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25. GRAPHIC SUMMARY OF GAS HYDRATE OCCURRENCE BY PROXY MEASUREMENTS ACROSS THE BLAKE RIDGE, SITES 994, 995, AND 997[1]

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INTRODUCTION

Although the occurrence of gas hydrate is perceived to be extensive in sediments of the Blake Ridge, recovery proved to be difficult during the coring efforts of the Ocean Drilling Program (ODP) Leg 164. With the exception of Site 996, an area of methane gas venting, gas hydrate recovery from core material was limited to only three cores. To understand the occurrence of gas hydrate in this environment, a collection of direct and indirect measurements of sediments was made.

Figure 1 (back-pocket foldout, this volume) summarizes some important measurements and observations pertaining to gas hydrate occurrence at Sites 994, 995, and 997. These sites comprise a transect of holes that penetrate below the base of gas hydrate stability within the same stratigraphic interval over a relatively short distance (9.6 km). A bottom-simulating reflection (BSR) is not observed at Site 994, a modest BSR occurs at Site 995, and a strong BSR is seen at Site 997. An account of the seismic line, USGS 95-1, can be found in Dillon et al. (1996).

GRAPH CONSTRUCTION

The presentation (Fig. 1) gives an overview of how each of these measurements fits together as a function of depth rather than to provide a precise comparison of data.

The single channel seismic depth section USGS 95-1 showing the Site 994–997 transect is the background. On the seismic section three principal features are present: sediment horizon reflections within the upper section, the area of seismic blanking below, and the BSR. Each downhole measurement was graphed, and then scaled to the depth scale on the seismic section. Relative scales for each measurement are given in the legend and as an absolute scale on the seismic section above or below each measurement. Each measurement and their significance are briefly described below. A more detailed description of each measurement and their implications regarding gas hydrate occurrence can be found in the Leg 164 *Initial Reports* (Paull, Matsumoto, Wallace, et al., 1996).

DESCRIPTION OF MEASUREMENTS

Downhole Logging

The quality of the log measurements were described by shipboard scientists at Sites 994 and 997 as significantly degraded by the size and rugosity of the borehole, whereas the log measurements at Site 995 were described as moderately degraded. Borehole conditions were especially degraded at Site 997 below the BSR, resulting in large-scale shifts in the electrical resistivity log. Despite poor borehole conditions, downhole logging along the transect did define areas of gas hydrate accumulation and free gas below the BSR. Three logs are plotted on the seismic section; electrical resistivity, acoustic velocity, and sediment porosity.

Electrical resistivity at each site was logged by a phasor dual induction–spherically focused resistivity tool. Because gas hydrate is an electrical insulator, the resistivity of gas hydrate and gas hydrate–bearing sediment is higher than that of surrounding sediment. The contrast is sharpest in sediments that contain salty water, such as marine sediments. Acoustic velocity well logs can be used to measure the amount of gas hydrate within a drilled sedimentary unit. On Leg 164 this measurement was done with a long-spaced sonic tool. Because gas hydrate has a high compressional velocity, the measured acoustic velocity increases where gas hydrate occurs. Conversely, acoustic velocity decreases where free gas bubbles exist, clearly seen below the BSR at Site 995.

Electrical resistivity and acoustic velocity well logs, when used together (Paull, Matsumoto, Wallace, et al., 1996) clearly show occurrences of gas hydrate in this transect. For example, at Site 994 two spike-shaped large-scale increases in electrical resistivity and acoustic velocity occur between about 220 and 250 mbsf (use internal depth scale for reference). Using this relationship, clear stratigraphic horizons of gas hydrate–rich sediments can be traced from Site 994 to 995, and possibly to Site 997.

Sediment Porosity

Sediment porosity curves were plotted from measurements made directly from the cores as described in the "Explanatory Notes" chapter of the Leg 164 *Initial Reports* (Paull, Matsumoto, Wallace, et al., 1996).

Vertical Seismic Profiles

Leg 164 vertical seismic profiles (VSPs) were acquired at all three sites, and the details of the experiment with results are found in Holbrook et al. (1996). VSPs accurately measure the seismic velocity of sediments and sharply delineate sediment containing free gas relative to sediment containing nonfree gas. These relationships are clearly visible when plotted on the seismic section, because the occurrence of seismic velocity drops dramatically below the BSR at Sites 995 and 997. Interpretations of where zones of free gas–containing sediment occur are made based primarily on VSP data and secondarily on acoustic velocity.

Adara and WSTP Temperature Measurements

In situ temperature measurements were made to depths as great as ~415 mbsf on the Blake Ridge in part to determine the gas hydrate stability field boundary. The measurements were made primarily by the Adara temperature tool and, in deeper sediment, by the water-

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sampling temperature and pressure tool (WSTP). Details of these experiments can be found in the Leg 164 *Initial Reports* (Paull, Matsumoto, Wallace, et al., 1996). One of the primary conclusions of these studies is that there is a discrepancy between the observed BSR and predicted base of gas hydrate stability (BGHS; Paull, Matsumoto, Wallace, et al., 1996). Our present understanding assumes that these horizons should be equivalent. The discrepancy between the BSR and the predicted BGHS is not only offset by at least 50 m; it is also quite variable between sites. Ruppel (1997) suggested the discrepancy may be due to capillary effects in pore spaces that inhibit gas hydrate formation.

Pore-Water Chlorinity Measurements

Gas hydrate decomposition during core recovery releases water and methane into the interstitial pores, resulting in a freshening of the pore water. The general chloride profile may represent a combination of several processes; however, the negative spikes of chloride concentrations can best be explained as artifacts of gas hydrate decomposition during core recovery. The relative amplitudes of the chloride anomalies are proportional to the amount of gas hydrate that dissociated within the sample during core recovery. In some cases, chlorinity spikes can be correlated from site to site.

In Situ Methane Concentration Measurements

During Leg 164, a pressure coring system tool was deployed several times, in part to measure in situ concentrations of methane. The results, compiled by Dickens et al. (1997), are reproduced in between Sites 995 and 997. A line denoting methane concentration at saturation for the range of depths is given as a reference. The maximum concentration occurs at the level of the BSR where free gas is trapped beneath gas hydrate–bearing sediment.

DIRECT OBSERVATIONS OF CORE MATERIAL

Most of the gas hydrate at the Blake Ridge probably occurs mainly as disseminated crystals in pore spaces, which likely dissociated before cores were processed on deck. Other less frequent occurrences included vein-filling or possibly fault-filling massive gas hydrate. Gas hydrate sampled from cores was likely limited to these types of gas hydrate habits. Two indirect measurements of gas hydrate dissociation were made on core material: (1) excess water from gas hydrate dissociation leaves affected core material with a texture that has been described as "soupy" (Westbrook et al., 1994), and (2) core temperature anomalies result from the endothermic reaction of gas hydrate dissociation, described in detail in the Leg 164 *Initial Reports* volume (Paull, Matsumoto, Wallace, et al., 1996). Each of these observations is mapped on the chart, and Table 1 lists gas hydrate occurrence with depth, along with other gas hydrate indicators in sediment.

Temperature anomalies can be caused by other factors, such as adiabatic expansion of gas within the core, whereas "soupy" sediment is likely to have been the direct result of gas hydrate dissociation, provided that proper core handling procedures were followed.

INTERPRETATIVE HORIZONS

Gas Hydrate

Gas hydrate appears to occur as traceable stratigraphic horizons between sites as denoted by a combination of downhole logging measurements, seismic structure (BSR), and chlorinity anomalies. Other site-localized gas hydrate indicators from direct observations are also suggested but do not continue to other sites. Recovered gas hydrate occurrences cannot be correlated from site to site. At Site 997, a massive gas hydrate vein was interpreted to be a near-vertical fault-filling feature and is depicted as a steeply dipping feature.

Gas hydrate is thought to occur wholly within the interval of about 180–460 mbsf based on shipboard data; however, two occurrences of soupy sediment documented in the core photos suggest that gas hydrate may have been present (Sections 164-994C-4H-5 through 7, 29.8–32.9 mbsf, and Section 164-997B-15P-1, 501.0 mbsf). Both suspected gas hydrate occurrences are found within the measured gas hydrate stability field but outside the interval of about 180–460 mbsf, as determined by the shipboard scientists (Paull, Matsumoto, Wallace, et al., 1996). If these cores did contain gas hydrate, then the area of gas hydrate occurrences can be expanded to the 30–501 mbsf interval and could significantly increase gas hydrate mass estimates of the Blake Ridge.

REFERENCES

Dickens, G.R., Paull, C.K., and Wallace, P., 1997. Direct measurement of in situ methane quantities in a large gas-hydrate reservoir. *Nature,* 385:426–428.

Dillon, W.P., Hutchinson, D. R., and Drury, R.M., 1996. Seismic reflection profiles on the Blake Ridge near Sites 994, 995, and 997. *In* Paull, C.K., Matsumoto, R., Wallace, P.J., et al., *Proc. ODP, Init. Repts.,* 164: College Station, TX (Ocean Drilling Program), 47–56.

Holbrook, W.S., Hoskins, H., Wood, W.T., Stephen, R.A., Lizzarralde, D., and the Leg 164 Science Party, 1996. Methane gas-hydrate and free gas on the Blake Ridge from vertical seismic profiling. *Science,* 273:1840–1843.

Paull, C.K., Matsumoto, R., Wallace, P.J., et al., 1996. *Proc. ODP, Init. Repts.,* 164: College Station, TX (Ocean Drilling Program).

Ruppel, C., 1997. Anomalously cold temperatures observed at the base of the gas hydrate stability zone on the U.S. Atlantic passive margin. *Geology*, 25:699–702.

Westbrook, G.K., Carson, B., Musgrave, R.J., et al., 1994. *Proc. ODP, Init. Repts.,* 146 (Pt. 1): College Station, TX (Ocean Drilling Program).

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Table 1. Summary of Leg 164 gas hydrate proxy measurements in sediment cores.

Hole	Core	Section	Interval (cm)	Depth (mbsf)	Gas hydrate indicator
994C	4H	5-7*	90; 70*	29.8-32.9	S (core photo)
994C	22X	5	70-80	180.1	S (core photo)
994C	31X	7	10-50	260.1	Recovered hydrate 10-cm thick
994C	32X	1	0-25	261.1	S
994C	36P	1	0-23	300.0	S (core photo)
994D	8X	2	65-105	398.3	TA
994C	53P	1	0-5	434.1	S (core photo)
994C	63X	6	130-150	591.0	TA
995A	27P	1	0-100	225.5	PCS gas, S, Cl^-
995A	29X	1	60-70	233.7	TA
995A	29X	1	135-140	234.5	TA
995A	29X	2	13-17	234.7	TA
995A	30X	1	60-110	243.3	TA
995A	32X	1	133-150	263.3	TA (frozen sediment, S)
995A	36P	1	15-40	300.6	S (core photo), Cl^-
995B	10P	1	0-68	319.9	S (core photo), Cl^-
995A	45P	1	0-60	376.5	PCS gas
995B	11X	4	15	414.5	Small wafer of gas hydrate
995A	54X	CC	0-20	444.9	TA
997A	25P	1	0-78	202.9	S
997A	28X	CC	0-26	231.3	TA
997A	29X	2	0-10	234.3	TA
997A	32X	4	255-256.5	256.0	TA
997A	42X	3	330-331.1	330.6	Massive hydrate, S, TA, Cl^-
997A	49P	1	0-50	395.4	S
997A	51P	1	0-20	404.9	S
997B	6P	1	0-26	433.6	S (core photo)
997A	55P	1	0-40	433.8	S
997B	11X	1-5		463-472	TA (below BSR) attributed to gas expansion
997B	12X	1-4		472-482	TA (below BSR) attributed to gas expansion
997B	13X	1-4		482-491	TA (below BSR) attributed to gas expansion
997B	15P	1	0-10	501.0	S (core photo)
997B	16X	1-7		501-510	TA (below BSR) attributed to gas expansion

Notes: Interval depths given at the interval start unless otherwise noted. * = for Core 4H, measurements were taken from Section 5, 90 cm, through Section 7, 70 cm. S = soupy sediments noted in notebooks or, where indicated, in core photos; TA = core temperature anomaly (much colder than surrounding sediment or frozen, as noted); PCS gas = pressure coring system methane saturation within gas hydrate–stability field; Cl^- = chlorinity anomaly; BSR = bottom-simulating reflection.