities beneath the BSR at Site 892 are more than 550 m/s slower than would be expected for sediments of similar porosity (Fig. 2, upper left panel, compare VSP to V_{calc}).

At Site 889, sonic-log velocity is about 100 m/s greater than predicted for sediments of similar porosity (Fig. 2, lower right panel) throughout the interval 130–220 m bsf. Although sonic logs for Site 889 do not show extremely low velocity beneath the BSR, their velocity is anomalously low with respect to porosity, indicating some free gas in the invaded zone adjacent to the borehole. VSP velocities beneath the BSR at Site 889 are more than 200 m/s slower than would be expected for sediments of similar porosity (Fig. 2, lower left panel; compare VSP to V_{calc}).

DISCUSSION

Velocity data from the Oregon and Vancouver sites suggest the presence of small concentrations of hydrate, but at neither location does hydrate produce sufficiently high velocity to generate the BSR. Instead, low velocity associated with small quantities (1%–5%) of free gas beneath the BSR produces the strong negative-polarity reflection.

Why Is There Free Gas?

At the Cascadia margin we see no evidence for a massive hydrate layer that might serve as a permeability barrier, as suggested for the Blake Ridge (Dillon and Paull, 1983). If gas were produced in situ, a trapping mechanism would not be required, but the quantity of organic matter beneath most BSRs is probably insufficient to locally create methane supersaturation (Hyndman and Davis, 1992). Alternatively, free gas may form in situ through dissociation of preexisting hydrate (Shipley and Didyk, 1981) if the base of the hydrate stability field moves upward as a result of sedimentation, tectonic uplift, or an increase in subbottom temperatures, all of which have occurred at the Cascadia sites. Depending on the speed with which gas migrates upward following the rise of the hydrate stability field, the BSR may mark a phase boundary across which the concentration of methane varies little. Because of the very strong velocity response to free gas, the negative impedance contrast that generates the BSR requires neither the presence of substantial quantities of hydrate nor a significant difference in concentration of methane across the boundary.

The presence of free gas without any apparent permeability barrier suggests a system of low upward mobility. Partial filling of cracks by hydrate may reduce the permeability, but the most probable reason for the "trapped" gas is its low concentration. For free-gas concentrations of only a few percent, gas permeability is at least three orders of magnitude less than the permeability of the formation water (Honarpour et al. 1986). Consequently, at low concentrations the gas will tend to move with the pore water rather than through it.

Where Is the "Base of Gas" Reflection?

An important question that remains unanswered is why, in Cascadia and elsewhere, we do not see a reflection from the base of the free-gas zone. It has normally been assumed that if free gas were present beneath the BSR, it must be a thin layer, less than 10 m thick, in order to not be resolved seismically. Data presented here, however, show low-velocity free-gas zones at least 50 m thick off Oregon, and at least 15 m thick off Vancouver; neither appears to produce a reflection from the base of the gas zone. Although this issue remains unresolved, our data conclusively demonstrate that the lack of a "base of gas" reflection does not reliably preclude the presence of free gas beneath the BSR.

CONCLUSIONS

The recognition that the BSR marks the *P*- and *T*-dependent base of the methane stability field, as well as the recovery of hydrates above the BSR, may have biased our perception of the role of hydrate in the formation of BSRs. Data presented here support a conceptual model of the BSR that is quite different from existing hydrate-focused models. In areas such as Cascadia, where small amounts of hydrate have a negligible effect on velocity, the BSR is more accurately envisioned as the *P*- and *T*-dependent phase boundary marking the top of a free-gas zone.

ACKNOWLEDGMENTS

Postcruise science support was received from U.S. Science Advisory Committee. In addition, MacKay received support from National Science Foundation grant OCE-9115924, Society of Exploration Geophysicists Scholarship Foundation, and the Honolulu Chapter of the American Association of University Women. We thank B. Appelgate, G. Moore, T. Shipley, A. Shor, B. Taylor, and W. Dillon for helpful reviews. Special thanks to the many fine technical support personnel of Ocean Drilling Program Leg 146. School of Ocean and Earth Science and Technology contribution 3506.

REFERENCES CITED

Bangs, N.L., Sawyer, D.S., and Golovchenko, X., 1993, Free gas at the base of the gas hydrate zone in the vicinity of the Chile triple junction: Geology, v. 21, p. 905–908.

Carson, B., Holmes, M.L., Umstattd, K., Strasser, J.C., and Johnson, H.P., 1991, Fluid expulsion from the Cascadia accretionary prism: Evidence from porosity distribution, direct measurements, and GLORIA imagery: Royal Society of London Philosophical Transactions, v. 335, p. 331–340.

Davis, E.E., Hyndman, R.D., and Villinger, H., 1990, Rates of fluid expulsion across the northern Cascadia accretionary prism: Constraints from new heat flow and multichannel seismic reflection data: Journal of Geophysical Research, v. 95, p. 8869–8889.

Dillon, W.P., and Paull, C.K., 1983, Marine gas hydrates—II: Geophysical evidence, *in* Cox, J.L., ed., Natural gas hydrates: Properties, occurrence and recovery: Boston, Butterworth, p. 73–90.

Domenico, S.N., 1976, Effect of brine-gas mixture on velocity in an unconsolidated sand reservoir: Geophysics, v. 41, p. 882–894.

Gal'perin, E.I., 1974, Vertical seismic profiling: Society of Exploration Geophysicists Special Publication 12, 270 p.

Goetz, J.F., Dupal, L., and Bowler, J., 1979, An investigation into the discrepancies between sonic log and seismic check shot velocities: APEA Journal, v. 19, p. 131–141.

Honarpour, M., Koederitz, L., and Harvey, A.H., 1986, Relative permeability of petroleum reservoirs: Boca Raton, Florida, CRC Press, 143 p.

Hyndman, R.D., and Davis, E.E., 1992, A mechanism for the formation of methane hydrate and sea floor bottom-simulating reflectors by vertical fluid expulsion: Journal of Geophysical Research, v. 97, p. 7025–7041.

Hyndman, R.D., and Spence, G.D., 1992, A seismic study of methane hydrate marine bottom simulating reflectors: Journal of Geophysical Research, v. 95, p. 6683–6698.

Hyndman, R.D., Foucher, J.P., Yamamo, M., Fisher, A., and Shipboard Scientific Party of Ocean Drilling Program Leg 131, 1992, Deep sea bottom-simulating-reflectors: Calibration of the base of the hydrate stability field as used for heat flow estimates: Earth and Planetary Science Letters, v. 109, p. 289–301.

Kastner, M., Elderfield, H., and Martin, J.B., 1991, Fluids in convergent margins: What do we know about their composition, origin, role in diagenesis and importance for oceanic chemical fluxes?: Royal Society of London Philosophical Transactions, v. 335, p. 243–259.

Kvenvolden, K.A., 1988, Methane hydrate—A major reservoir of carbon in the shallow geosphere?: Chemical Geology, v. 71, p. 41–51.

MacKay, M.E., Moore, G.F., Cochrane, G.R., Moore, J.C., and Kulm, L.D., 1992, Landward vergence and oblique structural trends in the Oregon margin accretionary prism: Implications and effect on fluid flow: Earth and Planetary Science Letters, v. 109, p. 477–491.

Miller, J.J., Lee, M.W., and von Huene, R., 1991, An analysis of a seismic reflection from the base of a gas hydrate zone, offshore Peru: American Association of Petroleum Geologists Bulletin, v. 75, p. 910–924.

Minshull, T., and White, R., 1989, Sediment compaction and fluid migration in the Makran accretionary prism: Journal of Geophysical Research, v. 94, p. 7387–7402.

Moore, J.C., Brown, K.M., Horath, F., Cochrane, G., and MacKay, M., 1991, Plumbing accretionary prisms: Effects of permeability variations: Royal Society of London Philosophical Transactions, v. 335, p. 275–288.

Pearson, C., Murphy, J., and Hermes, R., 1986, Acoustic and resistivity measurements on rock samples containing tetrahydrofuran hydrates: Laboratory analogue to natural gas hydrate deposits: Journal of Geophysical Research, v. 91, p. 14,132–14,138.

Serra, O., 1984, Fundamentals of well-log interpretation. 1. The acquisition of logging data: Amsterdam, Elsevier, 423 p.

Shipley, T.H., and Didyk, B.M., 1981, Occurrence of methane hydrate offshore southern Mexico, *in* Initial reports of the Deep Sea Drilling Project, Volume 66: Washington, D.C., U.S. Government Printing Office, p. 547–555.

Shipley, T.H., Houston M.H., Buffler, R.T., Shaub, F.J., McMillen, K.J., Ladd, J.W., and Worzel, J.L., 1979, Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises: American Association of Petroleum Geologists Bulletin, v. 63, p. 2204–2213.

Singh, S.C., Minshull, T.A., and Spence, G.D., 1993, Velocity structure of a gas-hydrate reflector: Science, v. 260, p. 204–207.

Stoll, R.D., 1974, Effects of gas hydrates in sediments, *in* Kaplan, I.R., ed., Natural gases in marine sediments: New York, Plenum, p. 235–247.

Westbrook, G., Carson, B., Musgrave, R., and Shipboard Scientific Party, 1993, Initial reports of the Ocean Drilling Program, Volume: 146 (pt. 1): College Station, Texas, 630 p.

Yamano, M.S., Uyeda, S., Aoki, Y., and Shipley, T.H., 1982, Estimates of heat flow derived from gas hydrates: Geology, v. 10, p. 339–343.

Manuscript received October 14, 1993
Revised manuscript received January 24, 1994
Manuscript accepted January 26, 1994