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THIRD PARTY BOREHOLE SEISMIC EXPERIMENTS DURING THE OCEAN DRILLING PROGRAM

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Abstract

Third party borehole seismic experiments on the Ocean Drilling Program began with an Oblique Seismic Experiment at Site 418 in the Western Atlantic south of Bermuda on Leg 102. The experiment confirmed the velocity structure of upper Layer 2 including Azimuthal anisotropy and azimuth dependent scattering. A normal incidence VSP was run in Hole 735B on Leg 118 on the Southwest Indian Ridge. This experiment measured velocities corresponding to Layer 3 which was consistent with the gabbroic petrology of the cores. Anomalously high attenuation was also observed which prompted the hypothesis that the gabbro cored may not actually represent the bulk of Layer 3 material. The VSP data acquired at Hole 504B in the eastern equatorial Pacific on Leg 148 helped to constrain the velocity-depth structure at the site and showed that upper Layer 3 at this site, at a depth of over 2km into the crust, did not consist of gabbros but rather consisted of the lower portions of the sheeted dykes. Both offset and normal incidence VSP_s were run on Leg 164 to study the seismic velocity structure of gas hydrates on the Blake Ridge. A new innovation on ODP was the deployment of broadband seismometers in boreholes. Whereas the conventional VSP_s mentioned above operate in the frequency range from 1 to 100Hz, broadband seismometers are used in earthquake seismology and operate in the frequency range from 0.001 to 10Hz. The first broadband seismometer test was carried out from the drill ship on Leg 128 in the Japan Sea. Subsequently four permanent broadband borehole seismic observatories were installed in the Western Pacific and Japan Trench on Legs 186, 191 and 195. The ODP era also saw the development of systems for re-entering boreholes from conventional research vessels and submersibles after the drill ship left the site. Borehole seismic experiments and installations that used this wireline re-entry technology were carried out in DSDP Holes 534 (Blake-Bahama Basin) and 396 (Mid-Atlantic Ridge at 23degrees north) and ODP Hole 843B (south of Oahu). The latter experiment (the Ocean Seismic Network Pilot Experiment) carried out a test of three configurations of broadband seafloor seismic installation in preparation for extending the Global Seismic Network to the deep ocean. The author would like to thank the Earthquake Research Institute at the University of Tokyo for a six-month Visiting Professorship during which this synthesis was carried out.

1. Introduction

The first borehole seismic experiments on DSDP and ODP were two-ship Oblique Seismic Experiments (Figure 1) *[Stephen, 1979; Stephen et al., 1979; Stephen et al., 1980; Swift et al., 1988]*. By recording on the drill ship and shooting explosives out to ranges of 8km, the upper 1.5km of the upper crust (Layer 2) adjacent to the borehole could be imaged (Figure 2) *[Stephen and Harding, 1983]*. Azimuthal anisotropy *[Shearer and Orcutt, 1985; Stephen, 1981; Stephen, 1985]* and lateral heterogeneity [Stephen, 1988; Swift and Stephen, 1989] could also be studied by shooting circles of shots at a fixed range from the borehole. The direct wave from the shot to the top of the borehole decays exponentially with depth (Figure 3) and is called the "Direct Wave Root".

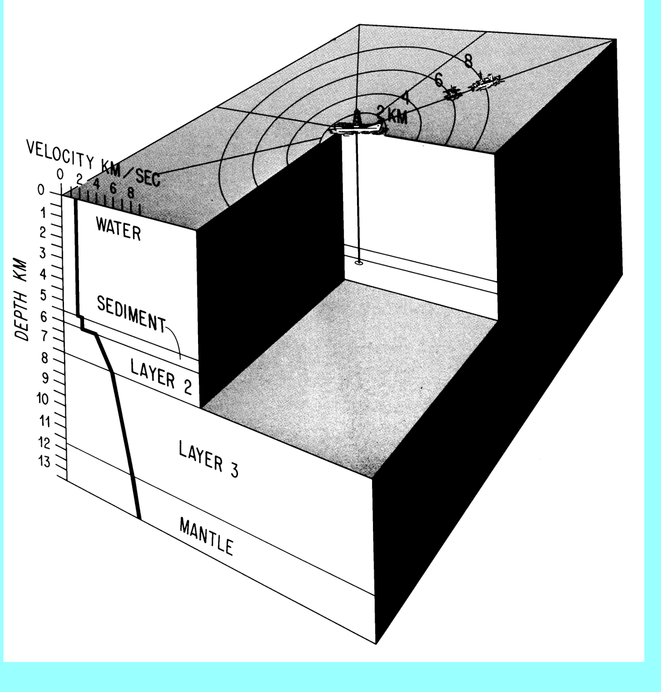

Figure 1: : In an Oblique Seismic Experiment the drill ship maintains its position over the borehole and monitors the downhole geophone while a shooting ship sails concentric circles and radial lines. A generalized oceanic crustal structure and velocity-depth function are shown. *[Little and Stephen, 1985]*

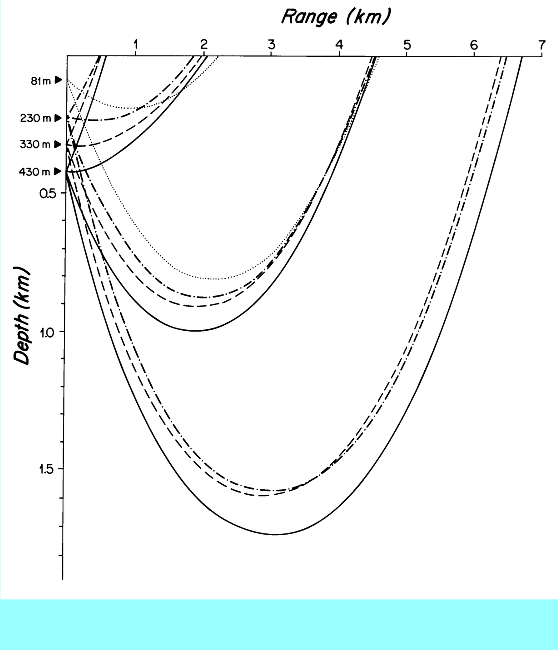

Figure 2: Rays traced through a typical velocity model for the upper oceanic crust are shown for just below the seafloor. The sources of the ray paths are near the sea surface in a 5.6km deep ocean at ranges of 2, 4, 6, and 8km. *[Swift et al., 1988]*

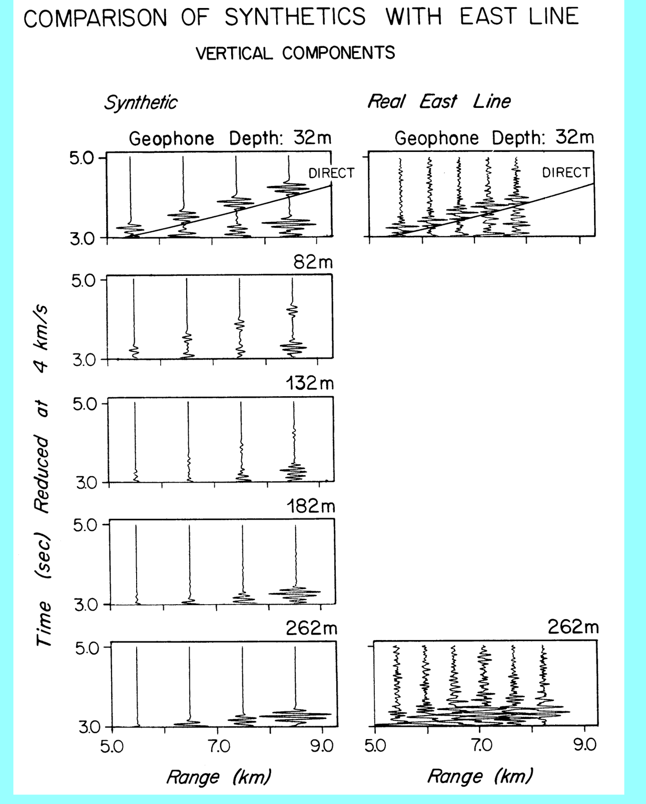

Figure 3: The evanescent behavior of the "direct wave root" is shown here on field data (at 32 and 262m into basement) and on synthetic seismograms. *[Stephen and Bolmer, 1985]*

2. Western Atlantic South of Bermuda (DSDP Hole 418, Leg 102)

Third party borehole seismic experiments on the Ocean Drilling Program began with an Oblique Seismic Experiment at Site 418 in the Western Atlantic south of Bermuda on Leg 102. The experiment confirmed the velocity structure of upper Layer 2 including Azimuthal anisotropy and azimuth dependent scattering (Figures 4 to 7). It is interesting to note that travel-time and amplitude data from two Oblique Seismic Experiments on 110ma crust in the slow-spreading western North Atlantic and fast-spreading Northwestern Pacific shows that compressional velocities within layer 2 are, within experimental error, identical *[Kong et al., 1985]*.

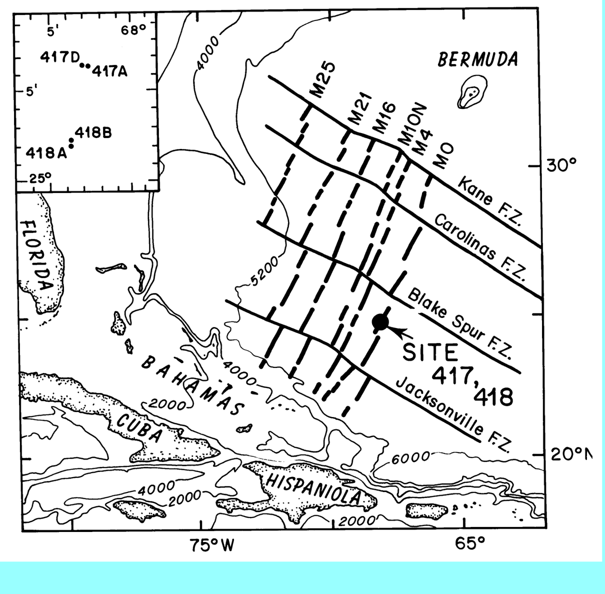

Figure 4: The first borehole seismic experiments on ODP were carried out at Sites 417 and 418 on Leg 102. *[Swift and Stephen, 1989]*

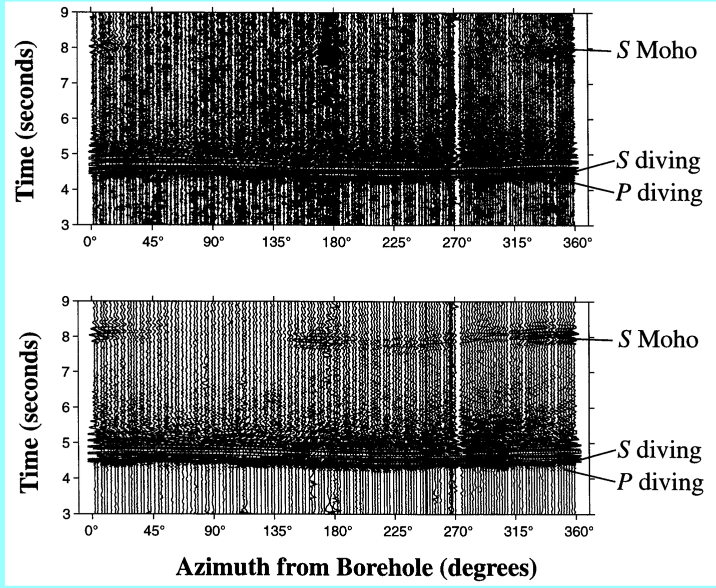

Figure 5: Raw (a) and filtered (b) data from the vertical channel at receiver depth 230m for the 4km airgun circle shot during ODP Leg 102. High frequency noise seen in the raw data (a) is most likely due to pipe banging in the borehole, the drill ship maneuvering during recording intervals, and/or debris falling down the borehole. Bandpass filtered data (b) have been processed using a Butterworth filter at 2 and 20Hz. *[Dougherty et al., 1995]*

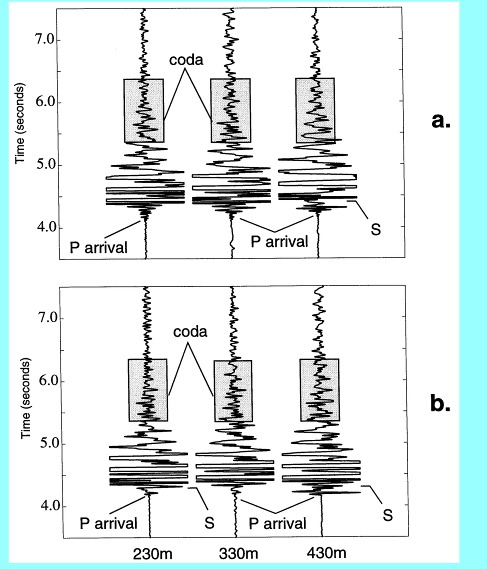

Figure 6: The coda after the principal P and S waves is caused by scattering from roughness and heterogeneity near the seafloor. Vertical channel data are compared for receivers at 230, 330, and 430m below the seafloor at azimuths parallel (a) and perpendicular (b) to the spreading direction. A summary of the Azimuthal dependence of the coda amplitude is given in Figure 7. *[Dougherty et al., 1995]*

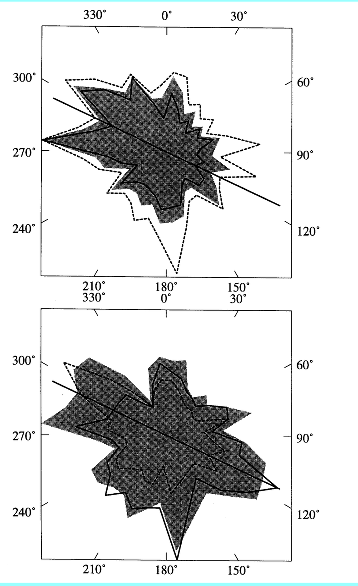

Figure 7: Polar plots of coda energy for receiver depths of 230m (a) and 430m (b). The solid line with azimuth of 295degrees indicates the spreading direction at the site based on magnetic lineations. In (a) the solid gray area, solid line and dashed line indicate different lengths of the coda window used (1.0, 0.5 and 1.5 sec respectively). In (b) the solid gray area, solid line and dashed line indicate the effects of the start time of the coda window after the S arrival (1.1, 0.8, and 1.4 sec respectively). *[Dougherty et al., 1995]*

3. Southwest Indian Ridge (Hole 735B, Leg 118)

Normal incidence VSP's [Balch and Lee, 1984] were carried out on ODP Legs 104, 109 and 111 *[Leg 88 Shipboard Scientific Party, 1987b; Leg 109 Shipboard Scientific Party, 1988]* before the VSP at Hole 735B on Leg 118 on the Southwest Indian Ridge. This experiment measured velocities corresponding to Layer 3 which was consistent with the gabbroic petrology of the cores. Anomalously high attenuation was also observed which prompted the hypothesis that the gabbro cored may not actually represent the bulk of Layer 3 material (Figures 8 to 10)..

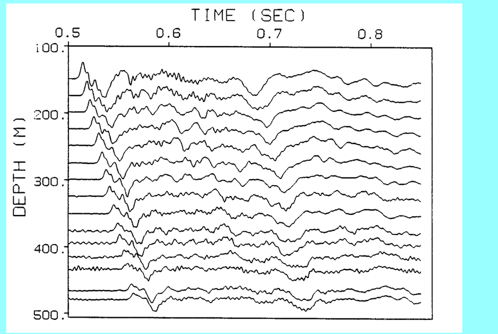

Figure 8: VSP seismograms collected at Hole 735B using a 1000 cubic inch airgun and a vertical component geophone. Depths in the borehole are given in meters below the seafloor; no sediments were found at Site 735. The seismograms were filtered to pass energy less than 250Hz; signal-to-noise ratios are 5-15dB in the 5-90Hz band. The small, upward deflection at about 25ms after the first arrival is an out-of-plane reflection - possibly from the hull of the drilling ship. The data have been corrected for gain changes and spherical attenuation, so the decay in amplitude with borehole depth is due solely to attenuation. The loss of high frequency energy in the initial 50ms over just 350m (less than a wavelength at 10Hz) can clearly be seen. *[Swift et al., 1991; Swift and Stephen, 1992]*

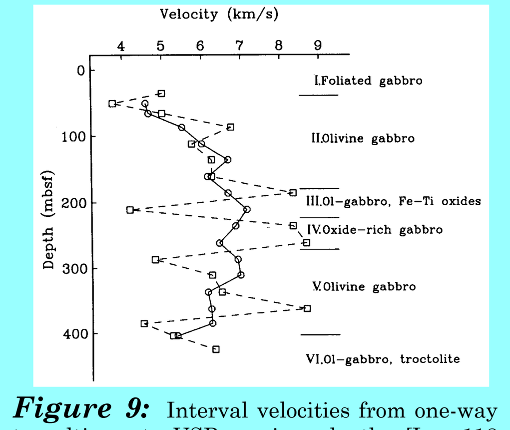

Figure 9: Interval velocities from one-way traveltimes to VSP receiver depths [Leg 118 Shipboard Scientific Party, 1989]. The dashed line connecting the squares represents raw velocities, which are sensitive to small subjective errors in the selection of seismic arrivals. The solid line connecting the circles indicates velocities after smoothing by a five-point moving average and is a more reliable indication of seismic velocity. The numbered annotations are the lithologic units drilled. *[Swift et al., 1991]*

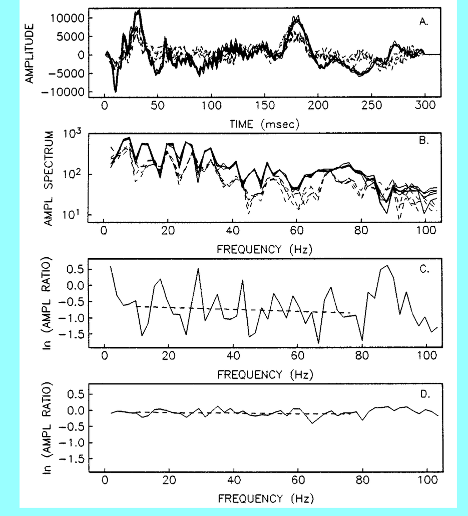

Figure 10: This is an example of the spectral ratio method used to infer Q from the data in Figure 8. (a) Solid lines are five traces obtained at 149mbsf; dashed lines are four traces obtained at 434m. The travel time to the first arrival has been removed and the trace truncated at a length of 0.3sec with a cosine taper. Note the decrease in amplitude of the primary pulse and the bubble pulse at about 180ms. (b) Spectra of the nine traces in (a) using the same line styles. Spectra at each depth are stacked before computing the amplitude ratios. (c) The dashed line is the linear regression fit to the amplitude ratios between 10 and 75Hz. Q is determined from the slope of the amplitude ratios as a function of frequency *[Hauge, 1981]*. The regression gives a Q of 46. (d) The stack of the spectral ratios obtained from 13 receiver pairs has a linear regression fit corresponding to a Q of 26. *[Swift and Stephen, 1992]*

4. Argo Abyssal Plain (Hole 765, Leg 123)

In thick sedimentary sequences VSP's can be very useful in correlating the drilling results with the seismic reflection profiling results. This was demonstrated on ODP Leg 123 which drilled in the Argo Abyssal Plain (Figure 11) *[Leg 123 Shipboard Scientific Party, 1990a; Leg 123 Shipboard Scientific Party, 1990b]*. VSP's were also carried out on ODP Legs 127/128, 129, 131 and 146 *[Hirata et al., 1992; Leg 123 Shipboard Scientific Party, 1990a; Leg 123 Shipboard Scientific Party, 1990b; Leg 131 Shipboard Scientific Party, 1991a; Leg 131 Shipboard Scientific Party, 1991b; Leg 146 Shipboard Scientific Party, 1994a; Leg 146 Shipboard Scientific Party, 1994b; Leg 146 Shipboard Scientific Party, 1994c; Leg 146 Shipboard Scientific Party, 1994d; Leg 148 Shipboard Scientific Party, 1993a; Leg 148 Shipboard Scientific Party, 1993b; Moore, 1993; Shinohara et al., 1992]*

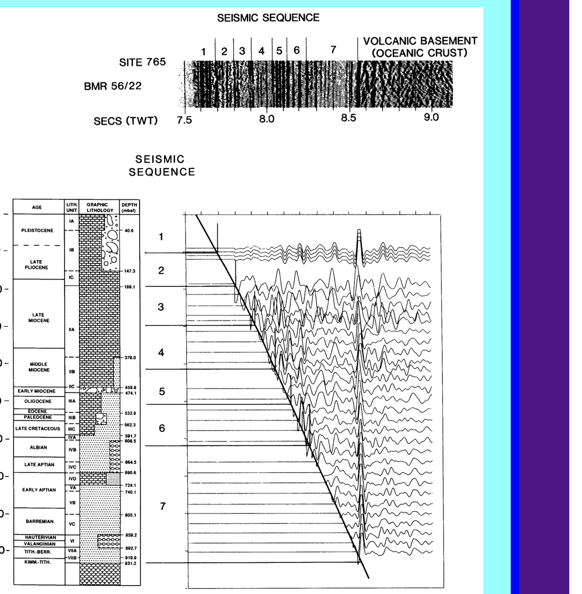

Figure 11: The Leg 123 VSP data was processed by separating the total field into separate upgoing and downgoing wavefields. This figure shows the upgoing wavefield for an airgun source. The processing revealed additional reflections in the sedimentary section between 8.25 and 8.55 sec and a sub-basement reflector at 8.86sec. The traces between 90 and 150mbsf are a stack of the deconvolved VSP data (traveltimes are for two-way propagation.) The VSP section can be used to correlate the BMR seismic reflection line (top) with the drilling results (left side). The seismic sequences are numbered. *[Bolmer et al., 1992]*

5. Costa Rica Rift (Hole 504B, Legs 111 and 148)

The VSP data acquired at Hole 504B in the eastern equatorial Pacific on Leg 148 helped to constrain the velocity-depth structure at the site *[Leg 109 Shipboard Scientific Party, 1988; Leg 148 Shipboard Scientific Party, 1993a; Leg 148 Shipboard Scientific Party, 1993b; Swift et al., 1996; Swift et al., 1998a; Swift et al., 1998b]* and showed that upper Layer 3 at this site, at a depth of over 2km into the crust, did not consist of gabbros but rather consisted of the lower portions of the sheeted dykes (Figure 12) *[Detrick et al., 1993]*. VSP's were also carried out on Leg 156 *[Leg 156 Shipboard Scientific Party, 1995a; Leg 156 Shipboard Scientific Party, 1995b; Leg 156 Shipboard Scientific Party, 1995c]*.

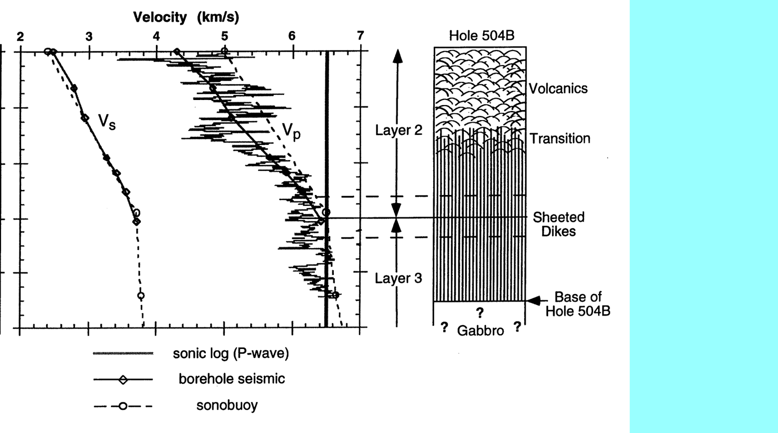

Figure 12: The variation in bulk resistivity downhole derived from logging in Hole 504B, the crustal velocity structure at the site, and the lithostratigraphy. The crustal velocity model is based on a Layer 3 velocity of 6.5km/sac derived from sonobuoy studies around Hole 504B (vertical bar) and a linear regression of the shallow crustal velocity gradient determined from travel-time and amplitude modeling of the borehole seismic experiment (thick solid line). For comparison, the thin grey line shows the sonic velocity log and the dashed line shows the sonobuoy velocity model. The change in the vertical velocity gradient that defines the seismic layer 2/3 boundary at 1.2+/-0.2km sub-basement, occurs within the sheeted-dyke section, about 660m above the base of the hole. At least the upper 400-800m of seismic layer 3 consists of dolerites and metadolerites rather than gabbro. *[Detrick et al., 1993]*

6. Gas Hydrates on the Blake Ridge (Holes 994, 995 and 997, Leg 164)

Both offset and normal incidence VSPs were run on Leg 164 to study the seismic velocity structure of gas hydrates on the Blake Ridge, offshore South Carolina (Figure 13 and 14). Seismic velocities measured in three drill holes through the gas hydrate deposit indicate that substantial free gas exists to at least 250meters beneath the bottom-simulating reflector (BSR) (Figure 15). Both methane hydrate and free gas exist even where a clear BSR is absent. The low reflectance, or blanking, above the BSR is caused by lithologic homogeneity of the sediments rather than by hydrate cementation. *[Holbrook et al., 1996; Leg 164 Shipboard Scientific Party, 1996a; Leg 164 Shipboard Scientific Party, 1996b; Leg 164 Shipboard Scientific Party, 1996c; Leg 164 Shipboard Scientific Party, 1996d]*

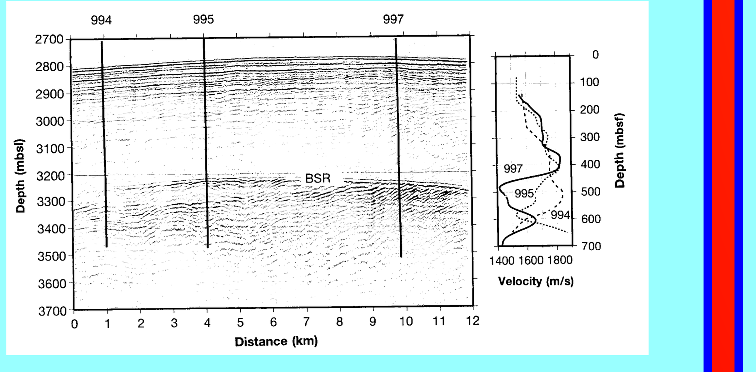

Figure 14: The positions of the three boreholes are shown on the single channel seismic data on the Blake Ridge (left). The depths were converted from travel-time inversion of the vertical seismic profile data (right). Two highly reflective zones are observed: one at 0 to 150mbsf and the other at and beneath the BSR at 3220 to 3250mbsl. *[Holbrook et al., 1996]*

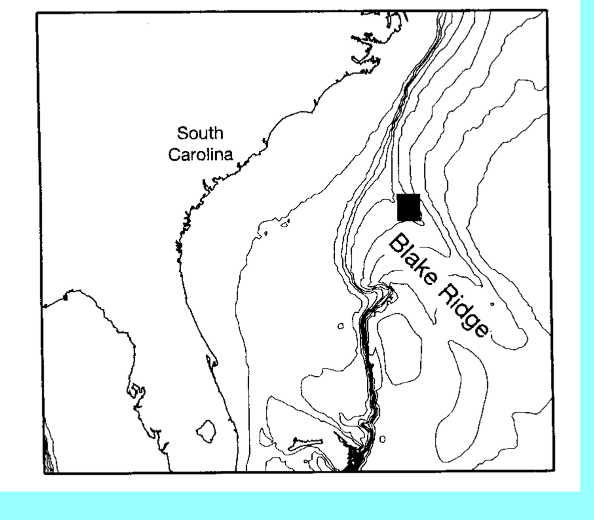

Figure 13: Location of ODP Leg 164 on the Blake Ridge. *[Holbrook et al., 1996]*

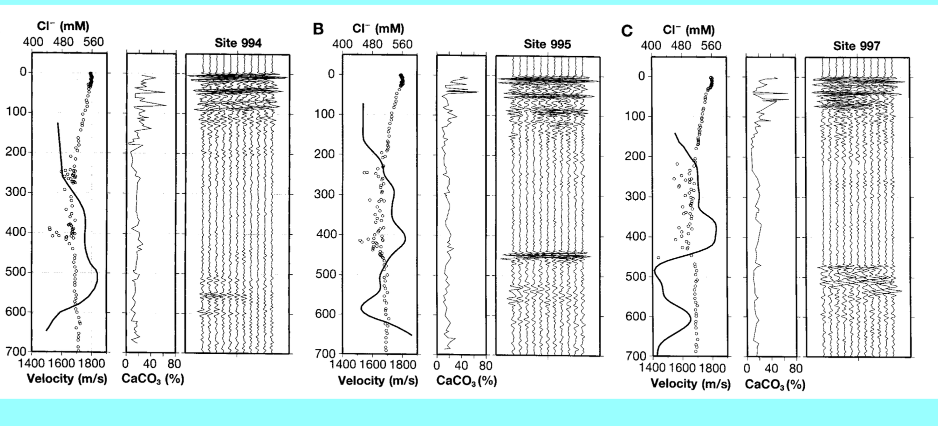

Figure 15: The seismic velocities from VSP's, the chlorinity, and the CaCO3 content are compared with the vertical-incidence seismic reflection data from (A) Site 1994, (B) Site 995 and (C) Site 97. Anomalous chlorinity values indicate that methane hydrate is present between 220 and 450mbsf at all three sites. Seismic reflections correlate with vertical lithological changes in the upper 150mbsf and with low seismic velocities indicative of free gas (bright spots) beneath the hydrate stability zone. The low reflectance above the BSR is the expected response of lithologically uniform sediments. *[Holbrook et al., 1996]*

7. Seismology with the Wireline Re-entry System

The ODP era also saw the development of systems for re-entering boreholes from conventional research vessels (Figure 16) and submersibles after the drill ship left the site *[Legrand et al., 1989; Montagner et al., 1994a; Spiess et al., 1992]*. Borehole seismic experiments and installations that used this wireline re-entry technology were carried out in DSDP Holes 534 (Blake-Bahama Basin) *[Bradley et al., 1997; Stephen et al., 1994]* and 396 (Mid-Atlantic Ridge at 23degrees north) *[Montagner et al., 1994a]* and ODP Hole 843B (south of Oahu) *[Collins et al., 2001; Dziewonski et al., 1992; Stephen et al., 2003; Sutherland et al., submitted]*. The latter experiment (the Ocean Seismic Network Pilot Experiment) carried out a test of three configurations of broadband seafloor seismic installation in preparation for extending the Global Seismic Network to the deep ocean.

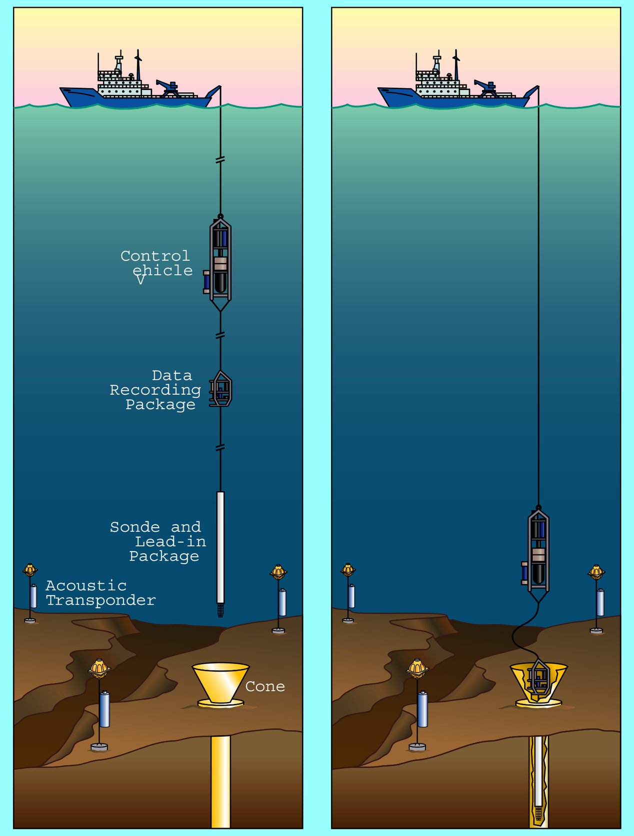

Figure 16: In the Wireline Re-entry System a borehole sonde, data recording package and control vehicle are suspended from a conventional research vessel on co-axial or fibre-optic cable (left). The control vehicle, navigated within a network of acoustic transponders, is used to guide the sonde into the borehole. The sonde is lowered into the borehole until the data recording package lands in the re-entry cone (right). When the seafloor and subseafloor systems are operating properly the control vehicle is disconnected from the data recording package and is recovered back onboard the ship. The borehole system acquires data autonomously for up to a year until the system is recovered by grappling. *[Spiess et al., 1992]*

8. Broadband Borehole Seismology

A new innovation on ODP was the deployment of broadband seismometers in boreholes. Whereas the conventional VSPs and offset VSPs mentioned above operate in the frequency range from 1 to 100Hz (similar to the band used for reflection and refraction seismology), broadband seismometers are used in earthquake seismology and operate in the frequency range from 0.001 to 10Hz. The first broadband borehole seismometer test was carried out from the drill ship on Leg 128 in the Japan Sea in the 1989 *[Kanazawa et al., 1992; Suyehiro et al., 1992]*. The first submersible assisted broadband borehole seismometer test was carried out on the Mid-Atlantic Ridge *[Montagner et al., 1994a; Montagner et al., 1994b]*. On the Ocean Seismic Network Pilot Experiment a broadband borehole sensor in ODP Hole 843B [*Dziewonski et al., 1992]* was compared with a shallow buried and a seafloor seismometer for a period of over three months (Figure 17) *[Collins et al., 2001; Stephen et al., 2003; Sutherland et al., submitted]*. Subsequently four permanent broadband borehole seismic observatories were installed in the Western Pacific and Japan Trench on Legs 186, 191 and 195 *[Araki, 1999; Suyehiro et al., 2002]*. Three other boreholes have been drilled specifically for borehole seismic installations: at the Ninety-east Ridge (Leg 179), near the Hawaii-2 Observatory (Leg 200), and in the equatorial Pacific (Leg 203).

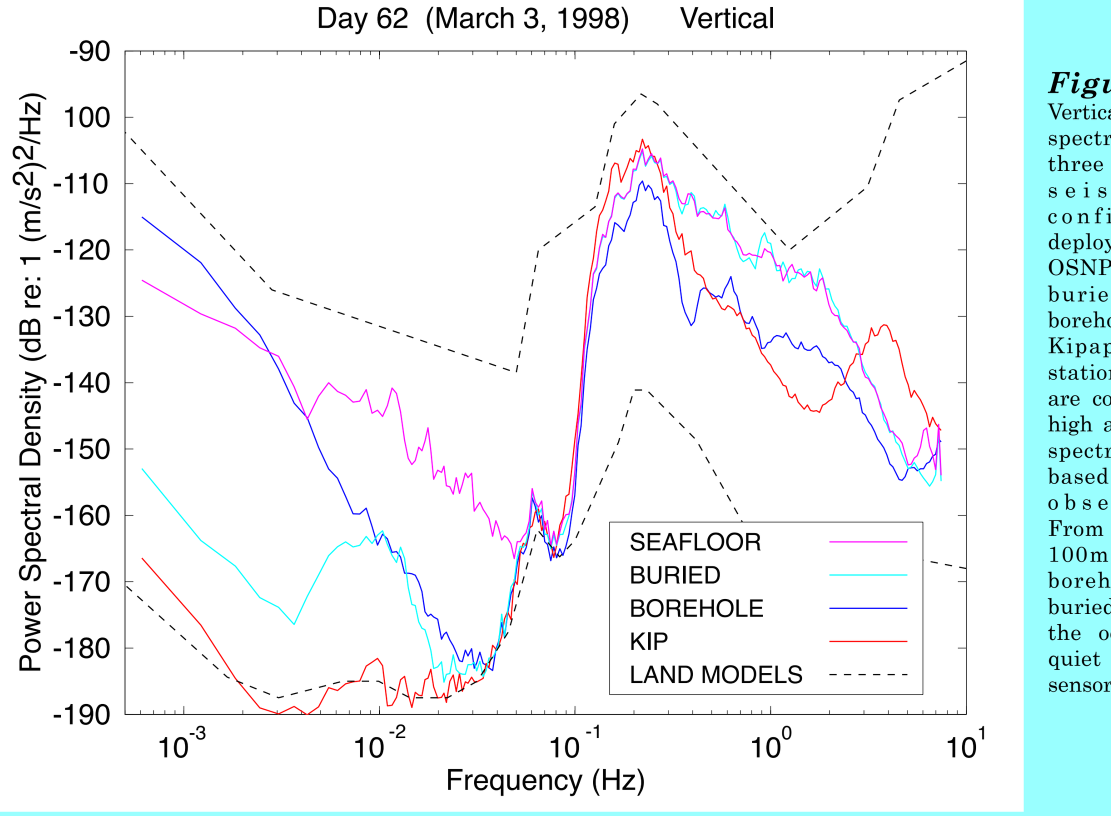

Figure 17: Vertical component spectra for the three broadband seismometer configurations deployed on the OSNPE (seafloor, buried and borehole) and the Kipapa GSN station on Oahu are compared with high and low noise spectral models based on land observations. From 20mHz to 100mHz the borehole and buried sensors in the ocean are as quiet as any land sensor.

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